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GROUP VIII

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VOLUME 2

## Materials

SUBVOLUME C

Metal Forming Data

Part 3

Non-ferrous Alloys - Heavy Metals

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Volume 2C

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Hans Warlimont  
Editor

# Materials

Subvolume C

Metal Forming Data – Part 3, Non-Ferrous Alloys – Heavy  
Metals

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# Preface

Design, planning and processing of deformation technologies rest upon profound knowledge of material behaviour during deformation, on specific types of the technical facilities considered as well as on the interactions between deformed material and equipment. Special knowledge of the material parameters is the pre-condition for every new development. This general statement is independent of whether the work pertains to experimental investigations or to numerical simulation. The latter shows an increasing application both in research as in practice. It describes the real processes the better, the more precise the response of the material, the processes at the interface between the material and the tool, and the material and the technical facilities, respectively, can be characterised. This includes the deformation behaviour (including flow curves), plasticity, physical material parameters and last but not least the mechanical properties. Thus, the deformation behaviour is affected by process and material related parameters and can be reflected by mathematical models only if these parameters are introduced as precisely as possible.

Specifically, the present volume „Metal Forming Data“ is treating the deformation behaviour of light metals in theory and practice. The basic principles are presented in a compact form. The chapter „modelling“ pays special attention to numerical simulation processes. Many examples demonstrate the technical applications. In particular, the variety of light metals discussed and the comparison of international standards emphasise the relevance of the book as a compendium both for scientists and researchers as well as for engineers in metallurgical plants.

The description of the deformation behaviour, of physical and mechanical properties (including specific characteristics) as a data bank comprising about 85 light metals is an invaluable pool of data for the user of numerical simulation and deformation processes. It is based on the long lasting continuous research work carried out at the Institute for Metal Forming of the Technical University Bergakademie Freiberg, which is highly appreciated and accepted by national and international experts. Moreover, it is based on extensive literature studies and on a computational treatment known as the “Freiberg-Model“ world-wide.

The book is addressed to students and scientists as well as to engineers in metallurgical plants and in plant engineering.

Freiberg  
September 2007

Prof. Dr.-Ing. Prof. E.h. R. Kawalla



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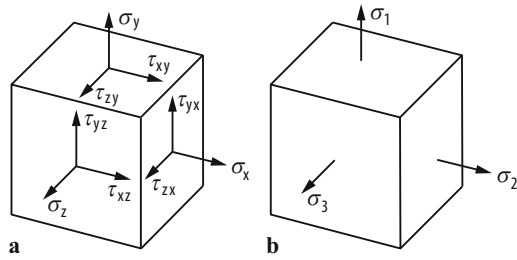
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# Deformation behavior of non-ferrous alloys and its measurement

## 1 Definitions and test methods

### 1.1 Flow stress

For a precise characterisation of deformation processes the mechanical stresses occurring in the deformation zone are allocated to the directions of a triaxial special coordinate system. In each of the directions, which are oriented at right angles to each other, stress components occur in the section plane: one normal stress  $\sigma$  and two shear stresses  $\tau$ , which are at right angles to each other (Fig. 1.1a).



**Fig. 1.1** (a) Normal stresses  $\sigma$  and shear stresses  $\tau$  in any position of a coordinate system. (b) Main stresses in a coordinate system, whose axes are parallel to the main axes

If in the usual manner the coordinate axes are placed parallel to the directions of the highest normal stresses, the stress state can be described by the parameters of the normal stresses  $\sigma_1, \sigma_2, \sigma_3$  alone, which are named principal stresses now (Fig. 1.1b), because the values of the shear stresses are zero. According to their values in this system the stresses are named from positive (tensile stresses) to negative (compression stress). According to the material flow hypotheses of Tresca, plastic flow, in other words the beginning of the deformation process, occurs, when a particular critical difference (stress gap) between the highest and the lowest principal stress ( $\sigma_1 > \sigma_2 > \sigma_3$ ) is exceeded [1.1]:

$$\sigma_1 - \sigma_3 = \sigma_F \quad (1.1)$$

$\sigma_F$  is called flow stress. It is a material parameter, which is decisive in deformation processes. Tresca's flow criterion states, that it is irrelevant, whether the plastic flow is caused by compression or tensile stresses, as long as the stress  $\sigma_F$  is exceeded.

The influence of the mean principal stress  $\sigma_F$  is not considered. However, according to investigations by Lode [1.2], v. Mises [1.3], Roš and Eichinger [1.4] such an influence does exist in reality. It is incorporated into the deformation energy hypotheses.

According to von Mises [1.3], Huber [1.5] and Hencky [1.6] the flow stress  $\sigma_F$  is then given by:

$$\sigma_F = \sqrt{\frac{1}{2} \left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2) \right]}. \quad (1.2)$$

If converted to the principal normal stresses  $\sigma_1, \sigma_2$  and  $\sigma_3$  it follows [1.3] that

$$\sigma_F = \sqrt{\frac{1}{2} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]}. \quad (1.2a)$$

Lode considered the influence of the mean principal normal stress  $\sigma_2$  by the equation [1.2, 1.7]



$$n_\gamma \sigma_F = \sigma_1 - \sigma_3, \quad (1.3)$$

with  $n_\gamma$  as an auxiliary parameter

$$n_\gamma = \frac{2}{\sqrt{3 + v^2}}, \quad (1.4)$$

which includes the influence of the mean principal normal stress  $\sigma_2$  by

$$v = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3} = \pm \frac{\sigma_2 - \frac{\sigma_1 + \sigma_3}{2}}{\frac{\sigma_1 - \sigma_3}{2}}. \quad (1.5)$$

At a uniaxial stress  $v$  has the value  $\pm 1.00$  (flow condition according to Tresca). If the mean principal stress  $\sigma_2$  has a value which is median between  $\sigma_1$  and  $\sigma_3$ , then it is  $n_\gamma = 1.155$ , which complies with the flow condition after von Mises.

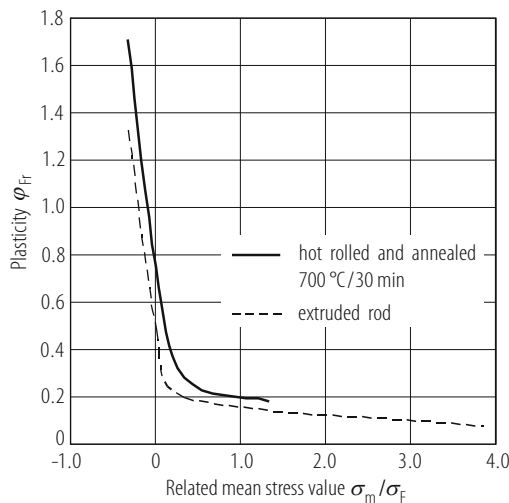
For hot and cold strip rolling it was found, that the mean principal stress  $\sigma_2$  is the arithmetic mean of the two other principal stresses  $\sigma_1$  and  $\sigma_3$ . Thus the flow stress has a value of  $1.155 \sigma_F = \sigma_1 - \sigma_3$ .

## 1.2 Plasticity

The forming process requires plastic behaviour of the material, namely the ability to change its form under the influence of external forces – which generate stresses inside the material – in a plastically adequate amount, without damaging the material cohesion, i.e. the formation of cracks.

At high plastic deformation this ability can be exhausted for further plastic deformation. The critical degree of deformation at which first cracks appear is termed  $\varphi_{Fr}$ .

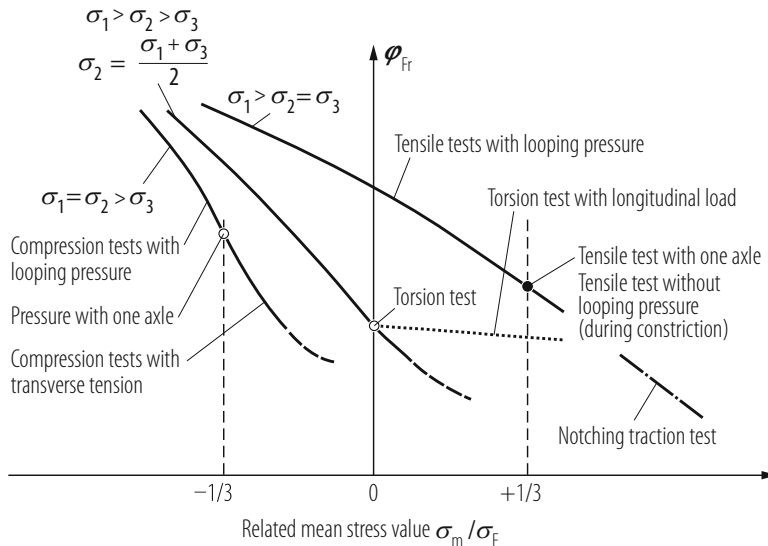
The material specific plasticity is determined by the deformation conditions, i.e. temperature, deformation rate and the residual hardening of the material after a preceding deformation process. In contrast to the flow stress  $\sigma_F$  the plasticity  $\varphi_{Fr}$  depends strongly on the stress state (Fig. 1.2). In Fig. 1.2a the dependence of the plasticity at fracture at room temperature on the stress-related mean stress value for two states of the material AgNi80/20 is applied. The different stress values were adjusted by means of the compression, torsion, tensile and notched tensile test (for an explanation of the test methodology, see 1.4). It is characteristic for both material states to be very sensitive to tensile stress. The highest absolute values of plasticity can be found for the annealed condition, and the lowest for the extruded state. The associated heat treatment improves the formability of an extruded rod to wire. After hot rolling at high temperatures it approaches the state of the annealed material.



**Fig. 1.2a** Forming limit diagram of AgNi 80/20. Specimen diameter: 7.0 mm, room temperature

The dependence of the plasticity on the related value of the mean stress is also determined by the ratio of the three principal stresses. The further the intermediate mean normal stress  $\sigma_m = 1/3(\sigma_1 + \sigma_2 + \sigma_3)$  lies in the pressure range, the higher the formability.

In cold forming the distribution of the total deformation on the single passes affects the plasticity  $\varphi_F$ . This should be noticed especially for brittle materials, if high degrees of deformation, which are near the plasticity limits, have to be realised. In such cases longitudinal or transverse cracks can appear (Fig. 1.2b).



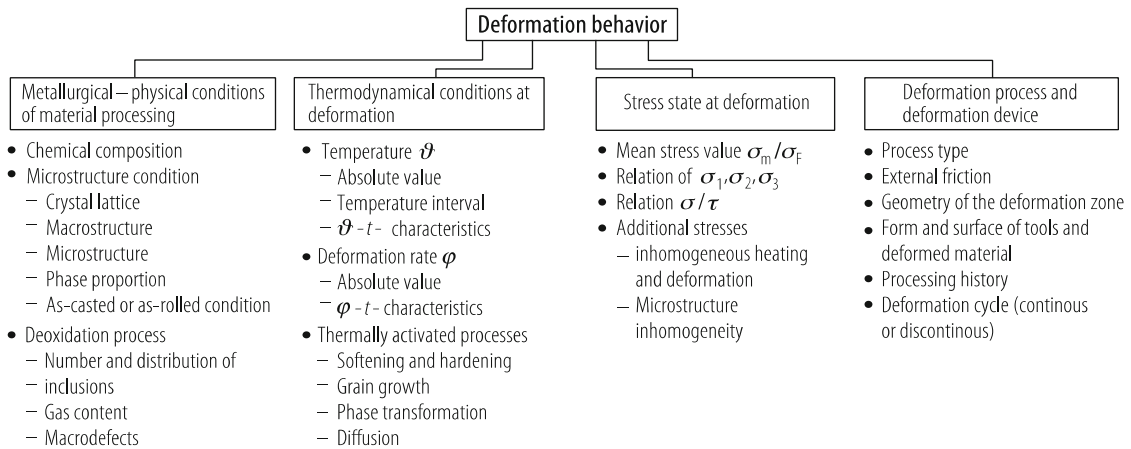
**Fig. 1.2b** Influence of the type of loading on the plasticity in correlation to the related mean stress value  $\sigma_m/\sigma_F$  [1.8]

### 1.3 Deformation behaviour

No explicit definition exists for the term deformation behaviour. It is understood as the material behaviour upon plastic deformation. In general a material is well formable if it is able to change its geometric form without forming cracks at low stress, has an even and precise surface and has a high yield and long durability.

Figure 1.3 gives an overview of the parameters which determine the forming behaviour of a material. In principle these can be divided into four groups:

- metallurgical-physical conditions of material processing,
- thermodynamic conditions during forming,
- stress state upon forming and
- forming process and forming device.



**Fig. 1.3** Parameters that influence the Deformation behaviour.

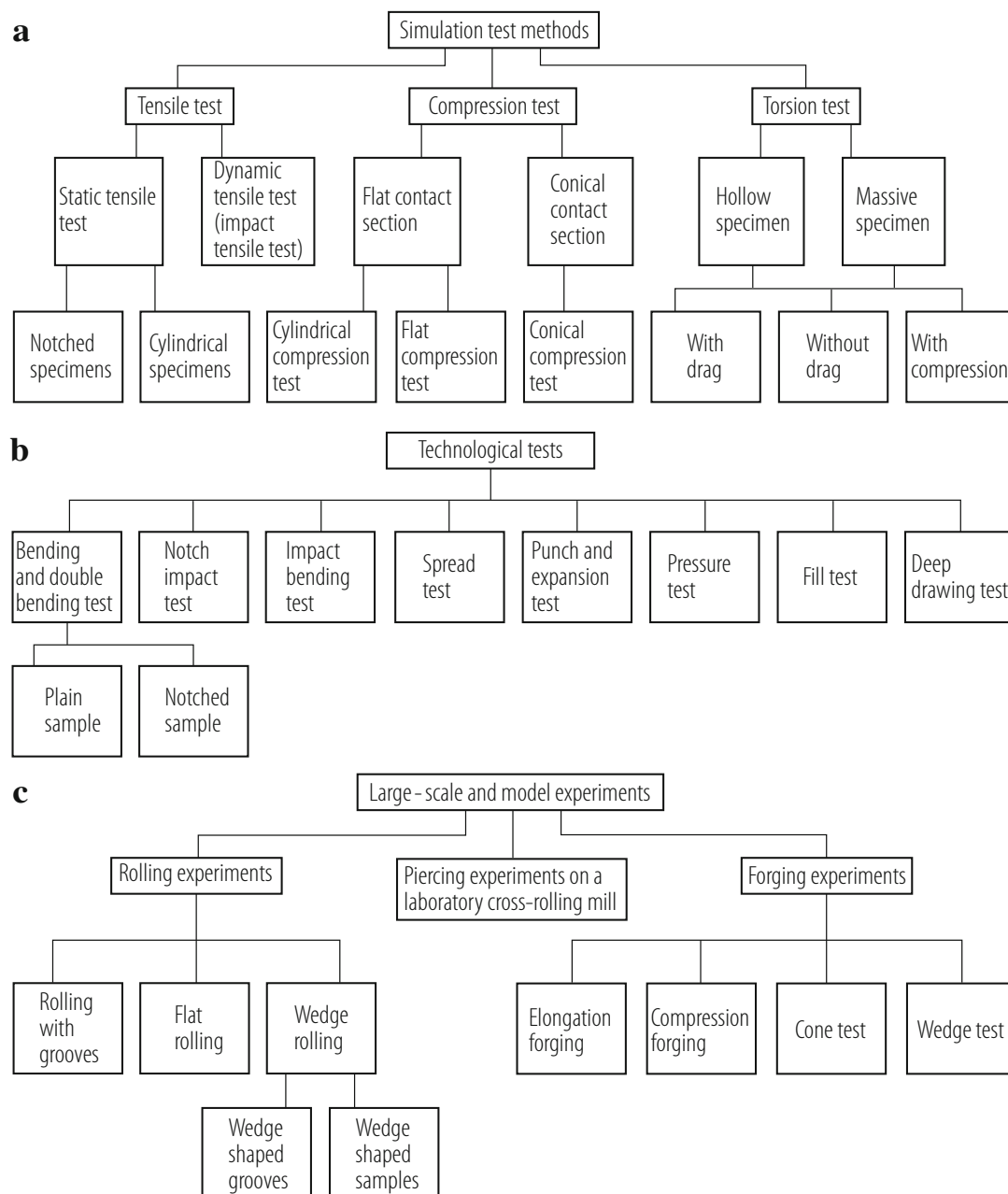
Many of the parameters presented in Fig. 1.3 depend on or affect each other. Because of this complexity of factors of influence deformation behaviour can only be treated in empirical technological parameters and relations rather than in terms of fundamental material science.

## 1.4 Methods to determine the deformation behaviour

### 1.4.1 Overview and specifications

The following methods are available for the determination of the deformation behaviour of a material as the basis of its forming behaviour (Fig. 1.4):

- a) Simulation test methods such as tensile, compression and torsion tests include many process options. The simulation test methods allow the investigation of the parameters of the conditions of deformation (temperature, degree and rate of deformation) as well as of the material related flow stress. These methods also permit to determine the parameters of the deformation behaviour in a special state of stress which depends on the conditions of the deformation process.
- b) Technological test methods such as tensile, compression, bending, transverse bending and bulging tests are mostly used for quality control and data for delivery, which allow a qualitative evaluation of specified process technologies, in particular in cold deformation. In general the technological test methods provide parameters, which depend on the specimen form. Their task is usually to determine the suitability of shapes of stock materials for further processing. Some of these tests are even suitable to assess process technologies. Besides standardised procedures, non-standardised tests also exist that meet the requirements of special production processes.
- c) The adaptation of deformation conditions, which are usual at industrial deformation processes, to smaller deformation machines has to account for the rules of process similarity.



**Fig. 1.4** Test methods for the deformation and forming behaviour

In general the results are well transferable to technical processes, but often both time and material consumption are demanding.

The test methods and their results have to comply with the following requirements:

- Determination of reproducible parameters to define the plasticity and the flow stress of materials.
- Coverage of a broad test range of plasticity, deformation temperature and deformation rate. Preferably these parameters should include the following conditions:

$$\varphi = 0.01 \dots 3.0$$

$$\dot{\varphi} = 10^{-3} \dots 10^3 \text{ s}^{-1}$$

$$\vartheta = 20 \dots 1500 \text{ }^{\circ}\text{C.}$$

- Covering of deformation parameters and deformation processes occurring in large-scale forming processes.
- Simple and economical application as qualification for process control.

The test methods meet the actual conditions of deformation only in part as may be seen by comparison with the data given in Table 1.1 which presents a summary of deformation rates, degrees of deformation and pause times between two successive deformation steps of common forming processes.

**Table 1.1** Strain rates, degrees of deformation and pause times of forming processes (typical value)

| Forming process         | Strain rate $\dot{\varphi}$ [ $s^{-1}$ ] | Individual degree of forming | Pause time $\Delta t$ [s] |
|-------------------------|------------------------------------------|------------------------------|---------------------------|
| Extruding press         | 1.0...400                                | 1.0...5.30                   |                           |
| Hot strip               | 0.50...500                               | 0.10...0.55                  | 70...6.0                  |
| roughing line           | 0.50...7.0                               |                              | 4.0...0.25                |
| finishing line          | 15...500                                 |                              |                           |
| Cross rolling mill (Cu) | 1.0...9.0                                | 0.70...1.70                  |                           |
| Heavy plate mill        | 1.00...80                                | 0.05...0.60                  | 20...4.00                 |
| Cold rolling strip mill | 70...2500                                | 0.008...0.50                 |                           |
| Cold upsetting press    | 1.00...60                                | 0.15...1.50                  |                           |
| Cold drawing            | 1.00...2000                              | 0.03...0.40                  |                           |

The degree of deformation  $\varphi$  is usually realised in a single pass. It is based on the change in cross sectional area by forming. In continuous forming processes total or partial softening of the material occurs during the time between two passes. Therefore, it is required of modern simulation facilities for forming behaviour, to realise such combinations of degree of deformation and rest time. If possible these variations should be combined with variable temperature and/or rate of forming. This would permit, for example, to simulate the forming conditions in the finishing stage of a hot strip line. This test methodology is increasingly gaining importance, since not only information about the force and work requirements of partially softened grain structure conditions are required, but also about the grain structure development through recovery and recrystallisation, onto which transformation and precipitation processes may be superimposed.

The dependence of the rest time on the forming speed is almost identical for different types of continuous rolling lines. Different combinations of degree of forming and rest time, with rest times of more than 0.15 s, can be performed in the compression test as in the torsion test up to the maximum possible forming speed of the test machine. With servo hydraulic test machines the minimal rest time depends on the switching time of the multi-step servo valves, while in torsion plastometers it depends on the switching time of the electromagnetic coupling. Significant reductions of these times are not to be expected in the future, since in plastometers, in contrast to continuous rolling facilities, the masses in motion (tools, specimen clamping) must be stopped and accelerated again during the rest time.

The influence of very short pause times on the stress-strain curve and on the hardening and softening behaviour can be investigated in principle. In many cases, however, it is not possible at the forming rates that are technically common, e.g. in a finishing line.

#### 1.4.2 Test methods for simulation

Since deformation parameters can be measured and controlled under well defined laboratory conditions, methods such as compression test, tensile test and torsion test are most commonly used (Fig. 1.5a). However, technological test methods provide useful, mostly quantitative, information about the influence of temperature and material properties on plasticity.



**Fig. 1.5a** Testing systems. Gleeble HDS-V40 (upper left). Servo hydraulic HDS 40 (upper right). Torsion plastometer (left)

Modern test systems permit to simulate the deformation conditions specified in Tables 1.2a and b.

**Table 1.2** Working ranges of simulation processes of the machines in Fig. 1.5a

| Simulation process        | Strain rate $\dot{\varphi}$ [ $\text{s}^{-1}$ ] | Step width in degree of forming | Rest time $t_P$ [s] |
|---------------------------|-------------------------------------------------|---------------------------------|---------------------|
| Torsion test              | 0.005...30                                      | 0.02...10                       | 0.10... > 100       |
| Flat compression test     | 0.01...500                                      | 0.01...2.50                     | 0.06... > 100       |
| Cylinder compression test | 0.01...50                                       | 0.01...1.70                     | 0.06... > 100       |

The working ranges for torsion and flat compression tests listed are those of the test facilities that are in operation at the Institute for Metal Forming of the TU Bergakademie Freiberg. They are based on the technical data of the torsion plastometer TPM 38 (Fig. 1.5a). The technical specifications of the servohydraulic test system SHM 400 and of the multifunctional simulation and test system Gleeble HDS-V40 are summarised in Table 1.3.

**Table 1.3** Technical parameters of SHM 400 [1.9, 1.10] and Gleeble HDS-V40 [1.11]

| Technical specification              | Servohydraulic testing system SHM 400 | GLEEBLE HDS-V40                   |
|--------------------------------------|---------------------------------------|-----------------------------------|
| Testing force [kN]                   | 400 (static)<br>320 (dynamic)         | 400 (vertical)<br>50 (horizontal) |
| Testing speed [ $\text{mm s}^{-1}$ ] | 0 ... 480                             | 0.1 ... 1700                      |
| Lift [mm]                            | $\pm 50$                              |                                   |
| Drive power [kW]                     | 75                                    |                                   |
| Control                              | force, distance or forming degree     |                                   |
| Loading modes                        | at rest, increasing or vibrating      |                                   |

(continued)

**Table 1.3** (continued)

|                                                |                                                                                                                                  |                                                                                                             |
|------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|
| Technical specification                        | Servohydraulic testing system SHM 400                                                                                            | GLEEBLE HDS-V40                                                                                             |
| Strain rate [ $\text{s}^{-1}$ ]                | max 40 in cylinder upsetting test                                                                                                | max 100                                                                                                     |
| Deformation temperature [ $^{\circ}\text{C}$ ] | 20 ... 1250                                                                                                                      | 20 ... 1800                                                                                                 |
| Specimen heating                               | – in upsetting tool (separate furnace)<br>– inductively with programmed control                                                  | – upsetting test and tensile test (conductive heating up)                                                   |
| Heating rate [ $\text{K s}^{-1}$ ]             | max 10                                                                                                                           | 5 ... 1000                                                                                                  |
| Cooling rate [ $\text{K s}^{-1}$ ]             | 3                                                                                                                                | 1 ... 330                                                                                                   |
| Max number of forming cycles                   | max 10                                                                                                                           | max 25                                                                                                      |
| Min downtime between two forming steps [s]     | 0.20                                                                                                                             | 0.15                                                                                                        |
| Technical specification                        | Servohydraulic testing system SHM 400                                                                                            | GLEEBLE HDS-V40                                                                                             |
| Testing methods                                | upsetting test: cylinder<br>cone<br>hollow cylinder<br>flat compression<br>tensile test: round<br>flat specimens<br>bending test | upsetting test: cylinder<br>cone<br>flat<br>tensile test: round<br>flat specimens<br>multiaxial deformation |

The operating range of torsion tests given in Table 1.4 is based on the conversion calculations of shear and shear rate into the corresponding compression parameter according to Nadai-Mises. In the flat test, a maximum degree of deformation of about 1.60 can be applied. With this, the range of standard reductions in most longitudinal and cross rolling processes can be covered. For extrusion pressing, only the lowest ranges of the operationally applied rates of elongation can be achieved. In the torsion test, there is no technical limit with respect to the degree of deformation; this depends on the plasticity of the material alone. Both test processes have in common that the maximum rate of deformation is substantially below that of standard continuous rolling processes. This applies especially to the rates of deformation in finishing lines.

**Table 1.4** Technical parameters of torsion plastometer [1.12]

|                                                 |                            |
|-------------------------------------------------|----------------------------|
| Technical specification                         | Torsion plastometer TPM 38 |
| Specimen size [mm]                              | Ø 6.0 x 12.0 ... 15.0      |
| Drive power [kW]                                | 2                          |
| Nominal moment [Nm]                             | 23.5                       |
| Permissible overload                            | 7                          |
| Rotational speed [ $\text{min}^{-1}$ ]          | 10 ... 2000                |
| Minimum rotation angle [ $^{\circ}$ ]           | 5                          |
| Maximum rotation angle [ $^{\circ}$ ]           | 60 000                     |
| Minimum rest time between two forming steps [s] | 0.10                       |
| Testing temperature [ $^{\circ}\text{C}$ ]      | 20 ... 1200                |
| Strain rate [ $\text{s}^{-1}$ ]                 | <25                        |
| Max number of forming cycles                    | 24                         |

The multidirectional metal forming simulator BÄHR MDS 0830 (Fig. 1.5b) is a new machine, providing novel possibilities of practical analysis of material behaviour and material development. The influence of heating method and cooling rate on the microstructure and property development and the effect of a multiaxial stress state can be examined. Structural changes including phase transformations and precipitation can be realized in the material and registered.



**Fig. 1.5b** Multidirectional metal forming simulator BÄHR MDS 0830

The equipment system has the possibility of a free change in direction of the externally applied deformation forces as well as a freely programmable, flexible and precise adjustment of technology parameters.

This modern test system permits to simulate the deformation conditions specified in Tables 1.5 and 1.6.

**Table 1.5** Working ranges of simulation processes for multidirectional metal forming simulator BÄHR MDS 0830

| Simulation process         | Strain rate $\dot{\varphi}$ [ $s^{-1}$ ] | Step width in degree of forming                             | Pause time $t_p$ [s]  |
|----------------------------|------------------------------------------|-------------------------------------------------------------|-----------------------|
| Torsion test               | 0.01...10                                | 0.02...10                                                   | 0.10... > 100         |
| Tensile test               | 0.01...10                                | 0.01...0.50                                                 | 0.06... > 100         |
| Cylinder compressions test | 0.01...50                                | 0.01...1.20                                                 | 0.06... > 100         |
| Multi-axial test           | 0.01...10                                | Variable, depending on the stress distribution<br>max ~ 0.5 | Variable min<br>60 ms |

Note: Depending on the material and specimen geometry

**Table 1.6** Technical parameters of multidirectional metal forming simulator BÄHR MDS 0830 [1.22]

| Technical specification | Compression test | Tensile test | Torsion test | Multiaxial stress                                                                                                   |
|-------------------------|------------------|--------------|--------------|---------------------------------------------------------------------------------------------------------------------|
| Testing force [kN]      | <250 kN          | <100 kN      | <75 Nm       | <100 kN                                                                                                             |
| Lift [mm]               | <15              | ±50          |              | tensile/compression:<br>±15 mm<br>tensile/torsion or<br>compression/torsion<br>compression: 5 mm;<br>tensile: 15 mm |

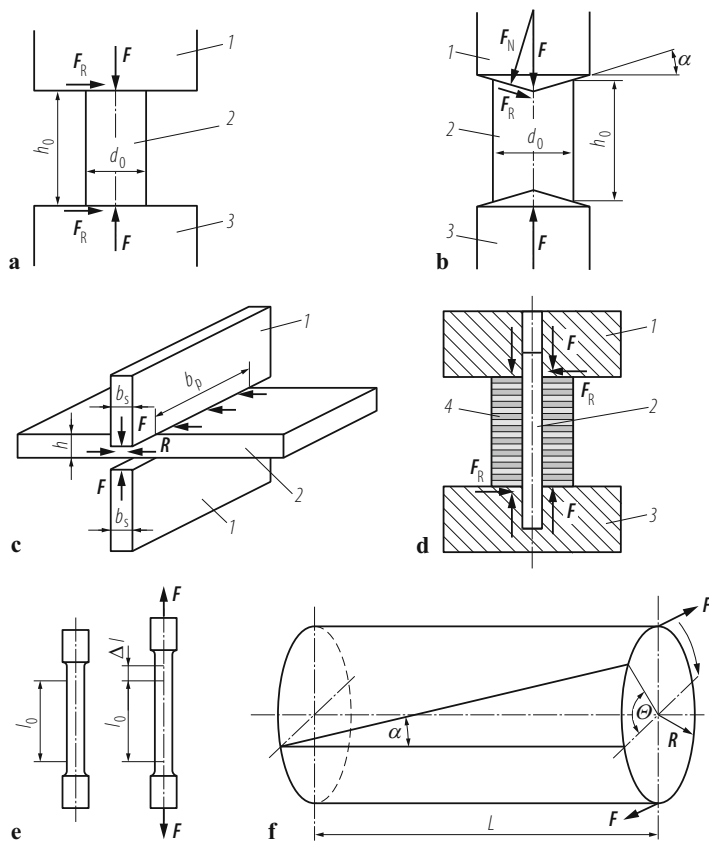
(continued)



**Table 1.6** (continued)

| Technical specification                     | Compression test                                          | Tensile test    | Torsion test           | Multiaxial stress |
|---------------------------------------------|-----------------------------------------------------------|-----------------|------------------------|-------------------|
| Nominal moment [Nm]                         |                                                           |                 | 25                     |                   |
| Control                                     | force, distance                                           | force, distance | moment, forming degree | force, distance   |
| Deformation temperature [°C]                | 20 ... 1500                                               |                 |                        |                   |
| Temperature precision [K]                   | $\pm 2$                                                   |                 |                        |                   |
| Specimen heating                            | inductively with programmed control                       |                 |                        |                   |
| Heating rate [K s <sup>-1</sup> ]           | 20                                                        | 10              |                        |                   |
| Cooling rate [K s <sup>-1</sup> ]           | <100                                                      | <100            | <100                   |                   |
| Max number of forming cycles                | freely selectable up max strain                           |                 |                        |                   |
| Min downtime between two forming steps [ms] | 60                                                        |                 |                        |                   |
| Atmosphere                                  | vacuum to 10 <sup>-5</sup> mbar, inert gas, air, hydrogen |                 |                        |                   |

Figure 1.6 summarises the most important laboratory test methods for the determination of the deformation behaviour. Table 1.7 lists the equations to calculate parameter characteristics of the deformation behaviour.



**Fig. 1.6** Schematic description of test methods [1.13]. (a) Cylindrical compression test. 1 - upper upsetting plate; 2 - specimen 3 - lower upsetting plate;  $F$  - acting force;  $F_R$  - friction force. (b) Conical compression test. 1 - upper upsetting tool; 2 - specimen 3 - lower upsetting tool;  $F$  - acting force;  $F_N$  - normal force;  $F_R$  - friction force. (c) Flat compression test. 1 - die; 2 - specimen;  $F$  - acting force;  $b_s$  - die width;  $b_p$  - specimen width. (d) Hollow cylinder compression test. 1 - upper upsetting plate; 2 - mandrel (locating pin); 3 - lower upsetting plate; 4 - specimen (8...20 rings);  $F$  - acting force;  $F_R$  - friction force. (e) Tensile test.  $F$  - tensile force;  $l_0$  - measured length;  $\Delta l$  - elongation. (f) Torsion test.  $F$  - radial force;  $R$  - sample radius;  $L$  - sample length;  $\alpha$  - shearing strain;  $\Theta$  - torsion angle

**Table 1.7** Equations for the calculation of parameters characterising the deformation behaviour [1.13]

|                                | Compression test                                                                                                                                                                           | Torsion test                                                                                                                                                                                                                                                                                   | Tensile test                                                                                                                                                                                                         |
|--------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Flow stress<br>$\sigma_F$      | $\sigma_F = \frac{\sigma_w}{1 + \frac{v}{3} \frac{d_x}{h_x}}$<br>with deformation stress<br>$\sigma_w = \frac{F}{A}$                                                                       | $\sigma_F = \sqrt{3}\tau$ (v. Mises)<br>$\sigma_F = 2\tau$ (Tresca)<br>with shear stress $\tau = \frac{3M_D}{2\pi R^3}$                                                                                                                                                                        | $\sigma_F = \frac{F}{A_x} = \frac{F}{A_0} (1 + \epsilon)^{-1}$<br>within the range of uniform elongation                                                                                                             |
| Strain $\varphi$               | $\varphi = \ln \frac{h_x}{h_0}$                                                                                                                                                            | $\varphi = \frac{\gamma^*}{\sqrt{3}}$ (v. Mises)<br>$\varphi = \frac{2}{\sqrt{3}} \ln \left( \frac{\gamma^*}{2} + \sqrt{\frac{\gamma^{*2}}{4} + 1} \right)$<br>(Nadai- v. Mises) with shearing strain:<br>$\tan \alpha = \gamma = \frac{R}{L} \Theta$ ;<br>$\gamma^* = \frac{0,75R}{L} \Theta$ | range of uniform elongation<br>$\varphi = \ln \frac{l_x}{l_0} = \ln (1 + \epsilon)$                                                                                                                                  |
| Strain rate<br>$\dot{\varphi}$ | $\dot{\varphi} = \frac{d\varphi}{dt} \approx \frac{\Delta\varphi}{\Delta t} = \frac{v}{h_x}$                                                                                               | $\dot{\varphi}_{NM} = \frac{\partial\varphi}{\partial t} = \frac{\partial\varphi}{\partial\dot{\gamma}} \cdot \dot{\gamma}$<br>$= \frac{\sqrt{3} \cdot \pi \cdot D \cdot \dot{n}}{4 \cdot L \cdot \sqrt{\frac{\gamma^2}{4} + 1}}$                                                              | $\dot{\varphi} = \frac{d\varphi}{dt} \approx \frac{\Delta\varphi}{\Delta t} = \frac{v}{l_x}$                                                                                                                         |
| Symbols                        | $F$ – compression force<br>$A$ – area<br>$\mu$ – coefficient of friction<br>$v$ – compression rate<br>$d_x$ – specimen diameter during the test<br>$h_x$ – specimen height during the test | $M_D$ – torque<br>$R$ – specimen radius<br>$D$ – specimen diameter<br>$L$ – gage length<br>$\Theta$ – torsion angle<br>$n$ – number of rotations                                                                                                                                               | $F$ – tensile force<br>$A_x$ – section during the test<br>$A_0$ – section before the test<br>$l_x$ – length during the test<br>$l_0$ – gage length<br>$\epsilon$ – elongation $= \Delta l / l_0$<br>$v$ – test speed |

It should be emphasised, that several equations are available for the calculation of the degree of deformation in the torsion test. They are all based upon the theory of plasticity, but the results can differ, especially at higher shear stresses. The authors use the conversion according to Nadai – v. Mises, because this method yields conforming results for characteristic points of hot flow curves found in compression and/or torsion tests. Although the torsion test has found wide acceptance for the determination of the behaviour at hot and cold deformation, it should be noted, that no technical forming process operates with shear stresses only and that the distribution of stress and deformation inside the specimen is inhomogeneous.

Table 1.8 describes the advantages and disadvantages of the most important test methods. Each one has its own advantages and disadvantages, which have to be noted implicitly for the evaluation and application of the specific data which are determined.

**Table 1.8** Comparison of the test procedures for the determination of yield stress and plasticity [1.14]

|            | Compression test                                                                                                                               | Torsion test                                                                                                                                                                                                                                                                                                                     | Tensile test                                                                                                                                                                                                                                     |
|------------|------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Advantages | + forming by compressive stresses similar to most longitudinal rolling<br>+ simple test procedure<br>+ high forming rate in the ballistic test | + simultaneous determination of yield stress, plasticity and forming behaviour<br>+ free of friction<br>+ simulation of the range of times in technical deformation processes without a cross sectional change of the test specimen<br>+ determination of formation of the first crack from the longitudinal stress distribution | + simultaneous determination of strength and plasticity values with small degrees of deformation<br>+ free of friction<br>+ rapid determination of the stress-strain behaviour and the yield stress of cold formed specimens at room temperature |

(continued)

**Table 1.8** (continued)

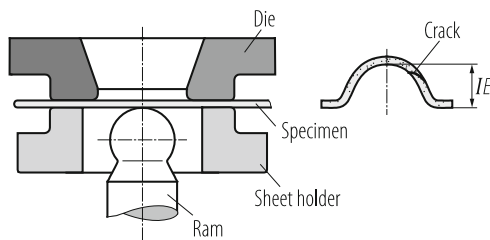
|               | Compression test                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Torsion test                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Tensile test                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|---------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Disadvantages | <ul style="list-style-type: none"> <li>– friction between specimen and tool</li> <li>– friction correction to stress-strain curve necessary</li> <li>– with bulging of the specimen, i.e. <math>\varphi \geq 0.35</math> undefined state of stress</li> <li>– buckling of slender specimens</li> <li>– degree of forming at fracture can only be determined for brittle materials</li> <li>– the absolute values depend on specimen geometry and size</li> </ul> | <ul style="list-style-type: none"> <li>– several different theories of plasticity and resulting sets of equations exist for calculating yield stress, degree of deformation and forming rate</li> <li>– homogeneous forming over <math>L/D \sim 1.5 \dots 2.5</math></li> <li>– at <math>\varphi \geq 3.0</math>, longitudinal stresses lead to cross section changes in non-alloy C - steels</li> <li>– <math>\dot{\varphi}_{\max} \sim 30 \text{ s}^{-1}</math></li> </ul> | <ul style="list-style-type: none"> <li>– multi-axial state of stress from constriction, i.e. for               <ul style="list-style-type: none"> <li>- hot forming at <math>\varphi \geq 0.30</math>, cold forming at <math>\varphi \geq 0.20</math></li> </ul> </li> <li>– no simulation of technical forming time distributions possible due to low degree of forming at fracture</li> <li>– forming by stressing under tension does not correspond to any technical forming process</li> </ul> |

### 1.4.3 Technological tests

In principle technological tests serve to determine parameters which depend on the specimen form. The aim is to test the appropriateness of preforms, especially of semi-finished products, for further processing or the applicability of special processes and process conditions.

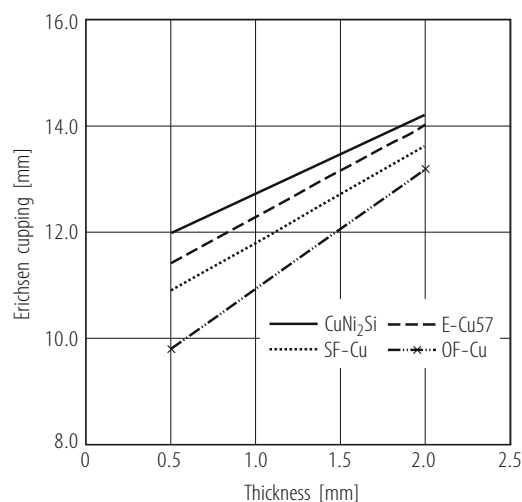
#### 1.4.3.1 Deep drawing test

In the deep drawing test according to Erichsen (DIN 50 101, 50 102), Fig 1.7 [1.17], a firmly clamped sheet or strip is bulged by a ball-shaped tool until the first crack appears. The measure of the plasticity is the depth of penetration of the spherical body to the incipient crack, the so-called cupping test. This must be greater than the value specified in the standards.



**Fig. 1.7** Deep drawing test according to Erichsen (DIN 50 101) [1.17]

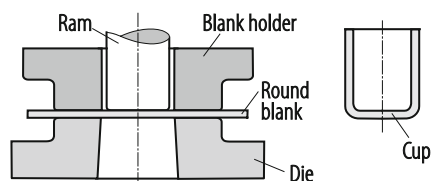
In addition it is possible to evaluate anisotropy from the curvature of a crack. For an isotropic material the crack is almost completely circular because the strip is subjected to a biaxial tensile load. A one-sided crack indicates an anisotropic texture of the sheet material. Hence it is less suitable for deep drawing. Also, the surface roughness permits to assess the effect of grain size. Materials with high grain size cannot be processed further; accordingly their test data indicate that they are unsuitable for deep drawing. Figure 1.8 shows the dependence of the cupping for annealed Cu-alloys on plate thickness for different grain sizes; with decreasing grain size there was a decrease in the cupping test.



**Fig. 1.8** Erichsen cupping of soft sheets of Cu and Cu alloys

In [1.16] it was shown that a relationship exists between the data obtained by the deep drawing test according to Erichsen and the largest possible reduction in cold rolling. High values of the data obtained by the deep drawing test suggest a good plasticity in cold rolling, low values indicate brittle behaviour.

In the deep drawing test presented in Fig. 1.9, sheet strips (round blanks) with different diameters  $D$  are drawn to cylindrical cups with a smaller diameter  $d$ .



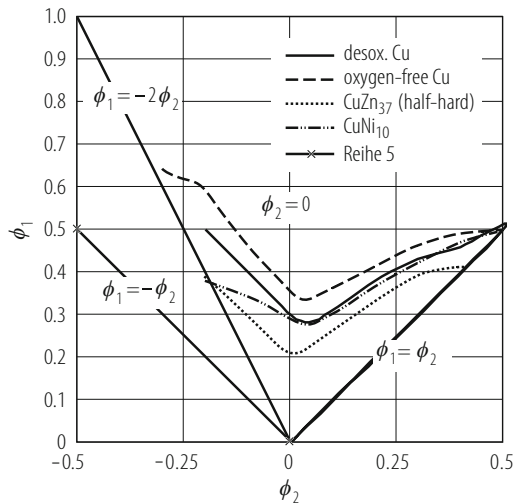
**Fig. 1.9** Deep drawing test according to Erichsen (DIN 50 101) [1.17]

During forming radial tensile stresses occur in the circular plate and in the cylinder formed. Tangential compressive stresses also occur. This is reflected in the forming limit curve according to Fig. 1.2b. Therefore the forming behaviour of the material according to the cupping test can appear to be superior to that obtained by the deep drawing test according to Erichsen.

Upon deformation, radial tensions inside the round blanks as well as axial tensions inside the cylinder and tangential compressive strains occur, that is why the material can be formed more plastically than in an indentation test. The limiting drawing ratio  $D/d$  is determined, when the cup bottom does not yet show any crack. In this test arrangement, besides the evaluation of the deformation behaviour the sheet anisotropy can also be found. Texture in the interior of the sheet leads to earing, which means, that the drawn cups have different heights. The earing height rises with the degree of cold deformation [1.18].

The limiting drawing ratio is the ratio of diameters  $D/d$  up to which the sample can be deformed without crack formation at the bottom. In addition to determining the limiting drawing ratio the deep drawing test can also be used to detect the anisotropy of the sheet material by the degree of “earing” of the cup.

Figure 1.10 shows an FLD–diagram for copper and copper alloys after results of Melander [1.19]. It was determined with a strain rate of 0.0014 [1/s] on samples with 0.70 mm thickness. The best cold forming response is observed for the two grades of pure copper, followed by the Cu–Ni alloy, while semi-hard CuZn37 has the lowest formability especially in tensile stress. One can see that the strain at the forming limit increases with the temperature of investigation, when the load changes from a uniform uniaxial tensile stress ( $\varphi_2 = 0$ ) into the direction of a “uniaxial tensile stress” ( $\varphi_1 = -2 \varphi_2$ ). The limiting curves shift with rising temperature to higher absolute values of  $\varphi_1$ .



**Fig. 1.10** Forming limit diagram (FLD) of Cu and Cu alloys at room temperature

$\varphi_1 = \varphi_2$ : deep drawing

$\varphi_1 = -2\varphi_2$ : uniaxial tensile stress

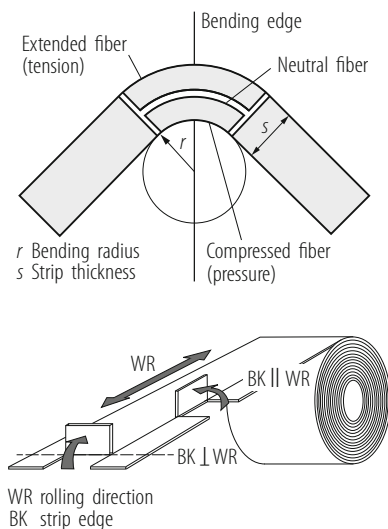
$\varphi_2 = 0$ : uniform uniaxial tensile stress

$\varphi_1 = \varphi_2$ : biaxial drawing

In the FLD diagram the effects of deformation temperature and speed, the work hardening and addition to the influence of the anisotropy of the material can also be represented. The increase of  $\varphi_1$  is increasing or decreasing strain and  $\varphi_2$  is lower for copper alloys than for light metals and steels. This is an expression of the high plasticity of these alloys.

#### 1.4.3.2 Bending test

On bending a flat specimen tensile stresses arise on the outside in the bending edge, while compressive stresses arise on the inside (Fig. 1.11 [1.15]).



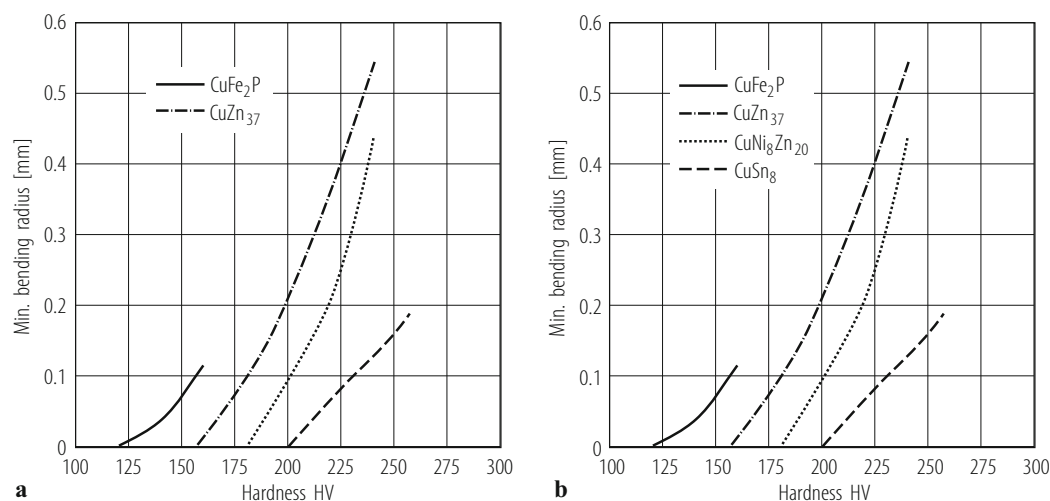
**Fig. 1.11** Bending test [1.15] top: tensile and compressive stresses during bending bottom: orientation of the bending line relative to the rolling direction

The flow of material during bending deformation and the deformation stresses lead to roughening with increasing bending angle, and finally to cracking with smaller bending radii. On the inside of the specimen folds arise. In the bending test, the smallest possible bending radius  $r$  (relative to the sheet thickness  $s$ ) before cracks form on the sample surface is identified.

The specific minimum relative bend radius  $r/s$  depends on:

- Material, its state of hardening and the grain size.
- Orientation of the bending edge to the rolling direction (Fig. 1.11). If the bending edge is perpendicular to the rolling direction, bending with smaller bending radii is possible.
- Thick strips of the same alloy and the same material state yield larger minimum bend radii than thinner strips.

In Fig. 1.12 the minimum bend radius as a function of the hardness HV is related to the orientation of the bending edge applied parallel and perpendicular to the rolling direction for some copper materials (cold worked and annealed condition). In all cases an increasing hardness requires larger bending radii; the increase is significantly larger for samples in parallel to the rolling direction.



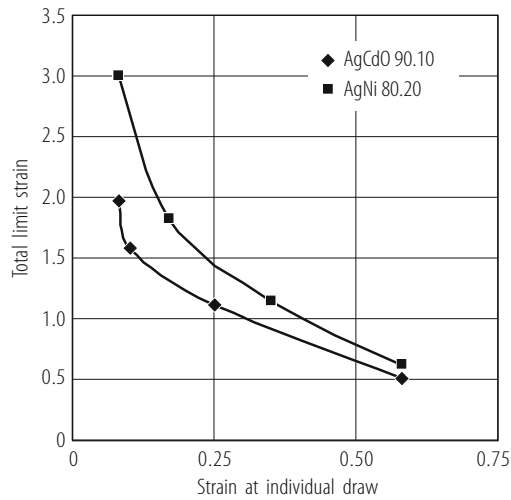
**Fig. 1.12** Bending behaviour of copper materials [1.15] **a)** Bending edge perpendicular to the rolling direction **b)** Bending edge in the rolling direction

#### 1.4.3.3 Rolling test

With the exception of flat compression tests (where the plasticity can only be determined under very special conditions) none of the described test methods operate with the state of stress ( $\sigma_1 = -\sigma_3$ ,  $\sigma_2 = (\sigma_1 + \sigma_3)/2$ ) and state of straining ( $\varphi_1 = -\varphi_3$ ,  $\varphi_2 = 0$ ) that occur in strip rolling. Hence it was tested whether it is possible to determine the critical degree of deformation in cold rolling with high reliability [1.20]. The following methods for determining the plasticity during cold rolling were used.

This test can be applied if the strips are rolled without lubrication at a constant low degree of reduction (5... 10%) considering the similarity and rolling technology, and a constant rate of deformation until the maximum deformation capacity (i.e. appearance of the first crack) is reached [1.20]. As a disadvantage of this method, a relatively wide scatter has to be accepted, especially at low degrees of deformation (up to 50%). This is partly caused by the formation of micro-cracks that cannot be detected visually but only by inductive crack detection. However, the number of necessary rolling tests would increase significantly because of the large number of parameters. In order to transfer the results to technical processes, the procedure has to follow the criteria of similarity (equal temperature and rate of deformation, equal roll gap ratio and equal friction conditions).

The method to determine the total limit strain, accumulation of small degrees of deformation up to the exhaustion of formability, which was described for the rolling process, is also used for other deformation processes, for instance for wire drawing. In this case the maximum achievable degree of deformation up to rupture of the wire strongly depends on the degree of deformation in the single draws, Fig. 1.13 shows the limit of total strain for two silver alloys. It is lower for AgCdO90.10 than for AgNi80.20, i.e. the latter shows higher plasticity. This observation confirms the statement made earlier that plasticity decreases with an increasing fraction of tensile stresses.



**Fig. 1.13** Total limit strain in wire drawing of Silver contact material, depending on the deformation degree in the single draw (initial diameter: 7.00 mm [1.21])

## Symbols and abbreviations

| Short form         | Full form                                                          |
|--------------------|--------------------------------------------------------------------|
| $\sigma_w$         | deformation stress                                                 |
| $\sigma_F$         | flow stress                                                        |
| $\dot{\varphi}$    | strain rate                                                        |
| $\Theta$           | torsion angle                                                      |
| $\varphi$          | strain                                                             |
| $n_\gamma$         | auxiliary parameter                                                |
| $\nu$              | uniaxial stress                                                    |
| $\mu$              | coefficient of friction                                            |
| $A$                | area                                                               |
| $A_0$              | section before the test                                            |
| $A_x$              | section during the test                                            |
| $b_p$              | specimen width                                                     |
| $b_s$              | die width                                                          |
| $D$                | specimen diameter                                                  |
| $D$                | different diameter                                                 |
| $d_x$              | specimen diameter during the test                                  |
| $F$                | compression force or tensile force or acting force or radial force |
| FLD                | forming limit diagram                                              |
| $F_N$              | normal force                                                       |
| $F_R$              | friction force                                                     |
| $h_x$              | specimen height during the test                                    |
| $L$ or $l_o$       | gage length                                                        |
| $l_o$              | measured length                                                    |
| $l_x$              | length during the test                                             |
| $M_D$              | torque                                                             |
| $n$                | number of rotations                                                |
| $R$                | specimen radius                                                    |
| $T$ or $\vartheta$ | temperature                                                        |
| $t_P$              | rest time or pause time                                            |
| $v$                | compression rate or test speed                                     |
| $\alpha$           | shearing strain                                                    |
| $\Delta l$         | elongation                                                         |

(continued)

| Short form     | Full form                 |
|----------------|---------------------------|
| $\varepsilon$  | strain ( $\Delta l/l_0$ ) |
| $\sigma$       | normal stress             |
| $\tau$         | shear stresses            |
| $\varphi_{Fr}$ | plasticity                |

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# Influence of chemical composition and forming conditions on flow stress

## 2 Flow stress

### 2.1 Influence of the chemical composition

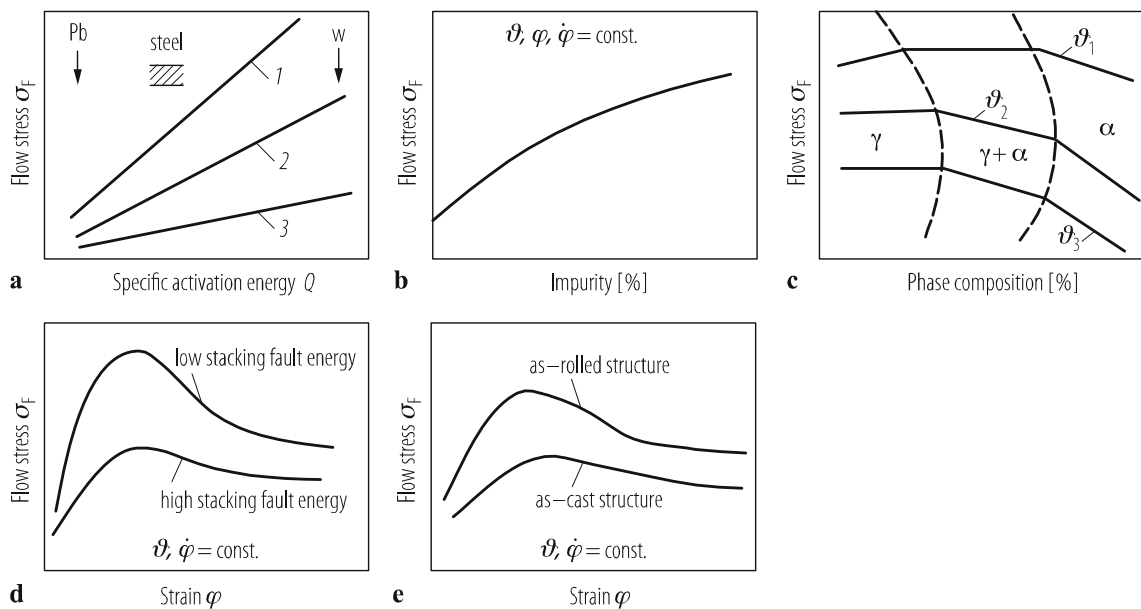
#### 2.1.1 Hot working

##### 2.1.1.1 Basic relationships

The effect of alloying and impurity elements on the flow stress during hot forming can be reduced to a few major factors. The hardening effect of elements in solid solution depends on the relative difference in atom size  $\delta$ , the relative difference in shear modulus  $\eta$  and the concentration of the elements  $C_{Ei}$ :

$$\sigma_F = \sigma_{F, \text{pure metal}} + \Delta\sigma_F(\delta, \eta, C_{Ei}). \quad (2.1)$$

An increase in flow stress caused by solid solution hardening is limited by the fact that there is a direct relationship between the solubility of the alloying atoms and their specific hardening effect: if  $\delta$  and  $\eta$  are high, the solubility is low (and vice versa) [2.21]. Figure 2.1 summarises the effects of the material dependent parameters on the flow stress in hot deformation.



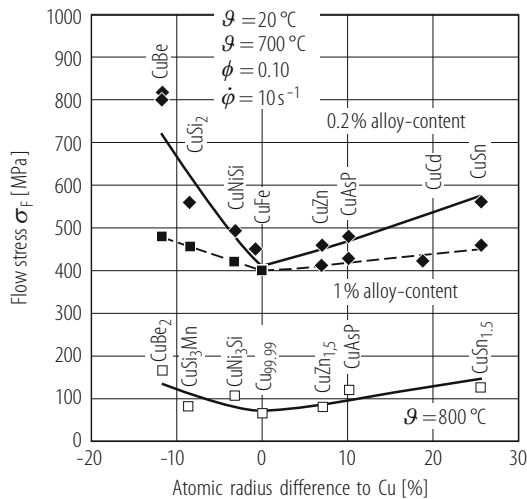
**Fig. 2.1** Material related parameters on flow stress in hot deformation. **(a) Material:**  $\sigma_F$  is a function of the material dependent activation energy at hot deformation  $Q$ . Three curves for different homologous deformation temperatures  $(T_d/T_m)_1 < (T_d/T_m)_2 < (T_d/T_m)_3$  are shown. **(b) Alloy composition:** an increase in solute content in solid solution yields an increase in  $\sigma_F$  compared to the pure metal. **(c) Phase composition:** at the same deformation conditions  $(\vartheta, \varphi, \dot{\varphi})$   $\sigma_F$  depends on the phase composition  $(\alpha, \gamma)$   $\vartheta_1 < \vartheta_2 < \vartheta_3$  due to differences of the intrinsic mechanical properties and the diffusion behaviour of the phases. **(d) Stacking fault energy:** hot flow curves for materials with high stacking fault energy (dynamic recovery) and low stacking fault energy (dynamic recrystallization). **(e) Microstructure before deformation:** at the same chemical composition the flow stress of an as-cast structure is lower by a factor of approximately 0.70–0.95 compared to pre-deformed structures. In general the maximum of  $\sigma_F$  occurs at higher degrees of deformation for as-cast structures and is not very pronounced

Table 2.1 lists the radii and shear modules of various alloying and impurity elements of copper [2.2, 2.3, 2.4].

**Table 2.1** Atomic radius and effect on the shear modulus of alloying elements of copper [2.2, 2.3, 2.4, 2.5, 2.6]

| Element   | Atomic radius $r$ [Å] | Atomic radius, difference to Cu $\Delta r$ [%] | Shear modulus $G$ [GPa] | Shear modulus, difference to Cu $\Delta G$ [GPa] | Solubility in Cu [mass-%]                         | at $\vartheta = 800$ °C |
|-----------|-----------------------|------------------------------------------------|-------------------------|--------------------------------------------------|---------------------------------------------------|-------------------------|
|           |                       |                                                |                         |                                                  | Maximum solubility (temperature $\vartheta$ [°C]) |                         |
| aluminium | 1.43                  | −11.72                                         | 26.2                    | 45.76                                            | 9.6 (570)                                         | 2.4                     |
| magnesium | 1.60                  | −25.00                                         | 17.3                    | 64.18                                            | 2.8 (722)                                         | 2.4                     |
| manganese | 1.30                  | −1.56                                          | 66.8                    | −38.30                                           | 35,0 (868)                                        | ~85                     |
| silicon   | 1.17                  | 8.59                                           | 39.2                    | 18.84                                            | 5.3 (842)                                         | 5.2                     |
| copper    | 1.28                  |                                                | 48.3                    |                                                  |                                                   |                         |
| iron      | 1.27                  | 0.78                                           | 81.6                    | −68.94                                           | 3.7 (1094)                                        | 0.9                     |
| zinc      | 1.37                  | −7.03                                          | 41.9                    | 13.25                                            | 32.5 (900)                                        | 34                      |
| chromium  | 1.28                  | 0.00                                           | 86.8                    | −79.71                                           | 0.55 (1060)                                       | 0.15                    |
| nickel    | 1.24                  | 3.13                                           | 76                      | −57.35                                           |                                                   |                         |
| titanium  | 1.46                  | −14.06                                         | 45.6                    | 5.59                                             | 6.3 (890)                                         | 4.5                     |
| zirconium | 1.60                  | −5.47                                          | 34.8                    | 27.95                                            | 1.0 (980)                                         |                         |
| tin       | 1.62                  | −26.56                                         | 18.00                   | 62.73                                            | 5.8 (520)                                         | 13.5                    |

In Fig. 2.2 the flow stress at a deformation of  $\varphi = 0.10$  and a strain rate of  $\dot{\varphi} = 10 \text{ s}^{-1}$  is applied to some binary copper alloys at  $\vartheta = 20$  and  $800$  °C as a function of the difference in atomic radius [2.7]. Due to solid solution hardening the flow stress increases with increasing difference in atomic radius. This also increases the influence of the alloy content.



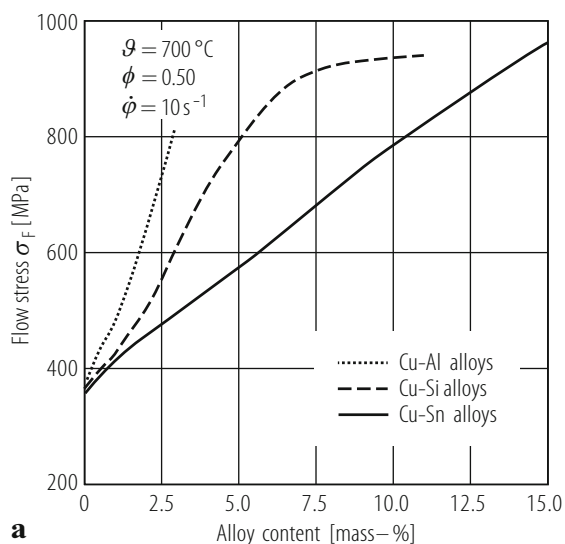
**Fig. 2.2** Relation between the difference in atomic radii and flow stress (solid solution hardening) in binary Cu alloys. Deformation parameters:  $\vartheta = 20$  °C and  $800$  °C,  $\varphi = 0.10$ ,  $\dot{\varphi} = 10 \text{ s}^{-1}$

Two % of zinc increases the flow stress  $\sigma_F$  by 55–60 [MPa] (at  $\vartheta = 20$  °C,  $\varphi = 0.10$  and  $\dot{\varphi} = 10 \text{ s}^{-1}$  (atomic radius difference  $-7.03\%$ ). One % of zinc increases  $\sigma_F$  by 10–15 [MPa]. Under the same conditions of deformation tin with an atomic radius difference of  $-26.56\%$ , leads to a difference in flow stress of 60–65 [MPa].

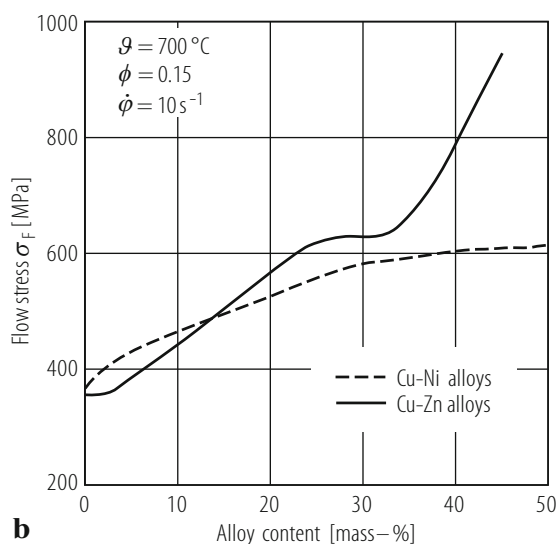
#### 2.1.1.2 Experimental and commercial materials

Figure 2.3 shows how selected alloy and impurity elements influence the flow stress of copper alloys in the cast state (homogenized at  $700$  °C) and by deformation of  $\varphi = 0.10$  at a strain rate of  $\dot{\varphi} = 10 \text{ s}^{-1}$  in compression tests. The samples were taken from 5 kg ingots perpendicular to the direction of

crystallization. Since Cu 99.999 was alloyed with the element to be considered the content of impurities was lower than 0.001%, so that the results about the influence of the chemical composition are not significantly influenced by impurities of the base metal.

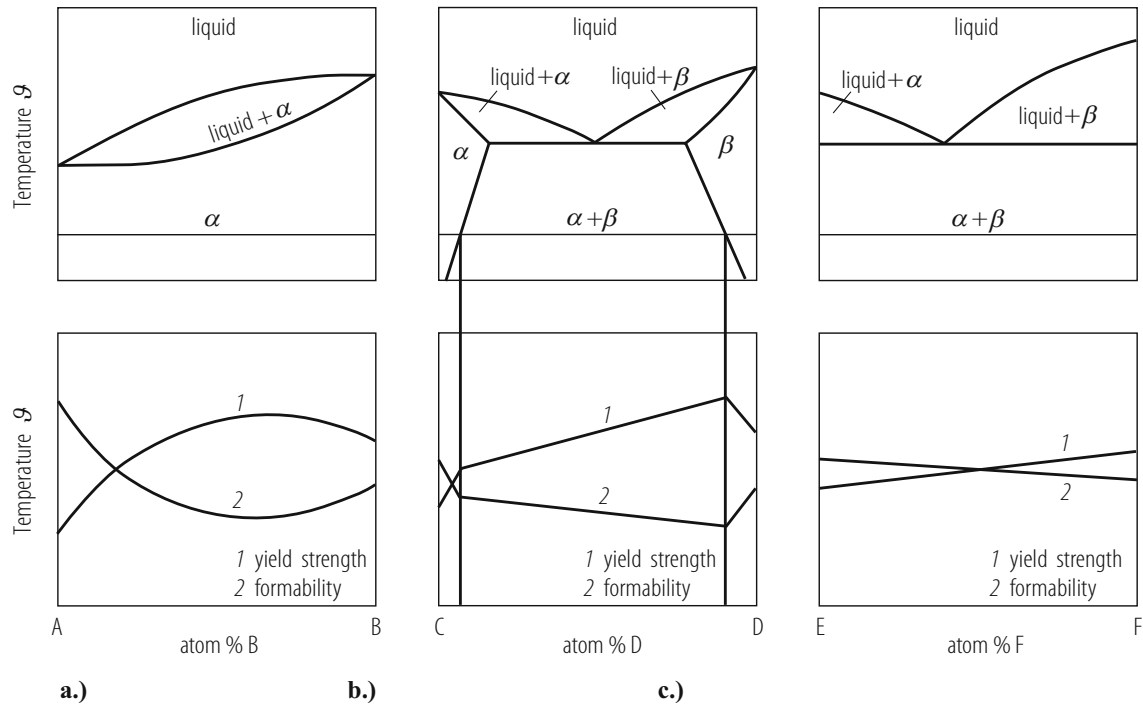


**Fig. 2.3a** Influence of alloying elements on the flow stress of binary Cu alloys. Deformation parameters:  $\vartheta = 700\text{ °C}$ ,  $\phi = 0.50$ ,  $\dot{\phi} = 10\text{ s}^{-1}$



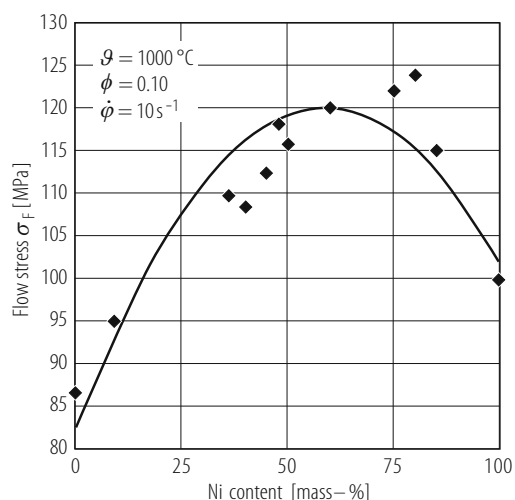
**Fig. 2.3b** Influence of alloying elements on the flow stress of binary Cu alloys. Deformation parameters:  $\vartheta = 700\text{ °C}$ ,  $\phi = 0.15$ ,  $\dot{\phi} = 10\text{ s}^{-1}$

In hot forming, the flow stress of copper alloys increases with increasing Al, Si, Sn, Ni and Zn content. Beyond the range of solid solution hardening by the influence of atomic radius differences and shear modulus differences, the level of yield stress is affected by heterogeneous phase composition. On exceeding the solubility limit, the deformation behaviour depends on the phase fractions, which also applies to eutectic alloys (Fig. 2.4).



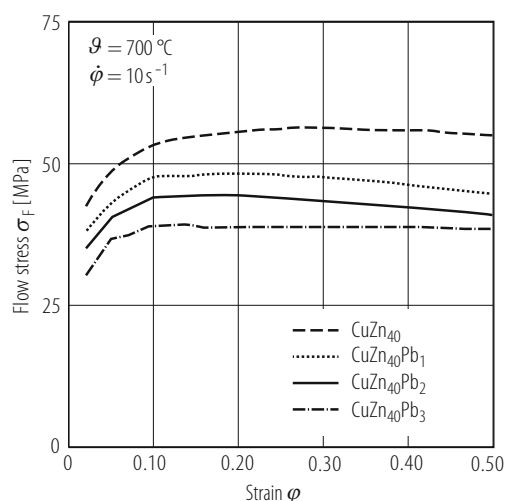
**Fig. 2.4** Schematic phase diagrams of binary alloys and their behaviour in deformation [2.8] **a)** complete miscibility in the liquid and solid state, Cu–Ni; Ag–Au; Cr–Mo; Cu–Au; **b)** complete miscibility in the liquid and partial solubility in the solid state, Ag–Cu; **c)** complete miscibility in the liquid state and complete insolubility in the solid state, Bi–Cd

If in a binary system both alloying elements are completely soluble, the flow stress increases, starting from each element to a maximum value. As an example data of the iron–nickel system are shown in Fig. 2.5a. The curve of the flow stress is a function of the nickel content for a strain of 0.10, a temperature of 1000 °C and a strain rate of 10 s<sup>-1</sup>. The maximum value of the yield stress was found for these conditions of FeNi80. The absolute values of the flow stress were determined in technical alloys.



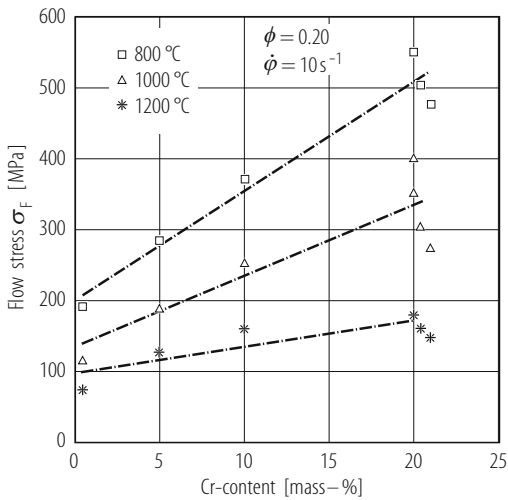
**Fig. 2.5a** Flow stress as a function of Ni content in Fe-Ni alloys. Deformation parameters:  $\theta = 1000\text{ }^{\circ}\text{C}$ ,  $\phi = 0.10$ ,  $\dot{\phi} = 10\text{ s}^{-1}$

When exceeding the solubility limit by heat treatments or hot deformation, intermetallic compounds or terminal phases may form. Finely dispersed or coarse second phase particles are obstacles to the motion of dislocations. Moreover, the intrinsic mechanical properties of second phases influence the flow stress. In Fig. 2.5b the dependence of the flow stress of a basic Cu–Zn alloy on additions of Pb is presented.



**Fig. 2.5b** Dependence of flow stress Cu–Zn–Pb alloys on the Pb content. Deformation parameters:  $\theta = 700\text{ }^{\circ}\text{C}$ ,  $\dot{\phi} = 10\text{ s}^{-1}$

The material system can be considered an alloy in which the content of two elements is kept constant (Mn, Zn), while the content of the third element is changed. The initial values of flow stress of the base alloys increase with respect to a pure copper alloy. The change is dependent on the content of the respective alloying element (Fig. 2.6).



**Fig. 2.6** Increase in flow stress of Ni–Cr alloys with increasing Cr content at different temperatures. Deformation parameters:  $\varphi = 0.20$ ,  $\dot{\varphi} = 10 \text{ s}^{-1}$

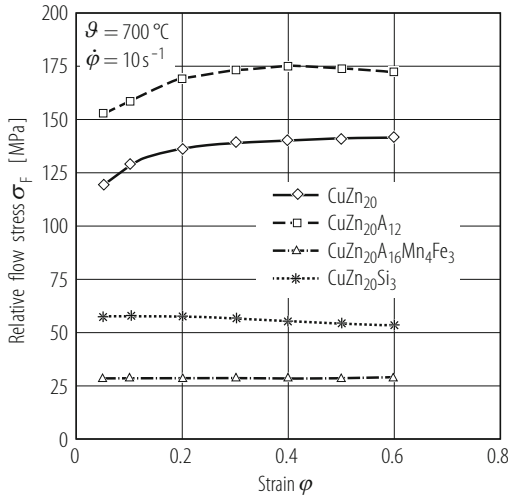
The increase of the flow stress by an alloying element can be described by a power function of the type (see [2.7]):

$$\sigma_F = A C_{\text{Ei}}^B, \tag{2.2}$$

with

|                 |                                      |
|-----------------|--------------------------------------|
| $A$             | constant,                            |
| $C_{\text{Ei}}$ | content of the element [mass -%] and |
| $B$             | alloy-specific exponent.             |

For Sn as an alloying element in Cu alloys  $B = -0.58$ . For Sn in Zn alloys, however,  $B = -0.368$ . For Ni in Cu alloys  $B = -0.641$ . An increase in the content of the second alloying element changes the relative yield stress with respect to the base alloy as shown in Fig. 2.7 in the Cu–Zn alloy group.



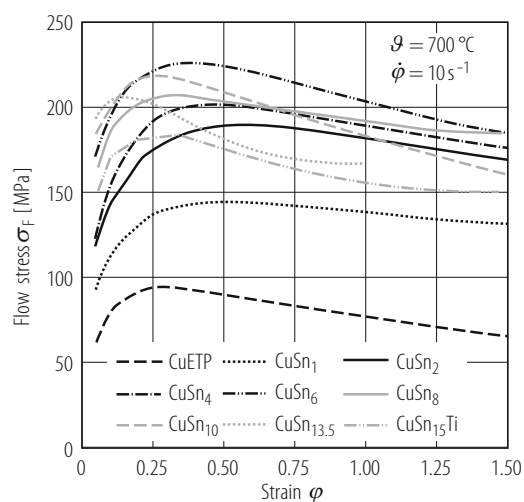
**Fig. 2.7** Relative flow stress increase compared to the Cu–Zn base alloy in hot deformation. Deformation parameters:  $\vartheta = 700 \text{ }^\circ\text{C}$ ,  $\dot{\varphi} = 10 \text{ s}^{-1}$

The influence of alloying and impurity elements on the flow stress of binary and ternary copper alloys in hot forming could be confirmed for commercial alloys. The absolute values are somewhat higher than for experimental alloys, due to the content of impurities and/or accompanying elements. Comparing the flow stress at 700 °C, at a deformation of  $\varphi = 0.10$  at a strain rate of  $\dot{\varphi} = 10 \text{ s}^{-1}$ , the differences listed in Table 2.2. were obtained.

**Table 2.2** Comparison of flow stress for experimental melts and commercial alloys

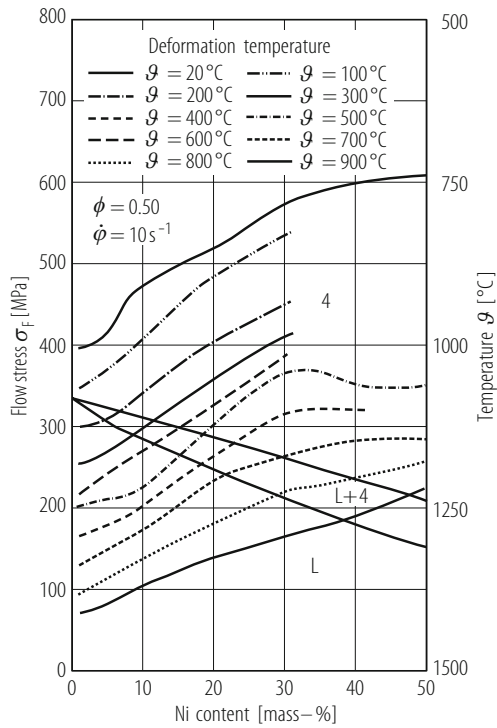
| Flow stress [MPa] | Sn content [mass-%] |       |       |       |       |       |
|-------------------|---------------------|-------|-------|-------|-------|-------|
|                   | 0                   | 1     | 2     | 4     | 6     | 8     |
| Test melt         | 74.2                | 95.4  | 138.5 | 143.4 | 160.5 |       |
| Brass             | 80.2                | 112.2 | 142.5 | 154.8 | 171.3 | 188.3 |

Figure 2.8 illustrates the influence of Sn content on the absolute value of the flow stress of commercial Cu base materials. The character of the flow stress curve varies. Such variations in flow stress for copper alloys in hot forming are also found in other alloys.



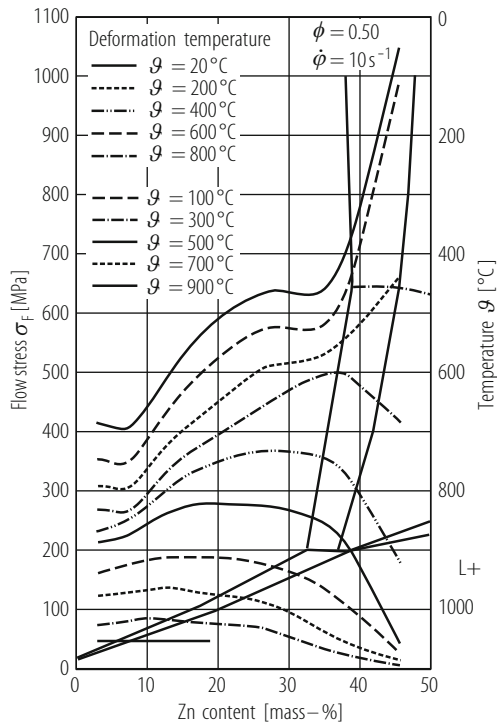
**Fig. 2.8** Flow stress of Cu–Sn alloys. Deformation parameters:  $\theta = 700 \text{ °C}$   $\dot{\varphi} = 10 \text{ s}^{-1}$

The variation of flow stress of Cu–Ni, Cu–Zn and Cu–Al alloys with alloy composition and temperature is shown in Figs. 2.9a to c. They show a continuous variation in physical properties.



**Fig. 2.9a** Influence of Ni content and temperature of deformation on the flow stress of Cu-Ni alloys.

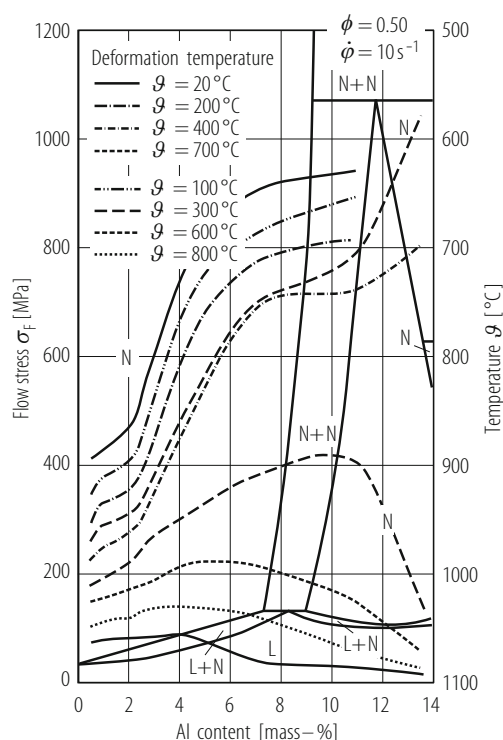
Deformation parameters:  $\theta = 20 - 900^\circ\text{C}$ ,  $\phi = 0.50$ ,  $\dot{\phi} = 10\text{ s}^{-1}$



**Fig. 2.9b** Effect Zn content and deformation temperature on the flow stress of Cu-Zn alloys.

Deformation parameters:  $\theta = 20 - 900^\circ\text{C}$ ,  $\phi = 0.50$ ,  $\dot{\phi} = 10\text{ s}^{-1}$





**Fig. 2.9c** Effect of Al content and deformation temperature on the flow stress of Cu–Al alloys. Deformation parameters:  $\theta = 20 \dots 900 \text{ }^{\circ}\text{C}$ ,  $\phi = 0.50$ ,  $\dot{\phi} = 10 \text{ s}^{-1}$

The following figures visualize the correlation between the material's microscopic structure and its macroscopic properties. As macroscopic property here the flow stress and its dependence on temperature is selected. This dependence is now projected onto the phase diagram (s. Fig. 2.4) of the associated material. The results can be seen in Figs. 2.9a–c.

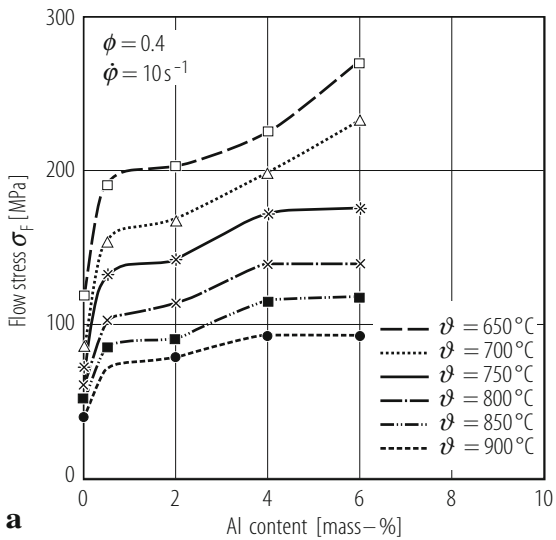
In the region of complete solubility the flow stress increases with increasing share of the alloying element, where the alloying element is Ni (Fig. 2.9a), Zn (Fig. 2.9b) or Al (Fig. 2.9c). At low temperatures, however, the flow stress increases with an increasing share of the alloying element.

The material's microstructure thus also contributes to its mechanical and physical properties apart from temperature and pressure.

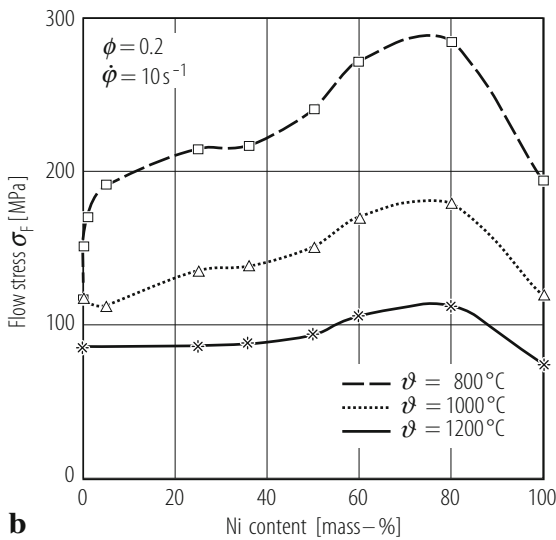
Brass shows the same behaviour in the single phase range. In the range of solid solution the flow stress rises with increasing Zn content between 20 and 700 °C. In the two-phase range  $\alpha + \beta$  above 300 °C a decrease in flow stress takes place due to lower absolute values of  $\beta$  brass (Fig. 2.9b).

Cu–Al alloys with <7.5% Al deform the single phase state between 20 and 900 °C. Below 600 °C the strongest increase in flow stress with increasing aluminium content is observed in the range of cold forming. The occurrence of the  $\beta$  phase above 560 °C leads to a significant decrease in the flow stress (Fig. 2.9c).

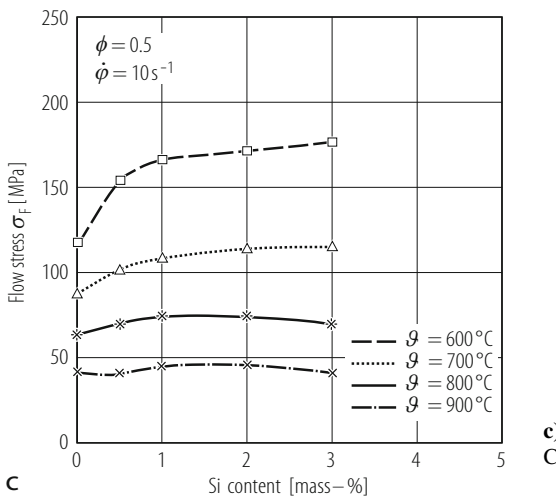
The variation of flow stress in Cu–Al, Cu–Ni and Cu–Si alloys with composition and temperature is shown in Figs. 2.10a to 2.10c



**Fig. 2.10** Influence of **a)** Al on the flow stress of Cu-ETP and Cu-Al alloys. Deformation parameters:  $\phi = 0.4$ ;  $\dot{\phi} = 10 \text{ s}^{-1}$

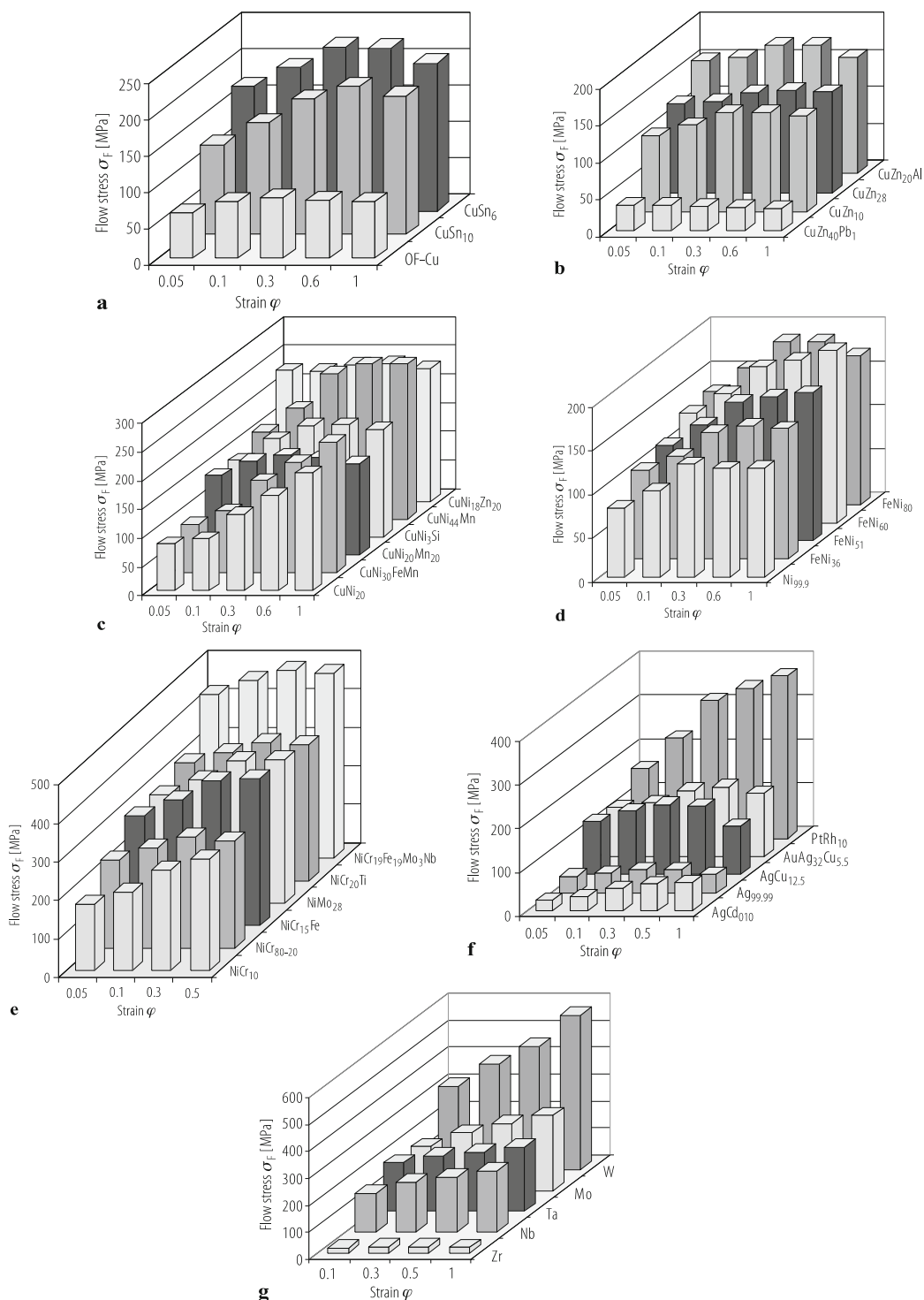


**b)** Ni on the flow stress of Cu-ETP and Cu-Ni alloys. Deformation parameters:  $\phi = 0.2$ ;  $\dot{\phi} = 10 \text{ s}^{-1}$



**c)** Si content and temperature on the flow stress of Cu-ETP and Cu-Si alloys. Deformation parameters:  $\phi = 0.5$ ;  $\dot{\phi} = 10 \text{ s}^{-1}$

A compilation of flow stress data of commercial Cu–Sn, Cu–Zn, Cu–Ni, Ni base and noble metal alloys, and selected heavy metals both according to the authors' experimental data and data taken from the literature [2.9, 2.10, 2.11, 2.12, and 2.13] is presented in Fig. 2.11.



**Fig 2.11** Flow stress comparison of commercial alloys in hot forming **a)** Cu–Sn, ( $\vartheta = 700\text{ }^{\circ}\text{C}$ ;  $\varphi = 0.5$ ;  $\dot{\varphi} = 10\text{ s}^{-1}$ ) **b)** Cu–Zn, ( $\vartheta = 700\text{ }^{\circ}\text{C}$ ;  $\varphi = 0.5$ ;  $\dot{\varphi} = 10\text{ s}^{-1}$ ) **c)** Cu–Ni, ( $\vartheta = 1000\text{ }^{\circ}\text{C}$ ;  $\varphi = 0.5$ ;  $\dot{\varphi} = 10\text{ s}^{-1}$ ) **d)** Fe–Ni, ( $\vartheta = 1000\text{ }^{\circ}\text{C}$ ;  $\varphi = 0.5$ ;  $\dot{\varphi} = 10\text{ s}^{-1}$ ) **e)** Ni–Cr, ( $\vartheta = 1000\text{ }^{\circ}\text{C}$ ;  $\varphi = 0.5$ ;  $\dot{\varphi} = 10\text{ s}^{-1}$ ) **f)** noble metals; ( $\vartheta = 1000\text{ }^{\circ}\text{C}$ ;  $\varphi = 0.5$ ;  $\dot{\varphi} = 10\text{ s}^{-1}$ ) **g)** selected heavy metals; ( $\vartheta = 1000\text{ }^{\circ}\text{C}$ ;  $\varphi = 0.5$ ;  $\dot{\varphi} = 10\text{ s}^{-1}$ )

The flow stress for pure Cu at  $\vartheta = 700\text{ }^{\circ}\text{C}$ ,  $\varphi = 0.10$  and  $\dot{\varphi} = 10\text{ s}^{-1}$  is relatively low, i.e. approximately 74–80 MPa. It increases with impurity content.

*High purity and pure copper* after solidification have a rather low yield stress (Fig. 2.11a) [2.14]. Dynamic recrystallization begins at high hot-forming temperature, even at low degrees of deformation ( $\varphi = 0.1\text{--}0.2$ ). After complete dynamic recrystallization flow stress is only weakly dependent on the degree of deformation.

*Copper–tin–alloys* containing tin 1 to about 15% were studied. For the Cu–Sn alloys studied in this range a homogeneous  $\alpha$ -Sn solid solution is retained in the entire range of hot forming. The formability of the investigated alloys in hot working should be well–cast.

*Copper–zinc–alloys* are currently produced with a maximum Zn content of about 40%. In some cases low amounts of Pb, Al, Mn, Si or Co are added. Fe is an alloying element that leads to a significant increase in flow stress. Alloying and accompanying elements cause all materials in the solid solution and/or precipitation to have an increase in yield stress and a decrease in deformability compared to the pure material.

*Copper–nickel–alloys* show a very weak dependence of flow stress on hot deformation. At  $700\text{ }^{\circ}\text{C}$  and a strain rate of  $\dot{\varphi} = 10\text{ s}$  the flow stress depends on the composition and varies between 200 and 250 MPa.

*Iron–nickel alloys* have a relatively high flow stress. The flow curve has a broad maximum. The flow stress  $\sigma_F$  is reduced only slightly by dynamic softening. Main alloying elements are Cr, Mo and Fe. A comparison of the concentration dependence of flow stress in *nickel–iron alloys* to the universal dependence of high–alloy austenitic Cr and Cr–Ni steels shows that they are at the upper limit of the distribution range for this group of materials.

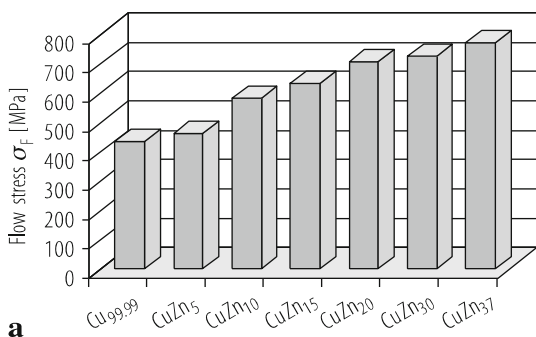
*Noble metals:* The hot flow curves of silver and silver alloys have a pronounced maximum at a deformation of about 0.4 which is observed for the as-cast structure at higher degrees of deformation.

## 2.1.2 Cold working

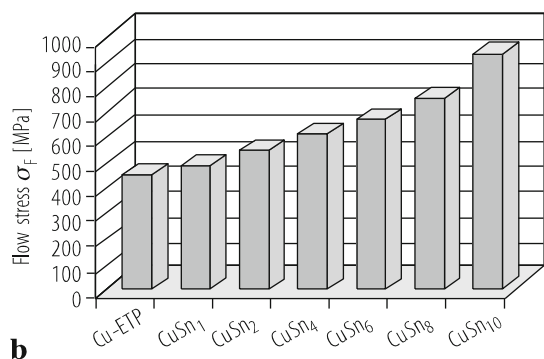
### 2.1.2.1 Basic relationships

From Fig. 2.2 it can be seen that the flow stress increases with increasing difference in atomic radius between the base and the alloying element.

The alloying of Zn to Cu with an atomic radius difference of  $-7.03\%$  leads to a moderate increase in flow stress during cold forming only, while Sn ( $-26.6\%$ ) results in a marked increase. This increase is shown in Fig. 2.12 for the binary alloy series Cu–Zn and Cu–Sn on cold forming to  $\varphi = 1.00$  at a strain rate of  $\dot{\varphi} = 10\text{ s}^{-1}$ .

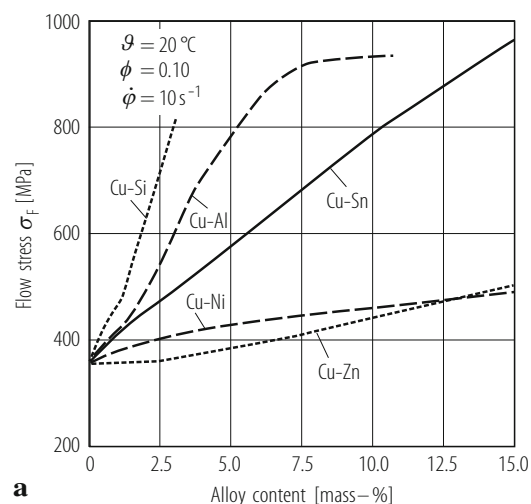


**Fig. 2.12a** Work hardening of binary copper–zinc– alloys with different alloying contents. Deformation parameters:  $\vartheta = 20\text{ }^{\circ}\text{C}$ ,  $\varphi = 1.00$ ,  $\dot{\varphi} = 10\text{ s}^{-1}$

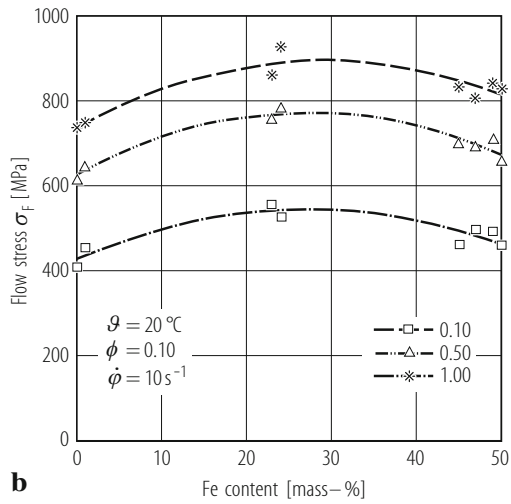


**Fig. 2.12b** Work hardening of binary copper–tin–alloys with different alloying contents. Deformation parameters:  $\vartheta = 20\text{ }^{\circ}\text{C}$ ,  $\varphi = 1.00$ ,  $\dot{\varphi} = 10\text{ s}^{-1}$

In this context it is interesting to note the difference between the flow stress of pure and commercial Cu99.99, Cu99.95 or Cu–DHP (Cu99.85) with a maximum of 0.1% impurities. The flow stress at room temperature increases by 194 to 224 MPa for Cu–OFE and Cu–DHP, respectively, at  $\vartheta = 20\text{ }^{\circ}\text{C}$ ,  $\varphi = 0.10$  and  $\dot{\varphi} = 10\text{ s}^{-1}$ . It was found for both cold and hot deformation that the increase in flow stress by the difference in atomic radii between the two elements of a binary alloy is independent of whether the difference is positive or negative. For binary alloys, the alloying elements tin, silicon, titanium, aluminium and zinc cause a significant increase in yield stress due to their large atomic radii and differences in the shear modulus (Fig. 2.13) while nickel, iron and chromium are not as effective [2.15].

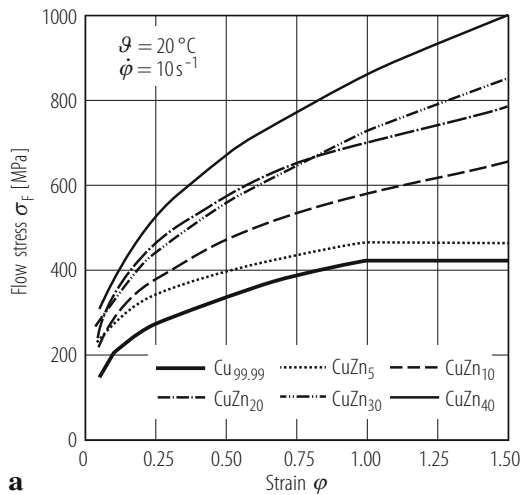


**Fig. 2.13a** Work hardening of binary copper alloys with different alloying elements Deformation parameters:  $\vartheta = 20\text{ }^{\circ}\text{C}$ ,  $\varphi = 0.10$ ,  $\dot{\varphi} = 10\text{ s}^{-1}$

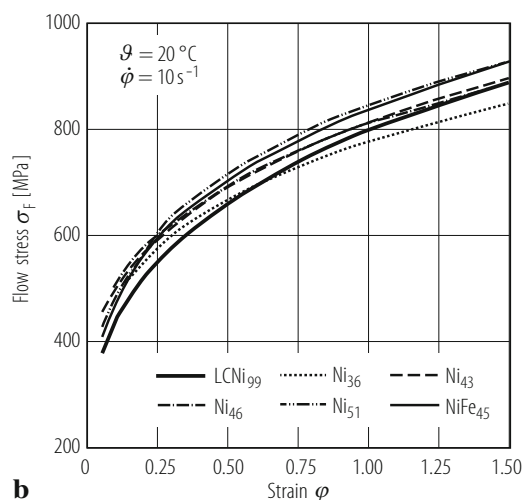


**Fig. 2.13b** Work hardening of copper–iron alloys with different alloying content Deformation parameters:  $\theta = 20\text{ }^{\circ}\text{C}$ ,  $\dot{\phi} = 10\text{ s}^{-1}$

Compared to hot forming, the order of the elements that cause an increase in flow stress is different in cold forming. This is due to the fact that the solubility of alloying elements at room temperature is significantly lower than at  $700\text{ }^{\circ}\text{C}$ . Therefore, the flow stress is both solid solution hardening and increases the excretion of other phases (Fig. 2.14).

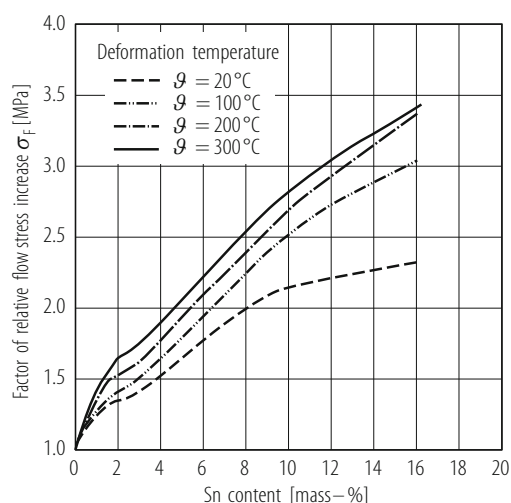


**Fig. 2.14a** Influence of zinc content on the flow curve at room temperature for Cu–Zn alloys. Deformation parameters:  $\theta = 20\text{ }^{\circ}\text{C}$ ,  $\dot{\phi} = 10\text{ s}^{-1}$



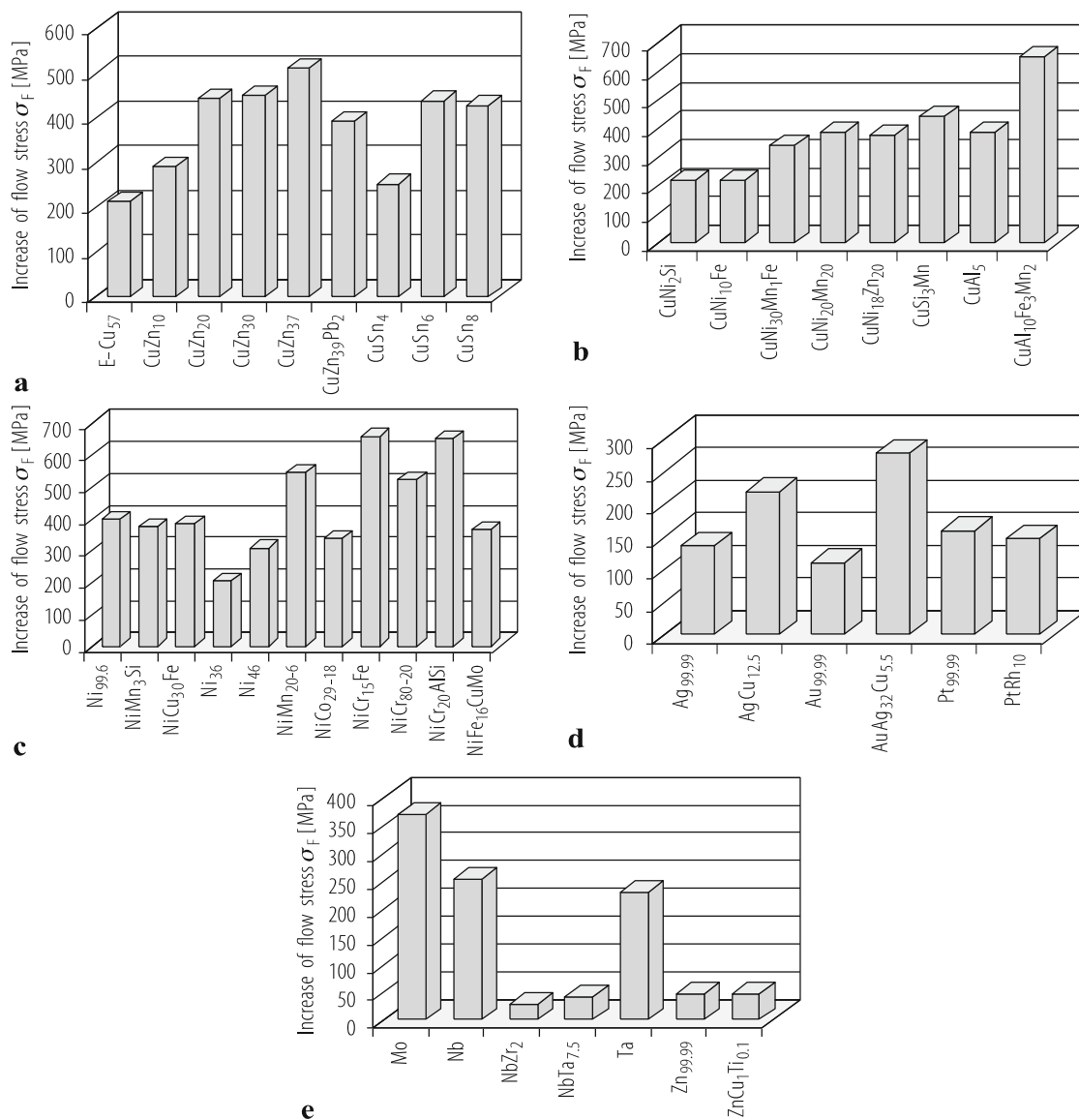
**Fig. 2.14b** Influence of Ni content on the flow curve at room temperature for Fe–Ni alloys. Deformation parameters:  $T = 20\text{ }^{\circ}\text{C}$ ,  $\dot{\phi} = 10\text{ s}^{-1}$

Thus, Sn increases the relative flow stress with increasing temperature by formation of solid solution in the range of cold deformation, as shown in Fig. 2.15. It can be seen that an increase in alloy content can cause a significant increase in flow stress, which can be more pronounced with increasing temperature [2.14].



**Fig. 2.15** Influence of the tin content on the increase in flow stress in Cu–Sn alloys by cold deformation. Deformation parameters:  $\phi = 0.40$ ;  $\dot{\phi} = 10\text{ s}^{-1}$

The specific work hardening behaviour of different materials, expressed in terms of the difference of flow stress at the degree of deformation of 1.00 and 0.10, respectively, is strongly dependent on the alloy and the alloy concentration [2.15, 2.16]. By increasing the degree of deformation from 0.10 to 1.00 pure copper is strain-hardened from 200 to 400 MPa (Fig. 2.16), for copper-zinc alloys with a zinc content of 40% the flow stress is increased by about 450 MPa. This information applies to the homogenized state. In the cold worked, hot-rolled and precipitation hardened state the levels of flow stress rise at small strains, so that the degree of work hardening may be reduced.



**Fig. 2.16** Influence of chemical composition on the strain hardening at room temperature. Deformation parameters:  $\theta = 20^\circ\text{C}$ ,  $\varphi = 0.20$ ,  $\dot{\varphi} = 10\text{ s}^{-1}$  a) Cu–Zn alloys b) Cu–Ni alloys and brass c) Ni alloys d) Noble metal alloys e) Various heavy metals

Alloys of Cu–Sn–Zn and Cu–Zn–Sn work harden less strongly; they can contain additional alloying elements such as aluminium, manganese, silicon and iron by which the degree of work hardening is increased further. In general, increasing the alloy content in otherwise identical conditions increases the flow stress, tensile strength, yield strength, hardness and the work hardening tendency, but reduces the plastic properties.



The above statements are derived from considering the question of how the permissible compositional variation of an alloy affects the flow stress. The answer as to what increases the strength, results from an analysis of differences in flow stress and is illustrated by three examples (Table 2.3) (state of material: soft annealed,  $\vartheta = 20\text{ }^{\circ}\text{C}$  and  $\dot{\varphi} = 10\text{ s}^{-1}$ ).

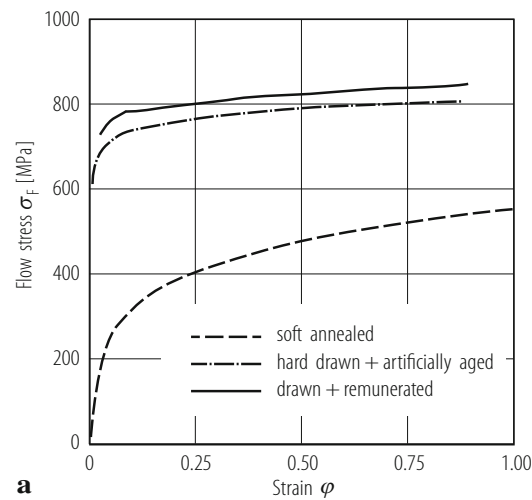
**Table.2.3** Effect of variations in composition on flow stress

|                  | Chemical composition [mass - %] |      |     |    |    |     |       |       | Flow stress [MPa] |                  |
|------------------|---------------------------------|------|-----|----|----|-----|-------|-------|-------------------|------------------|
|                  | Cu                              | Zn   | Si  | Al | Ni | Co  | Fe    | Pb    | $\varphi = 0.10$  | $\varphi = 0.50$ |
| CuZn30 CuZn31Si1 | 70                              | Bal. | -   | -  | -  | -   | <0.05 | <0.07 | 259.2             | 509.4            |
|                  | 71                              | 28   | 0.6 | -  | -  | -   | 0.11  | 0.035 | 380.6             | 696.4            |
| CuZn28Al4Ni3CoSi | 63                              | 28   | 0.5 | 4  | 3  | 0.5 | -     | 0.3   | 389.6             | 952.1            |

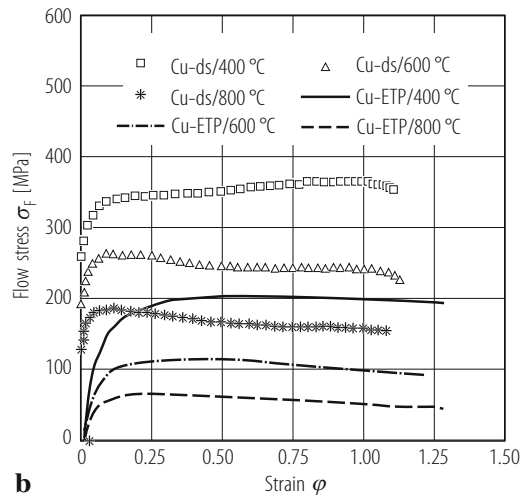
A comparative analysis of the average stress shows differences of  $\pm 12.5\text{--}15\%$ , which can be varied by additional alloying elements and/or precipitation up to 50%.

#### 2.1.2.2 Influence of pre-treatment condition

The state of pre-treatment of copper alloys has a considerable influence on the behaviour in cold forming (Fig. 2.17). The lowest flow stress for the same degree of deformation and strain rate is obtained in the soft annealed state, and the highest one in the precipitation hardened state.



**Fig 2.17a** Influence of the material condition on the flow stress on CuNi2Si. Deformation parameters:  $\vartheta = 20\text{ }^{\circ}\text{C}$ ;  $\dot{\varphi} = 10\text{ s}^{-1}$



**Fig 2.17b** Influence of the material condition on the flow stress of Cu-ETP and dispersion-strengthened copper (Cu-ds). Deformation parameters:  $\vartheta = 400; 600$  and  $800\text{ }^{\circ}\text{C}$ ;  $\dot{\varphi} = 10\text{ s}^{-1}$

In addition to the absolute initial value of flow stress the hardening behaviour will increase the "hardening exponent" from "softened" via "rolled" to "room temperature (natural) aging" and higher, while "high temperature aging", which is about the same magnitude as hot rolled, yields much higher values in flow stress (Fig. 2.17). Moreover, the flow stress and hardening behaviour are influenced by the aging conditions such as aging temperature and time within wide limits.

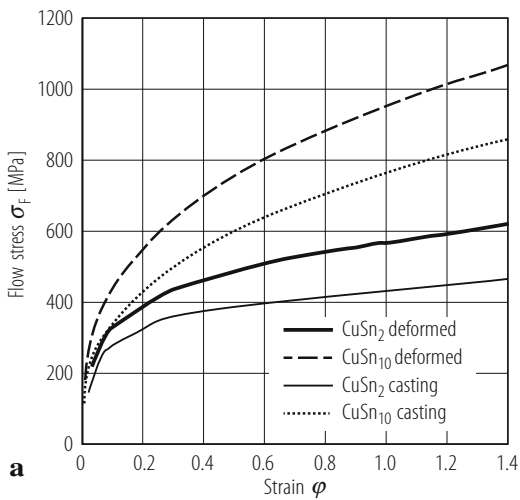
Increasing the time of aging increases the flow stress and reduces the strain hardening exponent. Similar results were found for the curing of other alloys at room temperature (Table 2.4).

**Table 2.4** Influence of flow stress and hardening exponent of natural aging

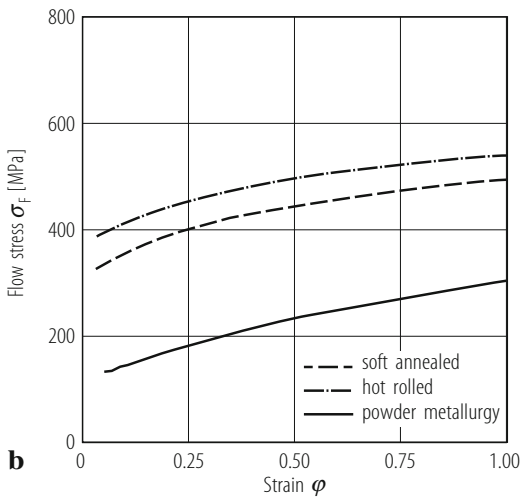
| Temperature at [ $^{\circ}\text{C}$ ] | Cu-ETP                                             |                    | Cu dispersion-strengthened (Cu-ds)                 |                    |
|---------------------------------------|----------------------------------------------------|--------------------|----------------------------------------------------|--------------------|
|                                       | Flow stress (at $\varphi = 0.4$ ) $\sigma_F$ [MPa] | Hardening exponent | Flow stress (at $\varphi = 0.4$ ) $\sigma_F$ [MPa] | Hardening exponent |
| 400                                   | 200.8                                              | 0.1913             | 345.7                                              | 0.0348             |
| 600                                   | 113.2                                              | 0.1120             | 245.4                                              | -0.0222            |
| 800                                   | 64.9                                               | 0.0726             | 173.1                                              | -0.0440            |

### 2.1.2.3 Initial structure

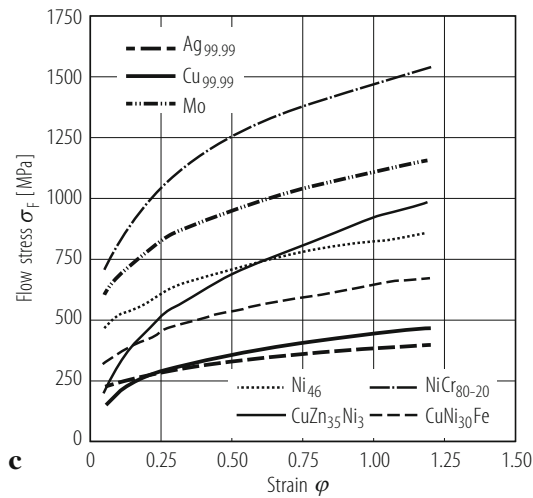
Heavy metals such as CuSn2 and CuSn10 cold deformed with the same conditions in the as-cast and hot-rolled strip form (Fig. 2.18a), and showed that a difference in  $\sigma_F$  of about 160–200 MPa exists between the two production alternatives for hot-rolled strip (cold rolling with a strain total of  $\varphi = 0.7$  ( $\epsilon \sim 100$ )). In cold rolling of cast strip with the same deformation conditions the difference between the two production variants is reduced to only 120–140 MPa. The increase in flow stress as a function of strain of CuSn2 and various heavy metals in different initial conditions are shown in Figs. 2.18b and 2.18c.



**Fig 2.18a** Flow stress of as-cast and hot rolled strip of CuSn<sub>2</sub> and CuSn10. Deformation parameters:  $\vartheta = 20\text{ }^{\circ}\text{C}$   $\dot{\varphi} = 10\text{ s}^{-1}$



**Fig 2.18b** Flow stress of CuSn<sub>2</sub> in different initial conditions. Deformation parameters:  $\vartheta = 20\text{ }^{\circ}\text{C}$ ,  $\dot{\varphi} = 10\text{ s}^{-1}$

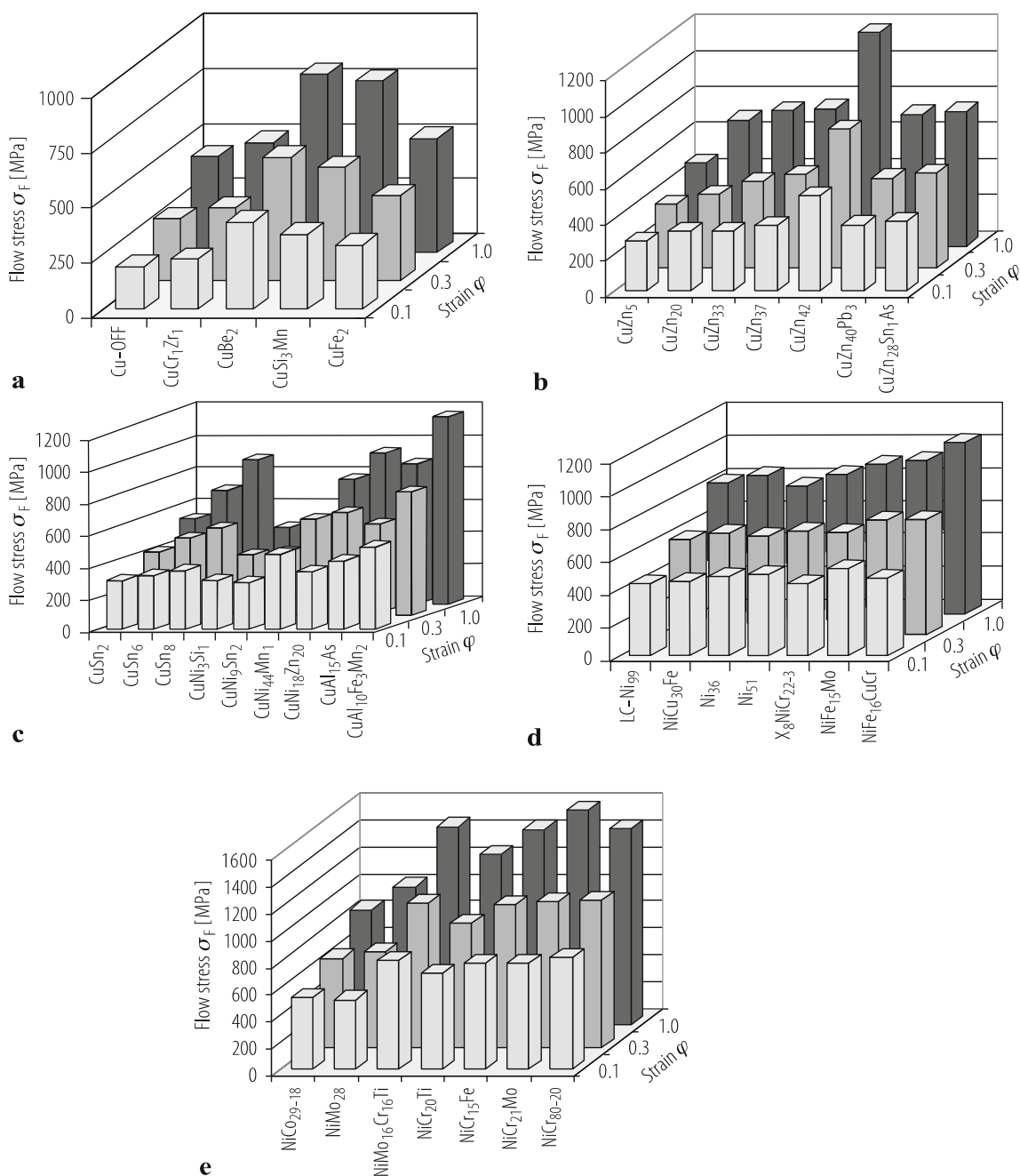


**Fig 2.18c** Strain dependence of the flow stress of heavy metals. Deformation parameters:  $\vartheta = 20\text{ }^{\circ}\text{C}$ .  $\dot{\varphi} = 30\text{ s}^{-1}$ ; annealed

These differences are caused by the different states of solution and precipitation of the alloying and impurity elements. These, in turn, are due to different solidification conditions during crystallization of the cast strip and of the continuously cast ingot as starting material for the hot strip. The flow stress data of our own experiments and data from the literature for three degrees of deformation of various heavy metal alloys of Cu, Cu–Zn–, Cu–Sn–, Ni and Ni–alloys are compared in Figs. 2.12, 2.17, 2.18 and 2.19. The comparison is at  $20\text{ }^{\circ}\text{C}$ .

In cold forming, the flow stress of low alloyed copper alloys, such as CuCr1Zr1 and CuFe2 at  $\varphi = 1.00$  does not reach 500 MPa (Fig. 2.19a). Alloys with beryllium (CuBe2) and silicon (CuSi3Mn) are strain-hardened more strongly even at low alloy content and reach a flow stress of approximately 750 MPa at  $\varphi = 1$ . Copper-zinc alloys at  $20\text{ }^{\circ}\text{C}$  and  $\varphi = 1$  achieves 650–700 MPa. If in addition to the  $\alpha$ -phase the  $\beta'$ -phase occurs in the structure at  $20\text{ }^{\circ}\text{C}$  the flow stress increases up to  $>1100\text{ MPa}$  for  $\varphi = 1.0$  (Fig. 2.19b).

Figure 2.19c shows that the flow stress of copper–tin, and copper–nickel and copper–aluminium alloys increases with increasing alloy content, respectively. In high–alloyed iron–copper–aluminium alloys



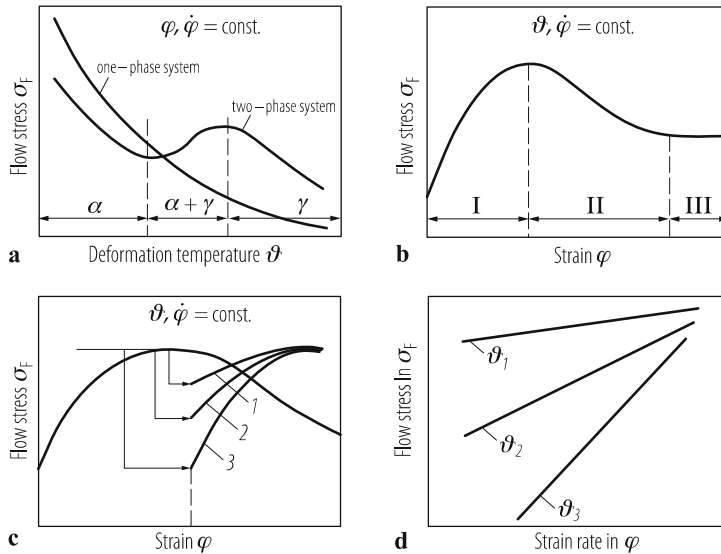
**Fig. 2.19** Comparison of flow stress of commercial Cu- and Ni-alloys in cold forming; Deformation parameters:  $\theta = 20^\circ\text{C}$ ,  $\dot{\varphi} = 10\text{ s}^{-1}$  a) Cu and different Cu-alloys b) Cu-Zn alloys c) Cu-Sn-, Cu-Al- and Cu-i alloys d) Ni-Fe alloys e) different Ni alloys

flow stress values up to 1200 MPa may be achieved. This observation confirms the significance of the atomic radius and shear modulus differences for the flow stress. Commercial binary nickel–iron alloys of different compositions have very much the same tendency in work hardening at  $\varphi = 1.0$  and  $20^\circ\text{C}$  (Fig. 2.19d). Multi-component nickel base alloys, however, can achieve much higher values (Fig. 2.19e).

## 2.2 Influence of forming conditions

### 2.2.1 Hot forming

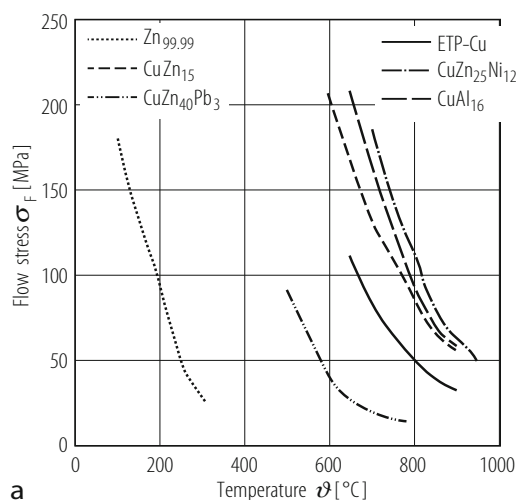
Figure 2.20 shows the influence of the deformation conditions on the flow stress of metals. The most important parameters will be discussed below.



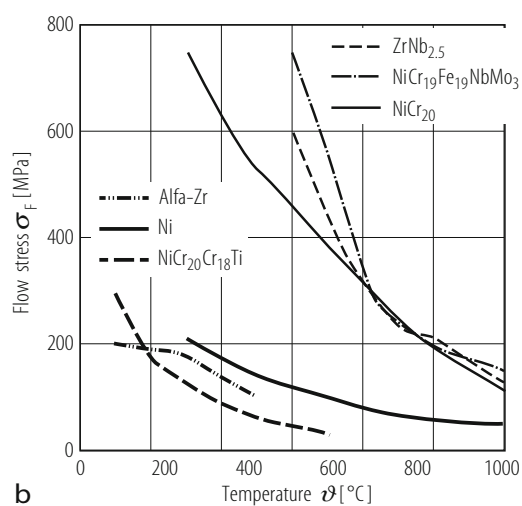
**Fig. 2.20** Material related variables that influence the flow stress at hot deformation. **(a) Deformation temperature:** in the single phase system, the flow stress decreases exponentially with higher temperatures. If several phases exist,  $\sigma_F$  increases. This effect is material-dependent. **(b) Degree of deformation:** the flow stress characteristics depend on material and deformation conditions. A hot flow curve consists of three ranges: I - hardening range ( $\sigma_F$  increases with increasing deformation); II - range of dynamical softening ( $\sigma_F$  decreases with increasing deformation); III - steady state range ( $\sigma_F$  is independent on the degree of deformation). **(c) Time between two steps of deformation:** if the total deformation is realized in two steps, then a partial recovery (1, 2) or a complete recovery (3) can occur in the time between the steps. **(d) Deformation rate:** in a double logarithmic diagram,  $\sigma_F$  depends linearly on the deformation rate. Three curves for different deformation temperatures  $\vartheta_1 < \vartheta_2 < \vartheta_3$  are shown

#### 2.2.1.1 Influence of the deformation temperature

The yield stress of pure copper and zinc, as well as various Cu alloys in relation to the deformation temperature can be seen in Fig. 2.21a. The flow stress decreases with rising temperatures. Generally, the temperature dependence of the flow stress is dependent on the strain rate only to a small extent. From the monotonous temperature dependence of the flow stress it can be concluded that in the temperature range considered no structural changes occur. Figures 2.21a and 2.21b are based on the results from a torsion test.



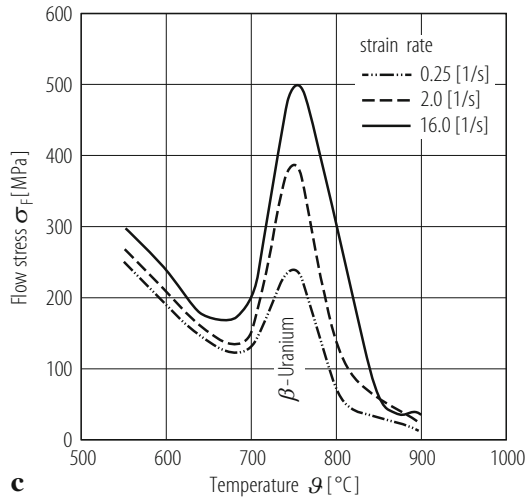
**Fig. 2.21a** Temperature dependence of the flow stress of Cu-, Zn- and Cu-Zn-alloys; Deformation parameters:  $\varphi = 0.30$ ;  $\dot{\varphi} = 1.0 \text{ s}^{-1}$



**Fig. 2.21b** Temperature dependence of the flow stress of Zr-alloys and different Ni-alloys; Deformation parameters:  $\varphi = 0.30$ ;  $\dot{\varphi} = 1.0 \text{ s}^{-1}$

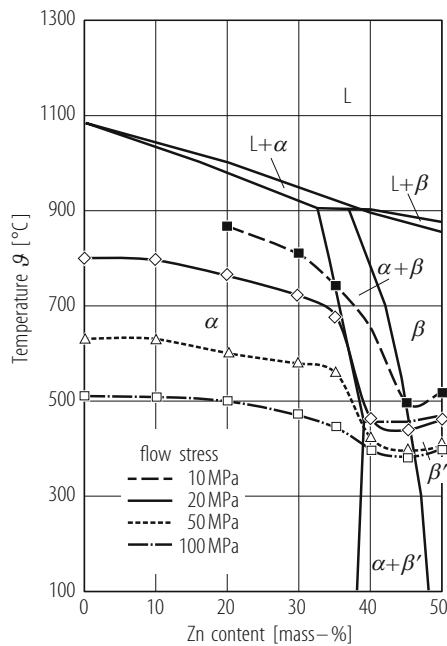
If the deformation takes place in a single-phase region the flow stress following the temperature dependence of an exponential function, which is derived from the Arrhenius expression, is usable if the deformation and the strain rate is constant. This applies to both hot and cold forming, with different exponents.

If in the observed temperature range, a phase transformation can change the exponent. There are especially strong changes of the exponent of the function during forming of uranium in the temperature range between 700 and 850 °C by the formation of  $\beta$ -uranium (Fig. 2.21c).



**Fig. 2.21c** Uranium; Deformation parameters:  $\varphi = 0.20$

In the range of a homogeneous  $\alpha$ -solid solution and with the same deformation conditions, the flow stress is only slightly dependent on the zinc content. This dependence is followed by a sharp drop in the two-phase region  $\alpha + \beta$  (Fig. 2.22).

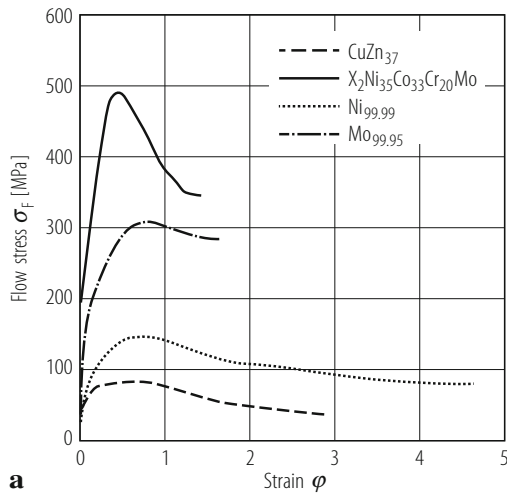


**Fig. 2.22** Lines of equal flow stress in the system copper–zinc. Deformation parameters:  $\varphi = 0.30$ ;  $\dot{\varphi} = 1.0 \text{ s}^{-1}$

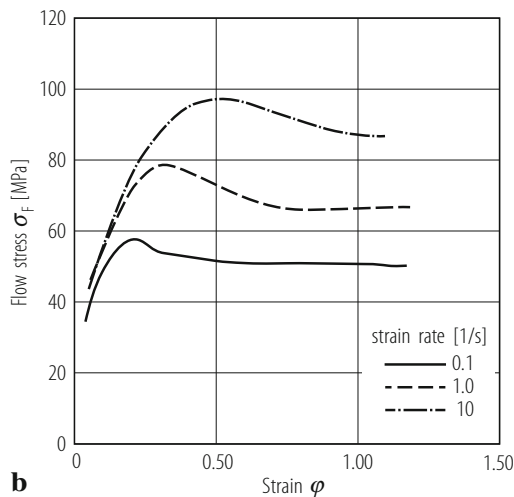
### 2.2.1.2 Influence of strain

Figures 2.23a and 2.23b confirm that the pattern shown in Fig. 2.20 describes a general dependence of the flow stress of deformation in hot forming of metals, while alloy specific differences are observed.





**Fig. 2.23a** Hot flow curves of different heavy metals. Deformation parameters:  $\dot{\epsilon} = 10.0 \text{ s}^{-1}$  Temperature: CuZn37 at  $700^\circ\text{C}$ , Ni99.9; Mo99.95; X2Ni35Co33Cr20Mo at  $1000^\circ\text{C}$

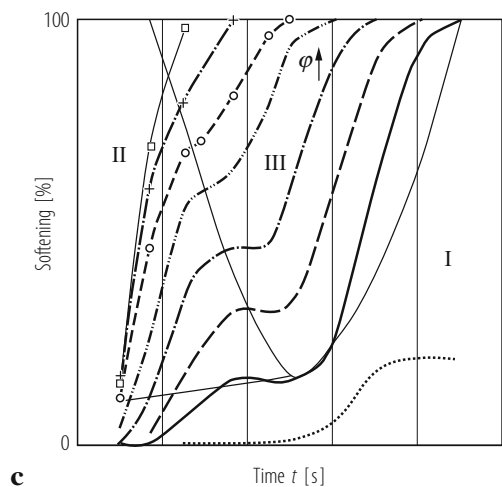


**Fig. 2.23b** Influence of strain on flow stress in hot forming of Cu-DHP;  $\vartheta = 650^\circ\text{C}$ .

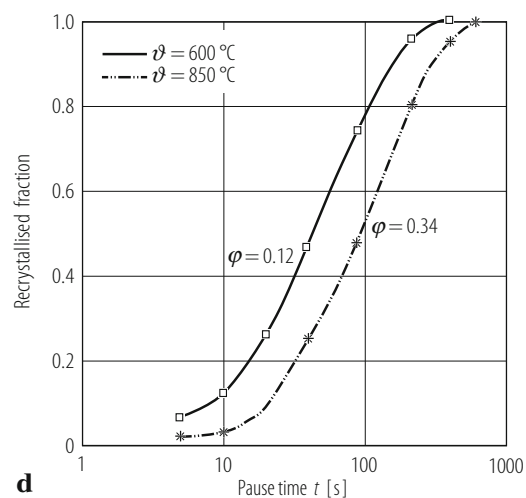
For heavy metal alloys the hardening exponent is higher at the onset than at higher degrees of deformation. Dynamic recrystallization sets in at the maximum point of the stress–strain curve and leads to a significant reduction in flow stress as the strain increases. Dynamic softening is more pronounced by increasing the deformation rate and degree of deformation during hot forming. It should be noted that work hardening is limited in hot deformation [2.8].

The progressive dynamic recrystallization leads to a flow stress which is independent of the strain. This value is higher than the stress at the start of forming at  $\varphi = 0$  and the selected deformation parameters. The flow stress at which dynamic softening ends is also dependant on the temperature and the strain rate. Decreasing temperatures and rising strain rates increase the stress.

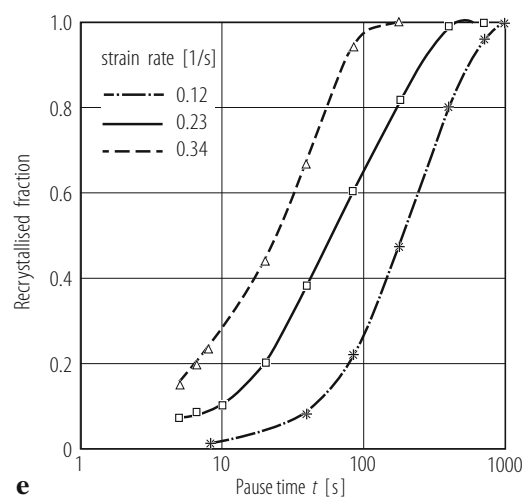
In principle as a function of time three methods can be distinguished for softening after hot working: Static recovery; metadynamic recrystallization and static recrystallization. Static recovery (region I in Fig. 2.23c) is based on rearrangement and resolution of dislocations which leads to a reduction in the strength. If during the hot forming new nuclei are formed at a sufficiently high temperature, a fast softening by metadynamic recrystallization (region II) takes place. In most cases the greatest amount of softening by static recrystallization (region III) takes place. In this time range the softening, the particle size and particle formation increases.



**Fig. 2.23c** Schematic profile of the softening behaviour in hot forming. I – Static recovery II – Metadynamic recrystallization III – Static recrystallization



**Fig. 2.23d** Static softening of CuZn30. Deformation at  $\dot{\varphi} = 2.0 \text{ s}^{-1}$

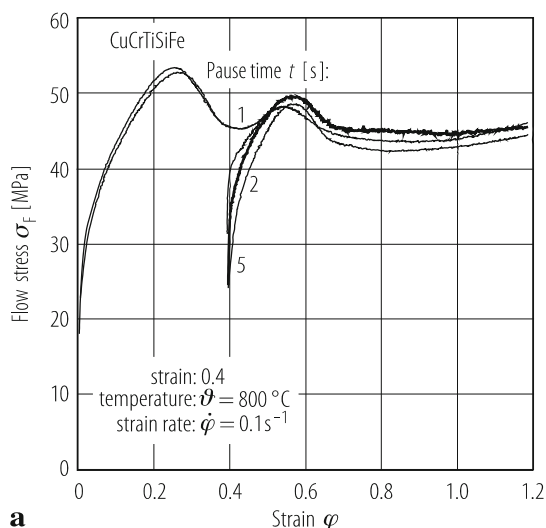


**Fig. 2.23e** Static softening of CuZn30. Deformation parameters:  $\vartheta = 700 \text{ °C}$ ;  $\dot{\varphi} = 2.0 \text{ s}^{-1}$

Softening of the material by meta-dynamic and static recovery, followed by recrystallization takes place after some time, in the intervals between two roll passes in hot forming. Therefore it is necessary to know the flow stress for the pass schedule design of a continuous rolling mill during the forming process, including the softening during the pause time.

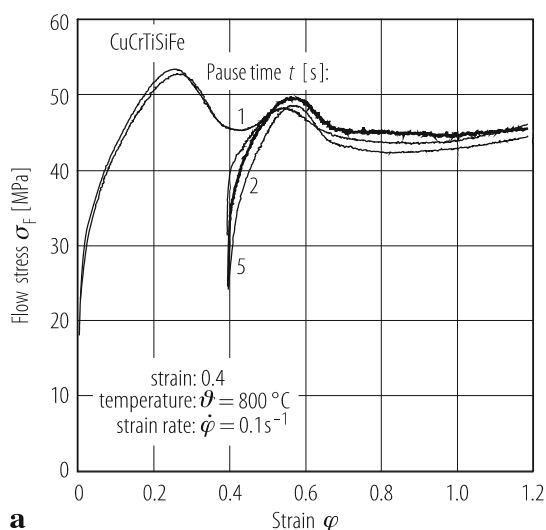
For the dependence of softening on time, Figs. 2.23d and 2.23e [after 2.41] show the variation of softening as a function of time for CuZn30 at two temperatures. The higher the temperature, the faster the increase in softening, which is complete after 400 s at 850 °C and  $\varphi = 0.12$ . Similarly, the rate of softening increases with increasing strain rate.

In Fig. 2.24a the static softening of CuCrTiSiFe by the time dependence of the flow stress at 800 °C is shown. The first step was performed with a  $\varphi = 0.4$ , after which pause times of 1, 2 and 5 s were realized before the second forming stage.

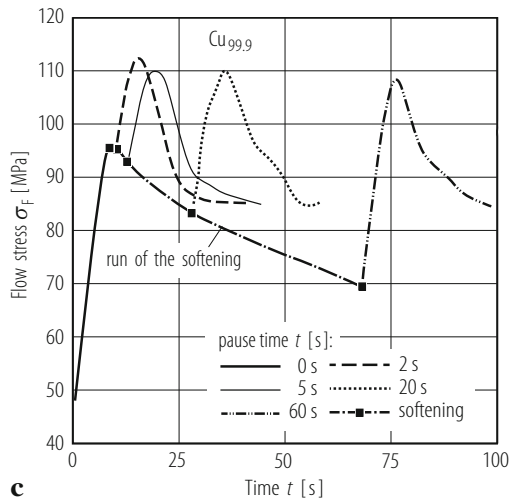


**Fig. 2.24a** CuCrTiSiFe. Two-step flow curves for different temperatures.

Similar dependences of the flow stresses of CuSn6 and Cu99 were determined for different pause times and forming parameters, Figs. 2.24b and 2.24c.



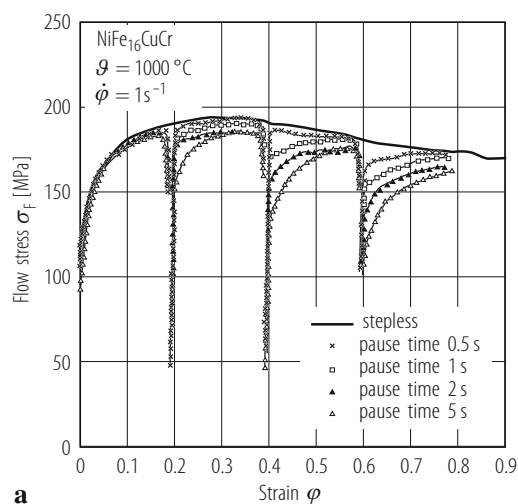
**Fig. 2.24b** CuSn6. Two-step flow curves for different temperatures. Deformation parameters:  $\vartheta = 600$  °C;  $\dot{\varphi} = 0.1$  s<sup>-1</sup>



**Fig. 2.24c** Cu99.9. Two-step flow curves for different temperatures. Deformation parameters:  $\vartheta = 500\text{ }^{\circ}\text{C}$ ,  $\dot{\varphi} = 0.018\text{ s}^{-1}$

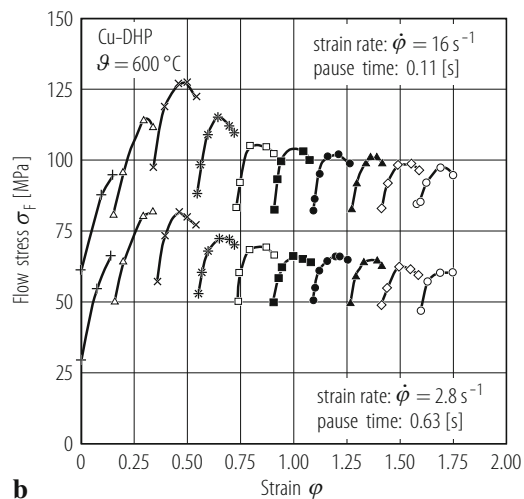
Theoretically, the flow stress curve of the second deformation stage should be the same as that of the first stage after complete softening or as that of the first deformation stage, shifted to the right only by the amount of the stage deformation strain.

As can be seen in a comparison between continuous and multi-step flow curves, both curves have the typical characteristics of hot flow curves. The deformation begins with work hardening, followed by dynamical softening. After completion of the dynamical softening, the flow stress is independent of the degree of deformation and is only affected by temperature and rate of deformation. If the degree of deformation of the first step is greater than the reduction ratio at the maximum flow curve, the maximum flow stress value of the second stage may be lower than the maximum value of the flow stress of the first step, which is valid for all three temperatures studied. The reason is the temperature rise caused by the heat of deformation. The static softening in the pause times leads neither to qualitatively different flow curve characteristics nor to a significant reduction of the absolute value of flow stress. Therefore, the evaluation of multi-stage forming processes for the same deformation conditions are seen for continuous hot flow curves. If precipitation processes occur in parallel to softening during the pause time between passes, they lead to a considerable increase in flow stress with an increasing number of passes and a decreasing deformation temperature. This can be seen in Fig. 2.25a for the alloy NiFe16CuCr which was rolled at  $1000\text{ }^{\circ}\text{C}$  in four passes ( $\varphi = 0.19$ ,  $\varphi_{\text{total}} = 0.78$ ) with pause times between 0.5 and 5.0 s. For small pause times (about 0.5 s) the continuous and the multi-stage flow curves are almost identical, in contrast, the difference is greater for almost complete softening. Flow curves differences increase with decreasing experimental temperature and increasing pause time.



**Fig. 2.25a** Effect of the pause time on the flow stress for NiFe<sub>16</sub>CuCr at  $\vartheta = 1000\text{ }^{\circ}\text{C}$  and strain rate  $1\text{ s}^{-1}$

Even very low-pause times ( $\sim 0.1\text{ s}$ ) are in the flow curve maximum significant softening region, as shown in Fig. 2.25b for Cu–DHP.



**Fig. 2.25b** Effect of the pause time on the flow stress for Cu–DHP at  $\vartheta = 600\text{ }^{\circ}\text{C}$

### 2.2.1.3 Influence of strain rate

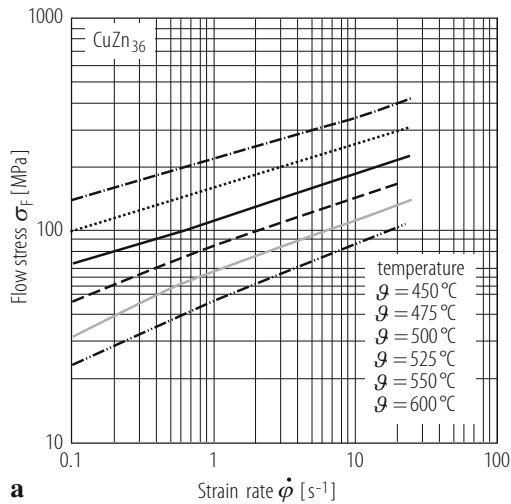
According to Alder and Philips [2.10], the equation:

$$\sigma_{F1} = \sigma_{F2} \left( \frac{\dot{\varphi}_1}{\dot{\varphi}_2} \right)^m, \quad (2.3)$$

applies to hot and cold forming.  $\sigma_{F1}$  and  $\sigma_{F2}$  are the values of flow stress corresponding to the strain rates  $\dot{\varphi}_1$  and  $\dot{\varphi}_2$  (at constant temperature and degree of deformation).

There is proportionality between the changes in strain and the deviating stresses, i.e. the flow stress depends on the deformation rate. This dependence is a straight line in the double logarithmic representation, where the rate exponent is a function of the temperature. It is significantly lower at cold deformation than at hot deformation.

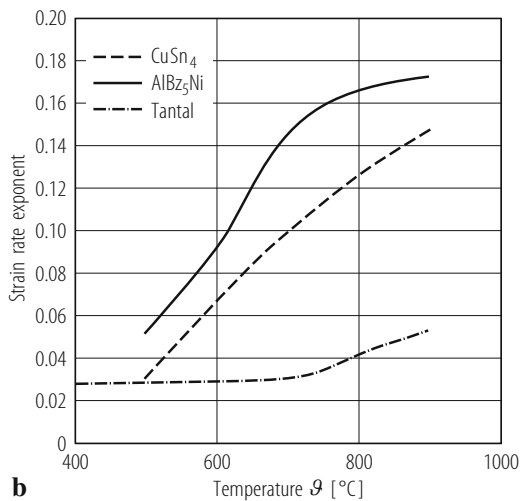
Increasing the strain rate raises the flow stress at constant temperature and at constant strain, which can be seen in Fig. 2.26a. The strain rate exponent  $m$ , which expresses the increase in flow stress with increasing strain rate, increases with increasing temperature from 0.2003 at  $450\text{ }^{\circ}\text{C}$  to 0.2834 at  $600\text{ }^{\circ}\text{C}$  in the case of CuZn36 (strain 0.30) and from 0.0207 at  $500\text{ }^{\circ}\text{C}$  to 0.0926 at  $1000\text{ }^{\circ}\text{C}$  in the case of Ni99.9.



**Fig. 2.26a** Influence of strain rate on flow stress in hot forming of CuZn36;  $\varphi = 0.30$

The strain rate exponent decreases with increasing deformation and increasing grain size. It is also dependent on the microstructure and strain rate.

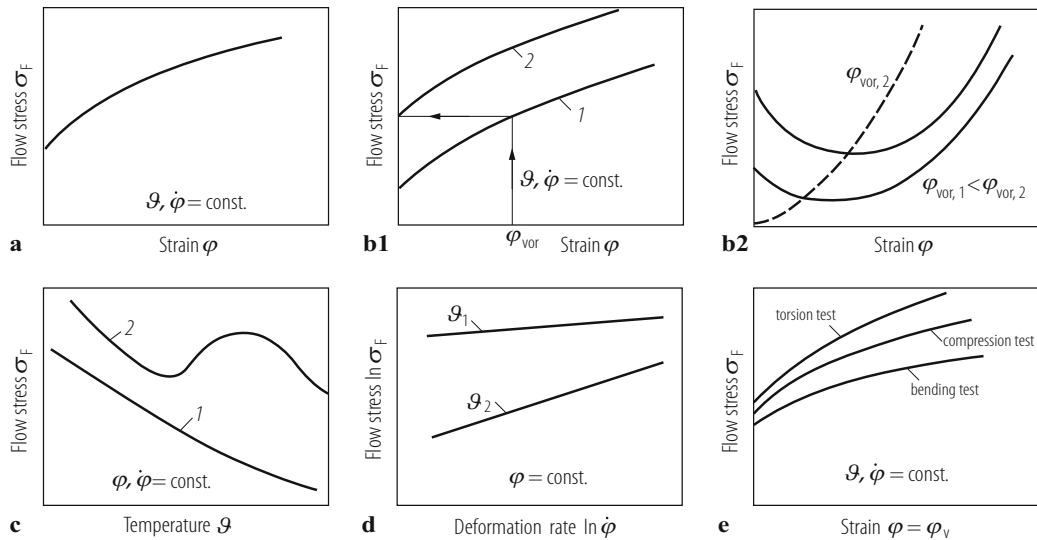
The rate exponent  $m$ , increases continuously with increasing forming temperature if no phase transformations and precipitation processes take place in the material (Fig. 2.26b).



**Fig. 2.26b** Strain rate exponent selected heavy metals;  $\varphi = 0.20$

### 2.2.2 Cold forming

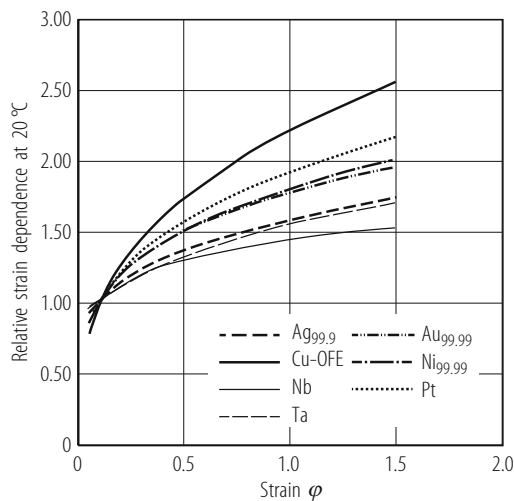
Figure 2.27 gives an overview of the influence of material-related parameters on the flow stress in cold deformation of metals. Degree, strain rate and temperature of deformation, will be discussed in more detail below.



**Fig. 2.27** Material-related parameters on the flow stress in cold deformation. **(a) Degree of deformation:** an increase of the flow stress  $\sigma_F$  as a result of hardening occurs until the plasticity limit is reached. In a double logarithmic diagram, a linear correlation between flow stress  $\sigma_F$  and degree of deformation  $\varphi$  occurs for certain ranges of degree of deformation **(b) Degree of pre-forming:** at constant load, pre-hardening leads to an increase of the flow stress  $\sigma_F$ . 1 - soft-annealed; 2 - preformed with  $\varphi_{pre}$ . A change of loading (tension vs. compression) leads to a mechanical hysteresis (Bauschinger-effect) **(c) Temperature:** in the single phase range the flow stress  $\sigma_F$  decreases with increasing temperature according to the Arrhenius-equation (curve 1). Precipitation processes can disturb the monotonous decrease (curve 2). **(d) Deformation rate:** in a double logarithmic diagram (with different temperatures  $\vartheta_1 < \vartheta_2$ ), a linear correlation between flow stress  $\sigma_F$  and deformation rate exists, although the slope is much smaller than at hot deformation. **(e) Method of determination:** despite a translation into reference stresses and reference degree of deformation, the flow stress depends on the method of investigation such as torsion test, compression test and bending test

### 2.2.2.1 Degree of forming

Cold forming leads to strain hardening until the capability of deformation of the material is exhausted. Strongest strain hardening is observed for cubic face-centred materials [2.19]. In Fig. 2.28, the strain hardening behaviour of several heavy metals at room temperature is compared.



**Fig. 2.28** Relative flow stress  $\sigma_F(\varphi)/\sigma_F(\varphi=0,1)$  of heavy metals at 20 °C

The tendency of strain hardening of heavy metals is very different. For Cu99.9 and CuZn37 an increase of the degree of forming from 0.10 to approximately 0.30 leads to an increase in flow stress by 15 at 20%.

For Ni99.9 and Mo 99.9 and for the same deformation conditions, an increase of the flow stress of about 40–45% is obtained.

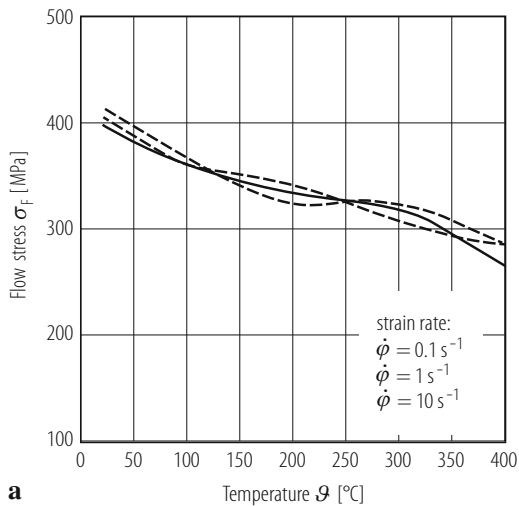
Hardening is expressed by the hardening exponent  $n$  quantifying the slope of the flow curve in a double logarithmic representation:

$$\sigma_F = \sigma_{F(\varphi=1,0)} * \varphi^n \quad \varphi, \vartheta = \text{const.}$$

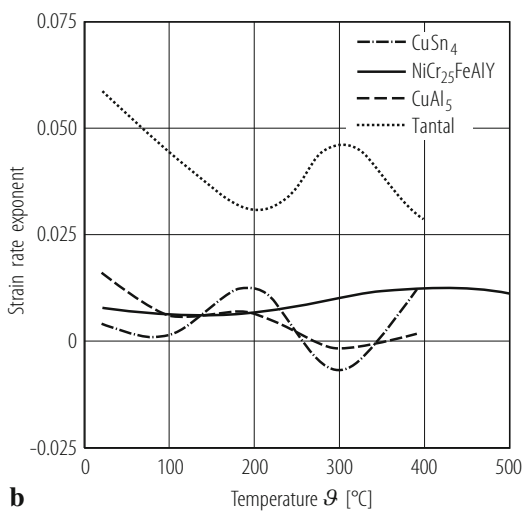
For many materials and material states, the hardening exponent  $n$  is not a constant but a function of the degree of forming [2.10, 2.9]. In a rough approximation, two ranges in the flow curve can be observed in which the hardening exponent is constant ("double- $n$ -behaviour" [2.20]).

### 2.2.2.2 Forming rate

In general, the rate exponent  $m$  increases with degree of cold deformation (Eq. 2.3); also, it increases continuously with increasing deformation temperature, when no phase transitions and precipitation processes take place. In cold forming of metals, the influence of the strain rate in certain temperature ranges is reversed, so that the rate exponent  $m$  is negative (Fig. 2.29a and 2.29b).



**Fig. 2.29a** Temperature dependence of the flow stress of CuSn4;  $\varphi = 0.2$



**Fig. 2.29b** Temperature dependence of the strain rate exponent for selected heavy metal alloys

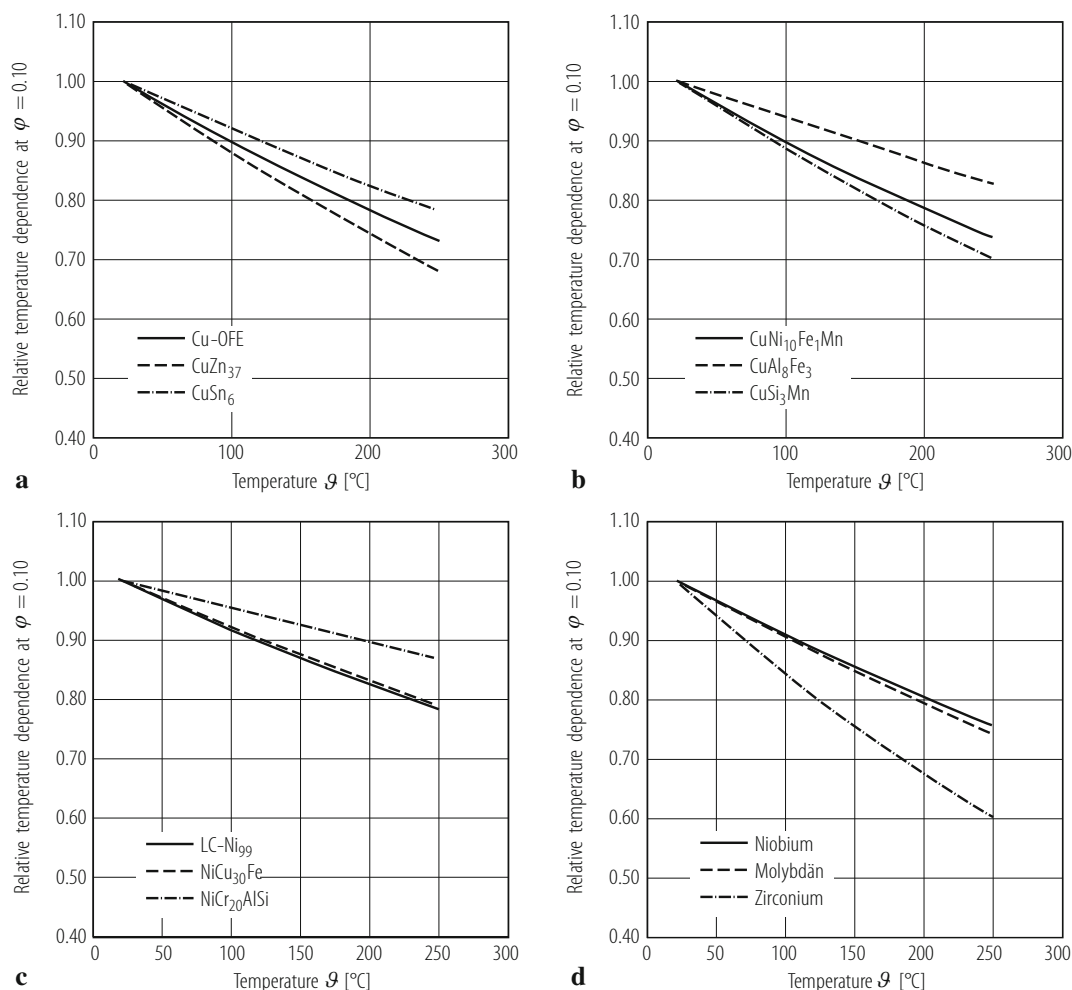
With increasing strain rate the flow stress increases only up to a limit, which is dependent on the material. At higher strain rates  $>100$  [1/s], the flow stress decreases again due to the heat of deformation.



Depending on the material, the strain rate exponent in cold forming of copper– and nickel alloys ranges between  $-0.01$  and  $0.02$ . In some cases it can be negative; especially when age hardened materials are deformed.

### 2.2.2.3 Forming temperature

The decrease in flow stress with increasing temperature at constant degree of deformation and deformation rate is shown for different heavy metals and heavy metal alloys in Fig. 2.30.



**Fig. 2.30** Relative temperature dependence of the flow stress in cold forming **a** and **b**) different Cu-alloys **c**) Ni-alloys **d**) heavy metals

The flow stress decreases with increasing temperature for the observed deformation at  $\varphi = 0.10$  at a strain rate of  $\dot{\varphi} = 10 \text{ s}^{-1}$ . The decrease is more pronounced for the pure metals than for the alloys. It is interesting that the flow stress of Cu–OFE, LC Ni99, Mo99.5 and niobium decreases almost identically between  $20^\circ\text{C}$  and  $250^\circ\text{C}$ . Figure 2.30 is based on compression tests.

## 2.3 Modelling

### 2.3.1 Influence of chemical composition

The following assumptions are made for hot forming of heavy metals and their alloys:

- the alloying elements are completely dissolved in the  $\alpha$  phase, hence their hardening is provided by their differences in atomic radii;
- the alloying elements do not form intermetallic compounds;
- the effect of an alloying element on the flow stress can be expressed by an exponential function;
- the material condition is homogeneous;
- the material is isotropic elastically.

$$\sigma_F = \sigma_{F-1\%} \cdot C_{Ei}^n. \quad (2.5)$$

with  $\sigma_{F-1\%}$  the flow stress at an alloy content  $C_{Ei}$  of 1%.

For the flow stress of these alloys at defined forming conditions, one can write [2.21, 2.22, 2.23]:

$$\sigma_{F0} = \sigma_{F0-pure\ metal} + A \cdot \prod_{i=4}^{i=x} C_{Ei}^{B_i}, \sigma_{F0-pure\ metal}, \quad (2.6)$$

Flow stress at  $\vartheta = 20\ ^\circ\text{C}$  or  $700\ ^\circ\text{C}$ ;  $\varphi = 0.1$  and  $\dot{\varphi} = 10\ \text{s}^{-1}$

$A$  – constant

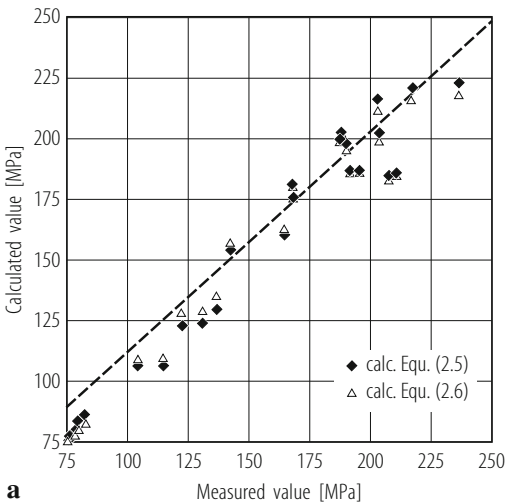
$C_{Ei}$  – content of the alloying element  $i$

$B_i$  – exponent of the content of the alloying element  $i$ .

The assumptions on which the modelling is based have the following physical background:

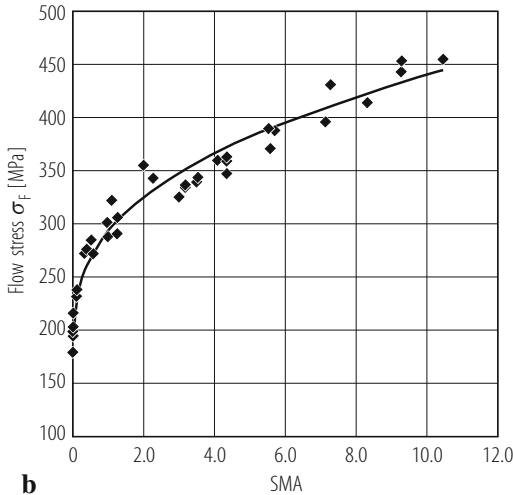
- Only elements that have a relative difference of the atomic radii to the base element smaller than 15% are dissolved. When these elements have a body-centred cubic or cubic face-centred structure, they dissolve very well in the face centred cubic host crystal lattice. This applies to copper for the alloying elements Zn, Ni and Al.
- If the tendency to form intermetallic compounds with the alloying element is low, then no significant influence on the flow stress exists during hot deformation.
- Apart from the chemical composition, the state of the grain structure determines the flow stress. It is known that under the same forming conditions the flow stress of cast grain structures is lower than the flow stress of deformed grain structures. Moreover, the flow stress of a dendrite cast structure is dependent on the direction.

Figure 2.31a shows the fit between measured and calculated flow stress data for  $\vartheta = 700\ ^\circ\text{C}$ ,  $\varphi = 0.10$  and  $\dot{\varphi} = 10\ \text{s}^{-1}$  and for Cu and Cu–Sn alloys. This diagram shows the results of binary test melts containing a very low content of impurities and commercial alloys. The discrepancy of the measured and calculated values is very small.



**Fig. 2.31a** Comparison of measured and calculated data of the flow stress at  $\vartheta = 700\text{ }^{\circ}\text{C}$ ,  $\varphi = 0.10$  and  $\dot{\varphi} = 10\text{ s}^{-1}$  for Cu and Cu–Sn alloys

Figure 2.31b shows the increase of the flow stress values with increasing amount of SMA. The amount of substance SMA characterizes the total alloy content of an alloy and is calculated as follows:



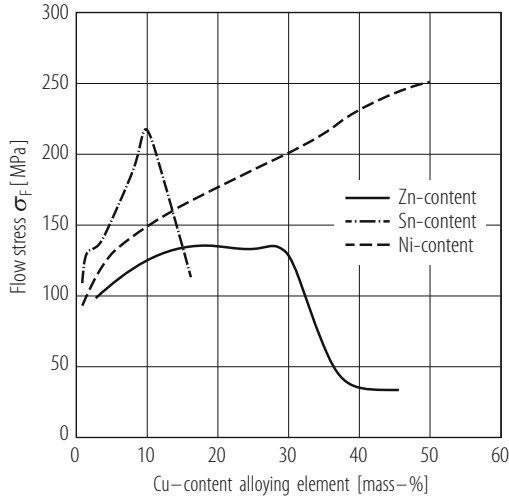
**Fig. 2.31b** Calculated data of the flow stress at  $\vartheta = 700\text{ }^{\circ}\text{C}$ ,  $\varphi = 0.10$  and  $\dot{\varphi} = 10\text{ s}^{-1}$  for Cu and Cu–Sn alloys

$$SMA = \sum C_{Ei} \cdot (A_{Cu}/A_i),$$

where

|          |                                    |
|----------|------------------------------------|
| $C_{Ei}$ | is the element content in (mass %) |
| $A_{Cu}$ | atomic mass of copper              |
| $A_i$    | atomic mass of element i.          |

Figure 2.32 shows flow stress results of the binary test melts at  $\vartheta = 700\text{ }^{\circ}\text{C}$ ,  $\varphi = 0.10$  and  $\dot{\varphi} = 10\text{ s}^{-1}$  in Cu–Zn, Cu–Sn and Cu–Ni alloys.



**Fig. 2.32** Flow stress results of the binary test melts at  $\vartheta = 700\text{ }^{\circ}\text{C}$ ,  $\varphi = 0.10$  and  $\dot{\varphi} = 10\text{ s}^{-1}$  in the group of Cu–Zn, Cu–Sn and Cu–Ni alloys

### 2.3.2 Influence of forming conditions

#### 2.3.2.1 Hot working

Flow stress models as a function of the deformation conditions can be calculated by using either the so-called thermodynamic factors (which include the influence of the temperature  $\vartheta$ , strain  $\varphi$  and strain rate  $\dot{\varphi}$ ) or the activation energy of hot deformation. Both methods are applicable for limited temperature ranges.

Further calculation models for hot flow curves, e.g. by Sellars and Tegart [2.24], Luton and Sellars [2.25], Laasraoul et al. [2.27], Avrami-Voce or Voce-Avrami-Zener-Hollomon (ref. Hensger [2.26]), do not yield any improvement of the approximation and extrapolation [2.28], although the authors take into account in their equations the dynamic softening and the difference in flow stress between the maximum and steady-state range.

##### 2.3.2.1.1 Modelling by means of the thermodynamic factors

The mathematical modelling of the hot stress–strain curve is based on multiplying a material-specific initial value by factors that express the influence of the conditions of deformation [2.29]:

$$\sigma_F = A \cdot K_{\vartheta} \cdot K_{\varphi} \cdot K_{\dot{\varphi}}. \quad (2.7)$$

The material-related basis considers the temperature influence by the Arrhenius term. The influence of strain is taken care of by a power law for strain hardening and by exponential functions for softening effects. Furthermore, the influence of the strain rate is included by the temperature dependent proportionality between changes in strain and flow stress.

Different model terms have been tried for the different thermodynamic factors  $K_{\varphi}$  [2.30]:

$$\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot \dot{\varphi}^{m_3} \quad (\text{term } 0), \quad (2.8)$$

$$\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3} \quad (\text{term } 1), \quad (2.9)$$

$$\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_3} \quad (\text{term } 2), \quad (2.10)$$

where  $A$  is a constant,  $m_1$  to  $m_8$  are exponents expressing the influence of the deformation conditions on the flow stress,  $\vartheta$  is the deformation temperature (in  $^{\circ}\text{C}$ ),  $\varphi$  is the strain and  $\dot{\varphi}$  the strain rate (in  $1/\text{s}$ ). The following comments can be made regarding the mathematical modelling of stress–strain curves as a function of the conditions of deformation:

Term 0 traces back to Zjuzin [2.30], Hajduk and Elfmark [2.31] and is suitable for defining stress–strain curves in a single phase range for hot deformation with a strain up to 0.35, because it does not allow for

dynamic softening. This disadvantage is mitigated by term 1, and the scope of application is extended to a strain up to approximately 1.00. However, the drawback of term 1 is that hardening and softening are not defined as a function of the temperature, which is also true for the influence of the strain rate on the stress–strain curve. In addition, the steady state range of the hot stress–strain curve is not computed correctly. The best agreement between measured and calculated hot stress–strain curves is hence obtained from term 2. This term is very suitable for the mathematical description of stress–strain curves in engineering calculations [2.31].

- If variations in flow stress due to precipitation or grain growth are small, the temperature dependence  $K_\vartheta$  can be expressed by a simple exponential function if the deformation occurs in a single-phase range:

$$K_\vartheta = e^{m_1 \vartheta}. \quad (2.11)$$

- The influence exerted by strain on flow stress as defined in term 1,

$$K_\varphi = \varphi^{m_2} \cdot e^{m_4/\varphi}, \quad (2.12)$$

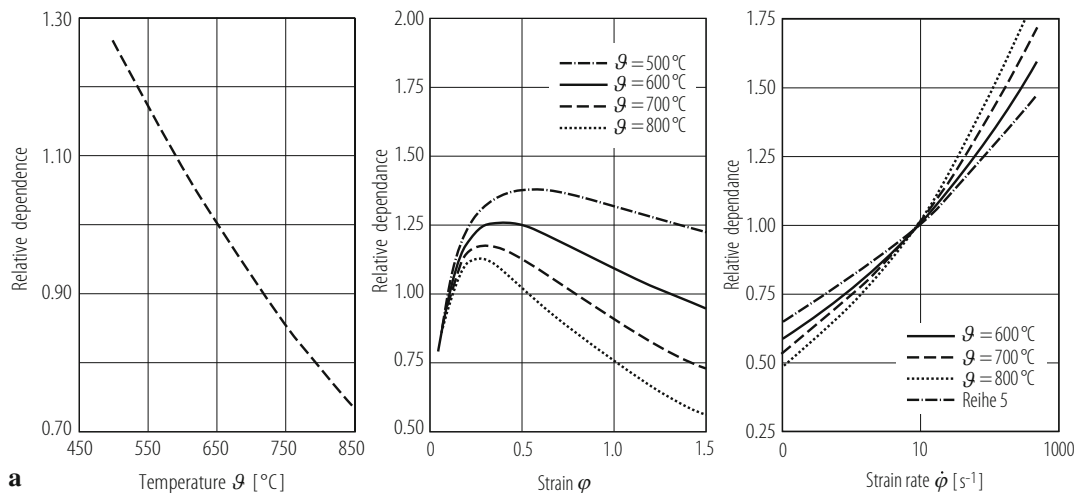
- is sufficiently accurate for some materials only. A marked improvement in determinations can be achieved by considering the temperature influence on hardening and softening,

$$K_\varphi = \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi}. \quad (2.13)$$

- A better agreement between measured and calculated flow stress is achieved if the power function for the strain rate  $\dot{\varphi}$  contains a temperature-dependent or a temperature-independent exponent.

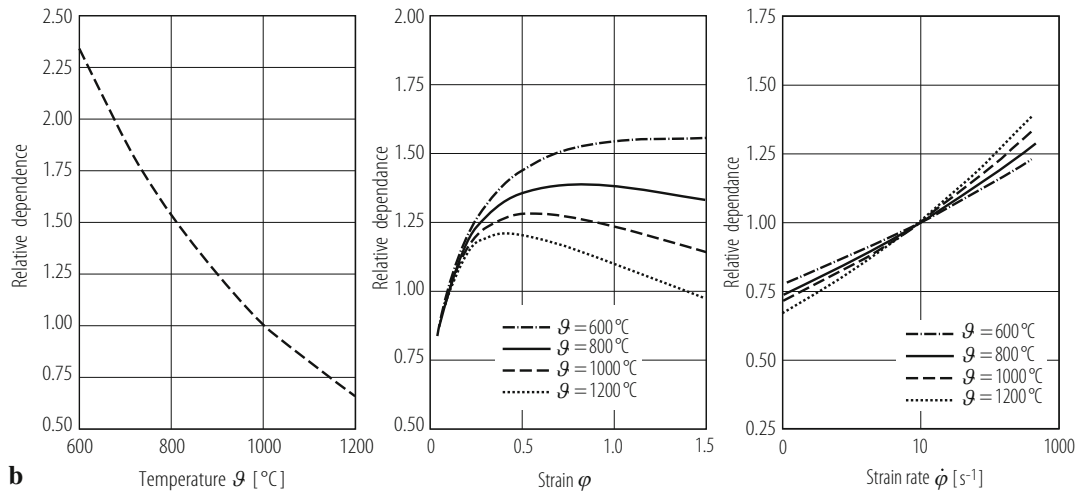
$$K_{\dot{\varphi}} = e^{m_3 \dot{\varphi}} \quad \text{or} \quad K_{\dot{\varphi}} = e^{m_8 \dot{\varphi}}. \quad (2.14)$$

Figure 2.33 shows the characteristics of relative dependencies of flow stress on temperature, deformation and strain rate for CuSn6 and for FeNi36, respectively. Term 2 (Eq. 2.10) describes the influence of deformation on the hot flow curve qualitatively. The hardening decreases with increasing temperature, however, the rate dependence of flow stress increases.



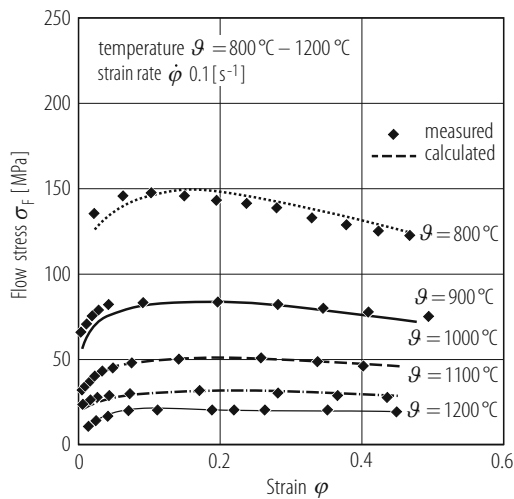
**Fig. 2.33a** Relative dependence of flow stress on the deformation parameters during the hot forming of CuSn<sub>6</sub>

Figure 2.34 shows how precisely the flow curve modelling, according to Eq. (2.10), matches with the measured values for a deformation temperature of  $\vartheta = 800\text{--}1200\text{ }^{\circ}\text{C}$  at the strain rate  $\dot{\varphi} = 0.01\text{ [1/s]}$  for the



**Fig. 2.33b** Relative dependence of flow stress on the deformation parameters during the hot forming of FeNi36

alloy FeCr29Co12Mo. Normally the correlation coefficient in modelling of the flow curve according to Eq. (2.10) is approximately 0.02 times higher than that according to Eq. (2.9). Equation (2.8) is not suitable for modelling of the flow curves with dynamic softening.



**Fig. 2.34** Comparison of calculated (curve) and measured (symbol) flow stress values of FeCr29Co12Mo at a strain rate of  $0.01 \text{ s}^{-1}$  and a temperature of  $\Theta = 800\text{--}1200 \text{ }^{\circ}\text{C}$

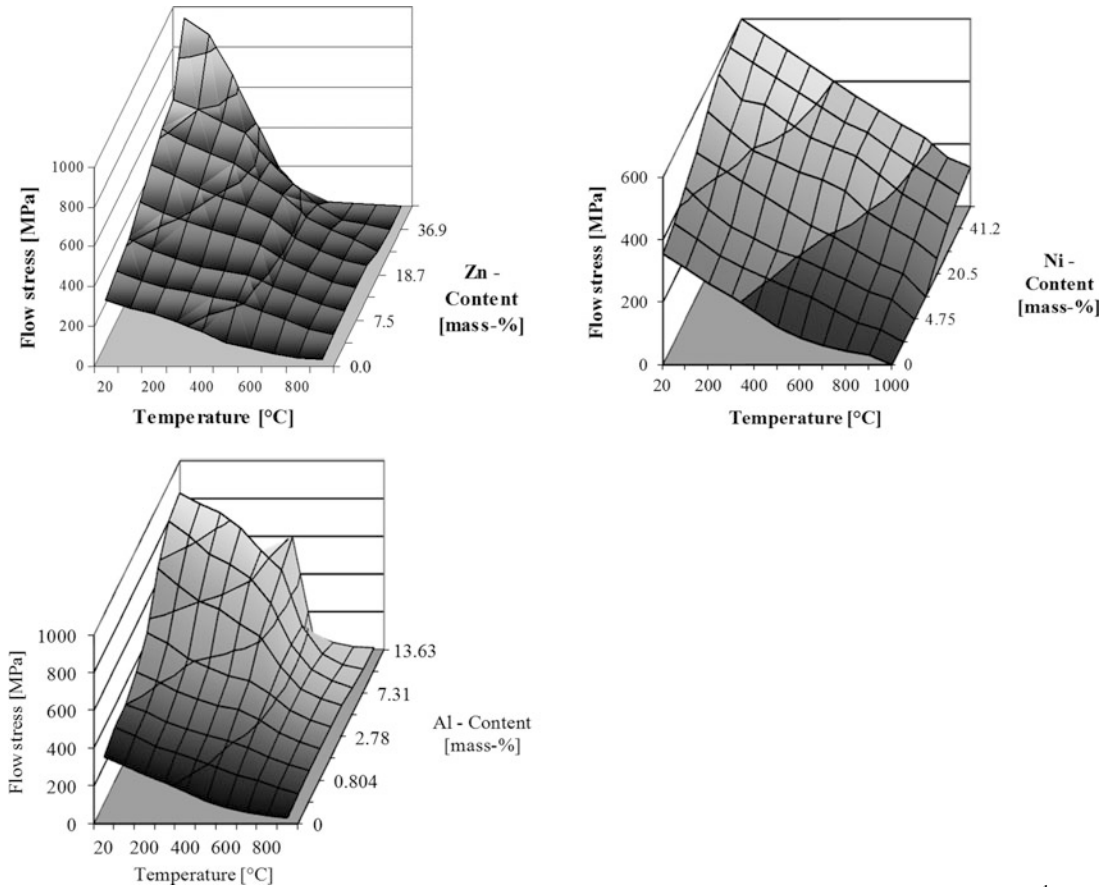
According to both terms, the flow stress decreases with increasing temperature. The modelling of flow stress according to Eq. (2.10 term 2) reflects the variation in flow stress with temperature very precisely, the whole term 1 maxima is well suited for low flow stress only. Term 2 also reflects the influence of dynamic recovery, while the mathematical model selected for term 1 does not incorporate the shifting of the flow curve maximum by the deformation conditions. It yields an average curve only for both the range of dynamic recovery and the range of steady state.

The relation between rate of deformation and flow stress with increasing temperature rises faster in term 2. As for the relation between degree of deformation and flow stress, term 1 yields a levelled relationship. At a low degree of deformation, values for  $\sigma_F$  are too high, near the maximum of the flow curve they are too low, and for high degrees of deformation they are too high again. Hence, term 2 is exclusively used for flow curve modelling.

Despite the high degree of agreement of more than 0.9800 for term 2 at several degrees of deformation, deviations between measured and calculated curves can occur (by more than 5% in some cases). Normally

the difference between measured and calculated values increases with decreasing deformation temperature, increasing degree of deformation and increasing rate of deformation.

The constants for calculation of the stress–strain curves of heavy metal alloys for hot deformation can be defined for the temperature range between 500 and 1200 °C. The constants are valid for the entire temperature range; see Fig. 2.35 for the Cu–Zn–, Cu–Ni– and Cu–Al–alloys.



**Fig. 2.35** Flow stress at on function of temperature and alloy content. Deformation parameters:  $\varphi = 0.5$ ,  $\dot{\varphi} = 1 \text{ s}^{-1}$  a) Cu–Zn alloys b) Cu–Ni alloys c) Cu–Al alloys

### 2.3.2.1.2 Calculation using the activation energy of hot deformation

A different model for the modelling of flow stress was established by Zener and Hollomon [2.28]:

$$\dot{\varphi} = A * \exp(-Q/RT) * [\sinh(\alpha * \sigma_F)^n], \quad (2.15)$$

with  $A$ ,  $\alpha$  and  $n$  constants,  $R = 8.317 \text{ J mol}^{-1}\text{K}^{-1}$  the gas constant,  $T$  the temperature and  $Q$  the activation energy of hot forming,

$$Q = -R \frac{\partial \ln \dot{\varphi}}{\partial (1/T)} \quad \text{for } \sigma_F = \text{const.} \quad (2.16)$$

According to Eq. (2.15), one can calculate the flow stress in the range of steady state of the hot stress–strain curve. A linear relationship is assumed between the flow stress and the logarithm of the Zener-Hollomon parameter

$$Z = \dot{\varphi} \cdot e^{\left(\frac{Q}{RT}\right)}, \quad (2.17)$$

and it is required that the activation energy of hot forming is known.

Equation (2.15), based on the Arrhenius equation, seems to offer a number of advantages in flow stress calculation, as it takes both the impact of temperature and rate of forming on flow stress into account. The measured flow stress values found during tests are in relatively good agreement with the calculated results. However, the linearity assumed in Eq. (2.15) is no longer correct for lower stresses, and the calculation is actually only valid for degrees of deformation that are considerably larger than applied in most technical hot forming processes. Hence numerous relationships have been developed from Eq. (2.15) in order to describe all ranges of the hot flow curve or to simplify it. Among those are, for example [2.33]

$$\sigma_F = A + B \cdot \ln Z, \quad (2.18)$$

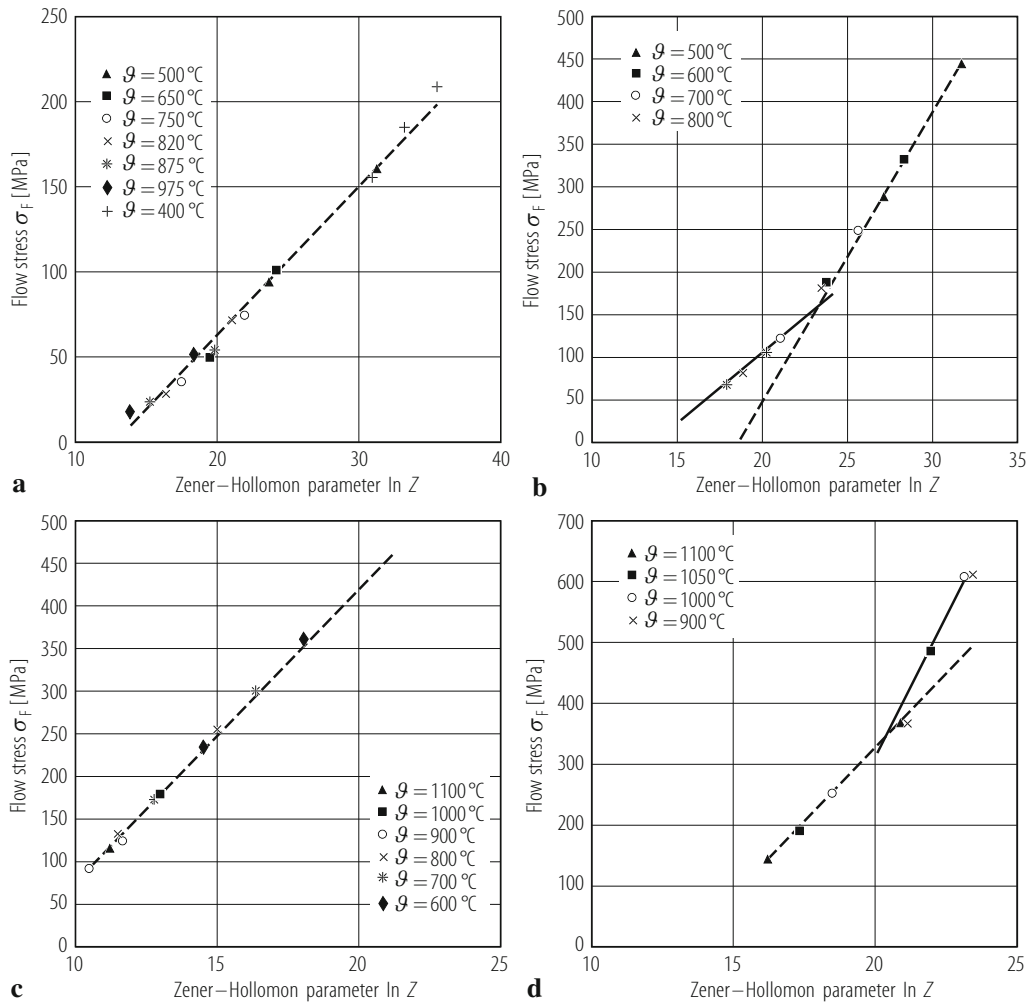
where the constants  $A$ ,  $B$  and the activation energy  $Q$  are determined as a function of the recorded stress–strain curves. Another approach is given in [2.34]:

$$\sigma_F = \sigma_{F,\max} \frac{\varphi}{\varphi_{\max}} \cdot \exp\left(1 - \frac{\varphi}{\varphi_{\max}}\right)^{C_\varphi}, \quad \dot{\varphi} = \text{const} \quad (2.19)$$

where  $C_\varphi$  is a temperature dependent function.

Equation (2.18) can be used for all three partial ranges of a hot stress–strain curve, using a strain-dependent activation energy. Flow stresses calculated with strain-independent activation energies are compared with measured results in Fig. 2.36. The figure also shows that the linear relationship between flow stress and the Zener-Hollomon parameter for higher absolute flow stress may differ from measured values by >20 MPa.



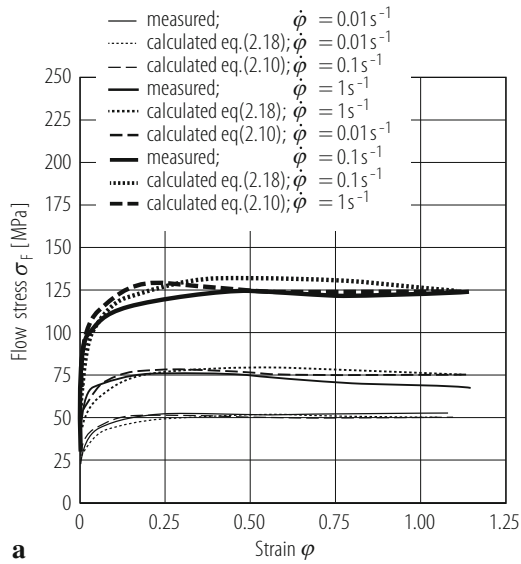


**Fig 2.36** Linear relation between flow stress and the Zener-Hollomon parameter for **a)** Cu99.99 **b)** CuSn6 **c)** Ni99.9 **d)** Inconel 718 (NiCr19NbMo)

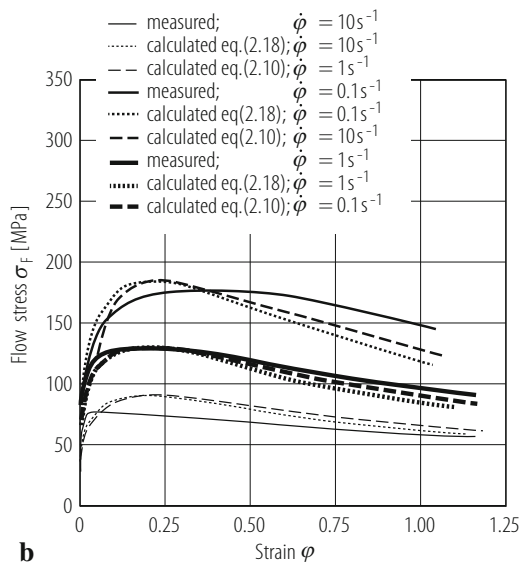
While the relation between flow stress and the Zener-Hollomon parameter is linear for Cu99.99 in the whole range of hot forming conditions studied (Fig. 2.36a and Fig. 2.36c), this relationship is described by two straight lines, intersecting at  $1100^\circ\text{C}$  for CuSn6 (Fig. 2.36b and Fig. 2.36d). The reason for this phenomenon could be a possible phase transformation ( $\beta \rightarrow \alpha + \beta$ ). The use of Eq. (2.16) for the flow stress calculation is limited to a single-phase range and a single deformation mechanism. A further disadvantage regarding Eqs. (2.16) and (2.14) is the requirement to determine the activation energy from test results over approximately four decades [2.35]. Such a wide range of test conditions is necessary for the determination of the activation energy with sufficient accuracy. Even little deviations from the "correct" value can cause major differences between the measured and calculated values because the flow stress is exponentially dependent on the activation energy.

Both base models of stress-strain curves allow calculations with relatively small deviations between measured and calculated values (Fig. 2.37) only if a sufficient number of measured data for a wide range of forming conditions is available. This is especially true for models in which the activation energy is used because this model is exponential in all measurement inaccuracies which enter these parameters. The comparison of the measured flow stress values with the values calculated by Eqs. (2.10) and (2.19) for three strain rates reveals that only small differences occur between measurement and calculation at the strain rates  $\dot{\phi} = 0.01$  and  $0.10 \text{ s}^{-1}$ . At a strain rate of  $10 \text{ s}^{-1}$ , resulting in deformation greater than 0.4 according to

Eq. (2.10 and 2.19), lower flow stress values are obtained. Thus, the difference from the measured values increases with increasing degree of deformation.



**Fig. 2.37a** Comparison of calculated and measured flow stress values of Nimonic 80a at a temperature of 1200 °C and at different strain rates between  $\dot{\phi} = 0.01 \text{ s}^{-1}$  and  $1 \text{ s}^{-1}$



**Fig. 2.37b** Comparison of calculated and measured flow stress values of CuZn30 at 800 °C at different strain rates between  $\dot{\phi} = 0.1 \text{ s}^{-1}$  and  $10 \text{ s}^{-1}$

The consistency of flow stress measurements with calculations according to Eqs. (2.10) and (2.19) for non-ferrous metals is as good as for steels [2.36] and provides an opportunity to perform a relatively simple mathematical modelling, when the input data are trustworthy.

### 2.3.2.2 Cold deformation

#### 2.3.2.2.1 Effect of the degree of deformation

Cold flow curves can be modelled mathematically under different aspects. If the effect of deformation is considered only, a characterization of the flow curve is possible according to [2.23]:

$$\sigma_F = \sigma_{F,\varphi=1.0} \cdot \varphi^{n_1}, \quad (2.20)$$

or by the Ludwik equation [2.37]

$$\sigma_F = \sigma_{F,A} + \Delta\sigma_{F,\varphi=1.0} \cdot \varphi^{n_2}, \quad (2.21)$$

where  $\sigma_{F,\varphi=1.0}$  is the flow stress [MPa] at  $\varphi = 1.0$ ,  $\sigma_{F,A}$  is the flow stress at  $\varphi = 0$ ,  $\Delta\sigma_{F,\varphi=1.0}$  is the hardening at  $\varphi = 1.0$  (which equals the increase in flow stress between  $\varphi = 0$  and  $\varphi = 1.0$ ) and  $n$  is the hardening exponent ( $n_1 \neq n_2$ ). The relations are valid for constant temperature and rate of deformation.

Equation (2.22) is a combination of power and exponential functions and avoids the use of two different strain hardening exponents [2.38].

$$\sigma_F = A \cdot \varphi^n \cdot e^{\left(\frac{B}{\varphi}\right)} \quad (2.22)$$

As  $\sigma_F = 0$  for  $\varphi = 0$ , Eq. (2.21) is not suitable for low degrees of deformation, for instance for a skin pass in rolling. Furthermore the equation does not consider the yield stress at the beginning of processing, which can be determined easily but is often a factor of uncertainty, for instance after heat treatments.

At the beginning of deformation, the hardening is obviously nearly twice as high as at high degrees of deformation. The cold flow curve at constant temperature can be represented by a polynomial function [2.39, 2.40]:

$$\sigma_F = \sigma_{FA} + C_1\varphi + C_2\varphi^2 + C_3\varphi^3 + C_4\varphi^4 + C_5\varphi^5, \quad (2.23)$$

where  $C_1 \dots C_5$  are material related constants. It correlates measured and calculated values very well. Even though for  $\varphi = 0$  the regression analysis yields a finite value, flow stress modelling is a problem. It only applies to the range of measured values within the validity range of  $\varphi = 0$ –1.50 for CuZn37 [2.40] with the following chemical analysis.

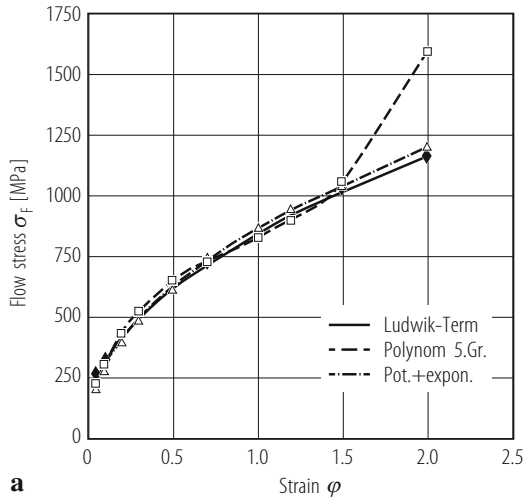
| Chemical composition [mass %] |          |          |         |
|-------------------------------|----------|----------|---------|
| Cu                            | Pb       | Fe       | Zn      |
| 64                            | max 0.07 | max 0.05 | balance |

The numerical values for calculating the flow stress of CuZn37 by various model approaches are given in Table 2.11.

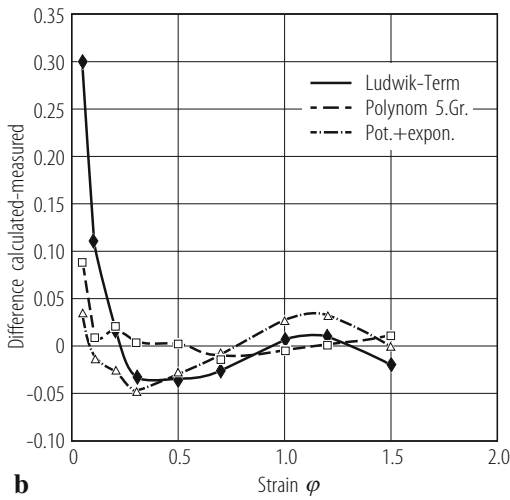
**Table 2.11** Numerical values of CuZn37 of the equations to calculate the flow stress at  $\vartheta = 20^\circ$

| Type of equation               | Equation | Equation for CuZn37 at $\dot{\varphi} = 0.15 \text{ s}^{-1}$                                                       | $R_{xy}$ |
|--------------------------------|----------|--------------------------------------------------------------------------------------------------------------------|----------|
| Ludwik equation                | (2.21)   | $\sigma_F = 728.1 * \varphi^{0.5275} + 116.1$                                                                      | 0.9721   |
| Power and exponential function | (2.22)   | $\sigma_F = 862.33 * \varphi^{0.46053} * e^{(-0.00115/\varphi)}$                                                   | 0.9890   |
| Polynomial                     | (2.23)   | $\sigma_F = 236.4 * \varphi^5 - 1219 * \varphi^4 + 2650 * \varphi^3 - 2938.4 * \varphi^2 + 1974 * \varphi + 130.5$ | 0.9984   |

The consequence of the use of the power and the exponential function, the Ludwik equation and polynomial function of fifth grade on the calculation of the flow stress as a function of degree of deformation is shown in Fig. 2.38.



**Fig. 2.38a** Description of the flow stress curve of CuZn37 at room temperature by an exponential and a polynomial function, Eq. (2.19)



**Fig. 2.38b** Difference between calculated and measured flow stress of CuZn37, as calculated by different functional descriptions

The differences between measured and calculated values are small in this range (Fig. 2.38b). An extrapolation beyond that range leads to drastic deviations between measured and calculated data, as the extrapolation is not based on effective material behaviour.

Equations (2.20) to (2.22) are rough approximations of measured flow curves because they only include the influence of the degree of deformation, and were determined at room temperature and low deformation rates as a rule. This does not correspond to real deformation conditions within the range of deformation of cold deformation processes.

#### 2.3.2.2.2 Influence of degree, temperature and rate of deformation

The mathematical modelling of the dependence on temperature, degree and rate of deformation was realized by multiplying the material-specific basic values by factors that reflect the influence of the deformation conditions:

$$\sigma_F = A \cdot K_\theta \cdot K_\varphi \cdot K_{\dot{\varphi}}. \quad (2.24)$$

$K_\theta$ ,  $K_\varphi$  and  $K_{\dot{\varphi}}$  are correction functions for the influence of the deformation temperature, degree of deformation and rate of deformation, respectively. At cold deformation, Eq. (2.24) is identical to Eqs. (2.7) and (2.9), respectively. For the thermodynamic factors  $K_\theta$ ,  $K_\varphi$  and  $K_{\dot{\varphi}}$  exponential functions based on physical laws are used:

$$K_{\vartheta} = A_1 \cdot e^{m_1 \vartheta}, \quad (2.24a)$$

$$K_{\varphi} = A_2 \cdot \varphi^{m_2} \cdot e^{m_4/\varphi}, \quad (2.24b)$$

$$K_{\dot{\varphi}} = A_3 \cdot \dot{\varphi}^{m_3}, \quad (2.24c)$$

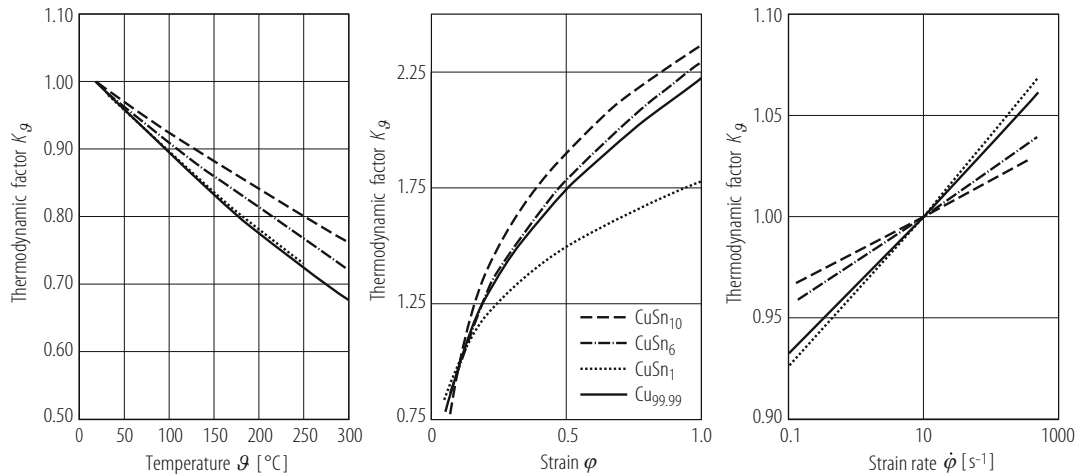
where  $\sigma_{F,0}$  is the reference flow stress at cold deformation at  $\vartheta = 20^\circ\text{C}$ ,  $\varphi = 0.10$  and  $\dot{\varphi} = 10\text{ s}^{-1}$  and the flow stress can be written as:

$$\sigma_F = \sigma_{F0} \cdot A_1 \cdot A_2 \cdot A_3 \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}, \quad (2.25)$$

or for  $20^\circ\text{C}$

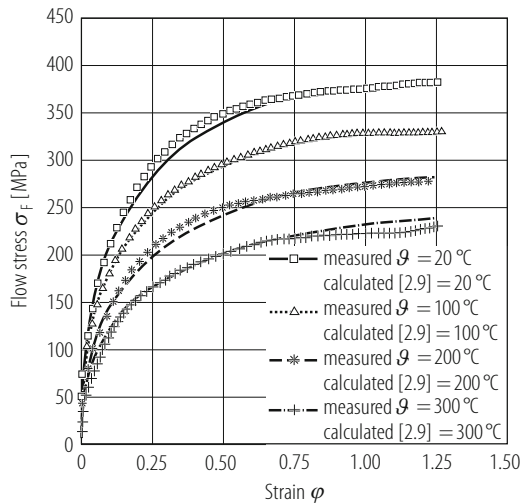
$$\sigma_F = \sigma_{F0} \cdot A_1 \cdot A_2 \cdot A_3 \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}.$$

The constants  $A_1$ ,  $A_2$  and  $A_3$  result from the definition that  $K_{\vartheta} = 20^\circ\text{C}$ ,  $K_{\varphi} = 0.10$  and  $K_{\dot{\varphi}} = 10\text{ s}^{-1}$  are set to 1. Figure 2.39 shows the relation between the thermodynamic factors  $K_{\vartheta}$ ,  $K_{\varphi}$  and  $K_{\dot{\varphi}}$  and the deformation temperature  $\vartheta$ , the degree of deformation  $\varphi$  and the rate of deformation  $\dot{\varphi}$  for Cu-alloys.



**Fig. 2.39** Thermodynamically factors  $K_{\vartheta}$ ,  $K_{\varphi}$  and  $K_{\dot{\varphi}}$  as a function of the deformation temperature  $\vartheta$ , the degree of deformation  $\varphi$  and the deformation rate  $\dot{\varphi}$  for Cu-alloys

In cold forming, the degree of deformation is the most important variable to calculate the flow stress. An increase in strain rate from  $10^{-3}\text{ s}^{-1}$  to  $100\text{ s}^{-1}$  leads to an increase in flow stress by only ca. 15%. An increase in temperature from  $20^\circ\text{C}$  to  $200^\circ\text{C}$  reduces  $\sigma_F$  ca. 33%. Apart from the degree of deformation, the composition of the material influences the flow stress strongly, as can be clearly seen in Fig. 2.40. The agreement between measured and calculated flow stress curves at these temperatures has been well studied.



**Fig. 2.40** Comparison between measured and calculated flow stress  $\sigma_F$  for Cu99.99 at  $\vartheta = 20; 100; 200$  and  $300\text{ }^{\circ}\text{C}$ ;  $\dot{\varphi} = 0.1\text{ s}^{-1}$

The strain hardening processes are dependent on temperature. In order to improve the accuracy of flow curve calculations at higher temperatures and deformation rates, it is useful to insert a temperature dependent factor into the functions  $K_{\varphi}$  and  $K_{\dot{\varphi}}$ . However, even considering the heat of deformation, cold deformation occurs mostly at temperatures below  $200\text{ }^{\circ}\text{C}$ , which is why flow curve calculations according to Eqs. (2.24)–(2.26) are sufficient in this case and are used for all data sheets of heavy metals in Chapter 5.

### Symbols and abbreviations

| Short form      | Full form                  |
|-----------------|----------------------------|
| $\sigma_F$      | flow stress                |
| $\dot{\varphi}$ | strain rate                |
| $\varphi$       | strain                     |
| $Q$             | activation energy          |
| $T_d$           | deformation temperatures   |
| $r$             | atomic radius              |
| $G$             | shear modulus              |
| $\vartheta$     | temperature                |
| $C_{\text{Ei}}$ | content of the element     |
| $B$             | alloy-specific exponent.   |
| ETP             | electrolytic tough pitch   |
| OFE             | oxygen free electronic     |
| DHP             | deoxidized high phosphorus |
| $Z$             | Zener-Hollomon parameter   |

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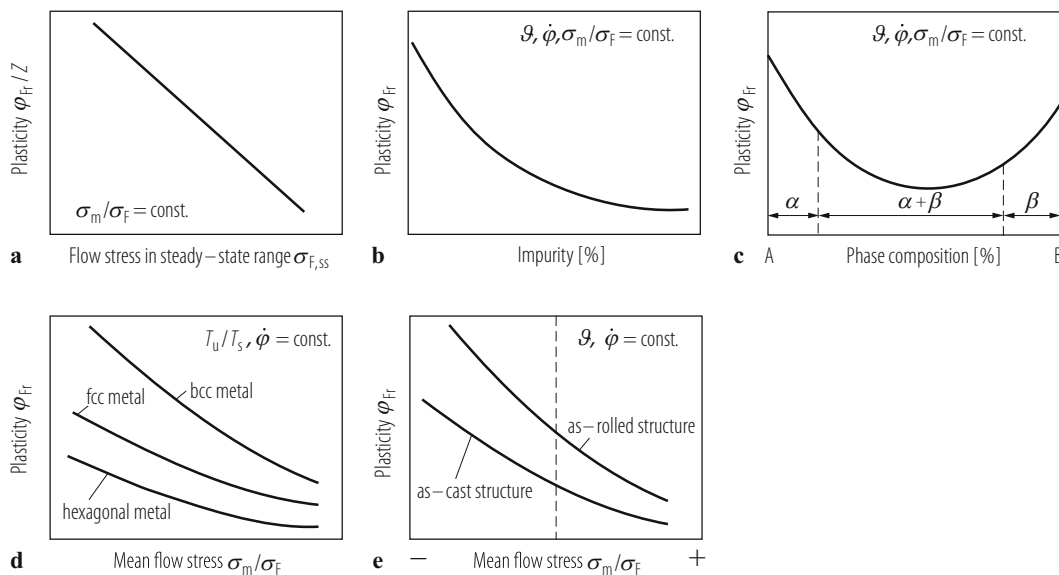
# Plasticity and its influencing parameters

## 3 Plasticity

The plastic behaviour of metallic materials during hot deformation can be assessed objectively only if reliable information about their plasticity is available. Plasticity is given by the strain  $\varphi_{Fr}$  up to which a material can be deformed without cracking. It permits to define the optimal ranges of temperature and rate of a forming process. If hot deformation is used to achieve the maximum plasticity, a high yield, satisfactory surface finish and accuracy in size are required. In the case of primary deformation, i.e. deformation in the as-cast condition, a detailed knowledge of plasticity is essential, because it limits the strain potential.

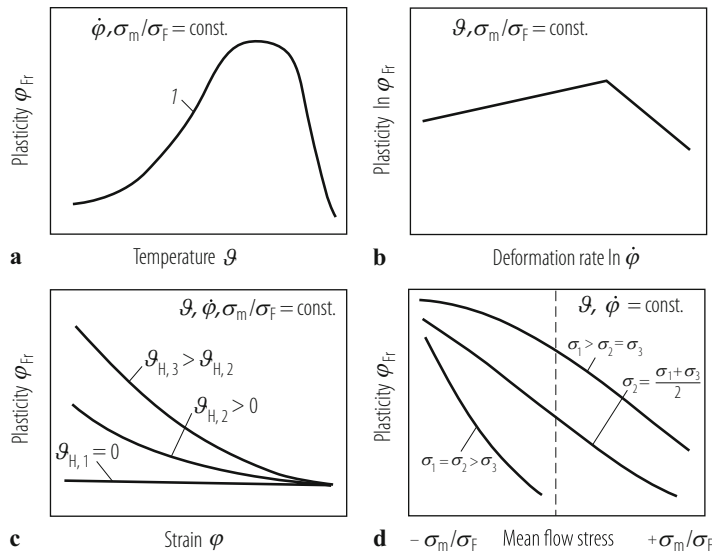
### 3.1 Hot plasticity

Figures 3.1 and 3.2 [3.1] summarize schematically the influence of material and process related factors on the plasticity in hot deformation. In the following chapters the most important parameters will be discussed by means of typical examples.



**Fig. 3.1** Influence of material related factors on the plasticity in hot deformation. **(a) Material:** in the single-phase range the plasticity is reduced with rising flow stress.  $\sigma_F$  in the steady state range  $\sigma_{F,ss}$ .  $Z$  denotes the Zener-Hollomon-Parameter,  $\sigma_m/\sigma_F$  is the mean flow stress. **(b) Purity:** at equal deformation conditions the plasticity is decreased by impurities and alloying elements. **(c) Phase composition:** multiphase materials have a lower plasticity than single-phase materials, the minimum value occurs at a second phase ratio between 25 and 40%. **(d) Crystal structure:** as a rule of thumb, the plasticity of body-centred cubic metals is higher than that of face-centred cubic and hexagonal metals (with deformation temperature  $T_d$  and solidus temperature  $T_{melt}$ ). **(e) Initial structure:** the plasticity of an as-cast structure is lower by a factor of 0.4–0.95 compared to an as-rolled structure. The factor depends on material and deformation conditions. For as-cast structures and other heterogeneous structures, the plasticity depends on the deformation direction and varies widely

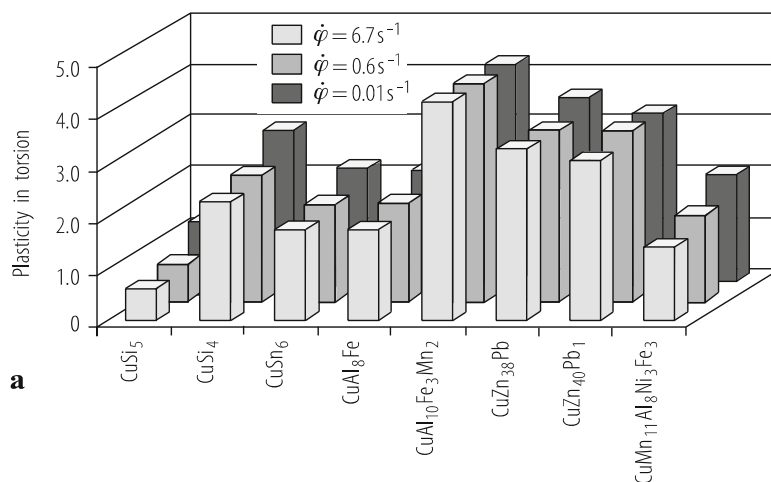




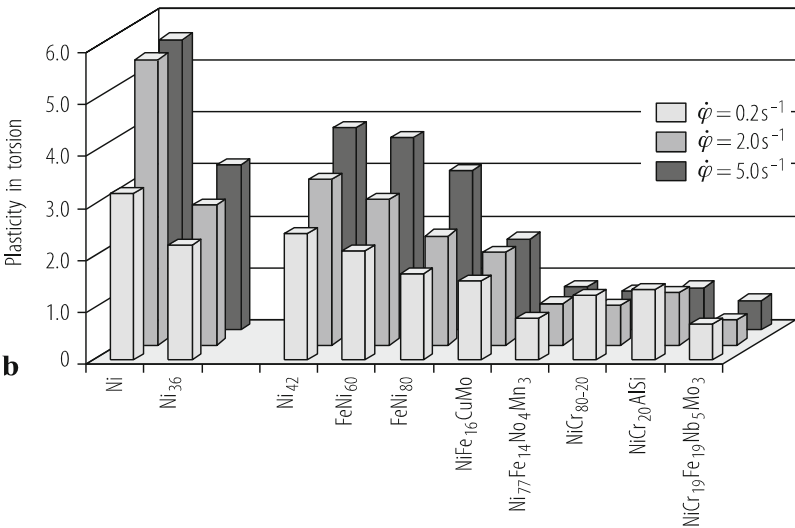
**Fig. 3.2** Process related parameters in hot deformation. **(a) Deformation temperature:** for single-phase materials, the plasticity rises with temperature up to 0.78–0.90  $T_{\text{melt}}$  [K]. After exceeding this temperature the plasticity decreases. During phase transformations, super plasticity may occur. **(b) Deformation rate:** at a specific rate which depends on the material and deformation conditions, the plasticity reaches its maximum value. In special cases and at a very low deformation rate, super plasticity may occur. **(c) Holding time:** if the strain up to the interruption is smaller than the degree of deformation at the maximum of the flow curve, the plasticity increases. The longer the holding time  $t_H$  and the smaller the degree of deformation before the interruption the steeper the increase. **(d) Mean stress:** the plasticity is strongly influenced by the mean flow stress  $\sigma_m/\sigma_F$  and the ratio of the main normal stresses. Compression stresses yield a higher plasticity, tensile stresses a lower plasticity

### 3.1.1 Influence of the material

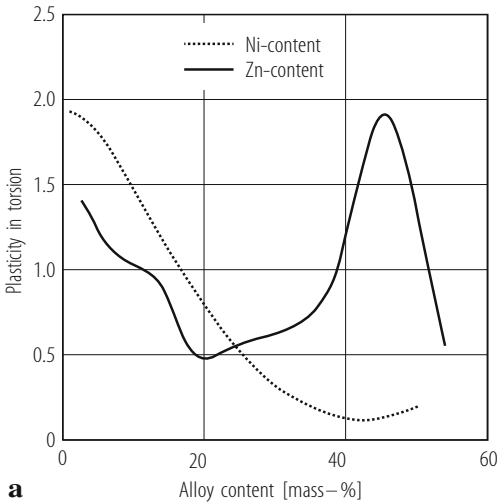
As can be seen in Fig. 3.3, the plasticity  $\varphi_{Fr}$  of various copper and nickel alloys depends strongly on the type of material and the content of Cu and Ni at all three rates of deformation. Pure Ni and the low-alloyed grades of Ni-alloys have the highest plasticity, ternary or higher alloyed eutectic alloys have the lowest plasticity. The reduced plasticity of Cu alloys can be explained by the content of alloying and impurity elements and their different effects. Figures 3.4a and b show the plasticity of Cu alloys with different alloying elements. This applies also at higher temperature. Figure 3.4c confirms for Ni alloys that binary alloys in general exhibit a lower plasticity than pure metals. The plasticity of noble metal alloys and of selected Cu alloys may behave very differently with increasing temperature (Fig. 3.4d).



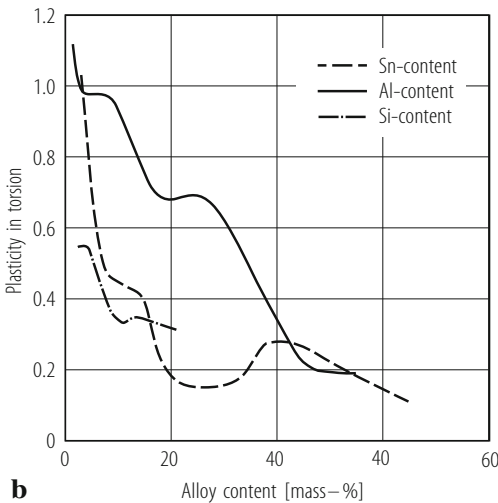
**Fig. 3.3a** Hot plasticity  $\varphi_{Fr}$  of Cu-alloys at  $\vartheta = 700^\circ\text{C}$



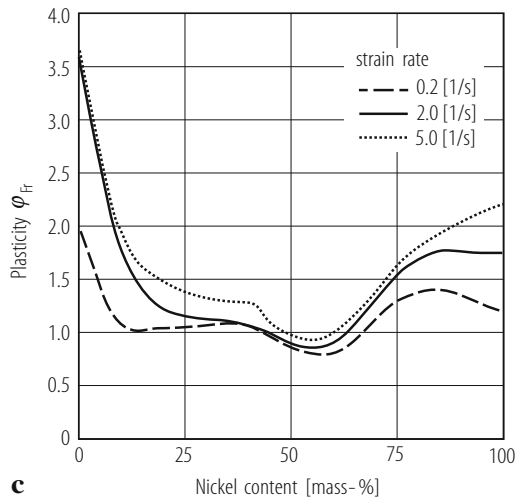
**Fig. 3.3b** Hot plasticity  $\varphi_{Fr}$  of Ni and Ni-alloys at  $\vartheta = 1000\text{ °C}$



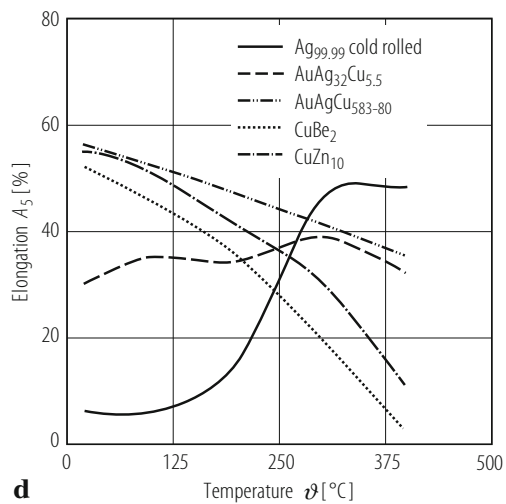
**Fig. 3.4a** Cu-alloys alloyed with Ni or Zn,  $\vartheta = 700\text{ °C}$ ;  $\dot{\varphi} = 5\text{ s}^{-1}$



**Fig. 3.4b** Cu-alloys alloyed with Sn; Al or Si,  $\vartheta = 700\text{ °C}$ ;  $\dot{\varphi} = 5\text{ s}^{-1}$



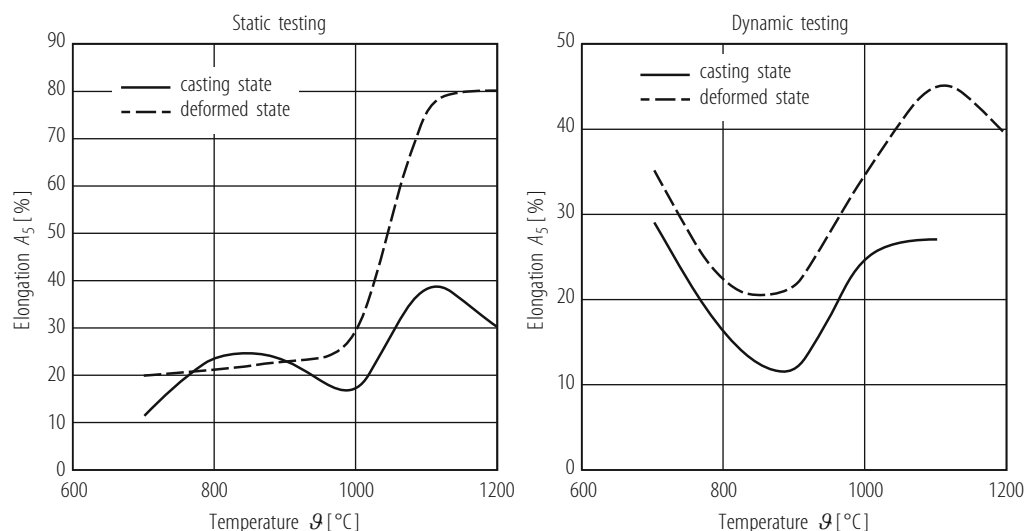
**Fig. 3.4c** Fe-Ni alloys  $\vartheta = 800\text{ }^{\circ}\text{C}$ ;  $\dot{\varphi} = 5\text{ s}^{-1}$



**Fig. 3.4d** Noble metal- and Cu-alloys,  $\dot{\varphi} = 10\text{ s}^{-1}$

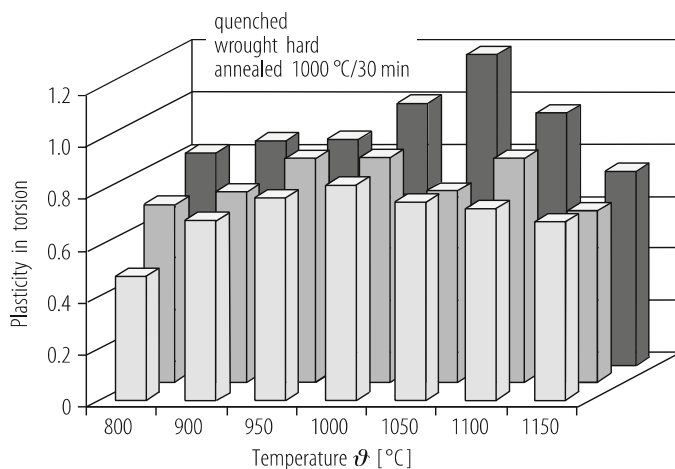
### 3.1.2 Material condition

As-cast structures have different values of plasticity than as-deformed structures. This is shown for NiMn3Si in Fig. 3.5.



**Fig. 3.5** Changes in elongation of NiMn3Si, as a function of temperature under static and dynamic testing conditions

This relation is influenced by the actual composition, processing condition, temperature and strain rate.



**Fig. 3.6** Influence of the processing condition on the plasticity of NiMo28 (torsion test)

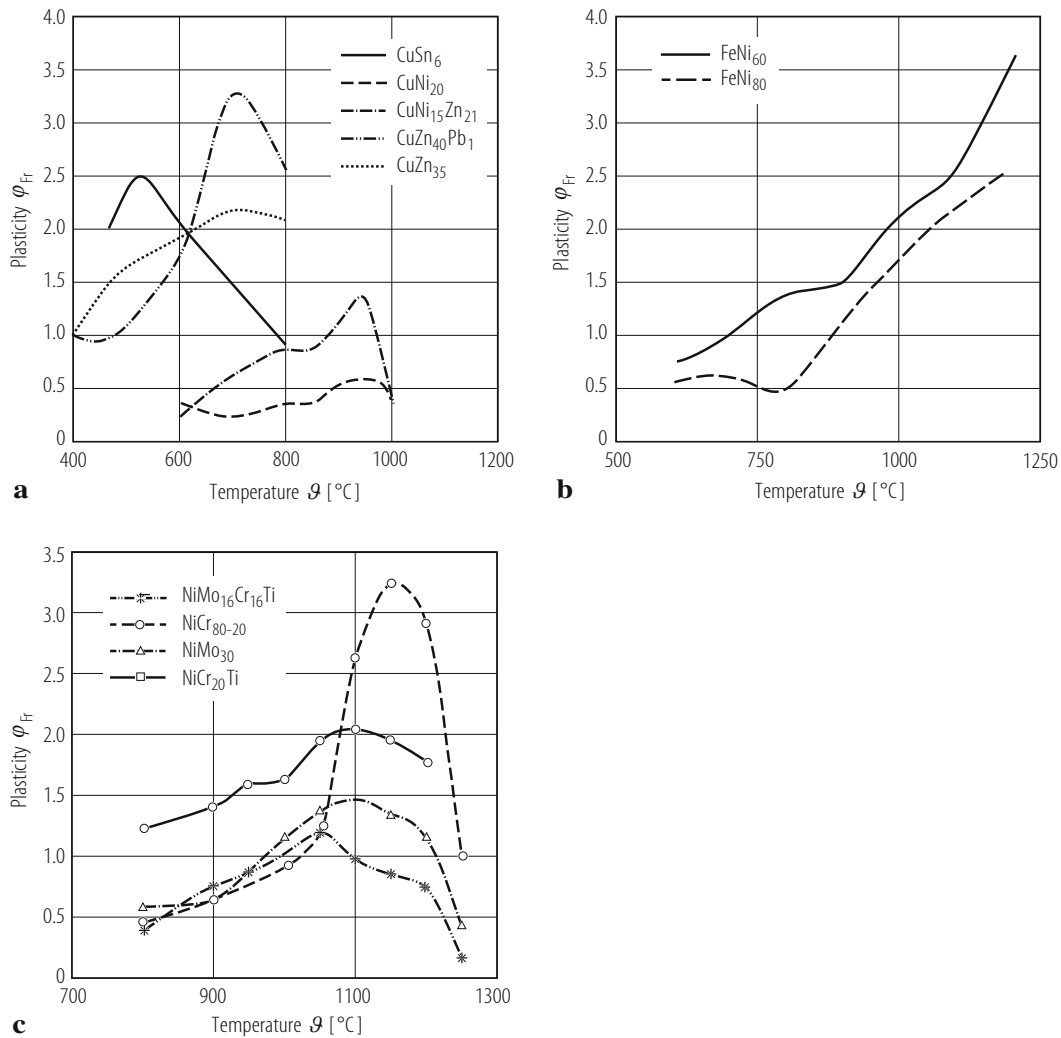
Figure 3.6 shows, how the degree of deformation at fracture of NiMo28 between 800 and 1150 °C is influenced by the processing conditions.

### 3.1.3 Influence of temperature and strain rate

The effects of deformation temperature and strain rate on the plasticity are determined by the following factors [3.2]:

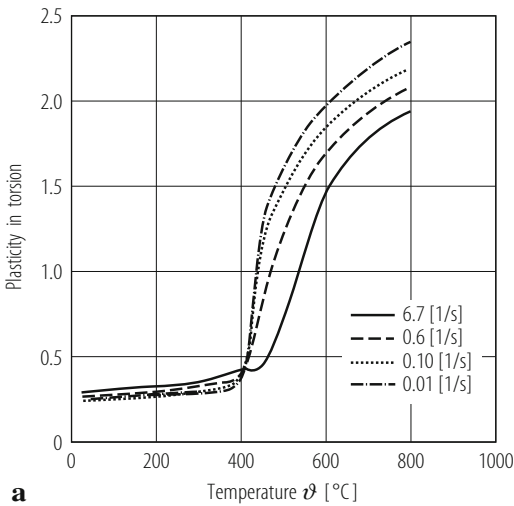
- Relation of strain rate to the rate of dynamic softening,
- Hot brittleness,
- Precipitation processes during deformation,
- Heat of deformation and
- Deformation mechanism.

In hot deformation the plasticity increases with temperature up to a maximum; after exceeding this value the plasticity decreases significantly even if the temperature still increases. This characteristic behaviour is shown in Fig. 3.7 for some Cu and Ni alloys in relation to the deformation temperature.

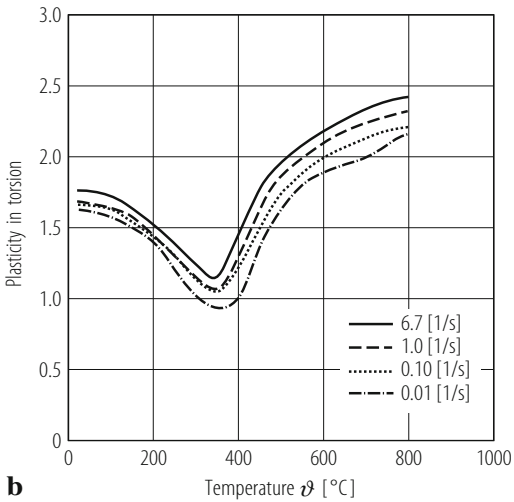


**Fig. 3.7a** Relation between plasticity and temperature **a)** of Cu alloys **b)** of Fe–Ni–alloys **c)** of Ni alloys.

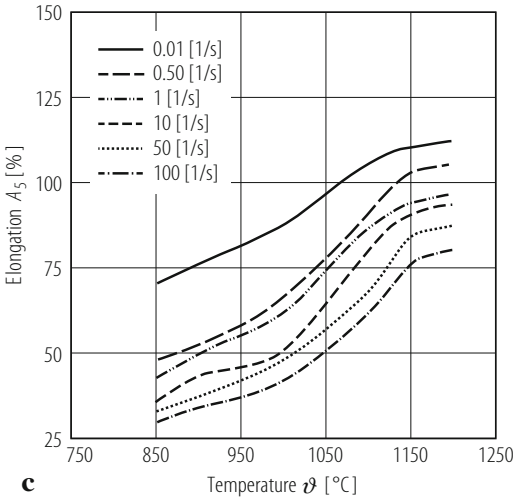
The plasticity of heavy metals varies. The increase in plasticity with increasing temperature is the result of both an acceleration of softening and an increase in dislocation mobility. Further contributions to this increase may be the dissolution of precipitates. A reduction of plasticity is caused by overheating, grain growth and other structural changes (Figs. 3.7, 3.8a, 3.8b, 3.8c). The plasticity of Ni–Cr alloys is still increasing beyond 1150  $^{\circ}\text{C}$  and for Ni–Fe alloys beyond 1200  $^{\circ}\text{C}$ . An increasing strain rate leads to a further slight improvement. The effect of strain rate on plasticity is not unique. Depending on the deformation conditions it can be positive or negative. The relation between strain rate and the rate of dynamic softening is essential, i.e. the kinetics of work hardening and softening processes (Fig. 3.7).



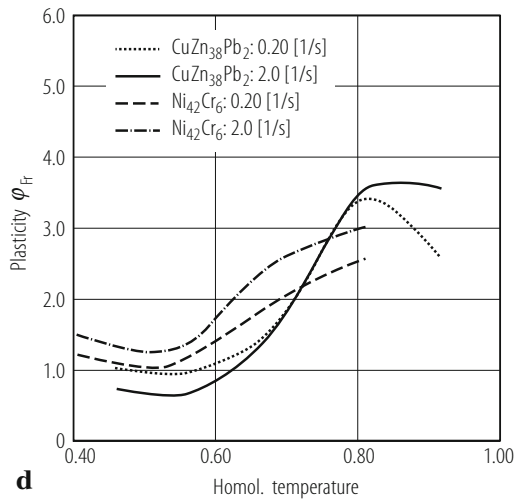
**Fig. 3.8a** Relation between plasticity and temperature of CuAl8Fe [3.19]



**Fig. 3.8b** Relation between plasticity and temperature of CuZn35 [3.19]



**Fig. 3.8c** Relation between plasticity and temperature of NiCr80-20

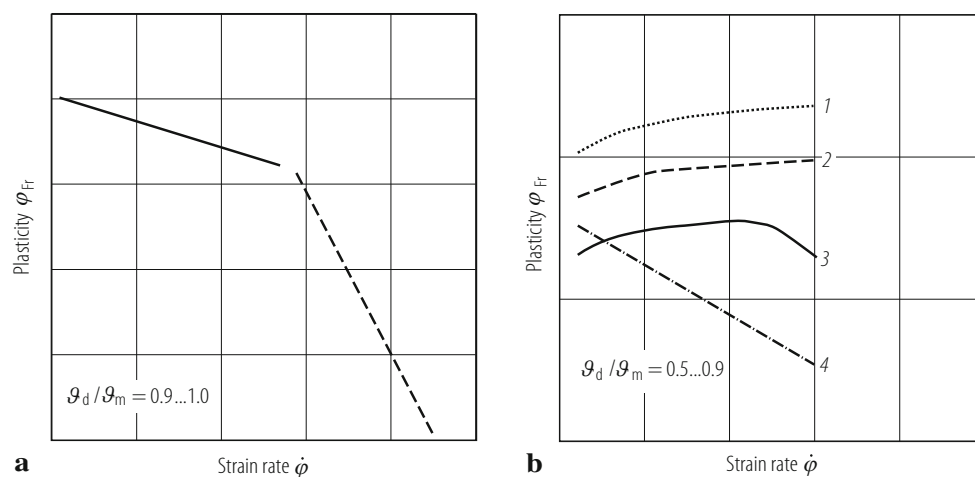


**Fig. 3.8d** Relation between plasticity and homologous temperature of Cu- and Ni-alloys

It is interesting to note that for all materials examined the maximum plasticity was found at nearly the same homologous deformation temperature of approximately 0.80 under the testing conditions applied (Fig. 3.8d). If the rate of dynamic softening is higher than the deformation rate, the dislocation density is reduced and dislocation motion is promoted. This leads to higher plasticity. If the rate of dynamic softening is lower than the strain rate, so that the material is work hardened during deformation, cracks can be formed and reduce plasticity.

It is possible to describe the effect of strain rate on plasticity schematically [3.3; 3.4]:

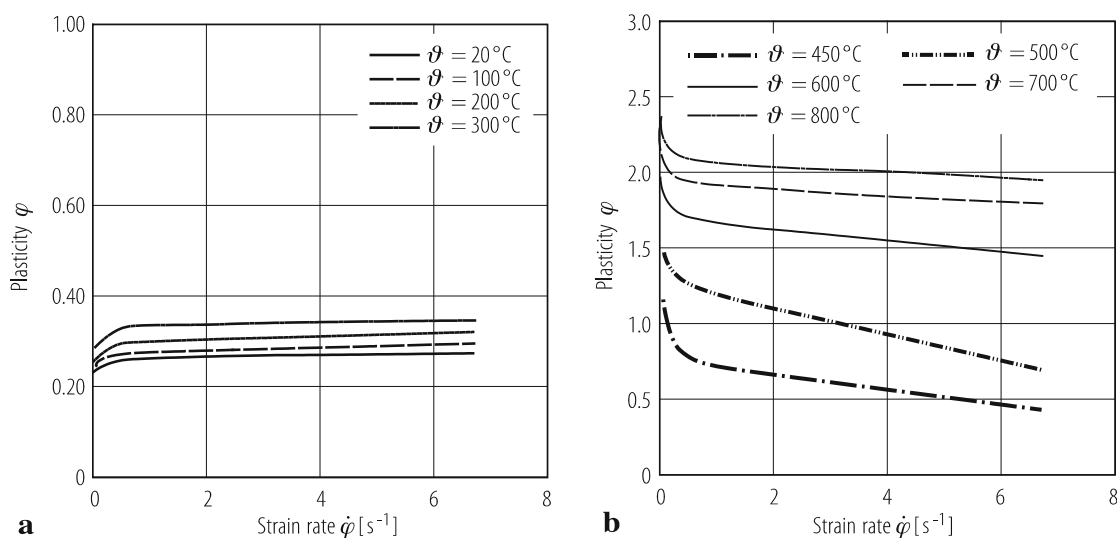
- In a temperature range between  $\vartheta_d/\vartheta_m = 0.90$ –1.00 (Fig. 3.9a) of the homologous deformation temperature the heat of deformation can lead to exceeding the critical temperature, which leads to reduced plasticity at increasing strain rates. Technically this can be significant in deformation processes with high degrees of deformation in single steps of forming in the upper range of deformation temperatures, for instance in extrusion.
- At homologous deformation temperatures between 0.50 and 0.90 (Fig. 3.9b) the plasticity of materials increases with increasing strain rate (curves 1 and 2). Alloys, which tend to dynamic precipitation, show higher plasticity with increasing strain rate (curve 1). With reduced ductility due to coarse grained structures in the as-cast condition, plasticity rises up to a certain rate of deformation, but after a maximum it decreases again (curve 3). For alloys with low stacking-fault energy plasticity may also decrease with increasing strain rate (curve 4).



**Fig. 3.9** Schematic presentation of the strain rate effects on plasticity in hot deformation;  $\vartheta$  in  $^{\circ}\text{C}$  (a)  $\vartheta_d/\vartheta_m = 0.9 \dots 1.0$ . (b)  $\vartheta_d/\vartheta_m = 0.5 \dots 0.9$ ;  $\vartheta_d$  – deformation temperature,  $\vartheta_m$  – melting temperature; for numbers of the curves: see text

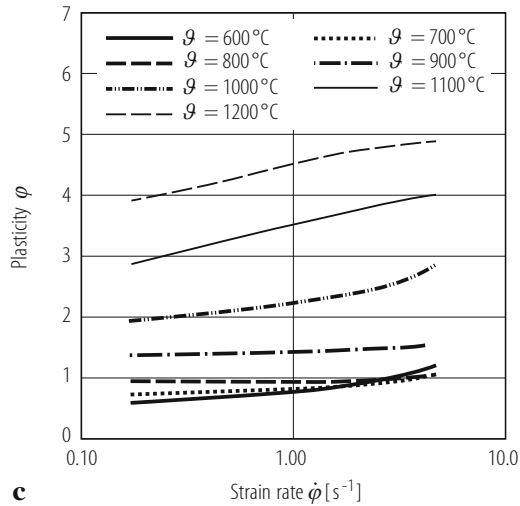
Figure 3.10a shows the relation between the degree of deformation at rupture in torsion as a function of strain rate for CuAl8Fe on cold and hot deformation. At deformation below  $300^{\circ}\text{C}$  an improved plasticity up to strain rates of  $\dot{\varphi} = 7 \text{ s}^{-1}$  is found. Thus the behaviour corresponds to curve 2 in Fig. 3.9b as described above.

If alloy CuAl8Fe is deformed in a torsion test, higher strain rates reduce the plasticity over the entire range (Fig. 3.10b). After reduction at strain rates  $< 1.0 \text{ s}^{-1}$  and temperatures between  $500$  and  $800^{\circ}\text{C}$ , the plasticity decreases rapidly and is almost constant at higher strain rates. An improvement in the formability with increasing strain rate is observed for the alloy FeNi46 in the entire temperature range of hot deformation (Fig. 3.10c).

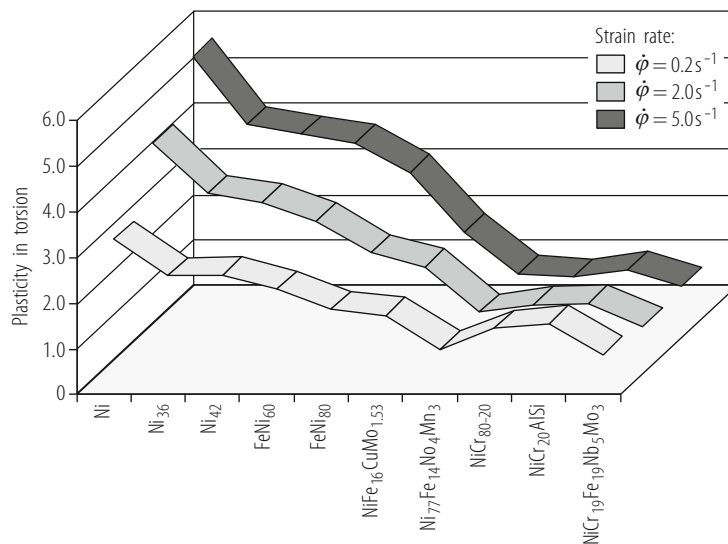


**Fig. 3.10a and b** Relation between plasticity and strain rate at CuAl8Fe a) cold deformation b) hot deformation





**Fig. 3.10c** Relation between plasticity and strain rate for FeNi 46



**Fig. 3.11** Relation between plasticity and strain rate for Ni and Ni-alloys at 1000 °C

A comparison of the plasticity of nickel alloys at 1000 °C and at three strain rates is shown in Fig. 3.11. Ni has the highest absolute value. In Ni-Fe alloys plasticity decreases with increasing Ni content. It is increasingly reduced by additional alloying elements such as Cr, Mo and W.

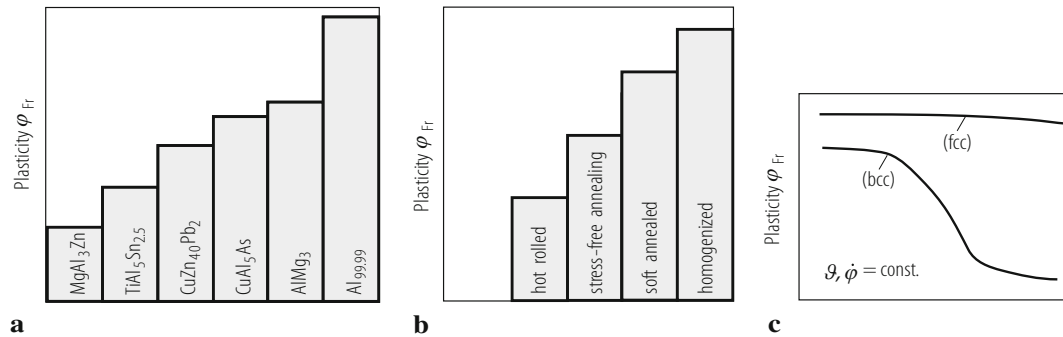
## 3.2 Cold plasticity

### 3.2.1 Factors influencing cold plasticity

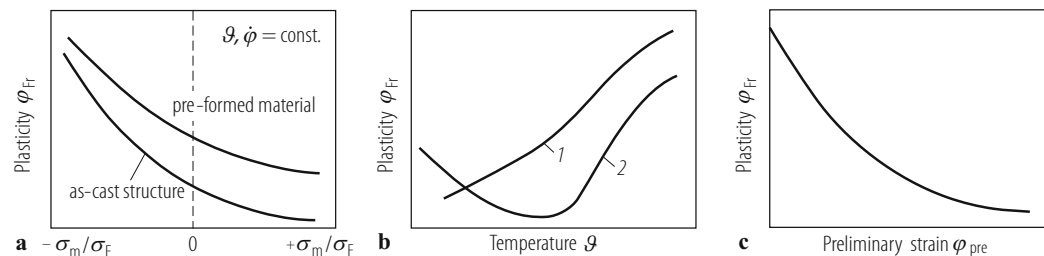
In addition to the chemical composition and structural state of the material the most important factors influencing the cold plasticity are the stress state during deformation expressed by the mean value of stress  $\sigma_m/\sigma_F$  and the relations of the principal normal stresses, the temperature and a possible pre-strain, for example by previous work hardening [3.5; 3.6]. Many factors of influence regarding material and process are interdependent. This makes the examination of cold plasticity rather difficult. Furthermore the mean stress value is difficult to quantify in deformation processes, which is why only qualitative evaluations are available in many cases.

### 3.2.2 Parameters of cold plasticity

The influence of material and processing on the plasticity in cold forming is shown in Figs. 3.12 and 3.13. In [3.1] the torsion test was used to determine the plasticity in cold forming and the results were combined with the results of tensile and impact tests.



**Fig. 3.12** Influence of material related parameters on the plasticity in cold deformation. **(a) Material:** plasticity in cold deformation depends strongly on the material properties. **(b) State of heat treatment:** plasticity can be widely affected by heat treatment (solution annealing, recrystallization annealing etc.). Apart from the annealing temperature and time or the re-heating and cooling rate, i.e. the entire thermal history affects the cold plasticity drastically. **(c) Grain size:** in fcc materials the cold plasticity decreases less steeply with higher grain size than in bcc materials. In bcc materials, a transition from ductile to brittle occurs in a small range of grain size



**Fig. 3.13** Influence of parameters of pre-processing on the plasticity in cold deformation. **(a) Initial structure:** pre-formed material conditions lead to a higher plasticity than materials with an as-cast structure. Also, as-cast structures are more sensitive to tensile stresses. **(b) Deformation temperature:** cold forming occurs below the recrystallization temperature range. If the phase structure is constant,  $\varphi_{Fr}$  raises in the temperature range of cold deformation (curve 1). In hot forming this curve can be interrupted at phase transformation and precipitations. For example a minimum exists for discrete Cu-alloys below 500 °C (curve 2). **(c) Degree of pre-forming:** the plasticity is reduced by a pre-forming process if the load is applied in the same direction (effect of work hardening), whereas the Bauschinger effect maxi occur on alternating the direction of loading

Other than the process related factors mentioned in Fig. 3.10, the relative mean stress value  $\sigma_m/\sigma_F$  as well as the relations between the main normal stresses have an essential effect on the plasticity, with high  $\varphi_{Fr}$  under compressive stress and low  $\varphi_{Fr}$  under tensile stress, corresponding to the effects in hot deformation Fig. 3.2(d).

Besides the differences in absolute values of cold plasticity caused by the mean stress values, the multitude of test procedures entails different characteristic values. The results of determinations of plasticity are comparable only if standard test methods and identical types of test specimens (flat products, bars, pipes) are used.

### 3.2.3 Influence of the material

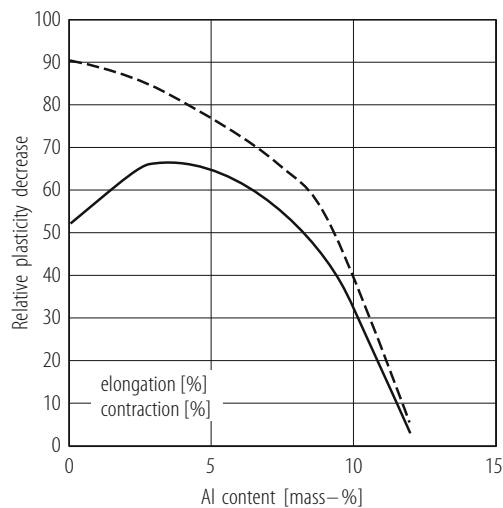
The degree of deformation at fracture in tensile test at room temperature may vary widely with the type of pre-treatment as Table 3.1 shows for Cu.

**Table 3.1** Comparison of the plastic properties of various types of copper at room temperature and  $\dot{\varphi} \sim 10 \text{ s}^{-1}$

| State by production           | Cast                       |                             | Deformed                   |                             |
|-------------------------------|----------------------------|-----------------------------|----------------------------|-----------------------------|
|                               | Elongation to fracture [%] | Contraction at fracture [%] | Elongation to fracture [%] | Contraction at fracture [%] |
| Without oxygen and deoxidizer | 54.7                       | 80.8                        | 58.8                       | 87.1                        |
| Deoxidized with phosphorus    | 49.3                       | 85.5                        | 59.0                       | 87.2                        |
| refined Electrolytically      | 27.5                       | 30                          | 60.0                       | 72.7                        |

The increase in the degree of purity of copper leads to an improvement in the plastic properties.

Figure 3.14 illustrates that an increase in solute content, e.g. in Cu–Al alloys, reduced the plasticity in the cold deformation range. In cold deformation of binary Cu–Al-alloys aluminium causes a significant reduction in plasticity.

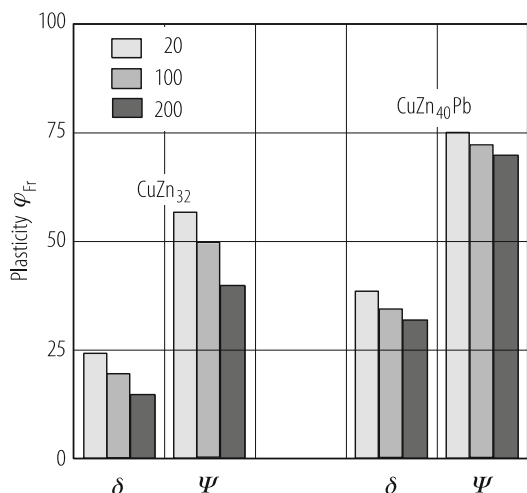


**Fig. 3.14** Influence of the Al-content on the reduction in plasticity of Cu–Al alloys in cold deformation

Besides the material and its crystal structure plasticity depends heavily on the state of processing and detailed treatment. Thus, softening by annealing of Cu-alloys can lead to improvement of plasticity by up to 30% compared to the hot rolled condition, especially at low deformation rates.

### 3.2.4 Temperature

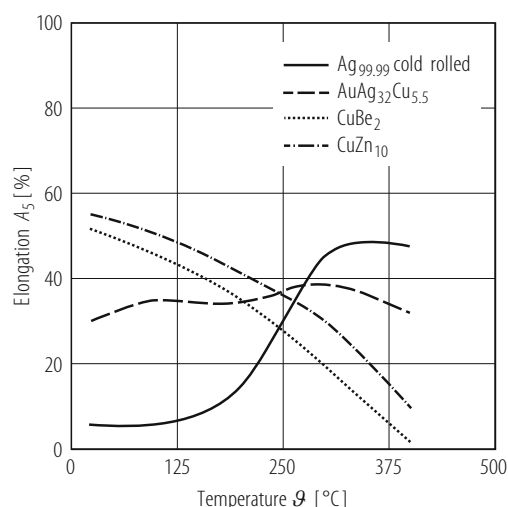
The effect of deformation temperature on the cold plasticity of copper alloys varies for different materials (Fig. 3.15).



**Fig. 3.15** Plasticity of Cu-alloys in cold deformation as a function of temperature  $\delta$  Elongation [%]  $\psi$  Contraction [%]

The plastic properties of copper and copper alloys can decrease with increasing temperature (Figs. 3.15 and 3.16). The decrease depends on the purity of the material and the content of harmful impurities contained in the compound. A temperature-dependent plasticity minimum is not observed in all types of alloys. This changes the plasticity between room temperature and 600 °C only slightly, such as in copper–tin alloys and nickel and iron–nickel alloys. Above this temperature results a significant increase in plasticity. This depends on material, the material condition and the verification procedure.

This enables an increase in temperature to lead, for example Ag99.9 to an increase in elongation between 150 and 350 °C (Fig. 3.16). With further increase in temperature the elongation increases slightly off due to grain growth.

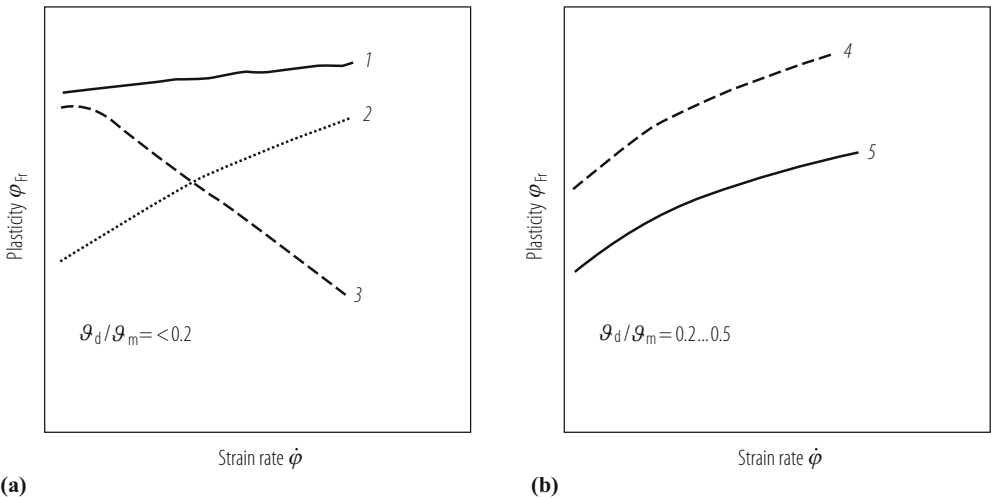


**Fig. 3.16** Elongation as a function of temperature in cold forming

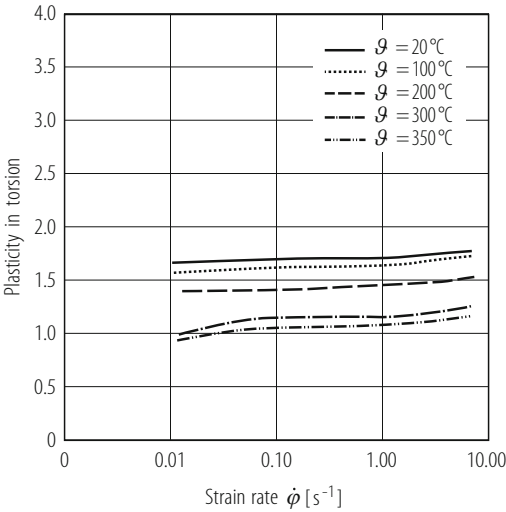
### 3.2.5 Strain rate

At a deformation temperature lower than  $0.20 \vartheta_m$  [°C] the effect of deformation rate on plasticity is low (curve 1, Fig. 3.17a). Plasticity is reduced for alloys, which are deformed by the mechanism of twinning (curve 3), but plasticity can be improved by application of higher temperature or lubricants inside the deformation zone (curve 2).

In cold or semi-hot deformation plasticity increases with increasing deformation rates (curves 4 and 5 Fig. 3.17b).



**Fig. 3.17** Schematic presentation of the deformation rate effects on plasticity in cold deformation;  $\vartheta$  in  $^{\circ}\text{C}$   $\vartheta_d$  – deformation temperature,  $\vartheta_m$  – melting temperature; for numbers of the curves: see text



**Fig. 3.18** Relation between plasticity and strain rate at CuZn35

If the deformation is realized below the temperature of recrystallization, as is the case in many alloys with low melting temperatures, which are deformed between 20 and  $\sim 200^{\circ}\text{C}$ , a moderate improvement of plasticity can be observed. This also holds for alloys, which tend to have precipitation hardening. The slight improvement of the plasticity of CuZn35 is shown in Fig. 3.18.

**Table 3.3** Strain at fracture for heavy metals

| Alloy     | Test type | $\vartheta$ [ $^{\circ}\text{C}$ ] | Cold plasticity $\varphi$ in a torsion test at $\dot{\varphi} =$ |                      |                      |
|-----------|-----------|------------------------------------|------------------------------------------------------------------|----------------------|----------------------|
|           |           |                                    | 0.20 s <sup>-1</sup>                                             | 2.00 s <sup>-1</sup> | 5.00 s <sup>-1</sup> |
| CuZn40Pb1 | torsion   | 20                                 | 1.10                                                             | 1.10                 | 1.10                 |
|           |           | 400                                | 0.98                                                             | 0.74                 | 0.6                  |
|           |           | 600                                | 1.7                                                              | 1.72                 | 1.48                 |
|           |           | 800                                | 2.56                                                             | 3.6                  | 3.13                 |
|           |           |                                    | 0.10 s <sup>-1</sup>                                             | 0.60 s <sup>-1</sup> | 6.70 s <sup>-1</sup> |

(continued)

**Table 3.3** (continued)

| Alloy            | Test type         | $\vartheta$ [°C] | Cold plasticity $\varphi$ in a torsion test at $\dot{\varphi} =$ |                      |                      |
|------------------|-------------------|------------------|------------------------------------------------------------------|----------------------|----------------------|
|                  |                   |                  | 0.20 s <sup>-1</sup>                                             | 2.00 s <sup>-1</sup> | 5.00 s <sup>-1</sup> |
| CuAl8Fe          | torsion           | 400              | 0.404                                                            | 0.383                | 0.411                |
|                  |                   | 600              | 1.83                                                             | 1.691                | 1.457                |
|                  |                   | 800              | 2.187                                                            | 2.084                | 1.944                |
| CuSi5            | torsion           |                  | 0.10 s <sup>-1</sup>                                             | 0.60 s <sup>-1</sup> | 6.70 s <sup>-1</sup> |
|                  |                   | 20               | 0.09                                                             | 0.112                | 0.187                |
|                  |                   | 400              | 0.112                                                            | 0.157                | 0.112                |
|                  |                   | 600              | 0.224                                                            | 0.369                | 0.542                |
|                  |                   | 800              | 0.97                                                             | 1.29                 | 1.496                |
| Ni36             | torsion           |                  | 0.17 s <sup>-1</sup>                                             | 2.07 s <sup>-1</sup> | 4.82 s <sup>-1</sup> |
|                  |                   | 600              | 1.06                                                             | 1.32                 | 1.5                  |
|                  |                   | 1000             | 2.17                                                             | 2.71                 | 3.1                  |
|                  |                   | 1200             | 2.84                                                             | 3.52                 | 4                    |
|                  |                   |                  | 0.2 s <sup>-1</sup>                                              | 2.0 s <sup>-1</sup>  | 5.0 s <sup>-1</sup>  |
| NiCr80-20        | torsion           | 800              | 0.47                                                             | 0.61                 | 0.47                 |
|                  |                   | 1000             | 0.75                                                             | 1.25                 | 0.76                 |
|                  |                   | 1200             | 2.65                                                             | 3.5                  | 2.87                 |
|                  |                   |                  | 2.0 s <sup>-1</sup>                                              | 5.0 s <sup>-1</sup>  | 8.0 s <sup>-1</sup>  |
| NiCr19Fe19Nb5Mo3 | torsion           | 1000             | 0.68                                                             | 0.49                 | 0.57                 |
|                  |                   | 1150             | 1.92                                                             | 1.75                 | 1.62                 |
|                  |                   |                  | 1.0 s <sup>-1</sup>                                              | 10 s <sup>-1</sup>   | 50 s <sup>-1</sup>   |
| AuAg583Cu80      | tensile test      | 20               | 29                                                               | 38                   | 48                   |
|                  | elongation %      | 300              | 38                                                               | 42                   | 48                   |
|                  |                   | 500              | 3                                                                | 8                    | 10                   |
| Ti-46Al-2Cr..    |                   |                  | 900 °C                                                           | 1100 °C              | 1200 °C              |
|                  | tensile test      |                  | 0.246                                                            | 0.246                | 0.157                |
|                  | torsion           |                  | 0.7                                                              | 0.7                  | 0.58                 |
|                  | compressions test |                  | 1.155                                                            | 1.16                 | 1.14                 |

### 3.2.6 Influence of the stress condition

The value of mean stress [3.5]:

$$\sigma_m/\sigma_F := (\sigma_1 + \sigma_2 + \sigma_3)/\sigma_F, \quad (3.1)$$

has a decisive impact on hot plasticity, while the relationship between the mean values of the normal stress  $\sigma_1$ ,  $\sigma_2$  and  $\sigma_3$  play an important role also. Plasticity is higher under compressive stress (negative related mean stress value) than under tensile stress. This basic dependence explains the difference in deformation behaviour of a material when subjected to different test methods. The related mean stress value is nearly zero in a torsion test, which is usually employed for the determination of plasticity.

## 3.3 Modelling of the plasticity in hot working

### 3.3.1 Modelling of the influence of the chemical composition

Figure 3.19 shows the effects of alloying and tramp elements on the degree of deformation at fracture, at a deformation rate of  $\dot{\varphi} = 2 \text{ s}^{-1}$  for the as-cast condition. The 5 kg tests ingots were machined to obtain specimens normal to the crystallization direction. The binary alloys of all elements investigated lead to a reduced plasticity, which is already very pronounced for low contents (<0.50%). The strong decrease in plasticity of alloys sets is already in the range of homogenous solid solution, partly far before the solubility limit. After exceeding the solubility limit, the plasticity reached a rapprochement with a lower limit, which is almost independent of the content of alloying elements, then determines the notch effect of unusual phases, the crack formation and crack propagation. For binary alloys in the cast state  $\varphi_{Fr}$  can be written for 700 °C and a strain rate of  $2.0 \text{ s}^{-1}$ .

Cu–Al alloys

$$\varphi_{Fr} = 0.7743 * \%[Al]^{-0.3681} \quad (3.2a)$$

Cu–Ni alloys

$$\varphi_{Fr} = 2.6546 * \%[Ni]^{-0.6414} \quad (3.2b)$$

Cu–Si alloys

$$\varphi_{Fr} = 0.4362 * \%[Si]^{-0.3865} \quad (3.2c)$$

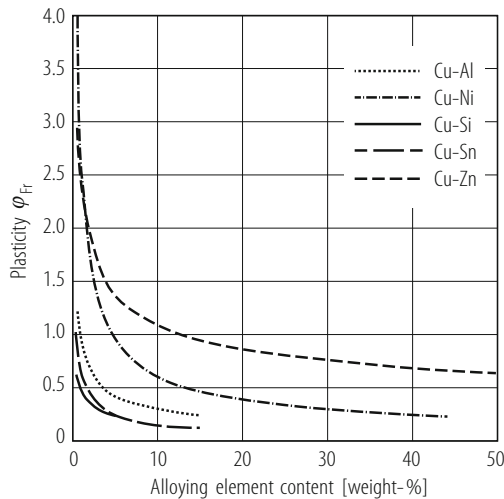
Cu–Sn alloys

$$\varphi_{Fr} = 0.6512 * \%[Sn]^{-0.5803} \quad (3.2d)$$

Cu–Zn alloys

$$\varphi_{Fr} = 2.2693 * \%[Zn]^{-0.3684} \quad (3.2e)$$

The element content in Eqs. (3.2a to e) is in mass % use.



**Fig. 3.19** Effect of alloying elements on the degree of deformation at fracture of Cu-alloys in the cast state at  $\vartheta = 700\text{ }^{\circ}\text{C}$  and  $\dot{\varphi} = 2\text{ s}^{-1}$

### 3.3.2 Influence of deformation conditions

#### 3.3.2.1 Modelling of temperature influence

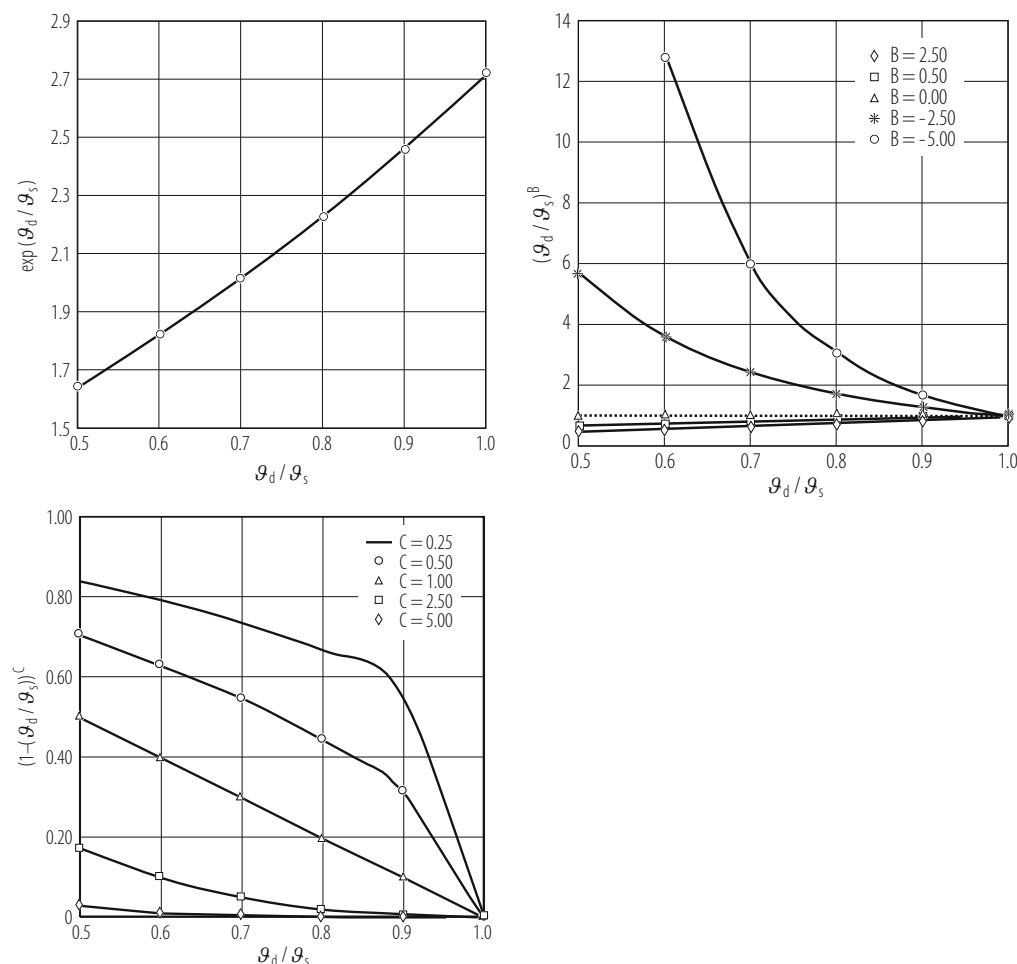
The dependence of hot plasticity on the temperature is mainly due to the acceleration of the softening, the dissolution of precipitations, phase transformations, grain growth and incipient grain boundary fusion at high temperatures.

A relationship between hot plasticity and the rate of softening exists in terms of a power function [3.8]. Because of the great number of processes that occur simultaneously during hot deformation it is not possible to model their influence on hot plasticity mathematically except for limited ranges of temperature and rate of deformation. For the single-phase range of alloys the relation:

$$\varphi_{Fr} = A \cdot \exp(\vartheta_d/\vartheta_s) \cdot (\vartheta_d/\vartheta_s)^B \cdot (1 - (\vartheta_d/\vartheta_s))^C, \quad (3.3)$$

with  $\vartheta_d$  and  $\vartheta_s$ , the deformation and solidus temperature (in  $^{\circ}\text{C}$ ) and  $A, B, C, D$  constants, can be used to define the influence of temperature on hot plasticity [3.7].

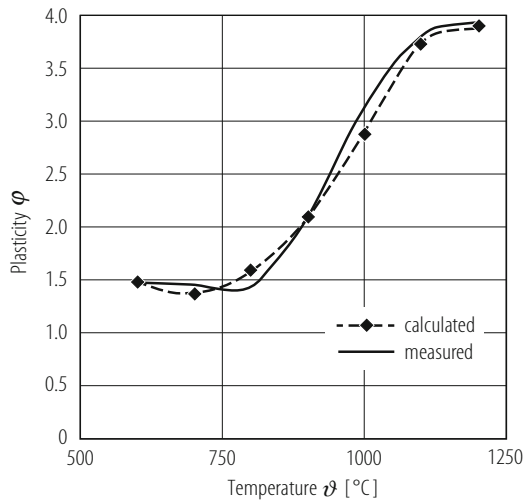
Figure 3.20 shows the temperature dependence of the individual factors in Eq. (3.3) for heavy metals and the typical range of exponents.



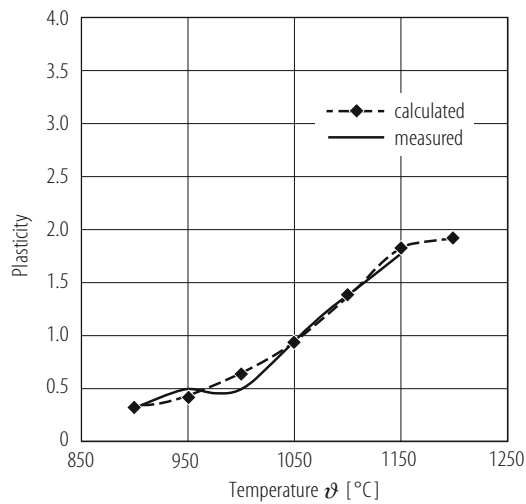
**Fig. 3.20** Temperature dependence of the individual factors in Eq. (3.3) for heavy metal alloys and the typical range of exponents

As can be seen, the product of the exponential and power function  $\exp(\theta_d/\theta_s) \cdot (\theta_d/\theta_s)^B$  offers the possibility to describe a non-linear increase of plasticity in deformation as dependent on the deformation temperature. The factor  $(1 - (\theta_d/\theta_s))^C$  characterizes the drop of plasticity in hot deformation in the temperature range between the maximum and the solidus temperature. In this context the exponent  $C$  plays a significant role for the intensity of the decrease. In Fig. 3.21 the calculated and the measured plasticity values of two heavy alloys are compared. In both cases, good agreement between the measured and calculated values is found over the entire temperature range. The relatively simple equation can be recommended for mathematical modelling of the temperature dependence at constant deformation rates.





**Fig. 3.21a** Comparison of measured and calculated (according to Eq. (3.3)) values of plasticity at hot deformation for FeNi 36;  $\dot{\varphi} = 5$  [1/s]



**Fig. 3.21b** Comparison of measured and calculated (according to Eq. (3.3)) values of plasticity at hot deformation for NiCr19Fe19Nb5Mo3;  $\dot{\varphi} = 5$  [1/s]

Table 3.5 summarizes the constants for the calculation of the deformation degree at fracture at hot deformation for selected non-ferrous metal alloys. These are based on torsion tests with a ratio  $L/D = 2.50$  and a translation of the shear factor  $\gamma$  to the respective amount of deformation according to Nadai–v. Mises.

**Table 3.5** Constants for the calculation of the degree of deformation at fracture as dependent on the temperature of deformation according to Eq. (3.3)

| Alloy          | Strain rate $\dot{\varphi}$ [s <sup>-1</sup> ] | $\ln A$ | $B$     | $C$     | Range of validity $\vartheta$ [°C] |
|----------------|------------------------------------------------|---------|---------|---------|------------------------------------|
| Ni 99.99       | 0.2                                            | 10.7783 | 10.9280 | 4.6390  | 600 ... 1100 °C                    |
| Ni 99.99       | 2                                              | 10.7732 | 10.5666 | 4.8640  | 600 ... 1100 °C                    |
| Ni 99.99       | 5                                              | 5.9487  | 6.6336  | 2.0667  | 600 ... 1100 °C                    |
| X2NiCoMo18-9-5 | 0.2                                            | 12.0563 | 12.1035 | 5.9639  | 800 ... 1200 °C                    |
| X2NiCoMo18-9-5 | 2                                              | 18.4330 | 19.5791 | 9.0702  | 800 ... 1200 °C                    |
| X2NiCoMo18-9-5 | 5                                              | 16.6084 | 18.7234 | 7.8856  | 800 ... 1200 °C                    |
| CuZn37         | 0.2                                            | 0.6378  | 1.1296  | 0.1743  | 400 ... 800 °C                     |
| CuZn37         | 2                                              | 0.9202  | 1.8974  | 0.1818  | 400 ... 800 °C                     |
| CuZn37         | 5                                              | 0.7243  | 1.8718  | 0.0257  | 400 ... 800 °C                     |
| CuFe2P         | 0.2                                            | 28.6579 | 29.5348 | 14.7119 | 600 ... 800 °C                     |
| CuFe2P         | 2                                              | 19.2974 | 18.8878 | 10.0853 | 600 ... 800 °C                     |

The correlation coefficient of the constants lies between 0.9576 (CuZn37) and 0.8672 (Ni99.99). The solidus temperature was determined by DTA or taken from a phase diagram.

### 3.3.2.2 Modelling of the influence of strain rate

The influence of the strain rate on hot plasticity is relatively weak. An increase of the strain rate over three orders of potencies generally results in a change in the plasticity of about 30% for most alloys. A correction in Eq. (3.3) with respect to the strain rate can be introduced by means of a product of a power function and an exponential function:

$$\varphi_{fracture}(\dot{\varphi}) = A \cdot \dot{\varphi}^B \cdot \exp(C/\dot{\varphi}) (\vartheta = \text{const}) \quad (3.4)$$

The constants for some alloys are listed in Table 3.6.

**Table 3.6** Constants to calculate the effect of strain rate on plasticity from Eq. (3.4)

| Alloy          | Testing method | Temperature $\vartheta$ [°C] | Constants |         |         |
|----------------|----------------|------------------------------|-----------|---------|---------|
|                |                |                              | $\ln A$   | $B$     | $C$     |
| Ni99.99        | torsion        | 1000                         | 1.7908    | -0.0292 | -0.1155 |
| X2NiCoMo18-9-5 | torsion        | 1000                         | 1.1859    | -0.1081 | -0.0381 |
| CuZn37         | torsion        | 700                          | 0.7819    | 0.1802  | 0.0665  |
| CuFe2P         | torsion        | 700                          | 1.3219    | -0.0804 | -0.0355 |

The equation above allows describing all relevant cases of the relation between plasticity and deformation rate:

- Increase with increasing deformation rate,
- Decrease with increasing deformation temperature and
- Maximum or minimum value within the range of deformation rate investigated.

It is also applicable for other procedures to determine plasticity.

## 3.4 Calculation of the forming limit in hot rolling

It is a basic assumption for calculating the forming limit in hot rolling that the octahedral slip in torsion tests is the same as the octahedral slip in the roll gap in rolling. The maximum possible strain over the height  $\varphi_H$  in rolling is [3.3]:

$$\varphi_H = \frac{\varphi_{Fr} \left( 1 + \frac{\mu}{2} \cdot \frac{l_d}{h_m} \right)}{\sqrt{1 + \frac{h_0 \cdot \Delta b}{b_0 \cdot \Delta h} + \left( \frac{h_0 \cdot \Delta b}{b_0 \cdot \Delta h} \right)^2}} \quad (3.5)$$

with  $\varphi_{Fr}$  the equivalent strain at fracture in torsion tests,  $\mu$  the friction coefficient in the roll gap,  $l_d$  the roll contact length (in mm),  $h_m$  the mean thickness of the rolled material in the roll gap (in mm),  $h_0$  and  $b_0$  the thickness and width before rolling, respectively (in mm);  $\Delta h$  and  $\Delta b$  are the variations of thickness and width during the pass.

Zajkov et al. [3.9] have suggested an equation for calculations of the forming limit  $\varepsilon_{H,Fr}$  in rolling that includes the structure and the microstructural states (as-cast or as-rolled) besides the plasticity in the torsion test. The correction factors account for the effects of quality of the material surface, state of material and the aspect ratio of the rolled samples [3.3]:

$$\varepsilon_{H,Fr} = \left(1 - \sqrt[n]{1 - \varphi_{Fr} \cdot K_{cs}}\right) \cdot K_{size} \cdot K_{surf}, \quad (3.6)$$

where  $\beta = 1.155$  is the Lode coefficient,  $n$  a factor for the stress state,  $K_{cs}$  a coefficient related to the state of the material (as-cast or as-rolled),  $K_{surf}$  a factor for the surface quality and  $K_{size}$  a size related correction factor. A formulation of the possible variants of calculation of the limiting degree of deformation in Eq. (3.6) is:

$$\varphi_{H,tot} = \left[ \frac{\varphi_{Fr} \left(1 + \frac{\mu}{2} \cdot \frac{l_d}{h_m}\right)}{\sqrt{1 + \frac{h_0 \cdot \Delta b}{b_0 \cdot \Delta h} + \left(\frac{h_0 \cdot \Delta b}{b_0 \cdot \Delta h}\right)^2}} \right] \cdot K_{cs} \cdot K_{size} \cdot K_{surf}. \quad (3.7)$$

According to this equation increased friction, greater roller diameter and smaller width to height ratio  $h_0/b_0$  lead to higher limits of the possible height reduction; the other side leads to greater geometric dimensions of a reduction. Since deformation in the roll gap is inhomogeneous it should be noted that the degree of deformation according to Eqs. (3.6, 3.7) reflects the maximum possible local degree of deformation.

A reduction of the roll diameter affects the limit of deformation only slightly. The values of the maximum possible reduction per pass are to be corrected by the factors  $K_{cs}$ ,  $K_{size}$  and  $K_{surf}$ .

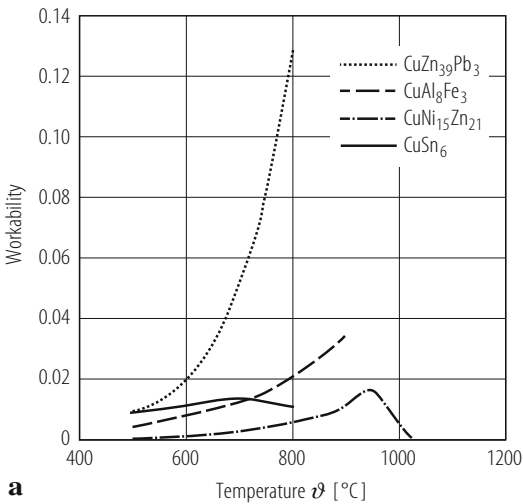
On the basis of the results with different rolling programs for Cu alloys, with the following factors as mean values for  $K_{size} = 0.80$  (variant by [3.3] between 0.75–0.85) and  $K_{surf} = 0.65$  (variant by [3.3] between 0.46–0.70) then  $K_{cs} = 0.50$  is used.

In flat rolling there is no complicated material flow and in practice the material flow in the width direction is very small, so that the values selected for  $K_{cs}$ ,  $K_{size}$  and  $K_{surface}$  are probably ensuring crack-free forming in rolling.

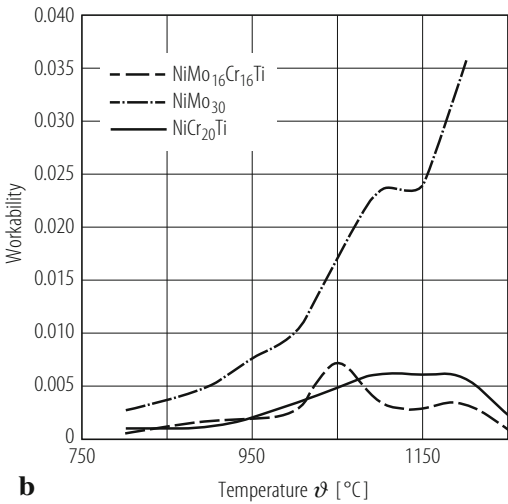
### 3.5 Calculation of the forming limit in hot extrusion

Workability is a complex property, which has no distinct definition. It is determined by the material and the forming process (see Fig. 1.3). In general a material is well formable if it is able to change its geometric form, requires a low energy of deformation, remains free of cracks, has a precise surface after forming and if the forming process is associated with a high yield and a high durability of the forming tool. The workability is determined by the deformation properties, in particular by the flow stress  $\sigma_F$  and the plasticity  $\varphi_{Fr}$ . The ratio  $\varphi_{Fr}/\sigma_F$  provides a characteristic parameter with the dimension  $[\text{mm}^3/\text{Nmm}]$ , which expresses the volume which can be deformed with an amount of work of 1  $[\text{Nmm}]$ . In simulation procedures the limiting strain is determined in tensile, torsion or compression tests. The possible limiting strain for technical processes differ significantly from the results of the simulation experiments, because they differ widely in their mean pressure  $-\sigma_m/\sigma_F$  (see Fig. 1.2). The results of the tests are converted to higher mean pressure  $-\sigma_m/\sigma_F$  so that they can be used for the hot extrusion. However, even though some equations have been proposed [3.10; 3.11; 3.12 and 3.14] quantitative congruence relations do not exist. Therefore present practice is limited to relying on the workability found in some simulation procedures and on the use of process-specific empirical data to classify the effects of material and deformation conditions.

As an example, workability of Cu- and Ni-alloys at hot deformation is shown in Fig. 3.22a and 3.22b.



**Fig. 22a** Workability of Cu–alloys by hot deformation; strain rate 2 [1/s]



**Fig. 22b** Workability of Ni–alloys by hot deformation; strain rate 2 [1/s]

According to investigations by extrusion of non-ferrous metals and high alloyed steels (Laue and Stenger [3.13]) the following classification was obtained:

| Workability in extrusion | $\varphi_{Fr}/\sigma_F$ |
|--------------------------|-------------------------|
| less suitable            | <0.01                   |
| moderate                 | 0.01...0.02             |
| good                     | 0.02...0.04             |
| very good                | >0.04                   |

The calculation of the relation  $\varphi_{Fr}/\sigma_F$  is based on a conversion of the shear strain  $\gamma$ , found in a torsion test, into a reference degree of deformation according to Nadai– v. Mises and of the flow stress in [MPa].

The relation  $\varphi_{Fr}/\sigma_F$  is strongly temperature-dependent. The classification of workability, presented here, coincides qualitatively with the processing instructions for hot forming in [3.15].

In general, the higher the alloy content and the flow stress of a material, the more difficult it is to extrude and the lower the limit of its extrusion rate.

The extrudability depends on temperature, strain rate and other deformation conditions such as lubrication and tool design.

## Symbols and abbreviations

| Short form           | Full form                             |
|----------------------|---------------------------------------|
| $\sigma_F$           | flow stress                           |
| $\dot{\varphi}$      | strain rate                           |
| $\varphi$            | strain                                |
| $Z$                  | Zener-Hollomon parameter              |
| $\vartheta$          | temperature                           |
| $\vartheta_d$        | deformation temperature               |
| $\mu$                | coefficient of friction               |
| A, B, C, D           | Constants                             |
| $b_0$                | Width before rolling                  |
| $D$                  | specimen diameter                     |
| $h_0$                | Thickness before rolling              |
| $h_m$                | mean thickness of the rolled material |
| $K_{size}$           | size related correction factor        |
| $K_{surf.}$          | factor for the surface quality        |
| $L$                  | gage length                           |
| $l_d$                | roll contact length                   |
| $T_d$                | deformation temperatures              |
| $T_{melt}$           | solidus temperature                   |
| $\varepsilon_{H,Fr}$ | forming limit                         |
| $\varphi_{Fr}$       | plasticity                            |
| $\vartheta_s$        | solidus temperature                   |
| $\delta$             | elongation                            |
| $\gamma$             | shear factor                          |
| $\Psi$               | contraction                           |

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# Mechanical and physical properties of alloys and metals

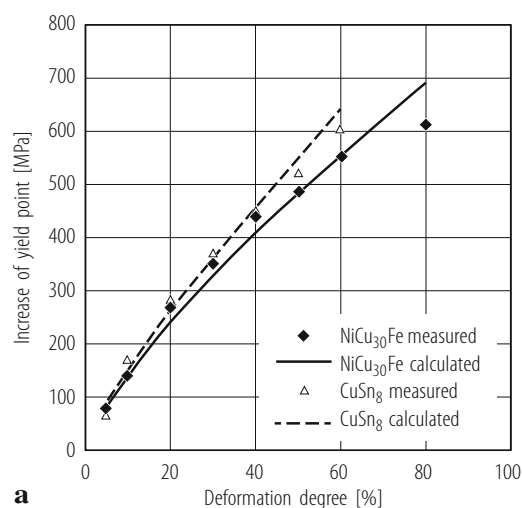
## 4 Mechanical and physical properties

### 4.1 Mechanical properties after cold deformation

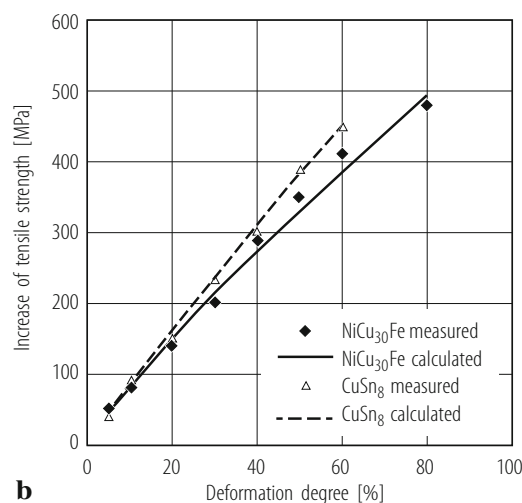
Cold deformation leads to higher yield strength, tensile strength and hardness. Yet the elongation and reduction in area are reduced. The effects of cold deformation will now be discussed in more detail.

#### 4.1.1 Yield point and tensile strength

As the increase in yield strength, tensile strength and hardness of the material can be attributed to work hardening, it is possible to express their dependence on strain and related strain by polynomials, similar to the cold stress–strain curves [4.1]. The influence of strain and related strain, respectively, on the yield strength, the tensile strength and the elongation of a material can be expressed by the Ludwik equation with a high degree of agreement between measured and calculated results. Figures 4.1a and 4.1b present the correlation between yield point and tensile strength for copper and nickel alloys.



**Fig. 4.1a** Compare measured and calculated values of yield point as a function of deformation



**Fig. 4.1b** Compare measured and calculated values of tensile strength as a function of deformation

The variation in mechanical properties caused by cold deformation can be calculated by:

$$R_p = R_{p-exit} + A \cdot \varepsilon^{n_1}, \quad (4.1)$$

$$R_m = R_{m-exit} + B \cdot \varepsilon^{n_2}, \quad (4.2)$$

with

|                  |                                                                   |
|------------------|-------------------------------------------------------------------|
| $R_p$            | yield strength [MPa],                                             |
| $R_m$            | tensile strength [MPa],                                           |
| $\varepsilon$    | related strain [%],                                               |
| $R_{p-exit}$     | yield strength in the initial state at $\varepsilon = 0$ [MPa],   |
| $R_{m-exit}$     | tensile strength in the initial state at $\varepsilon = 0$ [MPa], |
| $A, B$ and $n_i$ | constants [–].                                                    |

Obviously the calculated and measured values are in good accord. The influence of cold deformation – as expressed by the degree of deformation or the related strain – on yield point and tensile strength after cold deformation can be modelled by power and exponential functions.

#### 4.1.2 Elongation

The decrease in elongation to fracture at higher strain can describe by:

$$\Delta A_5 = C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}. \quad (4.3)$$

Hence the elongation is given by:

$$A_5 = A_{5-0} - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}. \quad (4.4)$$

Where:

|               |                                                           |
|---------------|-----------------------------------------------------------|
| $A_5$         | elongation [%],                                           |
| $\Delta A_5$  | decrease in elongation [%],                               |
| $A_{5-0}$     | elongation at the initial state at $\varepsilon = 0$ [%], |
| $\varepsilon$ | related strain,                                           |
| $C$ and $n_i$ | constants.                                                |

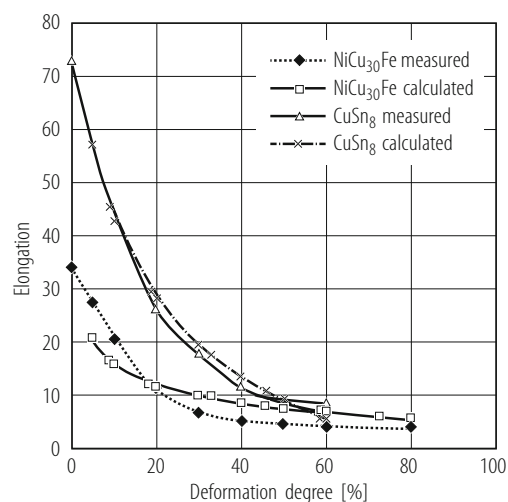
The correlation between the natural logarithm of elongation and the strain can be described mathematically by a polynomial or by a power function. For NiCu30Fe the following equations hold:

$$\Delta A_5 = 17.9595 \cdot \varepsilon^{0.1121} \cdot e^{-2.4189/\varepsilon}, \quad (4.5)$$

or

$$\ln \Delta A_5 = 4.7277 - 0.7921 \cdot \ln \varepsilon - 0.0043 \cdot (\ln \varepsilon)^2. \quad (4.6)$$

It was found that coefficients of the power functions for different alloys and treatment condition are nearly independent of the exact composition of melts of nominally the same alloy content. The correlation coefficient of the polynomial is higher than the coefficient of the combination of power and exponential function. Small deviations of the values can be observed in ranges of extrapolation which are not confirmed by measurements. The decrease in elongation with higher related strain, which is reflected in Eq. (4.4) for the above mentioned alloys, can be seen in Fig. 4.2. The correlation between measured and calculated values is good.



**Fig. 4.2** Measured and calculated values of the elongation as a function of degree of deformation for copper and nickel alloys

The measurement results shown in Figs. 4.1 and 4.2 were obtained from cold drawn and rolled samples but they are also applicable to the cold rolling of flat products.

## 4.2 Young's modulus

### 4.2.1 Definition and functional relationships

The three elastic moduli, i.e. the modulus of elasticity or Young's modulus  $E$ , the shear modulus  $G$  and the compression modulus  $D$ , characterize the proportionality of stress and elastic deformation caused by tension, shear or compression from all sides. The moduli are interrelated as follows:

$$E = 2G^*(\nu + 1) = 3D^*(1 - 2^*\nu), \quad (4.7)$$

and hence

$$G = E/2 \cdot (\nu + 1), \quad (4.7a)$$

$$D = E/3 \cdot (\nu - 1), \quad (4.7b)$$

$$\nu = \frac{E}{2 \cdot G} - 1, \quad (4.7c)$$

where  $\nu$  is the Poisson ratio, which ranges between 0.25 and 0.35 for most metals (Table 4.1) [4.2, 4.3]. As can be seen in Table 4.2, the elastic modulus  $E$  differs significantly for various metals [4.2... 4.5].

**Table 4.1** Poisson's ratio of metals and alloys

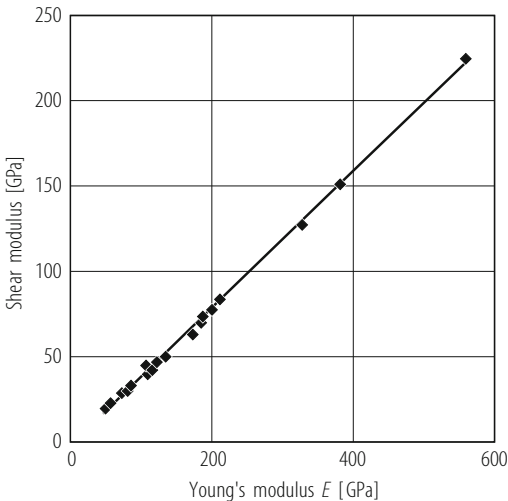
| Temperature $T$ [°C] | Poisson's ratio $\nu$ |            |         |           |             |        |
|----------------------|-----------------------|------------|---------|-----------|-------------|--------|
|                      | Tungsten              | Molybdenum | Niobium | CuZn39Pb3 | CuNi10Fe1Mn | FeNi36 |
| 20                   | 0.254                 | 0.335      | 0.35    | 0.41      | 0.35        | 0.28   |
| 200                  | 0.261                 | 0.355      | 0.31    | 0.41      | 0.36        | 0.29   |
| 400                  | 0.265                 | 0.366      | 0.31    | 0.41      | 0.36        | 0.27   |
| 600                  | 0.270                 | 0.352      | 0.34    |           |             |        |
| 800                  | 0.280                 | 0.360      | 0.34    |           |             |        |
| 1000                 | 0.280                 | 0.360      | 0.34    |           |             |        |



**Table 4.2** Elastic moduli of metals

| Metal or alloy | Young’s modulus $E$<br>[GPa] | Shear modulus $G$<br>[GPa] | Compression modulus $D$<br>[GPa] |
|----------------|------------------------------|----------------------------|----------------------------------|
| aluminium      | 70.6                         | 26.2                       | 75.2                             |
| iron           | 211.4                        | 81.6                       | 169.8                            |
| magnesium      | 44.7                         | 17.3                       | 35.6                             |
| copper         | 129.8                        | 48.3                       | 137.8                            |
| molybdenum     | 324.8                        | 125.6                      | 261.2                            |
| nickel         | 199.5                        | 76.0                       | 177.3                            |
| niobium        | 104.9                        | 37.5                       | 170.3                            |
| silver         | 82.7                         | 30.3                       | 103.6                            |
| tantalum       | 185.7                        | 69.2                       | 196.3                            |
| titanium       | 120.2                        | 45.6                       | 108.4                            |
| tungsten       | 467.8                        | 137.3                      |                                  |
| tin            | 54.0                         | 20.2                       |                                  |
| zinc           | 104.5                        | 41.9                       | 69.4                             |
| CuZn30         | 100.6                        | 37.3                       | 111.8                            |
| Ni36           | 144.0                        | 57.2                       | 99.4                             |

Because of the marginally different  $\nu$  – values of metals, the relation between shear and Young’s modulus is nearly the same. Figure 4.3 presents the relation between shear and Young’s modulus. The ratio  $G/E$  of cubic metals is  $\approx 0.357$ .



**Fig. 4.3** Shear modulus vs. Young’s modulus

The temperature coefficient of the three elastic moduli  $\alpha_E$  varies with temperature exactly in the same manner as that of the specific heat capacity, namely:

$$\alpha_E = \frac{12}{5} \pi^4 * R \cdot (T/\Theta)^3 \qquad \text{at } \Theta/T \gg 1, \tag{4.8}$$

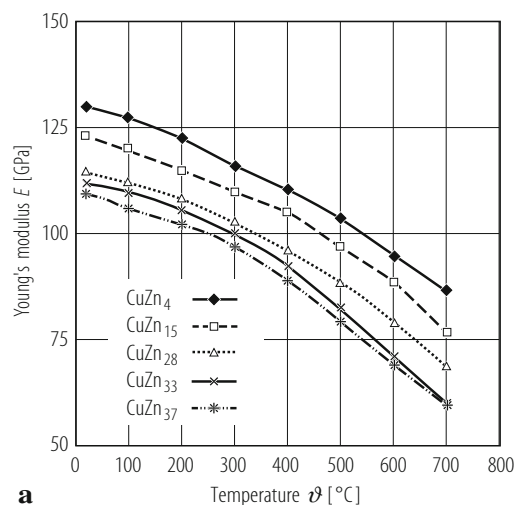
$$\alpha = 3 \cdot R \qquad \text{at } \Theta/T \ll 1, \tag{4.9}$$

with:

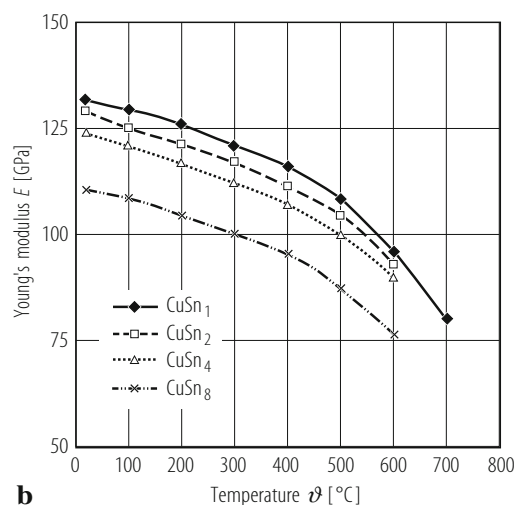
|            |                                                                |
|------------|----------------------------------------------------------------|
| $\alpha_E$ | temperature coefficient [–],                                   |
| $R$        | universal gas constant [J mol <sup>–1</sup> K <sup>–1</sup> ], |
| $T$        | temperature [K],                                               |
| $\Theta$   | Debye temperature [K],                                         |
| $T_s$      | melting temperature [K].                                       |

The two above equations mean that Young's modulus varies proportionally to  $T^4$  at low temperatures while a linear decrease must be expected for high temperatures ( $\Theta < T < 0.5 T_s$ ) [4.2]. Depending on the mode of calculation (based on absolute melting temperature or on specific heat capacity) the Debye temperature is found to be 329 or 315 [K] for Cu and 425 or 370 [K] for Ni.

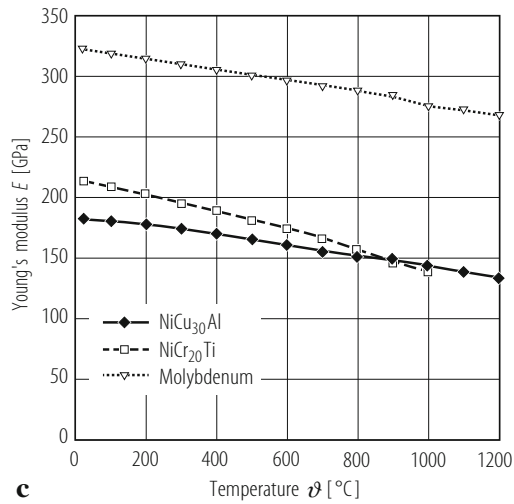
Figure 4.4 [4.3, 4.7, 4.8] shows the relation between Young's modulus and temperature for different compositions of Cu–Zn– and Cu–Sn alloys as well as for molybdenum, NiCr20Ti and NiCu30Al between 20 and 700 [°C]. The temperature dependence of Cu–Zn– (Fig. 4.4a) and Cu–Sn alloys (Fig. 4.4b) is shown for different alloy compositions. Increasing alloy content and higher temperatures lead to a reduction of Young's modulus. Also for molybdenum, NiCr20Ti, NiCu30Al decreases the Young's modulus with increasing temperature (Fig. 4.4c). The comparison of measured and calculated values of Young's modulus of different materials is shown in Fig. 4.4d.



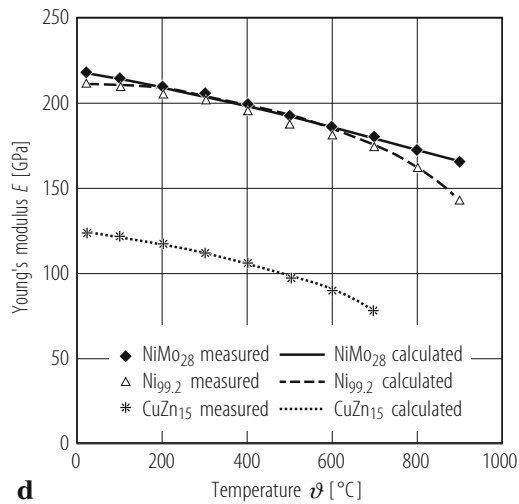
**Fig. 4.4a** Young's modulus as a function of temperature for CuZn4 ... CuZn37



**Fig. 4.4b** Young's modulus as a function of temperature for CuSn alloys



**Fig. 4.4c** Young's modulus as a function of temperature for NiCu30Al; NiCr20Ti and molybdenum



**Fig. 4.4d** Measured and calculated values of the Young's modulus as a function of the temperature for Ni- and Cu-alloys

#### 4.2.2 Temperature-dependent modelling of Young's modulus

Within the range between 20 °C and the melting temperature the temperature dependence of Young's modulus  $E$  of non-ferrous metals and their alloys cannot be represented adequately, neither by a temperature coefficient according to Eq. (4.8) nor as a linear dependence as in Eq. (4.8). Therefore, a function is used, which describes the temperature with an exponent  $> 1.0$ , and a fourth order polynomial

$$E(\vartheta) = E_{20} - (A_1 + A_2 \cdot \vartheta + A_3 \cdot \vartheta^2 + A_4 \cdot \vartheta^3 + A_5 \cdot \vartheta^4), \quad (4.10)$$

where  $\vartheta$ , the temperature [°C] and  $A_1 \dots A_5$  are constants. Figure 4.4d presents the comparison of measured and calculated Young's modulus of NiMo28, Ni99.2 and CuZn15 in the range 0...900 or 700 °C. Table 4.3 lists the constants for Eq. (4.10) for different non-ferrous metals and alloys.

**Table 4.3** Constants for calculation of Young's modulus for different non-ferrous metals and alloys according to Eq. (4.10)

| Metal or alloy  | Constants |          |           |                          |                           | Range of validity [°C] |
|-----------------|-----------|----------|-----------|--------------------------|---------------------------|------------------------|
|                 | $A_1$     | $A_2$    | $A_3$     | $A_4$                    | $A_5$                     |                        |
| Ni99.6          | −6.47206  | 0.35541  | −0.00166  | 0.000005                 | −2.48072*10 <sup>−9</sup> | 20...800               |
| Ni99.2          | 0.90479   | −0.02204 | 0.00028   | −4.5637*10 <sup>−7</sup> | 2.96677*10 <sup>−10</sup> | 20...900               |
| NiMo28          | −0.80603  | 0.04393  | 0.000028  | −2.6272*10 <sup>−8</sup> | 1.4721*10 <sup>−11</sup>  | 20...900               |
| NiCr15Fe        | −0.61286  | 0.04961  | −0.000016 | 6.593*10 <sup>−8</sup>   | −2..785*10 <sup>−11</sup> | 20...1200              |
| CuZn15          | −0.8625   | 0.03652  | 0.000041  | −7.1576*10 <sup>−8</sup> | 1.0816*10 <sup>−10</sup>  | 20...700               |
| CuZn40          | −1.21480  | 0.05486  | −0.000116 | 3.683*10 <sup>−7</sup>   | −2.4336*10 <sup>−10</sup> | 20...700               |
| CuAl10Ni5Fe     | −3.52660  | 0.18086  | −0.00143  | 0.0000051                | −4.82681*10 <sup>−9</sup> | 20...600               |
| Nb (cast state) | −0.29411  | 0.01334  | −0.000030 | 2.51811*10 <sup>−8</sup> | −6.3463*10 <sup>−12</sup> | 20...1600              |

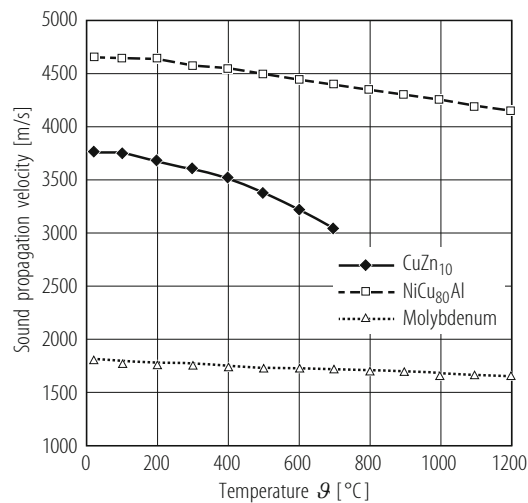
The knowledge of Young's modulus permits to determine the propagation of the sound velocity  $c_L$  according to relations [4.6]:

$$c_L = \sqrt{\frac{E}{\rho}} \quad \text{for thin rods respectively,} \quad (4.11)$$

$$c_L = \sqrt{\frac{E \cdot (1 - \nu)}{\rho \cdot (1 + \nu) \cdot (1 - 2\nu)}} \quad \text{for undefined shapes,} \quad (4.12)$$

with  $\rho$  the material density and  $\nu$  the Poisson's ratio.

Figure 4.5 shows the relation between velocity of sound propagation and temperature according to Eqs. (4.11 and 4.12). Since density and  $E$ -modulus decrease with increasing temperature, the velocity of sound propagation decreases accordingly.

**Fig. 4.5** Velocity of sound propagation versus temperature for different non-ferrous alloys

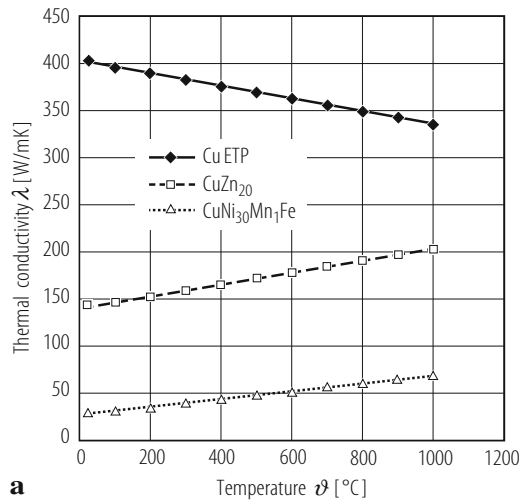
### 4.3 Thermal conductivity

#### 4.3.1 Characteristics of thermal conductivity

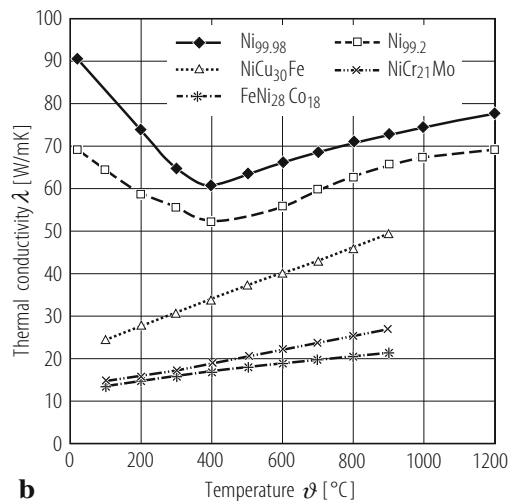
The thermal conductivity  $\lambda$  depends on the material and on temperature. Typical values for pure metals at 20 °C are [4.4, 4.5 and 4.6]:

|                   | Magnesium | Aluminium | Titanium | Copper | Nickel | Niobium | Zinc | Silver |
|-------------------|-----------|-----------|----------|--------|--------|---------|------|--------|
| $\lambda$ [W/m*K] | 157       | 230       | 17       | 394    | 92     | 54      | 113  | 431    |

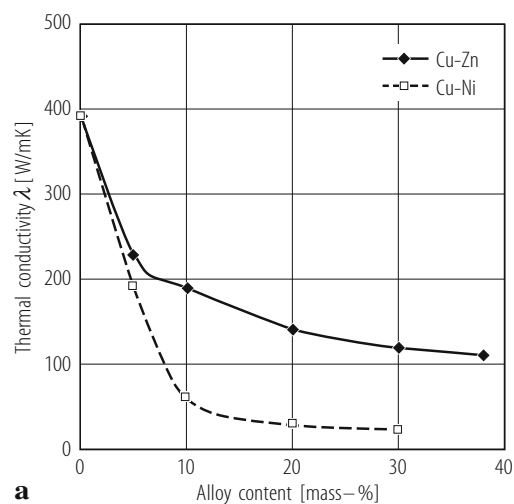
The thermal conductivity  $\lambda$  may increase or decrease as the temperature rises. Figures 4.6a and 4.6b show the temperature dependence of the thermal conductivity for copper and nickel alloys with different chemical composition. The thermal conductivity of most non-ferrous metal alloys [4.9. . 4.20] rises with increasing temperature (see CuZn20, Ni99.98 and Ni99.2 above about 400 [°C]). During the thermal conductivity of Cu-ETP the temperature range observed decreases, ending the decrease at Ni99.98 and Ni99.2 at 400 [°C]. Addition changes the thermal conductivity in this material group. Copper alloyed with Zn and Ni (Fig 4.7a) as well as with Sn and Al (Fig. 4.7b) has a decreasing thermal conductivity with increasing alloy content [4.10]. Figure 4.7c shows, that reducing the nickel of Fe–Ni–alloys reduces the thermal conductivity up to a nickel content of about 20%. Above that, it increases again. A minimum of the thermal conductivity of binary alloys is also observed in the system Ag–Au (Fig. 4.7d).



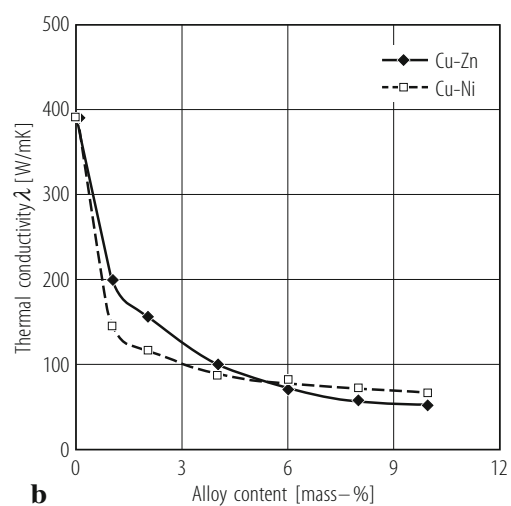
**Fig.4.6a** Thermal conductivity of copper alloys as a function of temperature



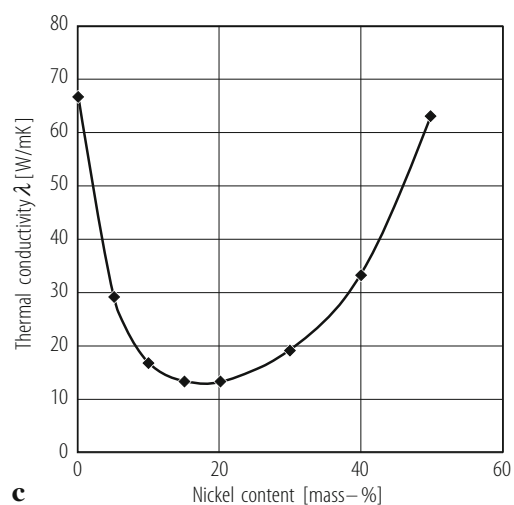
**Fig.4.6b** Thermal conductivity of Ni and Fe–Ni–alloys as a function of temperature



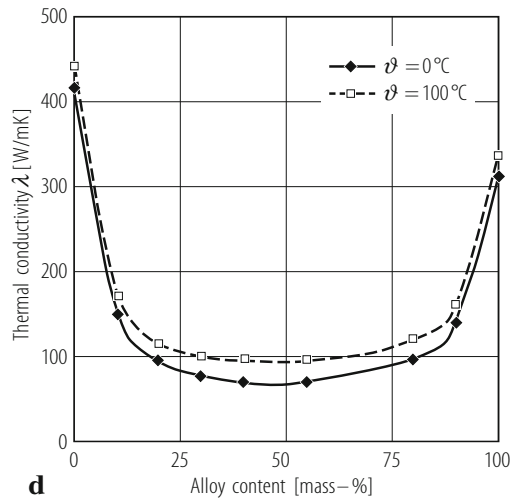
**Fig. 4.7a** Concentration dependence of thermal conductivity of copper–zinc– and copper–nickel–alloys [4.13]



**Fig. 4.7b** Concentration dependence of thermal conductivity of copper–tin– and copper–aluminium–alloys [4.9, 4.10]



**Fig. 4.7c** Thermal conductivity as a function of Ni– content of Fe–Ni–alloys



**Fig. 4.7d** Thermal conductivity of Ag–Au alloys as a function of Au content [4.9, 4.10]

The thermal conductivity of nonferrous alloys is further diminished by the structure of the alloy, which has a higher dislocation density.

Table 4.4 shows an example of the influence of the structural state on the thermal conductivity for CuBe2 in different states of heat treatment and deformation.

**Table 4.4** Thermal conductivity of CuBe2 in different states of heat treatment and deformation

| Treatment                                                                            | Thermal conductivity $\lambda$ [W/m <sup>2</sup> K] |        |
|--------------------------------------------------------------------------------------|-----------------------------------------------------|--------|
|                                                                                      | 20 °C                                               | 200 °C |
| annealed 0.5 h at 815 °C, quenched                                                   | 88                                                  | 105    |
| annealed 0.5 h at 815 °C, quenched and at 300 °C and 2 h hardened                    | 104                                                 | 118    |
| annealed 0.5 h at 815 °C, quenched and cold deformed                                 | 75                                                  | 90     |
| annealed 0.5 h at 815 °C, quenched, cold deformed and age-hardened at 300 °C for 2 h | 81                                                  | 100    |

The thermal conductivity increases with increasing temperature and extent of hardening, and is reduced by cold deformation.

### 4.3.2 Calculation of thermal conductivity

If no phase transition occurs in the temperature range considered, the variation of thermal conductivity with temperature can be expressed by the linear relation [4.2]:

$$\lambda = \lambda_0 \cdot (1 + \alpha \cdot T), \quad (4.13)$$

where  $\alpha$  is the temperature coefficient which is positive for a great number of alloys. A negative temperature coefficient is typical of several pure metals (Al, Cu, Mo and Ni). In the case of nickel the temperature coefficient is negative between room temperature and the Curie temperature but positive above 500 [°C].

The mathematical modelling of the thermal conductivity as a function of the temperature  $T$  on the basis of Eq. (4.13) is done by:

$$\lambda(\vartheta) = \lambda_0 + B \cdot \vartheta, \quad (4.14)$$

where  $B$  [1/°C] is the temperature coefficient. The results of this calculation are shown in Table 4.5 for a number of metals and alloys. Table 4.6 shows measured and calculated values of the thermal conductivity at different temperatures for the alloys CuNi30Mn1Fe and NiCr15Fe.

**Table 4.5** Constants for thermal conductivity calculation

| Material       | $\vartheta$ [°C] | $\lambda_0$ [W/mK] | $B$ [1/°C] | Author for the measured results |
|----------------|------------------|--------------------|------------|---------------------------------|
| Cu99.99        | −100...600       | 389.9              | −0.06280   | [4.17]                          |
| CuZn30         | −100...400       | 107.9              | 0.11900    | [4.2]                           |
| Zinc (99.993%) | 0...400          | 114.4              | −0.04810   | [4.17]                          |
| Ni99.6         | 400...1200       | 35.4               | 0.0308     |                                 |
| Ni99.2         | 0...400          | 72.2               | −0.0464    | [4.2]                           |
| Ni99.2         | 500...900        | 47.2               | 0.02081    | [4.2]                           |
| NiCu30Fe       | 20...            | 25.4               | 0.0179     |                                 |
| NiCu30Al       | 20...            | 17.3               | 0.0272     |                                 |
| NiCr23Co12Mo   | 20...            | 13.1               | 0.0155     |                                 |

**Table 4.6** Measured and calculated values of the thermal conductivity

| Temperature $\vartheta$<br>[°C] | Conductivity $\lambda$ [W/mK] |            |                   |            |
|---------------------------------|-------------------------------|------------|-------------------|------------|
|                                 | CuNi30Mn1Fe                   |            | NiCr15Fe          |            |
|                                 | measured<br>[4.3]             | calculated | measured<br>[4.3] | calculated |
| 0                               | 25.8                          | 25.8       | 14.5              | 14.2       |
| 100                             | 29.8                          | 30.1       | 15.9              | 15.8       |
| 200                             | 34.8                          | 34.3       | 17.3              | 17.4       |
| 300                             | 39.6                          | 38.5       | 18.9              | 19.1       |
| 400                             | 44.3                          | 42.7       | 20.4              | 20.7       |
| 500                             | 48.5                          | 47.0       | 22.2              | 22.3       |
| 600                             | 52.4                          | 51.2       | 23.9              | 23.9       |
| 700                             | 56.1                          | 55.4       | 25.6              | 25.6       |
| 800                             | 59.8                          | 59.6       | 27.3              | 27.2       |
| 900                             | 63.4                          | 63.9       | 29.1              | 28.9       |

An empirical equation permitting the calculation of thermal conductivity as a function of chemical composition and temperature of the material and its use for engineering computations was derived from an evaluation of data taken from the literature, namely:

$$\lambda(\vartheta, \psi) = \lambda_0(\psi) \cdot K_{\vartheta-\lambda}(\vartheta, \psi), \quad (4.15)$$

with

|                         |                                                                                                     |
|-------------------------|-----------------------------------------------------------------------------------------------------|
| $\lambda$               | thermal conductivity [Wm <sup>−1</sup> K <sup>−1</sup> ],                                           |
| $\lambda_0$             | thermal conductivity at 0 °C for a given chemical composition [Wm <sup>−1</sup> K <sup>−1</sup> ],  |
| $K_{\vartheta-\lambda}$ | correction function for the influence of temperature (as dependent on the chemical composition) and |
| $\psi$                  | percentage atomic mass ratio,                                                                       |

$$\psi = \sum C_{Ei} \cdot (A_{\text{basic element}}/A_i), \quad (4.16)$$

with

|                            |                                   |
|----------------------------|-----------------------------------|
| $C_{Ei}$                   | mass percent of element i,        |
| $A_{\text{basic element}}$ | atomic mass of the basic element, |
| $A_i$                      | atomic mass of element i,         |
| $\psi$                     | percentage atomic mass ratio.     |



For copper alloys  $\psi$  may be calculated as:

$$\begin{aligned} \psi = & 0.535 \cdot C_{Sn} + 2.355 \cdot C_{Al} + 2.263 \cdot C_{Si} + 1.157 \cdot C_{Mn} + 2.052 \cdot C_P + 1.222 \cdot C_{Cr} + 1.083 \cdot C_{Ni} \\ & + 1.327 \cdot C_{Ti} + 0,973 \cdot C_{Zn} + 1.138 \cdot C_{Fe} + 0,696 \cdot C_{Zr} + 0,307 \cdot C_{Pb} + .... \end{aligned} \tag{4.17}$$

For nickel alloys (except nickel-based materials)  $\psi$  may be calculated as:

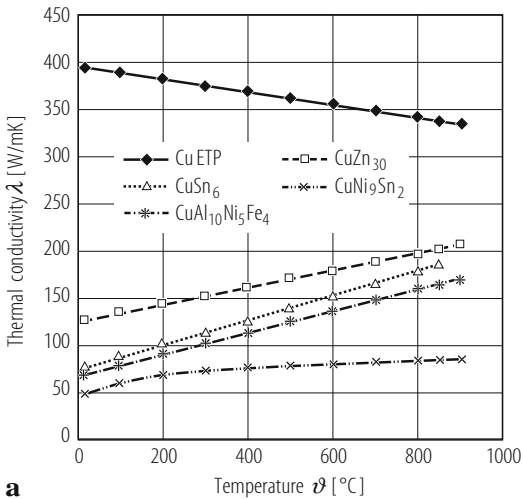
$$\begin{aligned} \psi = & 2.090 \cdot C_{Si} + 1.068 \cdot C_{Mn} + 1.129 \cdot C_{Cr} + 1.226 \cdot C_{Ti} + 0.924 \cdot C_{Cu} \\ & - - + 1.051 \cdot C_{Fe} + 0.996 \cdot C_{Co} + 0.612 \cdot C_{Mo} + 1.895 \cdot C_P + 2.175 \cdot C_{Al} + 0.489 \cdot C_C + . \end{aligned} \tag{4.18}$$

$A_i$  and  $C_{Ei}$  denote the atomic mass and the mass percent of i-th element, respectively.  $A_{\text{basic element}}$  is the atomic mass of basic element. The atomic masses were taken from [4.2].

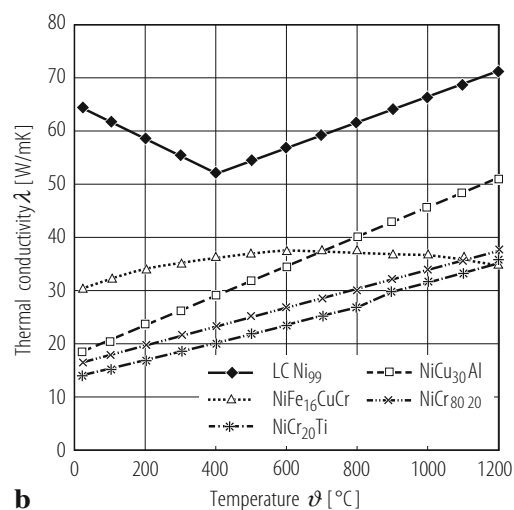
Figures 4.8a and 4.8b present the calculated relation between thermal conductivity and temperature for selected Cu– and Ni–alloys. As can be seen, the temperature dependence is nearly linear or almost linear (except for LC–Ni99). Some examples underline the conformity between measured and calculated values at different temperatures (Table 4.7).

**Table 4.7** Comparison between measured and calculated heat conductivity

| Alloy   | Thermal conductivity [W/m*K] |        |        |           |            |        |
|---------|------------------------------|--------|--------|-----------|------------|--------|
|         | measured                     |        |        | reference | calculated |        |
|         | 20 °C                        | 400 °C | 600 °C |           | 20 °C      | 400 °C |
| CuZn5   | 244                          | 255    |        | [4.16]    | 244        | 256.1  |
| CuZn40  | 106                          | 169    | 200    | [4.16]    | 106        | 167.4  |
| CuSi3Mn | 42.5                         | 56.1   | 58.8   | [4.16]    | 41.9       | 54.1   |
| NiCr10  | 17.1                         | 24.7   |        | [4.16]    | 17.4       | 24.5   |



**Fig. 4.8a** Values of the thermal conductivity of Cu–alloys

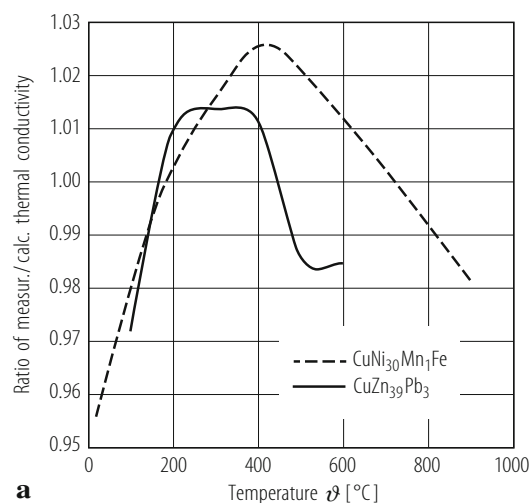


**Fig. 4.8b** Values of the thermal conductivity of Ni-alloys

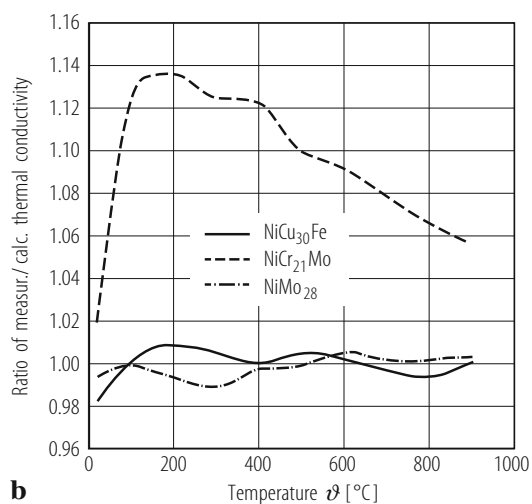
The differences between measured and calculated results stem mainly from:

- Analysis differences between measured and calculated materials. The heat conductivity calculation was always performed for an average analysis of the material concerned.
- Possible differing treatment conditions.
- Variations in measured values according to different authors and different analysis methods (direct experimental measurements, calculations based on the electric conductivity according to the law of Wiedemann–Franz).

Figures 4.9a and 4.9b show comparisons of measured and calculated values for the thermal conductivity for copper and nickel alloys. The relation between both values is satisfactory. Whereas for copper alloys the deviations between measured and calculated values were approximately 5% (Fig. 4.9a), chemical resistant and high temperature alloys can deviate by more than 10%, but also by significantly less (Fig. 4.9b).

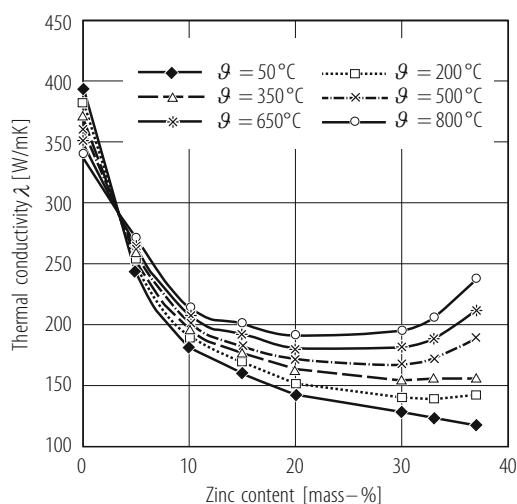


**Fig. 4.9a** Comparison of measured calculated thermal conductivities of Cu-alloys and [4.17]



**Fig. 4.9b** Ratio of the measured and calculated thermal conductivities of Ni alloys

Figure 4.10 shows the variation of thermal conductivity with rising content of alloying elements in a temperature range 50–800 [°C] for copper–zinc–alloys. The lower the absolute value, the higher the temperature dependence.



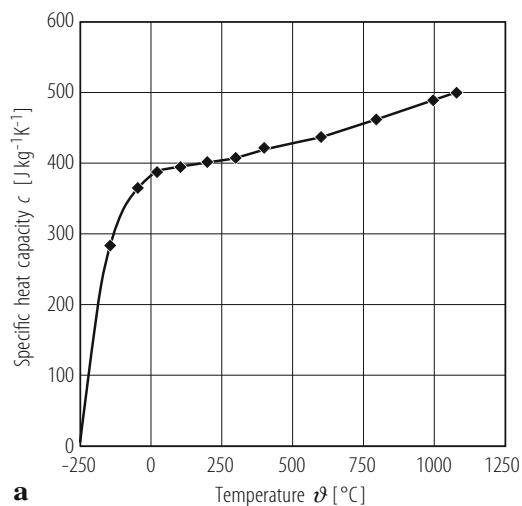
**Fig. 4.10** Thermal conductivity as a function of Zn-content of Cu–Zn alloys

## 4.4 Specific heat capacity

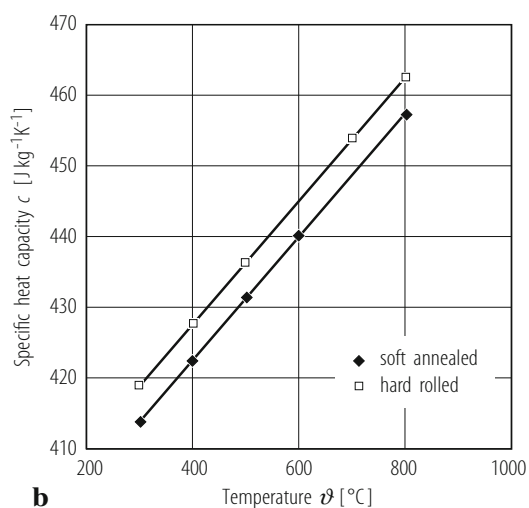
### 4.4.1 Definition and dependences

The specific heat or heat capacity  $c$  is the amount of thermal energy required to heat 1 kg of a material by 1 K. It depends on both material and temperature.

Figure 4.11a shows the heat capacity of copper between  $-250$  °C and melting temperature. According to Fig. 4.11b, the heat capacity of an influence of the material state is assigned. The increase in specific heat capacity with increasing temperature is the same for the annealed and rolled condition, the absolute values for the annealed condition being somewhat lower.

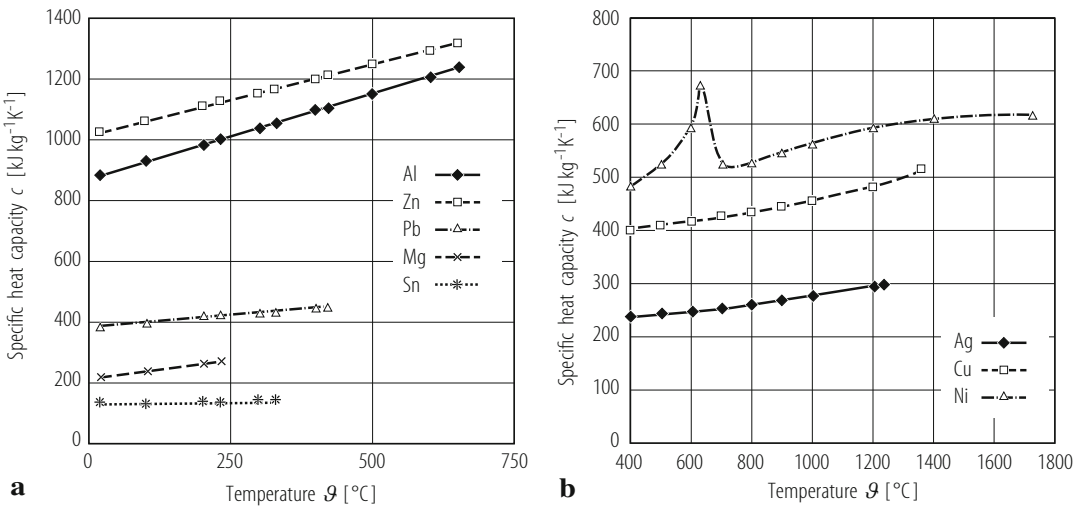


**Fig. 4.11a:** Specific heat capacity of the pure copper as a function of temperature [4.7]

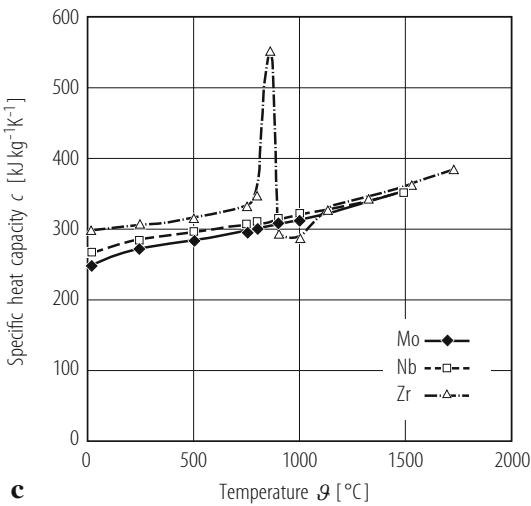


**Fig. 4.11b:** Influence on the material state specific heat capacity

Livschitz [4.2] excludes the electron theory of the specific heat, so the heat capacity is a linear function of temperature in small temperature intervals. The specific heat capacity of metallic materials differs considerably. Alloying elements affect the specific heat capacity. Figure 4.12a–4.12c gives an overview of characteristic variations in specific heat capacity and its temperature dependence.



**Fig.4.12a and b** Specific heat capacity of metals as a function of temperature [4.17]



**Fig. 4.12c** Specific heat capacity of metals as a function of temperature [4.17]

The anomalous increase in specific heat capacity which occurs when heating nickel up to the Curie—temperature (631 [K] respectively 358  $^{\circ}\text{C}$ )), is necessary to overcome the exchange forces, which cause the magnetic properties.

The discontinuity of the temperature dependency at zirconium is caused by the  $\alpha - \beta$ —transformation at 865  $^{\circ}\text{C}$ .

**4.4.2 Specific heat capacity calculation**

For a temperature range that starts at a sufficient distance from 0 [K] and ends at about 90% of the absolute melting temperature, the linear relation:

$$c_p = a + B \cdot T, \tag{4.19}$$

holds, with

|       |                                                                                                                     |
|-------|---------------------------------------------------------------------------------------------------------------------|
| $c_p$ | the specific heat capacity at constant pressure ( $[\text{J kg}^{-1} \text{K}^{-1}]$ ,                              |
| $T$   | the temperature (K),                                                                                                |
| $A$   | a constant and                                                                                                      |
| $B$   | a coefficient $[\text{K}^{-1}]$ that reflects the electron influence and crystal lattice expansion when heating-up. |

The mean specific heat capacity  $c_{pm}$  in a temperature range  $T_1 < T < T_2$  is defined by:

$$c_{pm} = \int_{\vartheta_1}^{\vartheta_2} c_p(\vartheta) d\vartheta, \quad (4.20)$$

and hence the temperature-dependent mean heat capacity is given by

$$c_{p,m}(T) = \int_{T_0}^T c_p(\vartheta) d\vartheta.$$

This equation can be used to calculate the thermal energy  $Q$  required to heat a material from  $T_0$  to  $T$ . However, this relation is applicable only if no phase transformation occurs in the temperature range considered. Therefore, the description of the temperature dependence of the mean specific heat capacity for non-ferrous metals and austenitic steels by Eq. (4.19) is only possible in the temperature ranges of single phases. Table 4.10, lists measured values of  $c_{pm}$  according to different authors.

**Table 4.10** Measured values of the mean specific heat capacity  $c_{pm}$  of nonferrous metals at 20 °C

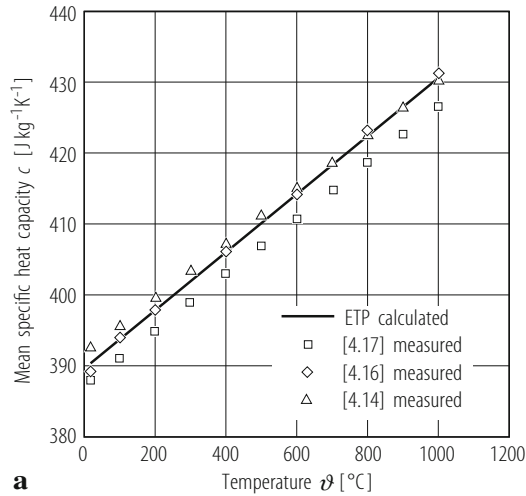
| Metal  | Mean specific heat capacity $c_{pm}$ [J/kg K] |                    |                   |                   |
|--------|-----------------------------------------------|--------------------|-------------------|-------------------|
|        | measured<br>[4.14]                            | measured<br>[4.20] | Measured<br>[4.4] | Measured<br>[4.5] |
| Cu–ETP | 401                                           | 385                | 390               | 385               |
| nickel | 448                                           | 456                | 440               | 511               |
| lead   | 127                                           | 129                | 130               | 130               |
| tin    | 226                                           | 382                | 226               | 226               |
| zinc   | 385                                           |                    | 384               | 387               |
| silver |                                               |                    |                   | 234               |

The temperature dependence of the mean specific heat of corrosion resistant Ni–Cr–(Mo)–alloys can be expressed by an exponential function with high accuracy.

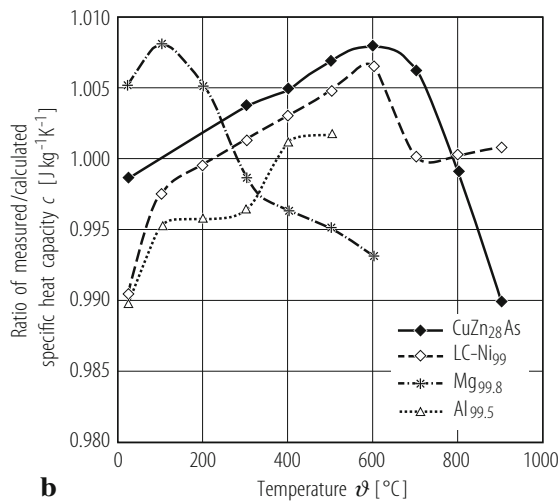
$$c_{pm}(\vartheta) = A^* \exp(B^*T) \quad (4.21)$$

For alloy 2.4852 NiCr21Mo the constants  $A$  and  $B$  are 460 and 0.00017, respectively.

In Fig. 4.13a can be seen, how according to Eq. (4.20) calculated mean specific heat capacity of CuETP corresponds to measured values from different authors. The measured values from [4.17] are slightly lower. Plotting the ratio of calculated/measured mean specific heat capacity as a function of temperature we obtain the curves shown in Fig. 4.13b. Deviations between calculated and measured values are near 2%, from which one can conclude that a temperature-dependent modelling of the mean specific heat capacity in this way is quite possible.



**Fig. 4.13a** Comparison of measured [4.14, 4.17] and calculated values of the mean specific heat of Cu-ETP



**Fig. 4.13b** Ratio of measured and calculated values of mean specific heat capacity by metallic alloys

## 4.5 Thermal expansion coefficient

### 4.5.1 Definition and factors of influence

Most solids expand when being heated. The mean linear coefficient of expansion  $\alpha_m$  is defined by:

$$\alpha_m = (1/L_1) \cdot (L_2 - L_1)/(T_2 - T_1). \quad (4.22)$$

$L_1$  and  $L_2$  are the lengths corresponding to the temperatures  $T_1$  and  $T_2$ . With  $L(T)$  the length at a temperature  $T$ , the differential coefficient of thermal expansion  $\alpha(T)$  is hence given by:

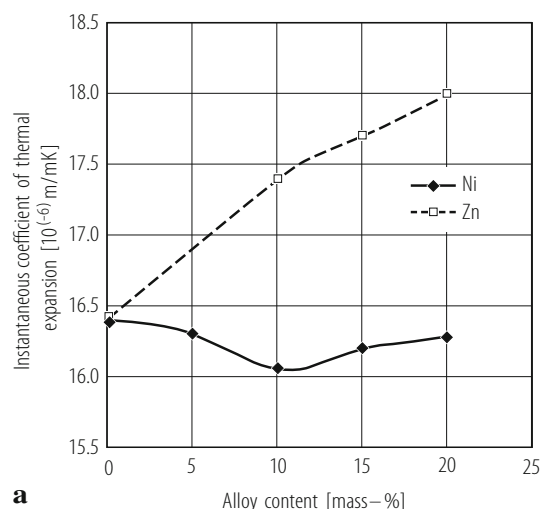
$$\alpha_T = \frac{1}{L(T)} \frac{dL(T)}{dT}. \quad (4.23)$$

In general the thermal expansion of crystals is anisotropic and the volume expansion coefficient  $\beta$  is given by:

$$\beta = \alpha_1 + \alpha_2 + \alpha_3, \quad (4.24)$$

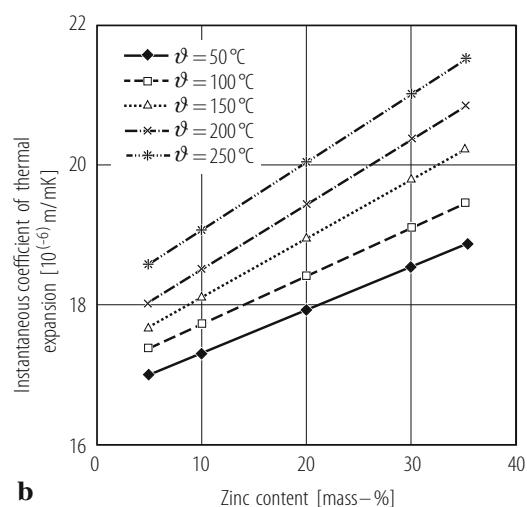
where  $\alpha_1$ ,  $\alpha_2$  and  $\alpha_3$  are the coefficients of linear expansion along the principal axes. As the following paragraphs refer to cubic metals only, such as aluminium, iron, nickel and copper, including their alloys, it follows that  $\alpha_1 = \alpha_2 = \alpha_3$  and therefore  $\beta = 3\alpha$ .

The linear coefficient of expansion of alloys depends on their chemical composition. In solid solutions alloying elements can increase or decrease compared to the base or metal. Figure 4.14 shows how alloying elements affect the coefficient of expansion at copper– and nickel–alloys.



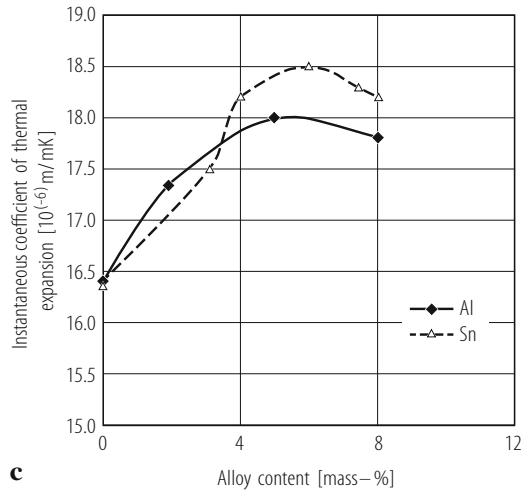
**Fig. 4.14a** Alloying effects of Ni and Zn on the coefficient of thermal expansion in Cu–Ni– and Cu–Zn–alloys [4.7]

In Figs. 4.14a to 4.14a the influence of alloying elements on the linear coefficient of thermal expansion of binary copper alloys at 20 °C is shown. Nickel additions influence the linear coefficient of thermal expansion only slightly (Fig. 4.14a). If Cu is alloyed with zinc, the linear coefficient of expansion increases significantly with both temperature and zinc content (Fig. 4.14b). Aluminium and tin also increase the coefficient of thermal expansion, but only up to about 6 mass % (Fig. 4.14c) beyond which it is decreased. The linear coefficient of thermal expansion of fcc Fe–Ni–alloys shows a steep drop between about 20 and 40% Ni leading to a pronounced minimum between 35 and 36% Ni a (Fig. 4.14d). This effect is due to magnetostriction which compensates for thermal expansion.

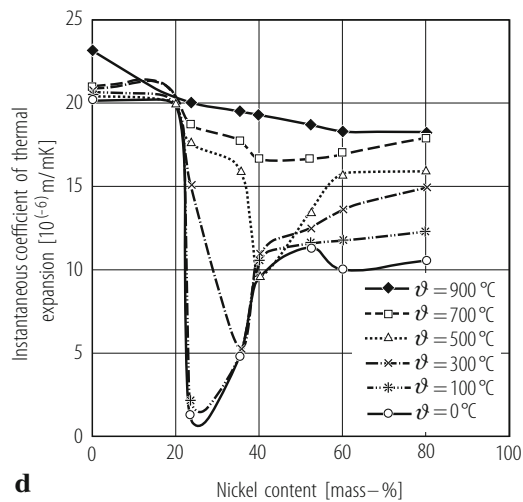


**Fig. 4.14b** Effect of alloying elements on the variation of the linear coefficient of thermal expansion in Cu–Zn–alloys [4.18]





**Fig. 4.14c** Effect of alloying elements in Cu alloys on the variation of the linear coefficient of thermal expansion [4.9]

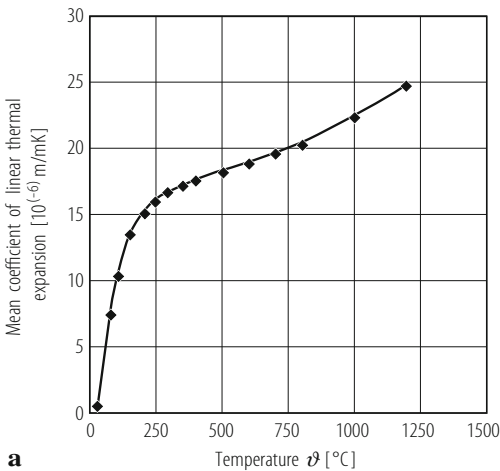


**Fig. 4.14d** Effect of Ni-content in Ni-Fe-alloys on the variation of the linear coefficient of thermal expansion [4.9]

#### 4.5.2 Influence of temperature on the coefficient of expansion

Regarding the influence of temperature on the linear coefficient of thermal expansion, different temperature ranges may be distinguished (Fig. 4.15a). At intermediate temperatures, the linear thermal expansion coefficient and the specific heat are proportional  $T^3$ . If  $T$  is much smaller than the Debye temperature  $\Theta$  thermal expansion is proportional to the temperature. For the non-ferrous metals and alloys the temperature dependence of the thermal expansion can be expressed by:

$$\alpha_m = \alpha_0 + \beta \cdot \vartheta. \quad (4.25)$$

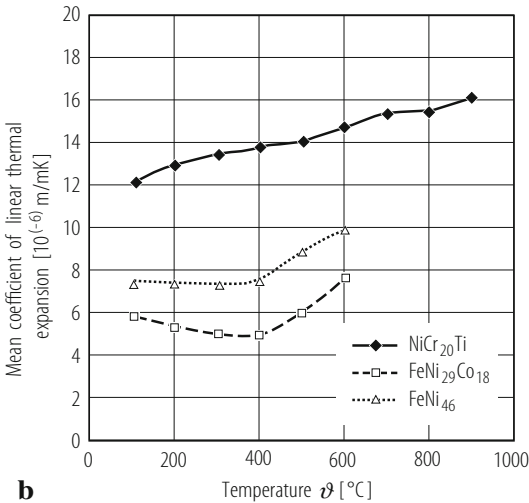


**Fig. 4.15a** Relation between the mean linear coefficient of thermal expansion and temperature for Cu99.99 [4.12]

Figure 4.15b shows the temperature dependence of the mean linear thermal expansion coefficient for NiCr20Ti, FeNi29Co18 and FeNi46 according to measurements in [4.20, 4.21]. For NiCr20Ti the relation is nearly linear between 50 and 900 °C. For the other alloys it passes through a minimum. The constants  $\alpha_0$  and  $\beta$  for copper and nickel alloys are listed in Table 4.11 for some copper and nickel alloys.

**Table 4.11** Constants for calculating the linear thermal expansion coefficients of copper and nickel alloys

| Material    | Linear thermal expansion coefficient<br>[10 <sup>-6</sup> K <sup>-1</sup> ] |         | Range of validity<br>[°C] |
|-------------|-----------------------------------------------------------------------------|---------|---------------------------|
|             | $\alpha_0$                                                                  | $\beta$ |                           |
| CuZn10      | 16.82                                                                       | 0.00443 | 20...600                  |
| CuZn20Al2As | 17.08                                                                       | 0.00821 | 20...600                  |
| CuNi30Mn1Fe | 14.92                                                                       | 0.00457 | 20...900                  |
| Ni99.6      | 13.13                                                                       | 0.00376 | 400...1200                |
| NiCu30Fe    | 13.11                                                                       | 0.01058 |                           |
| NiMo28      | 10.89                                                                       | 0.0015  | 800                       |
| NiCr22Mo9Nb | 12.09                                                                       | 0.0042  |                           |



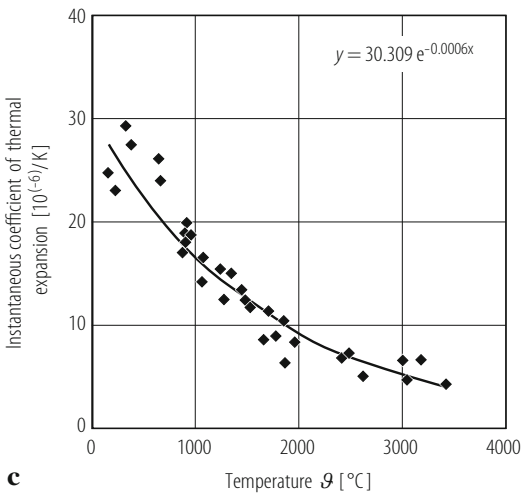
**Fig. 4.15b** Relation between the linear coefficient of thermal expansion and temperature for Ni alloys [4.20, 4.21]

The average linear expansion coefficient between 0 and 100 °C and the melting point of some technically pure metals are listed in Table 4.12.

**Table 4.12** Mean linear coefficient of thermal expansion and melting temperature

| Metal      | Mean linear coefficient of thermal expansion [ $10^{-6}/\text{K}$ ] | Melting temperature [ $^{\circ}\text{C}$ ] |
|------------|---------------------------------------------------------------------|--------------------------------------------|
| Tin        | 20.6                                                                | 232.0                                      |
| Zinc       | 38.7                                                                | 416.6                                      |
| Silver     | 18.7                                                                | 962.0                                      |
| Copper     | 17.0                                                                | 1083.0                                     |
| Nickel     | 13.3                                                                | 145.3                                      |
| Cobalt     | 12.5                                                                | 1495.0                                     |
| Molybdenum | 5.09                                                                | 2617.0                                     |

Figure 4.15c shows the relation between the melting temperature and the linear thermal expansion coefficient between 0 and 100 °C for various metals and alloys. According to this general relationship the absolute values of  $\alpha$  for alloy compositions with similar melting temperature do not differ very widely (e.g. Al–Mg:  $\alpha \sim 23$  [ $10^{-6}\text{K}^{-1}$ ], Cu–Zn:  $\alpha \sim 17.5$  [ $10^{-6}\text{K}^{-1}$ ]). Because of the simultaneous effect of magnetostriction this does not apply to Fe–Ni alloys.



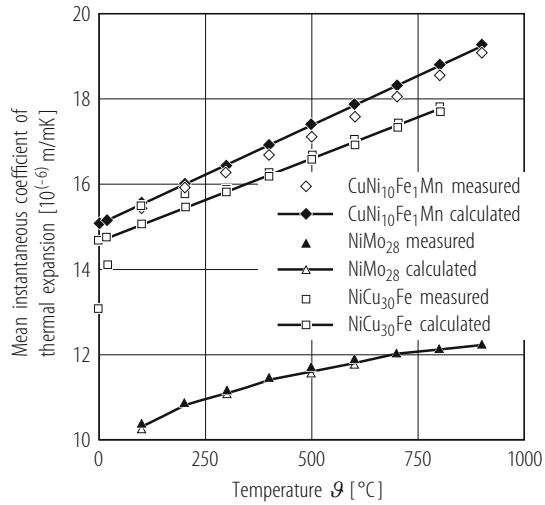
**Fig. 4.15c** Relation between melting point and linear coefficient of thermal expansion of various metals and alloys

Equation (4.25) is adequate for a description of the linear thermal expansion coefficient of nearly all non-ferrous metals. Differences result from differing measured values obtained by different authors, as is seen in Table 4.13.

**Table 4.13** Mean linear coefficient of thermal expansion  $\alpha_0$  between 0 and 100 °C according to various authors

| Material | Mean linear coefficient of thermal expansion<br>$\alpha_0$ [ $10^{-6}/\text{K}$ ] |             |             |
|----------|-----------------------------------------------------------------------------------|-------------|-------------|
| CuZn30   | 19.0 [4.22]                                                                       | 18.5 [4.23] | 18.5 [4.9]  |
| CuSn4    | 16.2 [4.3]                                                                        | 16.4 [4.23] | 17.5 [4.9]  |
| CuAl8Fe3 | 15.8 [4.3]                                                                        | 18.1 [4.23] | 17.8 [4.9]  |
| Ni99.2   | 14.3 [4.8]                                                                        | 13.3 [4.3]  | 13.3 [4.4]  |
| NiMo28   | 10.4 [4.3]                                                                        | 11.1 [4.8]  | 12.2 [4.22] |
| NiCr20Ti | 13.2 [4.8]                                                                        | 14.0 [4.3]  | 13.1 [4.21] |
| Pb99.97  | 29.1 [4.23]                                                                       | 28.3 [4.5]  | 29.0 [4.20] |
| ZnAl4    | 27.4 [4.23]                                                                       | 27.7 [4.20] |             |

Figure 4.16 shows, for selected Cu– and Ni–alloys, the conformity between measured and calculated mean linear coefficients of thermal expansion dependent on the temperature.



**Fig. 4.16** Comparison of measured and calculated values of the mean instantaneous coefficient of thermal expansion for various alloys

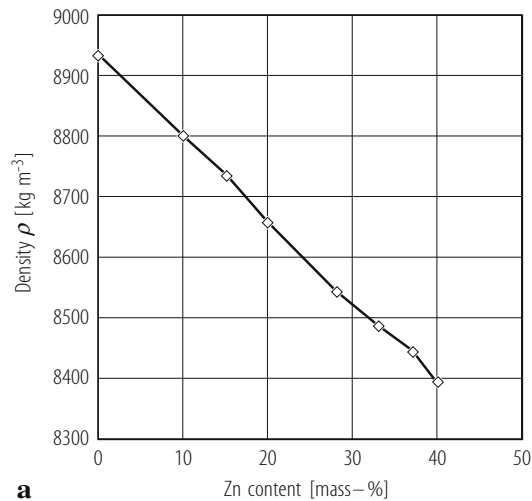
## 4.6 Density

### 4.6.1 Definition and factors of influence

The density  $\rho$  of a metal is defined as its mass  $m$  per unit volume  $V$ :

$$\rho = m/V. \quad (4.26)$$

$\rho(\text{Cu}) = 8930 \text{ [kg/m}^3\text{]}$ ,  $\rho(\text{Ni}) = 8902 \text{ [kg/m}^3\text{]}$ ,  $\rho(\text{Zn}) = 7140 \text{ [kg/m}^3\text{]}$  at  $20^\circ\text{C}$ . Alloying elements affect the density as shown for Cu–Zn alloys in Fig. 4.17a.



**Fig. 4.17a** Comparison of measured and calculated values of the density of Cu–Zn-alloys

$$\rho_{\text{alloy}} = \rho_{\text{element}} + \sum \Delta\rho_i \cdot C_i, \quad (4.27)$$

where  $\rho_{\text{element}}$  is the density of pure metals  $[\text{kg/m}^3]$ ,  $\Delta\rho_i$  the change in density for 1% of the respective alloying element  $i$   $[\text{kg/m}^3]$  and  $C_i$  density for the respective element content in [mass %].

Equation (4.27) refers to the soft annealed, defect-free condition. The density of metals and alloys is influenced not only by their chemical composition but also by their structural condition. It may be lower by

up to 10% than that calculated by Eq. (4.27) in the case of casted ingots. Also, phase transformations change the volume and therefore the density.

#### 4.6.2 Modelling the temperature dependence

The definition of density as a function of temperature [4.11] reads as:

$$\rho(\vartheta) = \rho_0(1 - \beta_m \cdot \vartheta), \quad (4.28)$$

where  $\rho_0$  is the density at 0 °C [kg/m<sup>3</sup>] and  $\beta_m$  the mean volume expansion coefficient from Eq. (4.23).

If the mean linear expansion coefficient varies linearly with temperature, Eqs. (4.23) and (4.28) yields

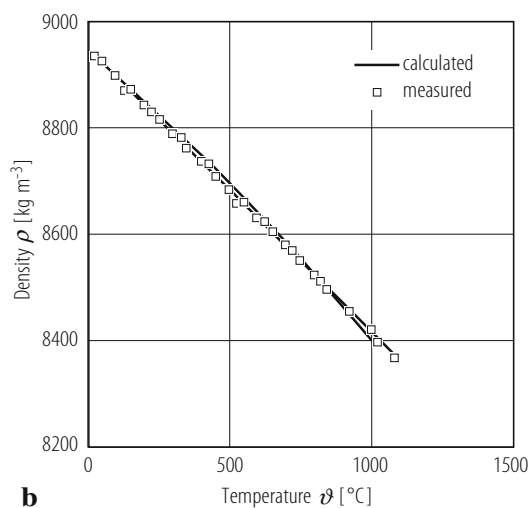
$$\rho(\vartheta) = \rho_0 \cdot (1 - 3 \cdot \alpha_m \cdot \vartheta) = \rho_0 \left[ 1 - 3 \cdot 10^{-6} \cdot \vartheta \cdot (\alpha_0 + B \cdot \vartheta) \right], \quad (4.29)$$

with  $\alpha_m$  as the mean linear expansion coefficient. According to Eq. (4.29), the reduction in density with increasing temperature is proportional to  $T^2$ . The comparison of measured and calculated density of Cu ETP is shown in Table 4.14 and in Fig. 4.17a for Cu–Zn alloys at 20 °C.

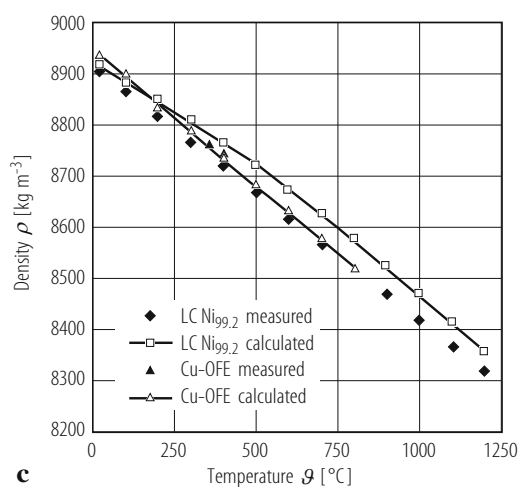
**Table 4.14** Measured and calculated density of Cu ETP as a function of temperature

| Temperature [°C] | Density [kg/m <sup>3</sup> ] |            |
|------------------|------------------------------|------------|
|                  | measured<br>(pycnometer)     | calculated |
| 50               | 8921.1                       | 8917.4     |
| 100              | 8894.5                       | 8894.4     |
| 150              | 8867.8                       | 8870.9     |
| 200              | 8841.2                       | 8846.9     |
| 250              | 8814.6                       | 8822.4     |
| 300              | 8788.0                       | 8797.5     |
| 400              | 8734.7                       | 8746.2     |
| 500              | 8681.5                       | 8693.0     |
| 600              | 8628.2                       | 8637.9     |
| 700              | 8575.0                       | 8581.0     |
| 800              | 8521.7                       | 8522.1     |
| 1000             | 8415.2                       | 8398.8     |

The density decreases with increasing zinc content and temperature (Fig. 4.17b). Calculation using the mean linear expansion coefficient of density (Eq. 4.29) agrees very well with pycnometric measurements, as shown for Cu ETP in Table 4.14 and for Cu and Ni in Fig. 4.17c.



**Fig. 4.17b** Comparison of measured and calculated values of the density for Cu–Zn–alloys for different temperatures



**Fig. 4.17c** Comparison of measured and calculated values of the density for Cu and Ni for different temperatures

## Symbols and abbreviations

| Short form                 | Full form                                            |
|----------------------------|------------------------------------------------------|
| $\Delta A_5$               | decrease in elongation                               |
| $\psi$                     | percentage atomic mass ratio                         |
| $\lambda$                  | thermal conductivity                                 |
| $A, B, C$ and $n_i$        | constants                                            |
| $A_5$                      | elongation                                           |
| $A_{5-0}$                  | elongation at the initial state at $\varepsilon = 0$ |
| $A_{\text{basic element}}$ | atomic mass of the basic element                     |
| $A_i$                      | atomic mass of element i                             |
| $c$                        | specific heat or heat capacity                       |
| $C_{\text{Ei}}$            | mass percent of element i                            |
| $c_L$                      | sound velocity                                       |
| $c_p$                      | specific heat capacity at constant pressure          |
| $c_{pm}$                   | mean specific heat capacity                          |
| $D$                        | compression modulus                                  |

(continued)

| Short form                          | Full form                                                  |
|-------------------------------------|------------------------------------------------------------|
| $E$                                 | modulus of elasticity or Young's modulus                   |
| ETP                                 | electrolytic tough pitch                                   |
| $G$                                 | shear modulus                                              |
| $K_{\theta-\lambda}$                | correction function                                        |
| $m$                                 | mass                                                       |
| $R$                                 | universal gas constant                                     |
| $R_m$                               | tensile strength                                           |
| $R_{m-exit}$                        | tensile strength in the initial state at $\varepsilon = 0$ |
| $R_p$                               | yield strength                                             |
| $R_{p-exit}$                        | yield strength in the initial state at $\varepsilon = 0$   |
| $T, \vartheta$                      | temperature                                                |
| $T_s$                               | melting temperature                                        |
| $V$                                 | unit volume                                                |
| $\Theta$                            | Debye temperature                                          |
| $\alpha_0$                          | linear coefficient of thermal expansion                    |
| $\alpha_1, \alpha_2$ and $\alpha_3$ | coefficients of linear expansion                           |
| $\alpha_E$                          | temperature coefficient                                    |
| $\alpha_m$                          | mean linear coefficient of expansion                       |
| $\beta$                             | volume expansion coefficient                               |
| $\beta_m$                           | mean volume expansion coefficient                          |
| $\varepsilon$                       | related strain                                             |
| $\lambda_0$                         | thermal conductivity at 0 °C                               |
| $\nu$                               | Poisson ratio                                              |
| $\rho$                              | material density                                           |
| $\rho_0$                            | density at 0 °C                                            |

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# Data bank of deformation parameters of alloy and heavy metals

## 5. Data bank of deformation parameters

### 5.1 Introduction

#### 5.1.1 Basis of the data bank

Based on measured data from deformation tests material-related data for heavy metals and their alloys were collected, which are frequently used together. These data, which are provided for direct use and for calculation of forming processes, are based on empirical determination. Functional relationships such as the temperature and concentration dependence are treated in terms of semi-empirical equations for:

- Flow stress in hot and cold forming,
- Plasticity,
- Mechanical and physical properties.

References used for designation of the chemical composition and of the material grades are:

- European Standards [5.1,5.3, 5.4],
- Copper, Nickel, Zinc, Tin, Zircon, Tantalum, Tungsten, Lead, Niobium, noble metals and their alloys, Beuth-Verlag, Berlin, Wien, Zürich [5.4],
- A comparison of international heavy metal grades in references [5.2, 5.5].

The range of chemical composition of material grades listed in different national standards does not always correspond to the range given in the DIN/EN standards.

#### 5.1.2 Hot and cold flow curves

In the majority of cases constants, specified in data sheets of single steels, allow flow stress calculations according to the following equations for several microstructure conditions and the indicated area of validity:

Hot forming:

$$\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}, \quad (2.8)$$

Cold forming:

$$\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}, \quad (2.7)$$

where:

|                 |                                                                                                   |
|-----------------|---------------------------------------------------------------------------------------------------|
| $\sigma_F$      | flow stress [MPa]                                                                                 |
| A               | constant [–]                                                                                      |
| $m_1 \dots m_8$ | exponents which contain the influence exerted by the conditions of deformation on flow stress [–] |
| $\vartheta$     | forming temperature [°C]                                                                          |
| $\varphi$       | strain [–]                                                                                        |
| $\dot{\varphi}$ | strain rate [s <sup>–1</sup> ].                                                                   |

Additionally the data sheets include the stress  $\sigma_{F0}$ . This value was basic ( $\vartheta = 20$  °C) as a condition for the calculation of flow stress during cold working,  $\varphi = 0.10$  and  $\dot{\varphi} = 10$  [s<sup>–1</sup>] determined.

During hot working the fundamental values for the calculation of the yield stress are  $\sigma_{F0}$ ,  $\varphi = 0.1$ ,  $\dot{\varphi} = 10$  [s<sup>–1</sup>].

An overview of temperatures for the stress  $\sigma_{F0}$  for selected materials is given below.

| Material         | Hot deformation |
|------------------|-----------------|
| Ag               | 700 °C          |
| Ag alloys        | 650 °C          |
| Au and Au alloys | 400 °C          |
| Cu and Cu alloys | 700 °C          |
| Mo               | 1200 °C         |
| Nb and Nb alloys | 1200 °C         |
| Ni and Ni alloys | 1000 °C         |
| Pb               | 200 °C          |
| Pt               | 1000 °C         |
| Sn               | 20 °C           |
| Ta               | 1200 °C         |
| U                | 1000 °C         |
| W                | 1200 °C         |
| Zn               | 250 °C          |
| Zn alloys        | 100 °C          |
| Zr and Zr alloys | 1000 °C         |

#### 5.1.2.1 Remarks to the flow stress constants

The constants for the calculation of hot and cold flow curves were based on compression and/or torsion tests with several heats, different microstructures and were realised partly with material from different manufacturers. In addition, flow curves were included in international publications to inform on the exact chemical composition, the test methods and material conditions. Hot and cold flow curves of metals discussed with identical alloys to international standards were also included in the regression calculations. The decision to accept flow curves from the literature for the data files of the regression calculations was based on the following criteria:

- For hot flow curves data of the structural state up to a strain of 1.00 minimum of four temperatures and three strain rates will be available.
- For cold flow curves a data matrix of three temperatures and three strain rates is needed. There is a temperature range of blue-brittleness, then the data matrix can be increased so that it clearly describes this phenomenon in temperature and velocity dependence. If two hardening zones appear in a cold flow curve the “double-n behaviour” is reflected with a good accuracy when, for both hardening zones, the same number of measured values exists.
- The multiple determination after linear multiple regression is higher than 0.9500.
- The maximum deviation between measured and calculated flow stress values for a material and a material condition with the same chemical composition averages  $\pm 3.0$  [%].
- For the same homologous temperature there exists a dependency between flow stress and activation energy at hot deformation.

Besides our own research results, the absolute flow stress value, its dependency on material, condition, temperature [5.45 ... 5.49], deformation degree and deformation rate, was assured by literature [5.6 ... 5.39, 5.50 ... 5.153]. These publications also delivered information for mathematical modelling.

#### 5.1.2.2 Extrapolation

Modern forming processes require stress–strain curves for conditions outside the limits of the deformation parameter that can be simulated using standard testing methods. Therefore the calculation of the stress with the constants of the regression is possible only under certain conditions. To the extrapolation to other forming conditions the following applies:

- *If the deformation temperature is valid, the calculated flow stresses should not be extrapolated beyond the range of measured values.*
- *If phase composition, precipitation condition and the state of stress in the forming, not in principle, not change and if the grain size is approximately constant, then the constants can be extrapolated to the lowest possible temperature deformation.*
- On the other hand, if the influence of the deformation rate can be extrapolated by a power function and the exponent expressed as a function of temperature, room temperature should be considered as the lower threshold.
- In cold forming, it is necessary to quantify the stress–strain change under the influence of the forming heat.
- The extrapolation of stress–strain curves beyond the forming range, for which they were determined, requires knowledge about the stress–strain curve distribution of the affected material group. In the steady state range of a flow curve the flow stress is constant; this allows an extrapolation to higher deformation degrees (e.g. forging processes).

### 5.1.3 Plasticity curves

Especially the plasticity curve of the data sheets have been determined in connection with the deformation conditions in torsion. In some cases these are based on the results of tensile- or wedge rolling experiments. Our own torsion tests and those of [5.110] were realised with massive specimens and a fixed clamping, the test specimens had a ratio test length/test diameter around ~2.50. This ratio guaranties minimal deformation in homogeneities over the test length. On the one hand the share of deformation in the specimen heads compared to the deformed total volume is relatively low. On the other hand, it is possible to eliminate any deformation of concentrations in the middle of the test length which would lead to a significant local temperature rise.

Results found in the literature [5.110, 5.116], which are based on massive specimens and a ratio test length/test diameter of 10.0, were converted to a ratio of 2.5 by material specific functions.

Besides our own investigations about the correlation between plasticity and

- deformation conditions, especially temperature, related mean stress and deformation rate,
- chemical composition, effect of alloying and accompanying elements or material conditions,
- effects of deformation processes including surface condition of the deformed material,
- valuation of possible extrapolations

the following publications were used: [5.30, 5.42, 5.71, 5.107 .. 5.123, 5.134 .. 5.149].

The following criteria were used to decide, if the data were appropriate for the data sheets or not.

- For the relevant deformation conditions the experimental acquired plasticity integrates into the relation  $\varphi_V = f(\sigma_{F-SS})$  in the single phase field.
- At the same deformation conditions and near the flow stress maximum, i.e. at the beginning of dynamic recrystallisation, there exists a qualitative correlation between plasticity and deformation degree, the higher the deformation, the lower the plasticity.
- In the single phase field plasticity follows rising temperatures by a power function up to its maximum.

Even with the numerous material and process parameters at the same deformation conditions, the stray fields of plasticity are established. Examples were Cu alloys and Ni alloys with various alloying content. More than 20 melts of these alloys were tested in parallel.

The aspects of an acceptance of torsion test results for the data sheets, as written above, was also the basis for data found in tensile tests and wedge rolling trials. Naturally the absolute values are not comparable because of different related mean stress values.

It is possible, to extrapolate the plasticity results, which are shown in the diagrams, but the following conditions have to be seen:

- In a double logarithmic presentation and when the same deformation and material conditions exists in the single phase range a linear correlation between plasticity and temperature exists. Therefore an

extrapolation is possible between the lowest temperature, at which the phase still exists, and the temperature of maximal plasticity, which is ca. 85% of melting (solidus) temperature.

- In the range of phase transformations stronger plasticity variations can be expected, dependent on temperature and deformation rate as the material condition. For this reason predictions of value and direction of plasticity are nearly impossible.
- In no case the absolute value of plasticity, found in simulations or semi-technical processes, can be directly transferred to a deformation process. The related stresses are not identical and the stress distribution in the deformation zone is temporal and locally inhomogeneous.
- In the case of transferring plasticity to other structure conditions (e.g. as-cast, as-rolled) it has been seen, that remarkable differences can appear [5.111], the higher the structure in homogeneities the higher the differences.
- Normally an extrapolation of plasticity to another deformation rate is possible, but it has to be seen in correlation with thermal activated processes, existing during hot deformation.

### 5.1.4 Mechanical and physical properties

The calculations constants for mechanical properties after cold deformation, used in the following equations,

$$R_p = A_0 + A \cdot \varepsilon^{n_1} \quad (4.1)$$

$$R_m = B_0 + B \cdot \varepsilon^{n_2} \quad (4.2)$$

$$A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon} \quad (4.3)$$

where:

|                          |                                                              |
|--------------------------|--------------------------------------------------------------|
| $R_p$                    | yield strength [MPa]                                         |
| $A_0$                    | yield strength at initial state at $\varepsilon = 0$ [MPa]   |
| $R_m$                    | tensile strength [MPa]                                       |
| $B_0$                    | tensile strength of initial state at $\varepsilon = 0$ [MPa] |
| $\varepsilon$            | related strain [–]                                           |
| $A, B, \text{ and } n_i$ | constants [–]                                                |
| $A_5$                    | elongation [%]                                               |
| $C_0$                    | elongation of the initial state at $\varepsilon = 0$ [%]     |
| $C \text{ and } n_i$     | constants [–]                                                |

were found after regression analyses of our own investigations research in literature [5.15, 5.17, 5.20, 5.30, 5.71, 5.113 and 5.156]. Partially these are for different material conditions; the specified range for the initial values for the yield strength, tensile strength and elongation in the under formed state resulting from several tested annealing.

The numerical values of temperature-dependent physical properties such as thermal conductivity, average specific heat capacity, average linear expansion coefficient, density and elastic modulus were calculated using the equations in Chapter 4.

These calculations are based on measured data [5.8, 5.30, 5.40.. 5.50, 5.61, 5.152 5.161]. More detailed information about the importance of the boundary values as the limits of its application can be found in [5.63]. Information from literature about Young's modulus of unalloyed, alloyed and high alloyed material [5.155, 5.157 and 5.158] could be combined with our own investigations. At an interpolation of the values for the physical properties it should be noted here that a temperature-dependent instability of the Curie temperature is provided.

## Symbols and abbreviations

| Short form        | Full form                                                                                     |
|-------------------|-----------------------------------------------------------------------------------------------|
| DIN               | German institute for standardisation (Deutsches Institut für Normung)                         |
| EN                | Euronorm                                                                                      |
| $\sigma_F$        | flow stress                                                                                   |
| A                 | constant                                                                                      |
| $m_1 \dots m_g$   | exponents which contain the influence exerted by the conditions of deformation on flow stress |
| $\vartheta$       | forming temperature                                                                           |
| $\varphi$         | strain                                                                                        |
| $\dot{\varphi}$   | strain rate                                                                                   |
| $R_p$             | yield strength                                                                                |
| $R_m$             | tensile strength                                                                              |
| $\varepsilon$     | related strain                                                                                |
| A, B, C and $n_i$ | constants                                                                                     |
| $A_5$             | Elongation                                                                                    |
| $A_0$             | yield strength at initial state at $\varepsilon = 0$                                          |
| $B_0$             | tensile strength of initial state at $\varepsilon = 0$                                        |
| $C_0$             | elongation of the initial state at $\varepsilon = 0$                                          |

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# Flow stress, mechanical and physical properties of oxygen-free electronic copper (Cu-OFE)

## 5.2 Copper- and Copper alloys

### 5.2.1 Pure Copper and low alloyed Copper

#### Designation

|             |               |               |               |            |               |
|-------------|---------------|---------------|---------------|------------|---------------|
| UNS number: | <b>C10100</b> | Chem. symbol: | <b>Cu-OFE</b> | EN number: | <b>CW009A</b> |
|-------------|---------------|---------------|---------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu    | P      | Pb     | Fe     | S      | Zn     | As     | Bi     | Ni     | Sb     | Sn     |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 99.95 | <0.005 | <0.005 | <0.005 | <0.005 | <0.003 | <0.002 | <0.002 | <0.002 | <0.002 | <0.002 |

#### International comparison of standards

| Euronorm              |  |                 |  | ISO            |            |
|-----------------------|--|-----------------|--|----------------|------------|
| EN 13604(2002)        |  | EN 1977         |  | ISO 431 : 1981 | ISO 4738   |
| EN 1652               |  |                 |  |                |            |
| Material number (DIN) |  |                 |  | DIN            |            |
| 2.0040                |  |                 |  |                |            |
| Japan                 |  |                 |  | Russia         |            |
| C1020                 |  |                 |  | 99.90<br>V3    | M00<br>M0b |
| USA                   |  |                 |  |                |            |
| ASTM                  |  |                 |  | UNS standard   |            |
| ASTM B 187            |  | ASTM F68 - 10   |  | C10100         |            |
| ASTM B187M - 11       |  | ASTM B249M - 12 |  |                |            |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material           | Hot deformation |                | Cold deformation     |                    |                 |
|-----------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                             | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]         |                 | 75.3           |                      | 194.1              |                 |
| A                           |                 | 1396.05        |                      | 433.177            |                 |
| Effect of temperature $K_8$ |                 |                |                      |                    |                 |
| $m_1$                       |                 | -0.00303       |                      | -0.00138           |                 |
| Effect of strain $K_\phi$   |                 |                |                      |                    |                 |
| $m_2$                       |                 | 0.4046         |                      | 0.34699            |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| m <sub>4</sub>                         |                 | 0.00149        |                      | −0.00002           |                 |
| m <sub>5</sub>                         |                 | −0.00304       |                      |                    |                 |
| m <sub>7</sub>                         |                 | 0.29813        |                      |                    |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| m <sub>3</sub>                         |                 |                |                      | 0.00987            |                 |
| m <sub>8</sub>                         |                 | 0.000180       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                       |                 | 600 ... 950    |                      | 20 ... 300         |                 |
| $\varphi$                              |                 | 0.03 ... 1.5   |                      | 0.03 ... 2.0       |                 |
| $\dot{\varphi}$ [1/s]                  |                 | <100           |                      | <100               |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

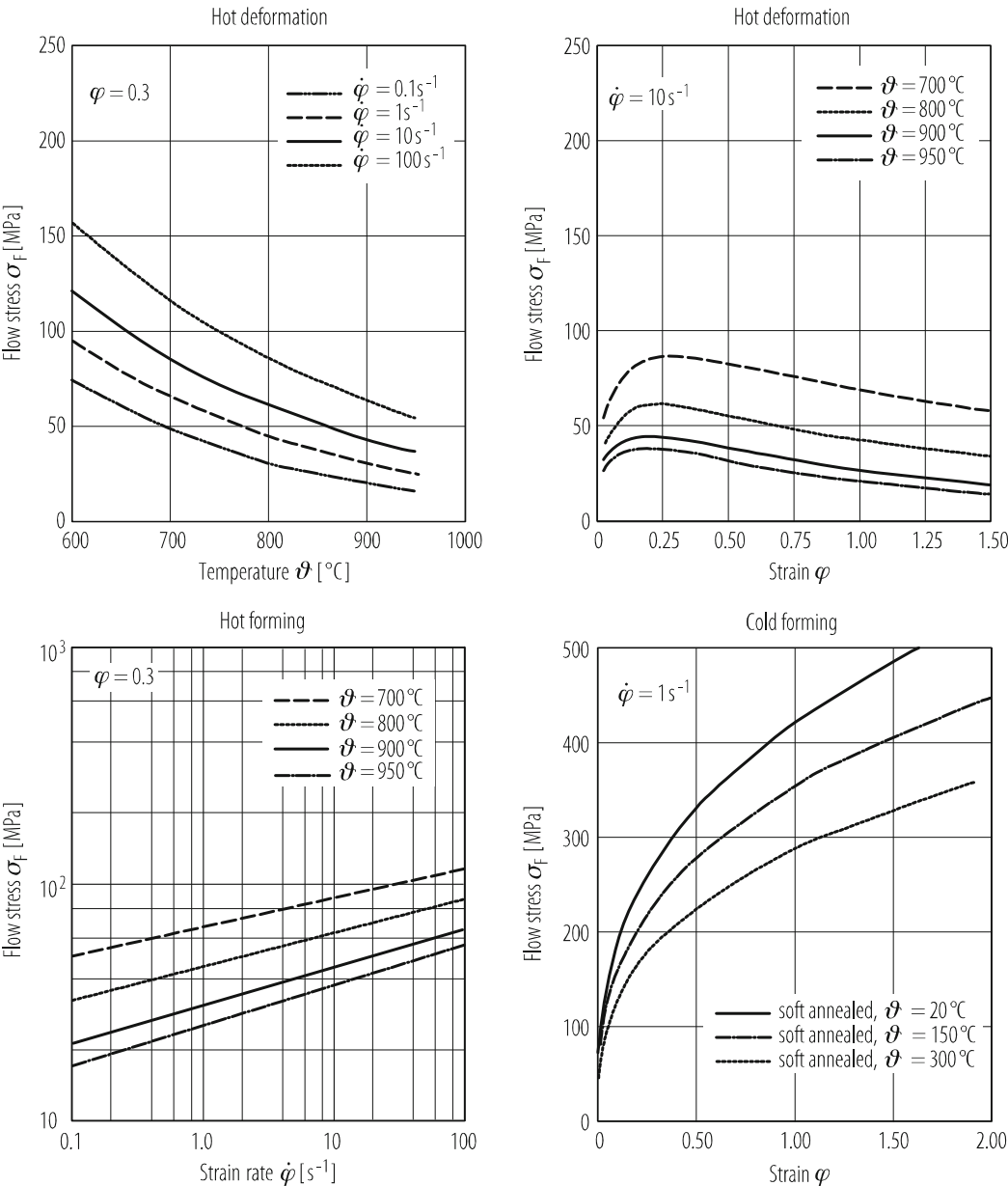


Fig. 5.1 Flow stress curves of Cu-OFE by hot and cold forming.

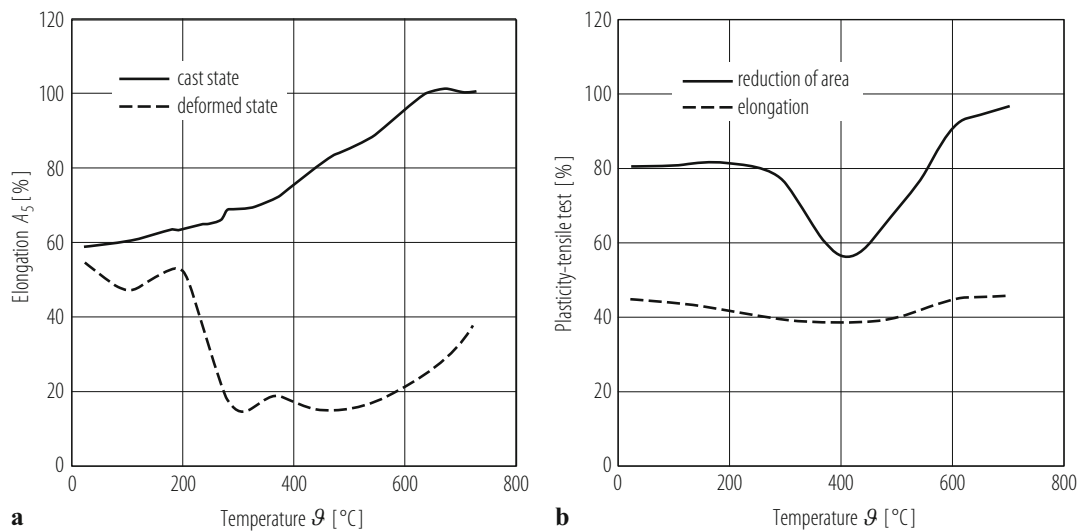
Mechanical properties after cold deformation

| State of material     | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-----------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                       | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| grain size 0.015 [mm] | 50...80                         | 48.99754 | 0.48457 | 200...250                           | 4.52533 | 0.92803 |
| grain size 0.040 [mm] | 50...80                         | 36.14469 | 0.52020 | 200...250                           | 7.88538 | 0.76501 |

| State of material    | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|----------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                      | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| grain size 0.015[mm] | 45...50                                 | 12.33326 | 0.38271 | −4.8281  | <60                        |
| grain size 0.040[mm] | 45...50                                 | 21.69236 | 0.14262 | −5.64843 | <70                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

### Plasticity in tensile test



**Fig. 5.2** Hot plasticity of Cu-OFE as a function of the temperature. a.) Compare cast and deformed state b.) Compare elongation and reduction of area

### Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 401.6                | 385.0              | 16.75                                   | 8936.9                      |                 |
| 100              | 395.3                | 389.1              | 17.04                                   | 8894.3                      |                 |
| 200              | 387.4                | 394.0              | 17.40                                   | 8841.1                      |                 |
| 300              | 379.5                | 398.9              | 17.77                                   | 8787.8                      |                 |
| 400              | 371.6                | 403.9              | 18.13                                   | 8734.6                      |                 |
| 500              | 363.7                | 408.8              | 18.49                                   | 8681.3                      |                 |
| 600              | 355.8                | 413.7              | 18.86                                   | 8628.1                      |                 |
| 700              | 347.9                | 418.7              | 19.22                                   | 8574.8                      |                 |
| 800              | 340.1                | 423.6              | 19.59                                   | 8521.6                      |                 |
| 900              | 332.2                | 428.5              | 19.95                                   | 8468.3                      |                 |
| 950              | 328.2                | 431.0              | 20.13                                   | 8441.7                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| OFE                 | oxygen-free electronic                                                |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of electrolytic-tough-pitch copper (Cu-ETP)

## 5.2 Copper- and Copper alloys

### 5.2.1 Pure Copper and low alloyed Copper

Abstract:

#### Designation

|             |               |               |                 |            |               |
|-------------|---------------|---------------|-----------------|------------|---------------|
| UNS number: | <b>C11000</b> | Chem. symbol: | <b>Cu - ETP</b> | EN number: | <b>CW004A</b> |
|-------------|---------------|---------------|-----------------|------------|---------------|

#### Composition (EN) [Weight-%]

|        |   |       |              |
|--------|---|-------|--------------|
| Cu     | P | Pb    | O            |
| >99.90 |   | <0.05 | 0.05...0.040 |

#### International comparison of standards

|                       |                |                 |            |
|-----------------------|----------------|-----------------|------------|
| Euronorm              |                | ISO             |            |
| EN 13601 : 2003       | EN 1652        | ISO 1337 : 1980 | ISO 1634-1 |
| EN 14436              | EN 13599       | ISO 1637-1      | ISO 1638   |
| EN 12165              |                | ISO 1635        |            |
| Material number (DIN) |                | DIN             |            |
| 2.0060                |                | DIN 1708 / 1787 |            |
| Japan                 |                | Russia          |            |
| C1100                 |                | M0              |            |
|                       |                | GOST 0859       |            |
| USA                   |                |                 |            |
| ASTM                  |                | UNS standard    |            |
| ASTM B187M - 11       | ASTM B 188     | C11000          |            |
| ASTM B372 - 12        | ASTM B640 - 12 |                 |            |
| ASTM F68-05           | ASTM F68 - 10  |                 |            |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

Flow curves

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                    | 76.7            | 74.6           |                      | 209.7              | 225.8           |
| A                                      | 1203.09         | 774.47         |                      | 457.135            | 452.865         |
| Effect of temperature $K_\theta$       |                 |                |                      |                    |                 |
| $m_1$                                  | −0.00258        | −0.00268       |                      | −0.00173           | −0.00156        |
| Effect of strain $K_\varphi$           |                 |                |                      |                    |                 |
| $m_2$                                  | 0.49126         | 0.2077         |                      | 0.27693            | 0.20984         |
| $m_4$                                  | 0.008806        | −0.0178        |                      | −0.01265           | −0.01831        |
| $m_5$                                  | −0.00401        | −0.001696      |                      |                    |                 |
| $m_7$                                  | 0.58803         | 0.0311         |                      |                    |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.00782            | 0.01231         |
| $m_8$                                  | 0.000189        | 0.000187       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                       | 550 ... 950     | 550 ... 950    |                      | 20 ... 300         | 20 ... 300      |
| $\varphi$                              | 0.03 ... 1.50   | 0.03 ... 1.50  |                      | 0.03 ... 2.00      | 0.03 ... 2.00   |
| $\dot{\varphi}$ [1/s]                  | <100            | <100           |                      | <100               | <100            |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

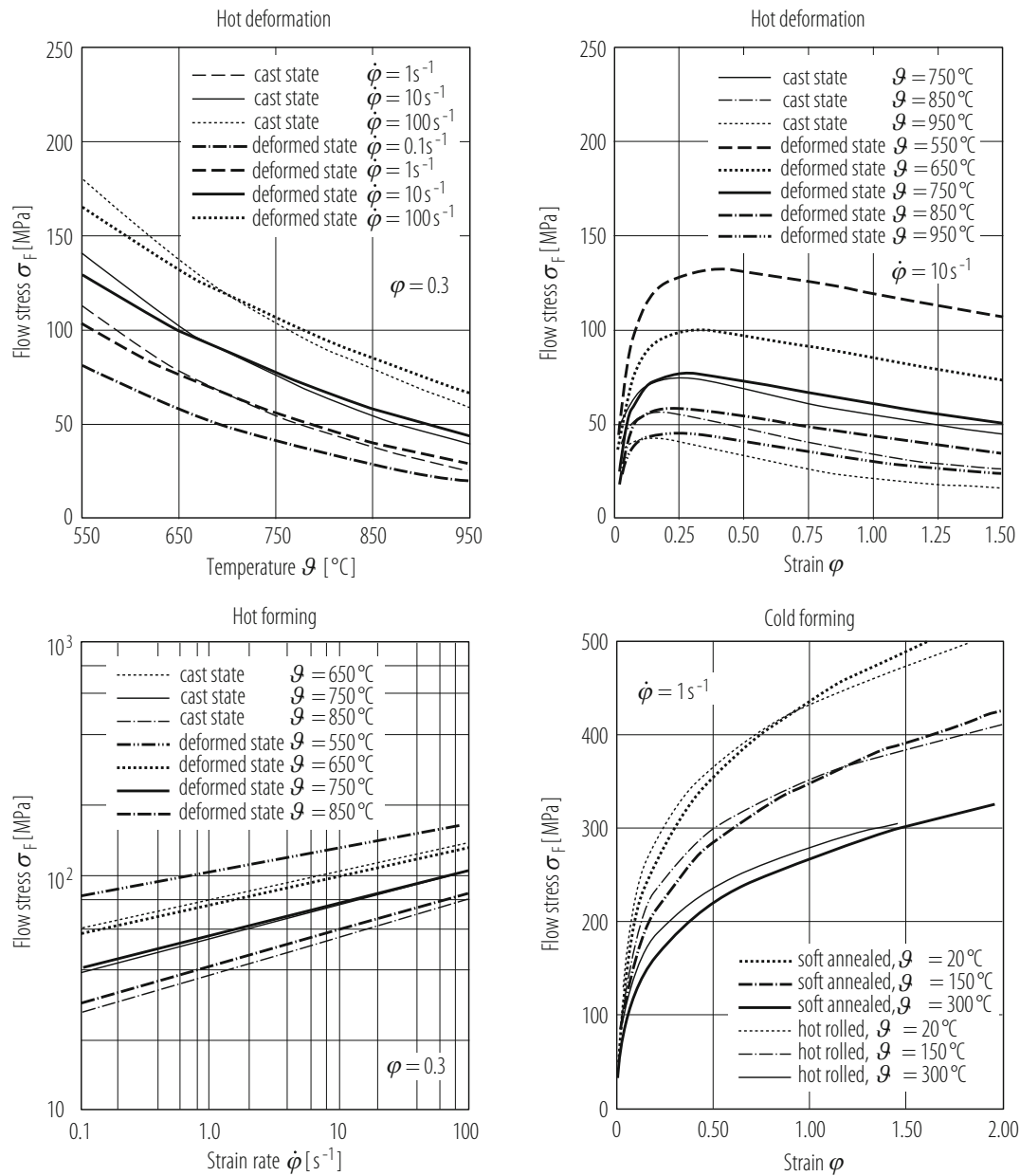


Fig. 5.3 Flow stress curves of Cu-ETP by hot and cold forming.

### Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa]         |          |          | Tensile strength $\Delta R_m$ [MPa] |         |                            |
|-------------------|-----------------------------------------|----------|----------|-------------------------------------|---------|----------------------------|
|                   | $A_0$                                   | $A$      | $n_1$    | $B_0$                               | $B$     | $n_2$                      |
| soft annealed     | 40...80                                 | 49.21508 | 0.46369  | 200...250                           | 5.27422 | 0.83079                    |
| State of material | Elongation to fracture $\Delta A_5$ [%] |          |          |                                     |         | Validity $\varepsilon$ [%] |
|                   | $C_0$                                   | $C$      | $n_3$    | $n_4$                               |         |                            |
| soft annealed     | 50...58                                 | 51.95666 | -0.00331 | -9.47912                            |         | <80                        |
| rolled            | 32...38                                 | 92.18339 | -0.20693 | -13.8528                            |         | <80                        |
| extruded          | 32...38                                 | 20.96638 | 0.09517  | -2.26465                            |         | <80                        |



|                                      |                                      |                                                                    |
|--------------------------------------|--------------------------------------|--------------------------------------------------------------------|
| Yield stress:                        | Tensile strength:                    | Elongation to fracture                                             |
| $R_p = A_0 + A \cdot \epsilon^{n_1}$ | $R_m = B_0 + B \cdot \epsilon^{n_2}$ | $A_5 = C_0 - C \cdot \epsilon^{n_3} \cdot \epsilon^{n_4/\epsilon}$ |
| [Equation (4.1), Chapter 5.1.4]      | [Equation (4.2), Chapter 5.1.4]      | [Equation (4.3), Chapter 5.1.4]                                    |
| [DOI: 978-3-642-14174-4_4]           | [DOI: 978-3-642-14174-4_4]           | [DOI: 978-3-642-14174-4_4]                                         |

Plasticity in tensile test

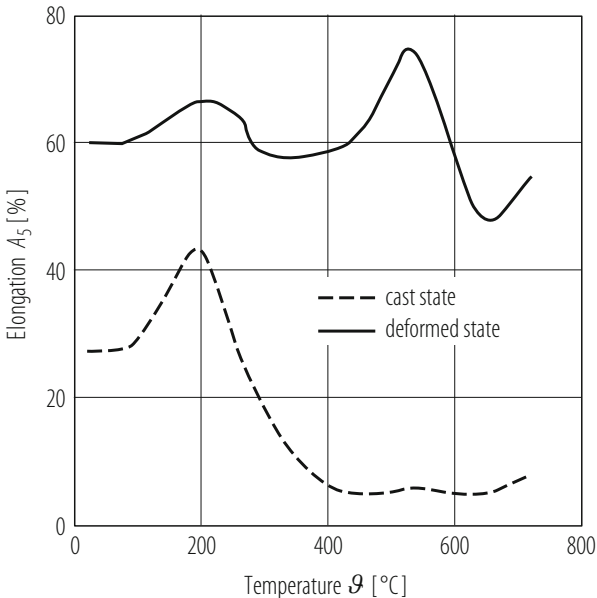


Fig. 5.4 Hot plasticity of Cu-ETP as a function of the temperature.

Physical properties

| Temperature      | Thermal conductivity             | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K <sup>-1</sup> ] | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 393.8                            | 390.2              | 16.72                                   | 8934.6                      | 130.0           |
| 100              | 388.4                            | 393.6              | 17.00                                   | 8912.6                      | 126.0           |
| 200              | 381.6                            | 397.7              | 17.36                                   | 8884.1                      | 122.0           |
| 300              | 374.8                            | 401.9              | 17.71                                   | 8854.5                      | 116.0           |
| 400              | 368.0                            | 406.0              | 18.06                                   | 8823.7                      |                 |
| 500              | 361.2                            | 410.2              | 18.42                                   | 8791.8                      |                 |
| 600              | 354.3                            | 414.4              | 18.77                                   | 8758.8                      |                 |
| 700              | 347.5                            | 418.5              | 19.12                                   | 8724.6                      |                 |
| 800              | 340.7                            | 422.7              | 19.47                                   | 8689.3                      |                 |
| 900              | 333.9                            | 426.8              | 19.83                                   | 8652.8                      |                 |
| 950              | 330.5                            | 428.9              | 20.00                                   | 8634.2                      |                 |

Symbols and abbreviations

| Short form | Full form                                      |
|------------|------------------------------------------------|
| UNS        | unified numbering system                       |
| EN         | Euronorm                                       |
| ISO        | international organisation for standardization |

(continued)

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| ASTM                | American society for testing and materials                            |
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $R_p$               | yield stress                                                          |
| $R_m$               | tensile strength                                                      |
| $\lambda$           | thermal conductivity                                                  |
| $c_{pm}$            | mean specific heat                                                    |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\rho$              | density                                                               |
| $E$                 | Young's modulus                                                       |
| ETP                 | electrolytic-tough-pitch                                              |
| $T, \vartheta$      | temperature                                                           |
| GOST                | gosudarstvennyy standart (state standard)                             |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |

# Flow stress, mechanical and physical properties of extra low phosphorous copper (Cu-PHC)

## 5.2 Copper- and Copper alloys

### 5.2.1 Pure Copper and low alloyed Copper

#### Designation

|             |         |               |        |            |        |
|-------------|---------|---------------|--------|------------|--------|
| UNS number: | C 10300 | Chem. symbol: | Cu-PHC | EN number: | CW020A |
|-------------|---------|---------------|--------|------------|--------|

#### Composition (EN) [Weight-%]

| Cu     | P              | Pb      | O | Sn      | As      | Ag      | Fe     | Mn      | Ni     | Bi      | S       |
|--------|----------------|---------|---|---------|---------|---------|--------|---------|--------|---------|---------|
| >99.99 | 0.0003...0.006 | <0.0005 |   | <0.0002 | <0.0005 | <0.0025 | <0.001 | <0.0005 | <0.001 | <0.0002 | <0.0015 |

#### International comparison of standards

| Euronorm                                                  | ISO                                                     |
|-----------------------------------------------------------|---------------------------------------------------------|
| CEN/TS 13388<br>EN 13601<br>EN 13599                      | EN 1977<br>EN 13148<br>EN 14436                         |
| Material number (DIN)                                     | DIN                                                     |
| 2.0070                                                    |                                                         |
| USA                                                       |                                                         |
| ASTM                                                      | UNS standard                                            |
| ASTM B 42<br>ASTM B743 - 12<br>ASTM B302<br>ASTM F68 - 10 | C 10300<br>ASTM B372 - 12<br>ASTM B187M-02<br>ASTM B280 |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

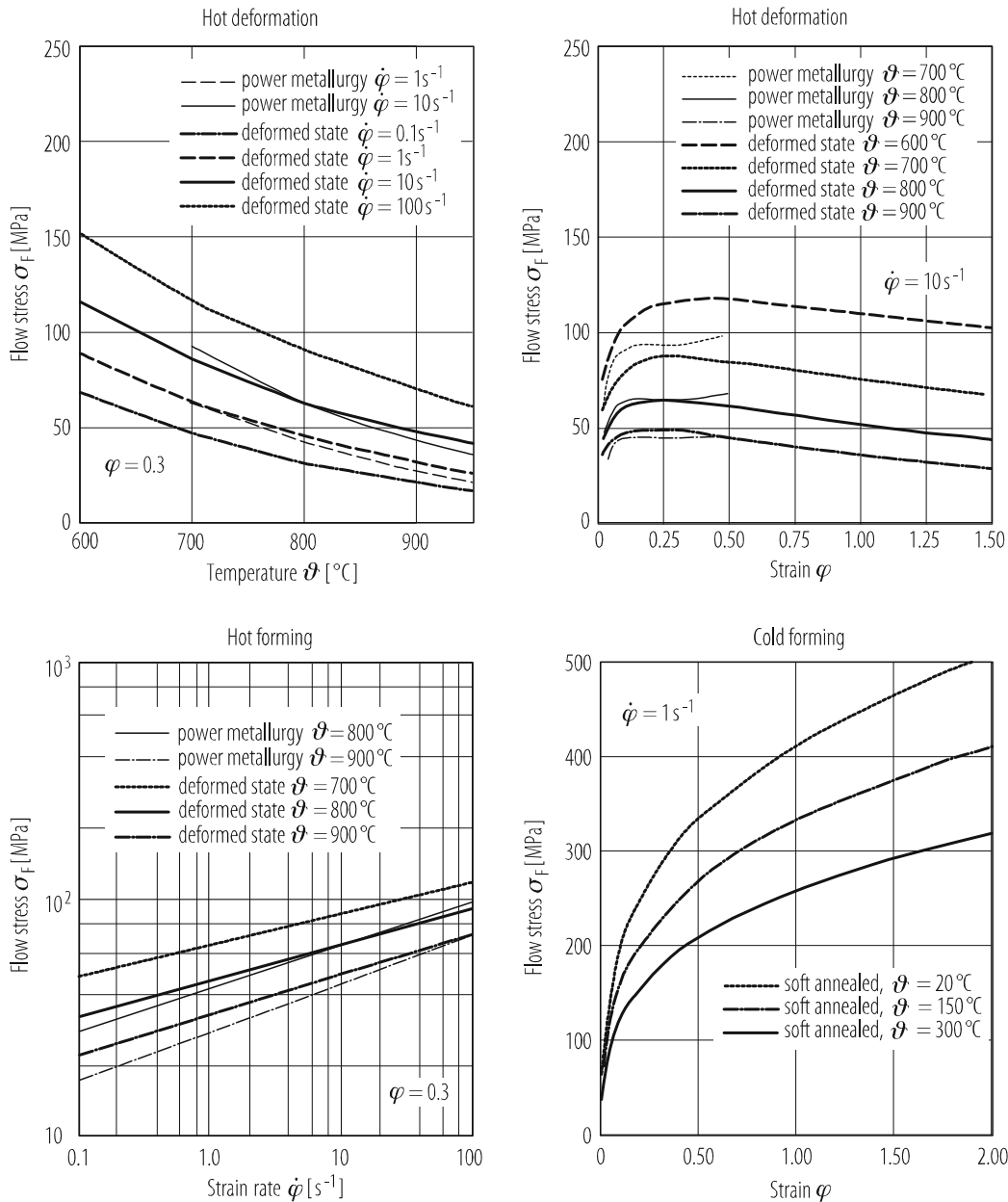
#### Flow curves

| State of material           | Hot deformation |                            | Cold deformation     |                    |                 |
|-----------------------------|-----------------|----------------------------|----------------------|--------------------|-----------------|
|                             | deformed state  | produced powder metallurgy | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]         | 78.2            | 90.7                       |                      | 200.5              |                 |
| A                           | 912.15          | 590.98                     |                      | 429.772            |                 |
| Effect of temperature $K_0$ |                 |                            |                      |                    |                 |
| $m_1$                       | −0.00290        | −0.00404                   |                      | −0.00167           |                 |
| Effect of strain $K_0$      |                 |                            |                      |                    |                 |
| $m_2$                       | 0.27161         | −0.38189                   |                      | 0.29432            |                 |
| $m_4$                       | 0.00059         | −0.03802                   |                      | −0.00847           |                 |
| $m_5$                       | −0.00193        | −0.00081                   |                      |                    |                 |
| $m_7$                       | 0.16492         | 1.42098                    |                      |                    |                 |

(continued)

| State of material                      | Hot deformation |                            | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------------------|----------------------|--------------------|-----------------|
|                                        | deformed state  | produced powder metallurgy | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                            |                      |                    |                 |
| $m_3$                                  |                 |                            |                      | 0.00935            |                 |
| $m_8$                                  | 0.000189        | 0.000227                   |                      |                    |                 |
| Range of validity                      |                 |                            |                      |                    |                 |
| $\vartheta$ [°C]                       | 600 ... 950     | 700...950                  |                      | 20 ... 300         |                 |
| $\varphi$                              | 0.03 ... 1.5    | 0.03 ... 0.50              |                      | 0.03 ... 2.00      |                 |
| $\dot{\varphi}$ [1/s]                  | <100            | <10                        |                      | <100               |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |



**Fig. 5.5** Flow stress curves of Cu-PHC by hot and cold forming.

### Mechanical properties after cold deformation

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|---------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$   |                            |
| soft annealed     | 32...38                                 | 32.10237 | 0.03663 | -6.5031 | <70                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m.K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 398.7                | 403.3              | 16.75                                   | 8934.6                      |                 |
| 100              | 391.9                | 405.4              | 17.04                                   | 8912.6                      |                 |
| 200              | 383.4                | 408.2              | 17.40                                   | 8884.0                      |                 |
| 300              | 374.8                | 411.2              | 17.77                                   | 8854.2                      |                 |
| 400              | 366.3                | 414.3              | 18.13                                   | 8823.3                      |                 |
| 500              | 357.7                | 417.6              | 18.49                                   | 8791.2                      |                 |
| 600              | 349.2                | 421.1              | 18.86                                   | 8757.9                      |                 |
| 700              | 340.7                | 424.7              | 19.22                                   | 8723.5                      |                 |
| 800              | 332.1                | 428.5              | 19.59                                   | 8687.9                      |                 |
| 900              | 323.6                | 432.4              | 19.95                                   | 8651.1                      |                 |
| 950              | 319.3                | 434.5              | 20.13                                   | 8632.2                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                                 |
|---------------------|---------------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                               |
| $\varphi$           | strain                                                                    |
| $\dot{\varphi}$     | strain rate                                                               |
| $A_5$               | elongation to fracture                                                    |
| $A, B, C$ and $n_i$ | constants                                                                 |
| ASTM                | American society for testing and materials                                |
| CEN                 | European committee for standardization (comité Européen de normalisation) |
| $c_{pm}$            | mean specific heat                                                        |
| DIN                 | German institute for standardisation (Deutsches institut für normung)     |
| $E$                 | Young's modulus                                                           |
| EN                  | Euronorm                                                                  |
| ISO                 | international organisation for standardization                            |
| PHC                 | extra low phosphorous copper                                              |
| $R_m$               | tensile strength                                                          |
| $R_p$               | yield stress                                                              |
| $T, \vartheta$      | temperature                                                               |
| TS                  | technical specification                                                   |
| UNS                 | unified numbering system                                                  |
| $\alpha_m$          | average coefficient of linear expansion                                   |
| $\lambda$           | thermal conductivity                                                      |
| $\rho$              | density                                                                   |

# Flow stress, mechanical and physical properties of phosphorous deoxidised copper (Cu-DHP)

## 5.2 Copper- and Copper alloys

### 5.2.1 Pure Copper and low alloyed Copper

#### Designation

|             |               |               |               |            |                 |
|-------------|---------------|---------------|---------------|------------|-----------------|
| UNS number: | <b>C12200</b> | Chem. symbol: | <b>Cu-DHP</b> | EN number: | <b>CC040A/A</b> |
|-------------|---------------|---------------|---------------|------------|-----------------|

#### Composition (EN) [Weight-%]

|        |               |       |       |       |
|--------|---------------|-------|-------|-------|
| Cu     | P             | Pb    | As    | P     |
| >99.85 | 0.015...0.040 | <0,03 | <0,04 | <0,04 |

#### International comparison of standards

|                       |                 |                 |               |
|-----------------------|-----------------|-----------------|---------------|
| Euronorm              |                 | ISO             |               |
| EN 1976 : 1998-05     |                 | ISO 1337 : 1980 | ISO 1634-1    |
|                       |                 | ISO 431 : 1981  | ISO 1637      |
| Material number (DIN) |                 | DIN             |               |
| 2.0109                |                 | DIN 17655       |               |
| Japan                 |                 | Russia          |               |
| C 1220                |                 | M2r             | GOST 859 - 78 |
| H 5120                |                 |                 |               |
| USA                   |                 | UNS standard    |               |
| ASTM                  |                 |                 |               |
| ASTM B640 - 12        | ASTM B249M - 12 | C12200          |               |
| ASTM B837 - 10        | ASTM B302       |                 |               |
| ASTM B743 - 12        |                 |                 |               |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

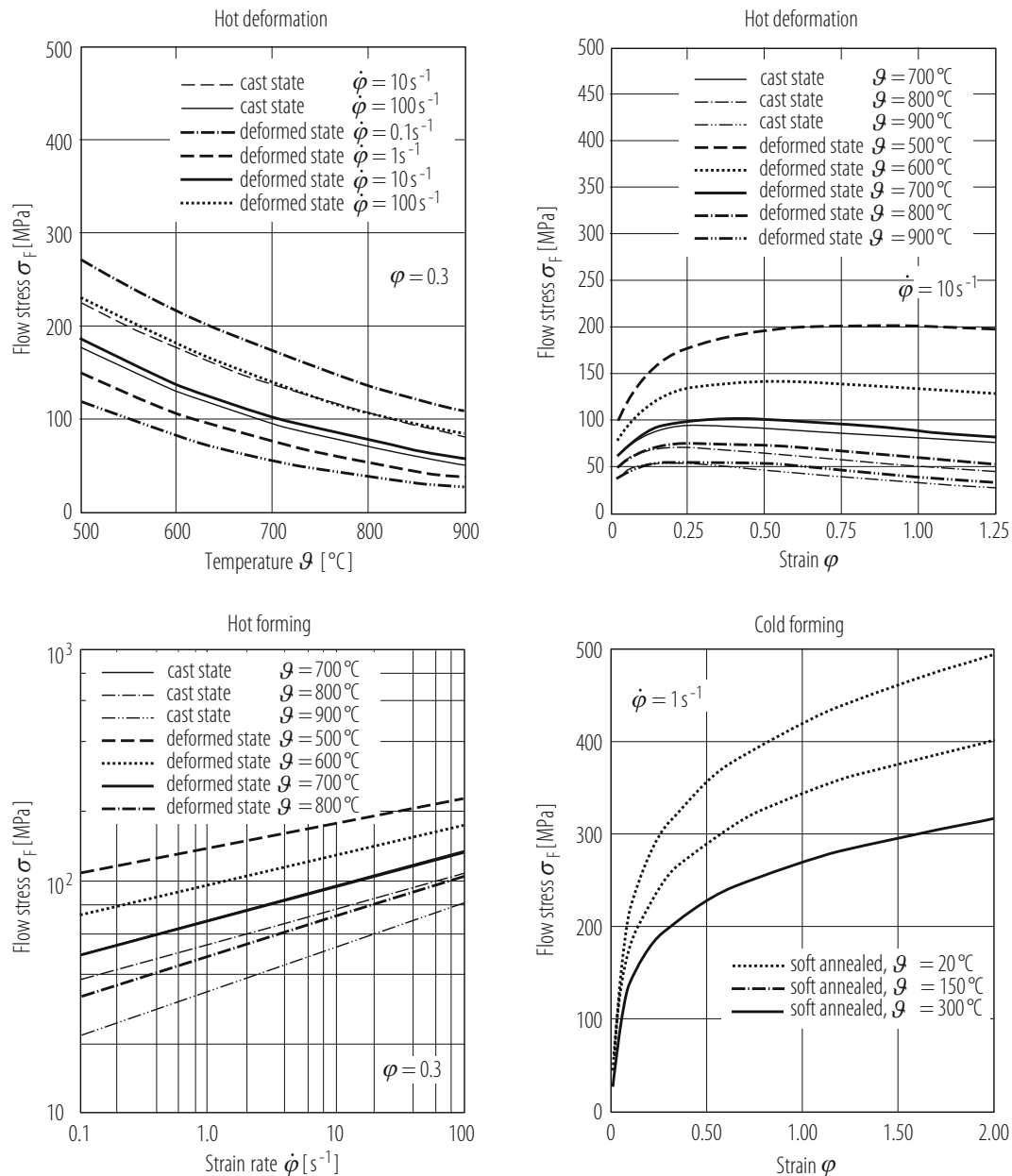
| State of material           | Hot deformation |                | Cold deformation     |                    |                 |
|-----------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                             | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]         | 82.06           | 84.1           |                      | 224.60             |                 |
| A                           | 1223.35         | 1346.35        |                      | 442.27             |                 |
| Effect of temperature $K_9$ |                 |                |                      |                    |                 |
| $m_1$                       | -0.00258        | -0.00280       |                      | -0.00158           |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| Effect of strain $K_\varphi$           |                 |                |                      |                    |                 |
| $m_2$                                  | 0.49126         | 0.44772        |                      | 0.21369            |                 |
| $m_4$                                  | 0.008806        | −0.017981      |                      |                    |                 |
| $m_5$                                  | −0.00381        | −0.00246       |                      |                    |                 |
| $m_7$                                  | 0.58803         | 0.122          |                      |                    |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.01123            |                 |
| $m_8$                                  | 0.000212        | 0.000190       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                       | 500...900°C     | 500...900°C    |                      | 20 ... 300         |                 |
| $\varphi$                              | 0.03 ... 1.25   | 0.03 ... 1.25  |                      | 0.03 ... 2.00      |                 |
| $\dot{\varphi}$ [1/s]                  | <100            | <100           |                      | <100               |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.2), Chapter 2.3.2.2.2]                                                                        |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |





**Fig. 5.6** Flow stress curves of Cu-DHP by hot and cold forming.

### Mechanical properties after cold deformation

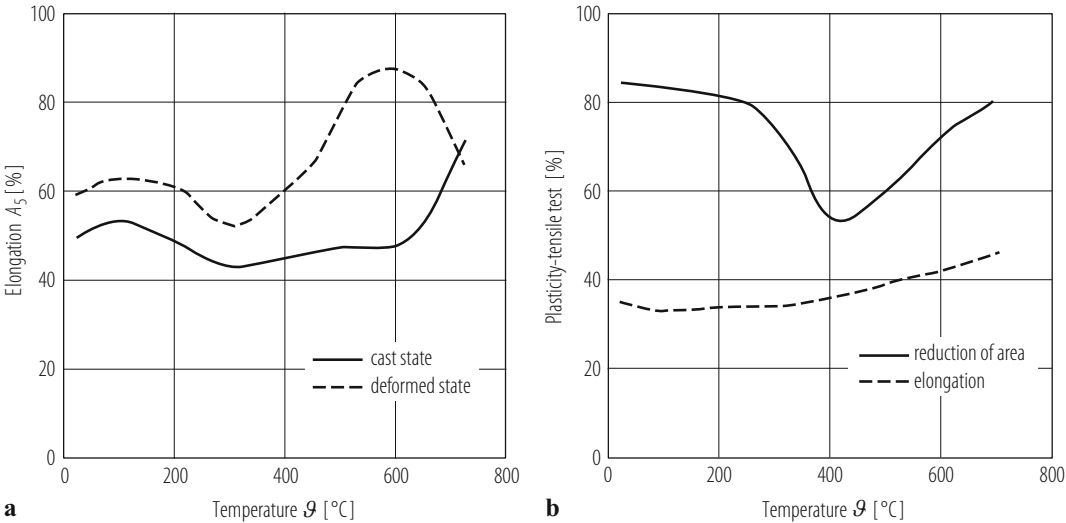
| State of material | Yield stress $\Delta R_p$ [MPa] |     |       | Tensile strength $\Delta R_m$ [MPa] |          |         |
|-------------------|---------------------------------|-----|-------|-------------------------------------|----------|---------|
|                   | $A_0$                           | $A$ | $n_1$ | $B_0$                               | $B$      | $n_2$   |
| soft annealed     |                                 |     |       | 200...250                           | 17.10293 | 0.54414 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| soft annealed     | 40...45                                 | 44.66097 | 0.00523 | -8.17753 | <70                        |

|                                      |                                      |                                                             |
|--------------------------------------|--------------------------------------|-------------------------------------------------------------|
| Yield stress:                        | Tensile strength:                    | Elongation to fracture                                      |
| $R_p = A_0 + A \cdot \epsilon^{n_1}$ | $R_m = B_0 + B \cdot \epsilon^{n_2}$ | $A_5 = C_0 - C \cdot \epsilon^{n_3} \cdot e^{n_4/\epsilon}$ |
| [Equation (4.1), Chapter 5.1.4]      | [Equation (4.2), Chapter 5.1.4]      | [Equation (4.3), Chapter 5.1.4]                             |
| [DOI: 978-3-642-14174-4_5]           | [DOI: 978-3-642-14174-4_5]           | [DOI: 978-3-642-14174-4_5]                                  |

Plasticity in tensile test



**Fig. 5.7** Hot plasticity of Cu-DHP as a function of the temperature. a.) Compare cast and deformed state b.) Compare elongation and reduction of area

Physical properties

| Temperature | Thermal conductivity                   | Mean specific heat | Average coefficient of linear expansion | Density                | Young's-modulus |
|-------------|----------------------------------------|--------------------|-----------------------------------------|------------------------|-----------------|
| Θ [°C]      | λ [W m <sup>-1</sup> K <sup>-1</sup> ] | $c_{pm}$ [J/kg·K]  | α <sub>m</sub> [10 <sup>-6</sup> /K]    | ρ [kg/m <sup>3</sup> ] | E [GPa]         |
| 20          | 352.5                                  | 385.7              | 16.75                                   | 8936.9                 | 132.0           |
| 100         | 354.1                                  | 390.4              | 17.04                                   | 8894.3                 | 128.0           |
| 200         | 356.1                                  | 396.3              | 17.40                                   | 8841.1                 | 122.0           |
| 300         | 358.0                                  | 402.2              | 17.77                                   | 8787.8                 | 118.0           |
| 400         | 360.0                                  | 408.1              | 18.13                                   | 8734.6                 |                 |
| 500         | 362.0                                  | 414.0              | 18.49                                   | 8681.3                 |                 |
| 600         | 364.0                                  | 419.8              | 18.86                                   | 8628.1                 |                 |
| 700         | 366.0                                  | 425.7              | 19.22                                   | 8574.8                 |                 |
| 800         | 367.9                                  | 431.6              | 19.59                                   | 8521.6                 |                 |
| 900         | 369.9                                  | 437.5              | 19.95                                   | 8468.3                 |                 |
| 950         | 370.9                                  | 440.5              | 20.13                                   | 8441.7                 |                 |

Symbols and abbreviations

| Short form     | Full form              |
|----------------|------------------------|
| σ <sub>F</sub> | flow stress            |
| φ              | strain                 |
| $\dot{\phi}$   | strain rate            |
| A <sub>5</sub> | elongation to fracture |

(continued)

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $A, B, C$ and $n_i$ | Constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DHP                 | phosphorous deoxidised                                                |
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuAg<sub>0.10</sub>

## 5.2 Copper- and Copper alloys

### 5.2.1 Pure Copper and low alloyed Copper

#### Designation

|             |                |               |                            |            |               |
|-------------|----------------|---------------|----------------------------|------------|---------------|
| UNS number: | <b>C 11600</b> | Chem. symbol: | <b>CuAg<sub>0.10</sub></b> | EN number: | <b>CW013A</b> |
|-------------|----------------|---------------|----------------------------|------------|---------------|

#### Composition (EN) [Weight-%]

|        |               |        |        |        |        |
|--------|---------------|--------|--------|--------|--------|
| Cu     | Ag            | Bi     | Pb     | Sb     | As     |
| >99.90 | 0.050...0.100 | <0.001 | <0.005 | >0.002 | <0.002 |
| Fe     | Ni            | Sn     | Zn     | S      | O      |
| <0.005 | <0.002        | <0.002 | <0.003 | <0.004 | <0.04  |

#### International comparison of standards

|                        |                 |                 |            |
|------------------------|-----------------|-----------------|------------|
| Euronorm               |                 | ISO             |            |
| EN 1976 : 1998         | EN 13599        | ISO 1336 : 1980 | ISO 1634-1 |
| EN 13601               | EN 50149 : 2001 | ISO 1637        | ISO 1638   |
| EN 1977                |                 |                 |            |
| Material number (DIN)  |                 | DIN             |            |
| 2.1203                 |                 | DIN 17666       |            |
| United Kingdom         |                 | Russia          |            |
| BS 6017 : 1981         | Cu-Ag-4         | GOST 18175      |            |
| USA                    |                 |                 |            |
| ASTM                   |                 | UNS standard    |            |
| ASTM B152 / B152M - 09 |                 | C11600          |            |
| ASTM B187 / B187M - 11 |                 |                 |            |
| ASTM B5 - 11           |                 |                 |            |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material            | Hot deformation |                | Cold deformation     |                    |                 |
|------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                              | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]          |                 | 83.63          |                      | 202.1              |                 |
| A                            |                 | 960.422        |                      | 427.493            |                 |
| Effect of temperature $K_8$  |                 |                |                      |                    |                 |
| $m_1$                        |                 | -0.00280       |                      | -0.00156           |                 |
| Effect of strain $K_\varphi$ |                 |                |                      |                    |                 |
| $m_2$                        |                 | 0.32805        |                      | 0.30909            |                 |
| $m_4$                        |                 | 0.00129        |                      | -0.00361           |                 |
| $m_5$                        |                 | -0.00119       |                      |                    |                 |
| $m_7$                        |                 | -0.14296       |                      |                    |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| m <sub>3</sub>                         |                 |                |                      | 0.01231            |                 |
| m <sub>8</sub>                         |                 | 0.000220       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| θ [°C]                                 |                 | 550...750 °C   |                      | 20 ... 300         |                 |
| φ                                      |                 | 0.03 ... 1.50  |                      | 0.03 ... 2.00      |                 |
| $\dot{\varphi}$ [1/s]                  |                 | <100           |                      | <100               |                 |

|                                                                                                                                                                       |                                                                                                         |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                      | Cold deformation                                                                                        |
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                  | [Equation (2.25), Chapter 2.3.2.2.2]                                                                    |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                           | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                             |

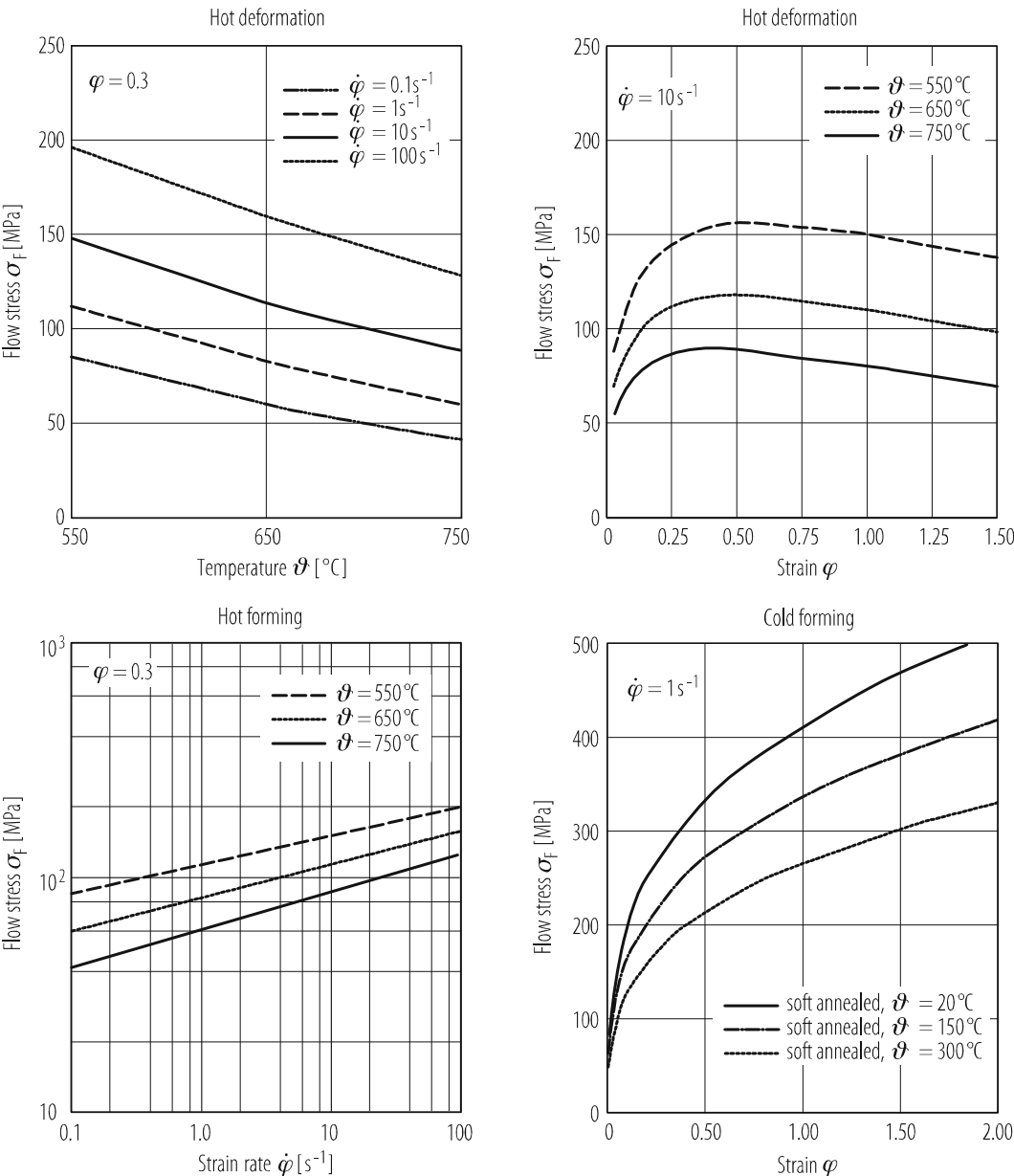


Fig. 5.8 Flow stress curves of CuAg<sub>0.10</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material     | Yield stress $\Delta R_p$ [MPa]         |          |         | Tensile strength $\Delta R_m$ [MPa] |                            |         |
|-----------------------|-----------------------------------------|----------|---------|-------------------------------------|----------------------------|---------|
|                       | $A_0$                                   | $A$      | $n_1$   | $B_0$                               | $B$                        | $n_2$   |
| grain size 0.035 [mm] | 50...80                                 | 45.29334 | 0.47780 | 200...250                           | 3.24956                    | 0.95571 |
| State of material     | Elongation to fracture $\Delta A_5$ [%] |          |         |                                     |                            |         |
|                       | $C_0$                                   | $C$      | $n_3$   | $n_4$                               | Validity $\varepsilon$ [%] |         |
| grain size 0.035 [mm] | 40...45                                 | 26.85226 | 0.12736 | -7.22925                            | <70                        |         |

|                                      |                                      |                                                                    |
|--------------------------------------|--------------------------------------|--------------------------------------------------------------------|
| Yield stress:                        | Tensile strength:                    | Elongation to fracture                                             |
| $R_p = A_0 + A \cdot \epsilon^{n_1}$ | $R_m = B_0 + B \cdot \epsilon^{n_2}$ | $A_5 = C_0 - C \cdot \epsilon^{n_3} \cdot \epsilon^{n_4/\epsilon}$ |
| [Equation (4.1), Chapter 5.1.4]      | [Equation (4.2), Chapter 5.1.4]      | [Equation (4.3), Chapter 5.1.4]                                    |
| [DOI: 978-3-642-14174-4_5]           | [DOI: 978-3-642-14174-4_5]           | [DOI: 978-3-642-14174-4_2]                                         |

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m.K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 389.8                | 400.2              | 16.72                                   | 8886.9                      | 125.0           |
| 100              | 384.4                | 402.9              | 17.00                                   | 8844.3                      |                 |
| 200              | 377.6                | 406.3              | 17.36                                   | 8791.1                      |                 |
| 300              | 370.8                | 409.6              | 17.71                                   | 8737.8                      |                 |
| 400              | 364.0                | 412.9              | 18.06                                   | 8684.6                      |                 |
| 500              | 357.2                | 416.3              | 18.42                                   | 8631.3                      |                 |
| 600              | 350.3                | 419.6              | 18.77                                   | 8578.1                      |                 |
| 700              | 343.5                | 423.0              | 19.12                                   | 8524.8                      |                 |
| 800              | 336.7                | 426.3              | 19.47                                   | 8471.6                      |                 |
| 900              | 329.9                | 429.6              | 19.83                                   | 8418.3                      |                 |
| 950              | 326.5                | 431.3              | 20.00                                   | 8391.7                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| UNS                 | unified numbering system                                              |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| DIN                 | Deutsches institut für normung (German institute for standardisation) |
| BS                  | British standards                                                     |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ASTM                | American society for testing and materials                            |
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $R_p$               | yield stress                                                          |
| $R_m$               | tensile strength                                                      |
| $\lambda$           | thermal conductivity                                                  |
| $c_{pm}$            | mean specific heat                                                    |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\rho$              | density                                                               |
| $E$                 | Young's modulus                                                       |
| $A, B, C$ and $n_i$ | constants                                                             |
| $A_5$               | elongation to fracture                                                |
| $T, \vartheta$      | temperature                                                           |

# Flow stress and physical properties of CuCr<sub>1</sub>

## 5.2 Copper- and Copper alloys

### 5.2.1 Pure Copper and low alloyed Copper

#### Designation

|             |                |               |              |            |               |
|-------------|----------------|---------------|--------------|------------|---------------|
| UNS number: | <b>C 18200</b> | Chem. symbol: | <b>CuCr1</b> | EN number: | <b>CW105C</b> |
|-------------|----------------|---------------|--------------|------------|---------------|

#### Composition (EN) [Weight-%]

|      |    |    |   |
|------|----|----|---|
| Cu   | Cr | Pb | O |
| Bal. | ~1 |    |   |

#### International comparison of standards

|                       |                 |              |            |
|-----------------------|-----------------|--------------|------------|
| Euronorm              |                 | ISO          |            |
| EN 12163              | ISO 1336 : 1980 | ISO 1637     |            |
| EN 12165              | EN 12420        | ISO 1639     | ISO 1640   |
| Material number (DIN) |                 | DIN          |            |
| 2.1291                |                 | DIN 17666    |            |
| Japan                 |                 | Russia       |            |
|                       |                 | BrH1         | GOST 18175 |
| USA                   |                 |              |            |
| ASTM                  |                 | UNS standard |            |
| ASTM F9               |                 | C18200       |            |
| MIL-C-19311           |                 |              |            |

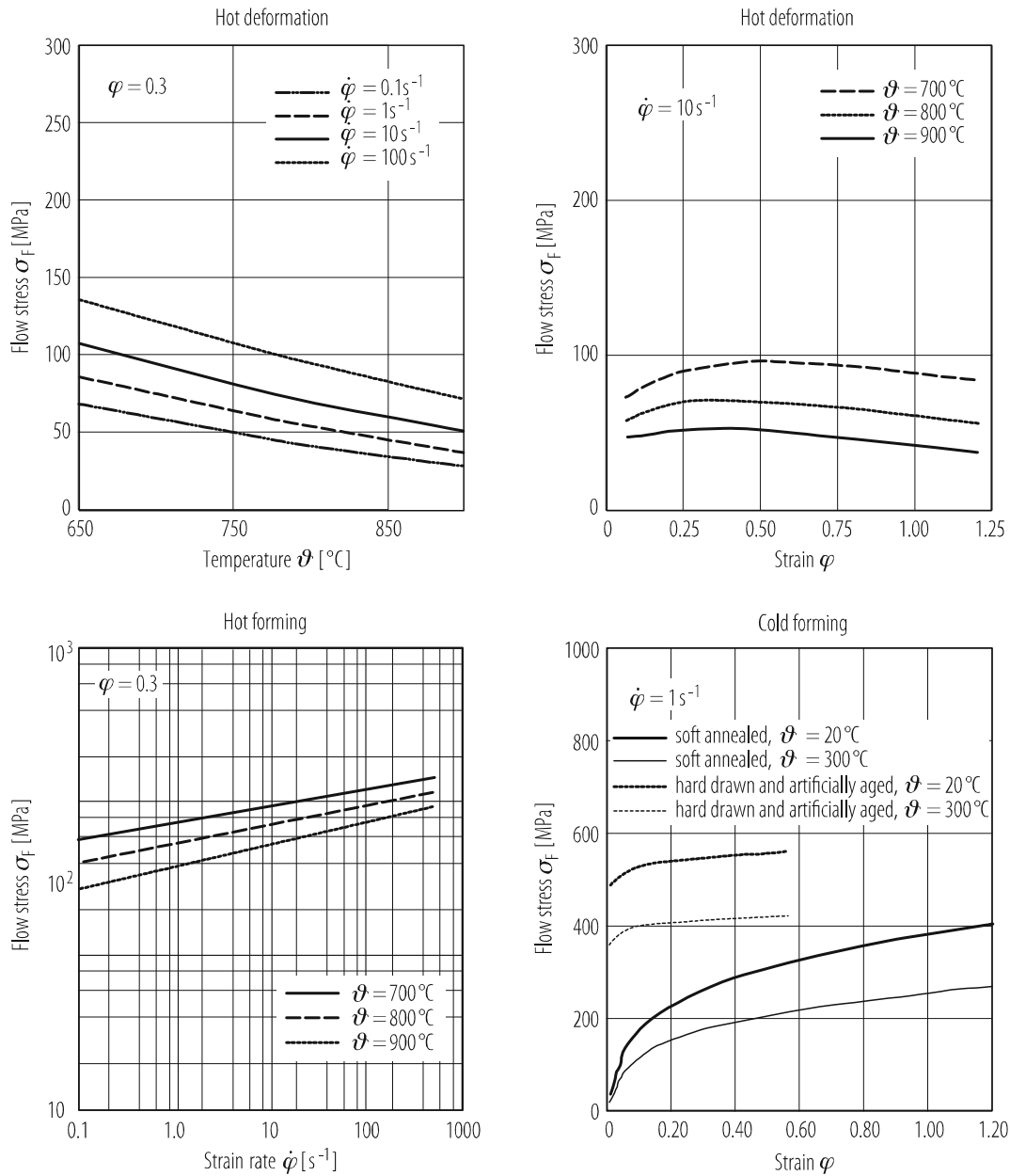
It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                   | Hot deformation |                | Cold deformation   |                                          |
|-------------------------------------|-----------------|----------------|--------------------|------------------------------------------|
|                                     | cast state      | deformed state | soft annealed (sa) | hard drawn + artificially aged (ha + ar) |
| $\sigma_{F0}$ [MPa]                 |                 | 76.8           | 182.1              | 544.2                                    |
| A                                   |                 | 1291.093       | 401.484            | 585.930                                  |
| Effect of temperature $K_8$         |                 |                |                    |                                          |
| $m_1$                               |                 | −0.00262       | −0.00142           | −0.00157                                 |
| Effect of strain $K_\phi$           |                 |                |                    |                                          |
| $m_2$                               |                 | 0.60372        | 0.2767             | 0.02991                                  |
| $m_4$                               |                 | 0.03088        | −0.01534           | −0.00035                                 |
| $m_5$                               |                 | −0.00236       |                    |                                          |
| $m_7$                               |                 | 0.022101       |                    |                                          |
| Effect of strain rate $K\dot{\phi}$ |                 |                |                    |                                          |
| $m_3$                               |                 |                | 0.01311            | 0.01298                                  |
| $m_8$                               |                 | 0.000154       |                    |                                          |
| Range of validity                   |                 |                |                    |                                          |
| $\vartheta$ [°C]                    |                 | 650...900 °C   | 20 ... 300         | 20 ... 300                               |
| $\phi$                              |                 | 0.03 ... 1.20  | 0.03 ... 1.20      | 0.03 ... 0.60                            |
| $\dot{\phi}$ [1/s]                  |                 | <100           | <100               | <100                                     |



| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                                                 |



**Fig. 5.9** Flow stress curves of CuCr<sub>1</sub> by hot and cold forming.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 311.4                | 385.7              | 16.28                                   | 8894.9                      |                 |
| 100              | 325.2                | 388.3              | 16.74                                   | 8852.3                      |                 |
| 200              | 331.4                | 391.7              | 17.30                                   | 8799.1                      |                 |
| 300              | 335.0                | 395.0              | 17.86                                   | 8745.8                      |                 |
| 400              | 337.7                | 398.4              | 18.43                                   | 8692.6                      |                 |
| 500              | 339.7                | 401.7              | 18.99                                   | 8639.3                      |                 |
| 600              | 341.4                | 405.1              | 19.56                                   | 8586.1                      |                 |
| 700              | 342.8                | 408.4              | 20.12                                   | 8532.8                      |                 |
| 800              | 344.0                | 411.7              | 20.68                                   | 8479.6                      |                 |
| 900              | 345.1                | 415.1              | 21.25                                   | 8426.3                      |                 |
| 950              | 345.6                | 416.7              | 21.53                                   | 8399.7                      |                 |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches institut für normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| GOST            | gosudarstvennyy standart (state standard)                             |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, mechanical and physical properties of CuCr<sub>1</sub>Zr

## 5.2 Copper- and Copper alloys

### 5.2.1 Pure Copper and low alloyed Copper

#### Designation

|             |               |               |                           |            |               |
|-------------|---------------|---------------|---------------------------|------------|---------------|
| UNS number: | <b>C18150</b> | Chem. symbol: | <b>CuCr<sub>1</sub>Zr</b> | EN number: | <b>CW106C</b> |
|-------------|---------------|---------------|---------------------------|------------|---------------|

#### Composition (EN) [Weight-%]

|      |             |             |        |
|------|-------------|-------------|--------|
| Cu   | Cr          | Zr          | Others |
| Bal. | 0.30...1.20 | 0.03...0.30 | 0.20   |

#### International comparison of standards

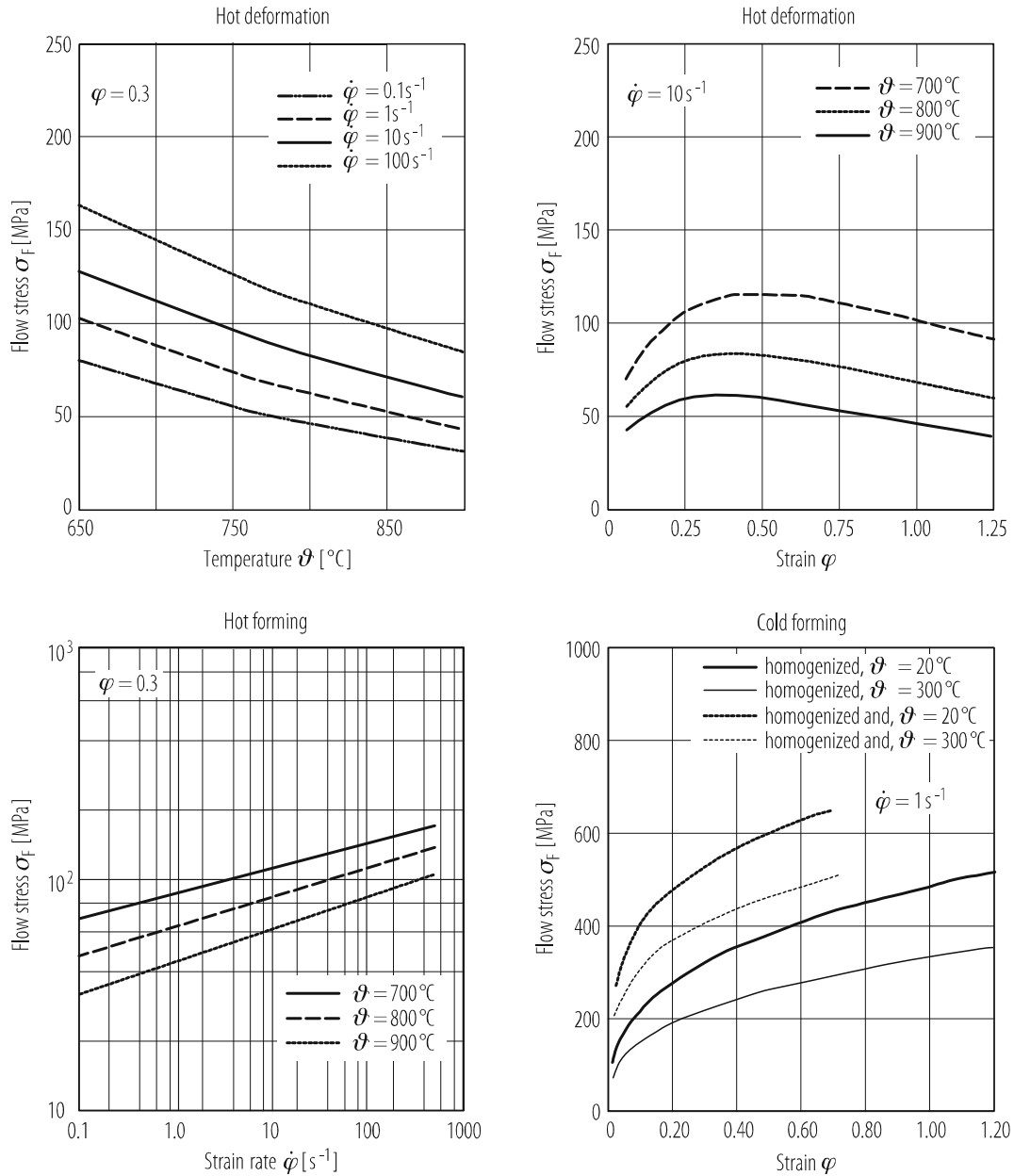
|                       |                  |                 |          |
|-----------------------|------------------|-----------------|----------|
| Euronorm              | ISO              |                 |          |
| EN 12420 : 1999       | EN 12165         | ISO 1336 : 1980 | ISO 1637 |
| EN 12167              | EN 12166         | ISO 1640        |          |
| Material number (DIN) | DIN              |                 |          |
| 2.1293                | DIN 17666 : 1983 |                 |          |
| USA                   |                  |                 |          |
| ASTM                  | UNS standard     |                 |          |
|                       | C 18150          |                 |          |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation  |                                          |
|----------------------------------------|-----------------|----------------|-------------------|------------------------------------------|
|                                        | cast state      | deformed state | homogenized (hom) | homogenized + artificially aged (hom + ) |
| $\sigma_{F0}$ [MPa]                    |                 | 80.7           | 228.5             | 415.0                                    |
| A                                      |                 | 2225.641       | 501.339           | 729.003                                  |
| Effect of temperature $K_{\theta}$     |                 |                |                   |                                          |
| $m_1$                                  |                 | -0.00283       | -0.00136          | -0.00144                                 |
| Effect of strain $K_{\phi}$            |                 |                |                   |                                          |
| $m_2$                                  |                 | 0.70605        | 0.33982           | 0.24387                                  |
| $m_4$                                  |                 | 0.02132        | -0.00097          | -0.00059                                 |
| $m_5$                                  |                 | -0.00217       |                   |                                          |
| $m_7$                                  |                 | -0.32525       |                   |                                          |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                   |                                          |
| $m_3$                                  |                 |                | 0.01403           | 0.01384                                  |
| $m_8$                                  |                 | 0.000157       |                   |                                          |
| Range of validity                      |                 |                |                   |                                          |
| $\vartheta$ [°C]                       |                 | 650...900 °C   | 20 ... 300        | 20 ... 300                               |
| $\phi$                                 |                 | 0.03 ... 1.25  | 0.03 ... 1.20     | 0.03 ... 0.70                            |
| $\dot{\phi}$ [1/s]                     |                 | <100           | <100              | <100                                     |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                                                 |



**Fig. 5.10** Flow stress curves of CuCr<sub>1</sub>Zr by hot and cold forming

**Mechanical properties after cold deformation**

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| soft annealed     | 90...130                        | 16.92429 | 0.62290 | 220...270                           | 6.09830 | 0.83658 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$   | $n_4$    |                            |
| soft annealed     | 35...40                                 | 6.41161 | 0.40319 | -5.16248 | <90                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

**Physical properties**

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 307.1                | 371.6              | 15.80                                   | 8914.9                      | 130.0           |
| 100              | 320.7                | 408.3              | 16.32                                   | 8893.8                      |                 |
| 200              | 326.8                | 426.2              | 16.97                                   | 8865.5                      |                 |
| 300              | 330.4                | 437.4              | 17.62                                   | 8835.1                      |                 |
| 400              | 333.0                | 445.6              | 18.27                                   | 8802.7                      |                 |
| 500              | 335.0                | 452.2              | 18.92                                   | 8768.1                      |                 |
| 600              | 336.6                | 457.7              | 19.57                                   | 8731.5                      |                 |
| 700              | 338.0                | 462.4              | 20.22                                   | 8692.8                      |                 |
| 800              | 339.2                | 466.5              | 20.87                                   | 8652.0                      |                 |
| 900              | 340.3                | 470.3              | 21.52                                   | 8609.1                      |                 |
| 950              | 340.8                | 472.0              | 21.84                                   | 8586.8                      |                 |

**Symbols and abbreviations**

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| $E$                 | Young's modulus                                                       |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| EN             | Euronorm                                       |
| ISO            | international organisation for standardization |
| $R_m$          | tensile strength                               |
| $R_p$          | yield stress                                   |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |

# Flow stress, mechanical and physical properties of CuNi<sub>2</sub>Si

## 5.2 Copper- and Copper alloys

### 5.2.1 Pure Copper and low alloyed Copper

#### Designation

|             |               |               |                |            |               |
|-------------|---------------|---------------|----------------|------------|---------------|
| UNS number: | <b>C18000</b> | Chem. symbol: | <b>CuNi2Si</b> | EN number: | <b>CW111C</b> |
|-------------|---------------|---------------|----------------|------------|---------------|

#### Composition (EN) [Weight-%]

|      |             |             |       |       |       |       |
|------|-------------|-------------|-------|-------|-------|-------|
| Cu   | Ni          | Si          | Fe    | Sn    | Zn    | Pb    |
| Bal. | 1.80...2.20 | 0.50...1.00 | <0.30 | <0.10 | <0.10 | >0.10 |

#### International comparison of standards

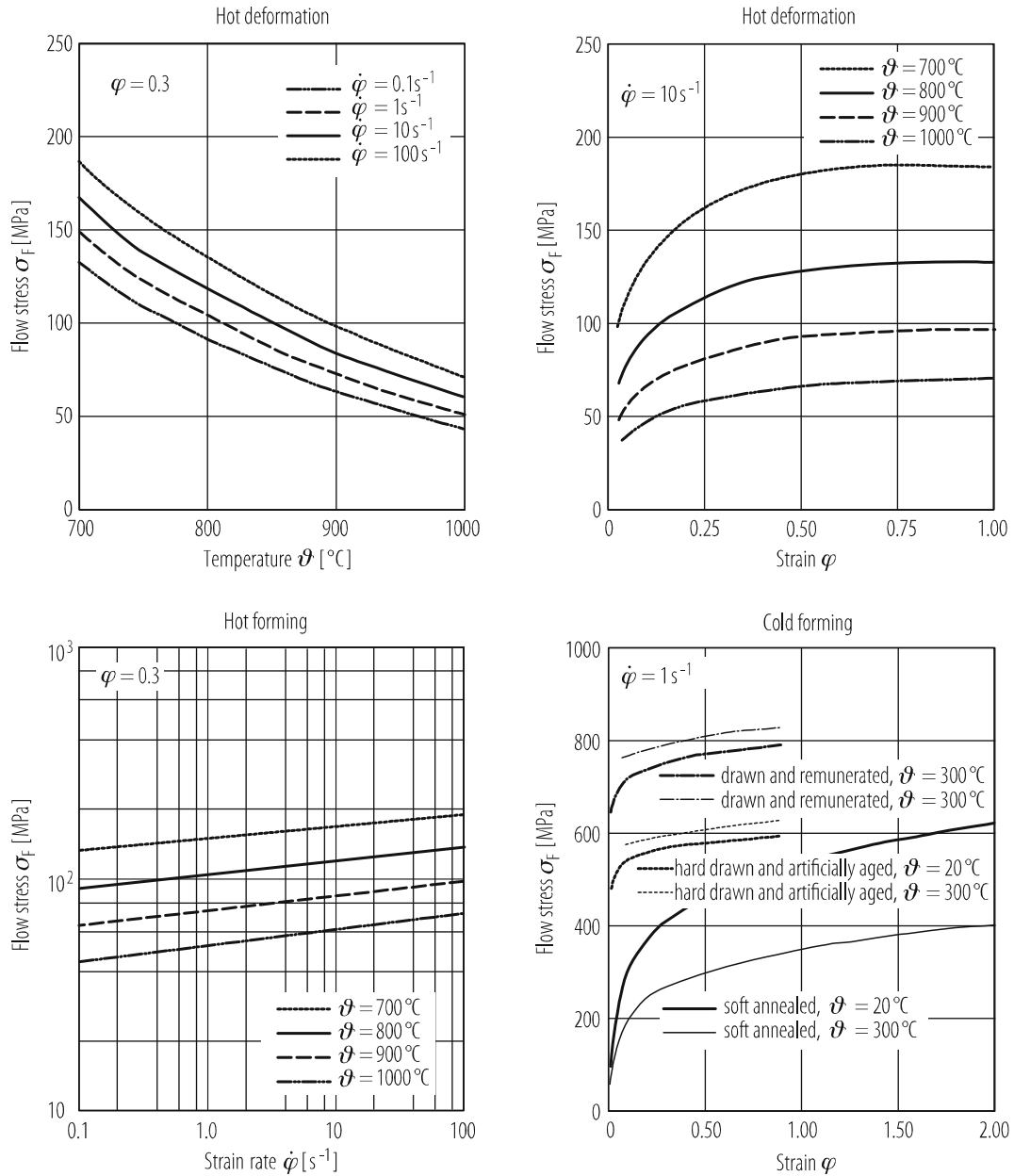
|                       |                |                 |            |
|-----------------------|----------------|-----------------|------------|
| Euronorm              |                | ISO             |            |
| EN 1652 : 1997        | EN 1654        | ISO 1187 : 1983 | ISO 1634-1 |
| EN 13148              | EN 14436       | ISO 1638        |            |
| Material number (DIN) |                | DIN             |            |
| 2.0855                |                | DIN 17666       |            |
| USA                   |                |                 |            |
| ASTM                  |                | UNS standard    |            |
| ASTM B422 - 10        | ASTM B422 - 06 | C18000          |            |
| ASTM B411M - 08       |                |                 |            |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                         | Hot deformation |                | Cold deformation   |                                          |                                |
|-------------------------------------------|-----------------|----------------|--------------------|------------------------------------------|--------------------------------|
|                                           | cast state      | deformed state | soft annealed (sa) | hard drawn + artificially aged (ha + ar) | drawn + remunerated (dr + rem) |
| $\sigma_{F0}$ [MPa]                       |                 | 132.7          | 316.0              | 738.2                                    | 783.8                          |
| A                                         |                 | 2787.694       | 559.753            | 813.885                                  | 854.013                        |
| Effect of temperature $K_{\theta}$        |                 |                |                    |                                          |                                |
| $m_1$                                     |                 | -0.00369       | -0.00153           | -0.00156                                 | -0.00155                       |
| Effect of strain $K_{\varphi}$            |                 |                |                    |                                          |                                |
| $m_2$                                     |                 | 0.23675        | 0.20058            | 0.03988                                  | 0.05736                        |
| $m_4$                                     |                 | -0.0015        | -0.01111           | -0.00046                                 | 0.00494                        |
| $m_5$                                     |                 | 0.00045        |                    |                                          |                                |
| $m_7$                                     |                 | -0.47129       |                    |                                          |                                |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                    |                                          |                                |
| $m_3$                                     |                 |                | 0.01326            | 0.01298                                  | 0.01211                        |
| $m_8$                                     |                 | 0.000071       |                    |                                          |                                |
| Range of validity                         |                 |                |                    |                                          |                                |
| $\theta$ [°C]                             |                 | 700...1000     | 20...300           | 20...300                                 | 20...300                       |
| $\varphi$                                 |                 | 0.03...1.00    | 0.03...2.0         | 0.03...0.90                              | 0.03...0.90                    |
| $\dot{\varphi}$ [1/s]                     |                 | <100           | <100               | <100                                     | <100                           |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                                                 |



**Fig. 5.11** Flow stress curves of CuNi<sub>2</sub>Si by hot and cold forming.



Mechanical properties after cold deformation

| State of material               | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |          |         |
|---------------------------------|---------------------------------|----------|---------|-------------------------------------|----------|---------|
|                                 | $A_0$                           | A        | $n_1$   | $B_0$                               | B        | $n_2$   |
| 850 °C/0.5 h/water              | 80. . . 120                     | 34.21828 | 0.60792 | 270. . . 320                        | 3.06103  | 1.04979 |
| 850 °C/0.5 h/water + hot rolled | 80. . . 120                     | 29.44311 | 0.64329 | 500. . . 550                        | 12.75789 | 0.74471 |

| State of material               | Elongation to fracture $\Delta A_5$ [%] |          |          |          | Validity $\epsilon$ [%] |
|---------------------------------|-----------------------------------------|----------|----------|----------|-------------------------|
|                                 | $C_0$                                   | C        | $n_3$    | $n_4$    |                         |
| 850 °C/0.5 h/water              | 40. . . 45                              | 39.43170 | −0.0238  | −6.67176 | <70                     |
| 850 °C/0.5 h/water + hot rolled | 18. . . 23                              | 89.45628 | −0.49188 | −9.49046 | <80                     |

|                                      |                                      |                                                             |
|--------------------------------------|--------------------------------------|-------------------------------------------------------------|
| Yield stress:                        | Tensile strength:                    | Elongation to fracture                                      |
| $R_p = A_0 + A \cdot \epsilon^{n_1}$ | $R_m = B_0 + B \cdot \epsilon^{n_2}$ | $A_5 = C_0 - C \cdot \epsilon^{n_3} \cdot e^{n_4/\epsilon}$ |
| [Equation (4.1), Chapter 5.1.4]      | [Equation (4.2), Chapter 5.1.4]      | [Equation (4.3), Chapter 5.1.4]                             |
| [DOI: 978-3-642-14174-4_5]           | [DOI: 978-3-642-14174-4_5]           | [DOI: 978-3-642-14174-4_5]                                  |

Plasticity in tensile test

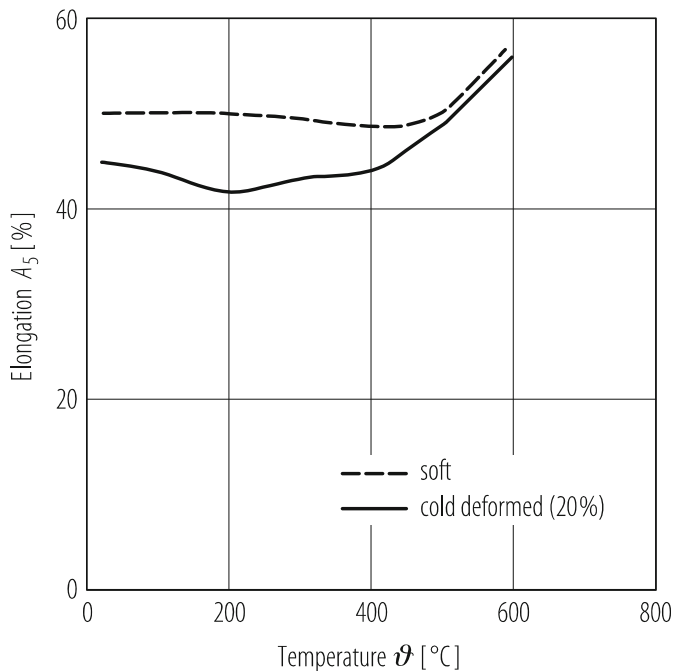


Fig. 5.12 Hot plasticity of CuNi<sub>2</sub>Si as a function of the temperature.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 132.1                | 348.4              | 15.50                                   | 8880.0                      | 137.0           |
| 100              | 155.0                | 354.5              | 16.02                                   | 8859.4                      |                 |
| 200              | 166.1                | 362.1              | 16.67                                   | 8831.7                      |                 |
| 300              | 173.0                | 369.7              | 17.32                                   | 8801.9                      |                 |
| 400              | 178.0                | 377.3              | 17.97                                   | 8770.1                      |                 |
| 500              | 182.0                | 385.0              | 18.62                                   | 8736.1                      |                 |
| 600              | 185.3                | 392.6              | 19.27                                   | 8700.1                      |                 |
| 700              | 188.2                | 400.2              | 19.92                                   | 8662.0                      |                 |
| 800              | 190.7                | 407.8              | 20.57                                   | 8621.9                      |                 |
| 900              | 193.0                | 415.4              | 21.22                                   | 8579.6                      |                 |
| 950              | 194.0                | 419.2              | 21.54                                   | 8557.7                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuBe<sub>2</sub>

## 5.2 Copper- and Copper alloys

### 5.2.1 Pure Copper and low alloyed Copper

#### Designation

|             |               |               |              |            |               |
|-------------|---------------|---------------|--------------|------------|---------------|
| UNS number: | <b>C17200</b> | Chem. symbol: | <b>CuBe2</b> | EN number: | <b>CW101C</b> |
|-------------|---------------|---------------|--------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu     | Fe    | Be            | Ni + Co | Ni + Fe + Co | Others |
|--------|-------|---------------|---------|--------------|--------|
| >96.80 | <0.20 | 1.80 . . 2.10 | >0.20   | <0.60        | <0.50  |

#### International comparison of standards

| Euronorm              |                      | ISO             |            |
|-----------------------|----------------------|-----------------|------------|
| EN 1654 : 1997        | EN 12163             | ISO 1187 : 1983 | ISO 1634-3 |
| EN 1652               | EN 13148             |                 |            |
| EN 14436              | EN 12166             |                 |            |
| Material number (DIN) |                      | DIN             |            |
| 2.1247                |                      | DIN 17666       |            |
| Japan                 |                      | Russia          |            |
| C1720                 |                      | BrB2            |            |
|                       |                      | GOST 18175      |            |
| USA                   |                      | UNS standard    |            |
| ASTM; AMS and SAE     |                      | C 17200         |            |
| ASTM B 194 / 2000     | ASTM B 643           |                 |            |
| ASTM B 888            | ASTM B 197 / B 197 M |                 |            |
| AMS 4650              | AMS 4535             |                 |            |
| AMS 4725              | SAE J463             |                 |            |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

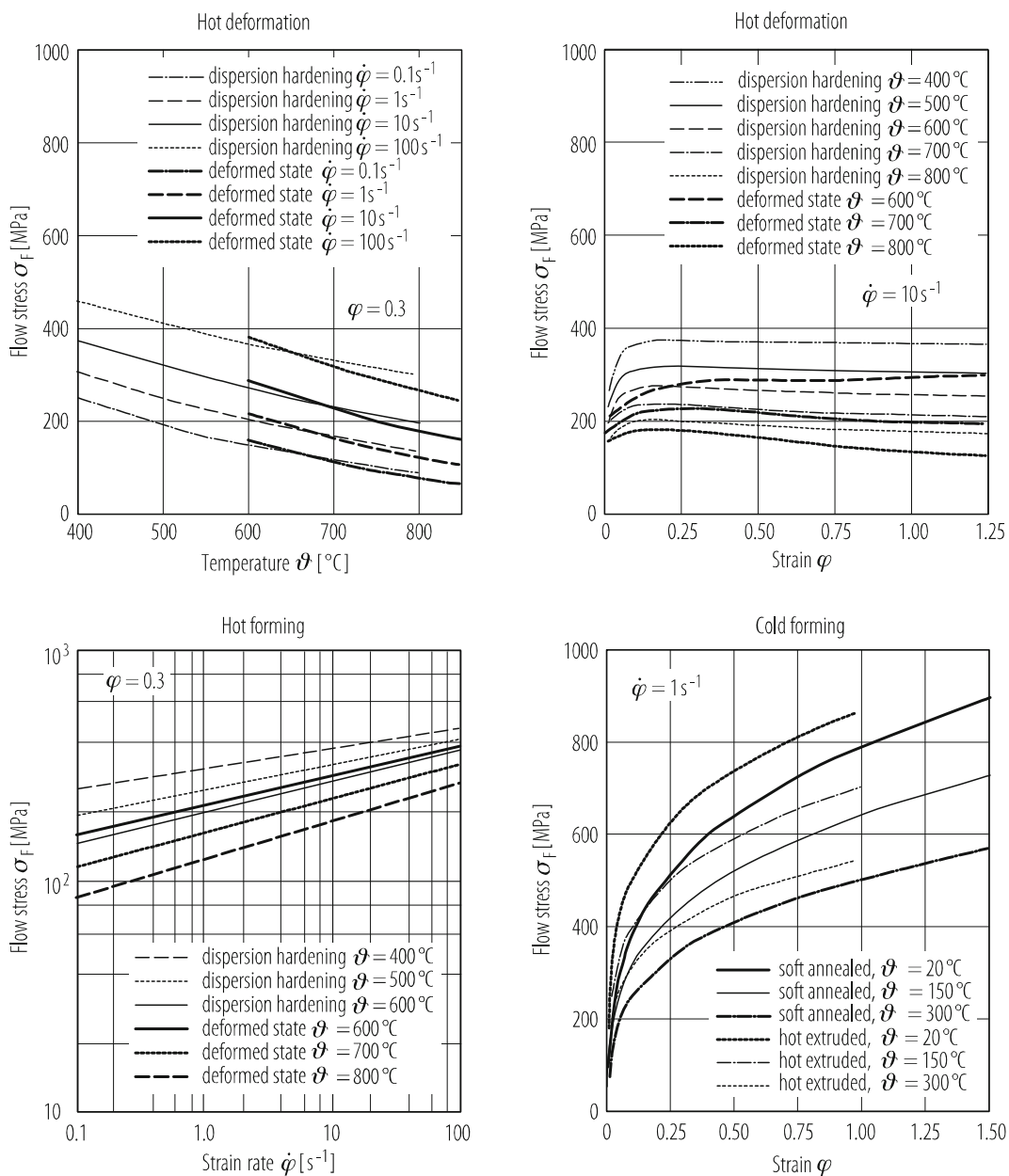
#### Flow curves

| State of material           | Hot deformation |                       | Cold deformation   |                   |
|-----------------------------|-----------------|-----------------------|--------------------|-------------------|
|                             | deformed state  | dispersions-hardening | soft annealed (sa) | hot extruded (he) |
| $\sigma_{F0}$ [MPa]         | 213.48          | 231.20                | 397.46             | 518.11            |
| A                           | 1254.029        | 692.7                 | 819.47             | 901.13            |
| Effect of temperature $K_9$ |                 |                       |                    |                   |
| $m_1$                       | -0.00183        | -0.00197              | -0.00159           | -0.00167          |
| Effect of strain $K_\phi$   |                 |                       |                    |                   |
| $m_2$                       | 0.31475         | -0.01888              | 0.29912            | 0.22933           |
| $m_4$                       | 0.0051          | -0.00926              | -0.00349           | -0.00267          |
| $m_5$                       | -0.00339        | -0.00051              |                    |                   |

(continued)

| State of material                       | Hot deformation |                       | Cold deformation   |                   |
|-----------------------------------------|-----------------|-----------------------|--------------------|-------------------|
|                                         | deformed state  | dispersions-hardening | soft annealed (sa) | hot extruded (he) |
| m <sub>7</sub>                          | 0.84725         | 0.10118               |                    |                   |
| Effect of strain rate K $\dot{\varphi}$ |                 |                       |                    |                   |
| m <sub>3</sub>                          |                 |                       | 0.01326            | 0.01462           |
| m <sub>8</sub>                          | 0.000210        | 0.00022               |                    |                   |
| Range of validity                       |                 |                       |                    |                   |
| $\vartheta$ [°C]                        | 600...850       | 400...800             | 20...300           | 20...300          |
| $\varphi$                               | 0.03...1.20     | 0.03...1.20           | 0.03...150         | 0.03...1.00       |
| $\dot{\varphi}$ [1/s]                   | <100            | <100                  | <100               | <100              |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |



**Fig. 5.13** Flow stress curves of CuBe<sub>2</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material  | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|--------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                    | $A_0$                           | A        | $n_1$   | $B_0$                               | B       | $n_2$   |
| solution treatment | 190. . .250                     | 34.87290 | 0.69932 | 410. . .540                         | 8.65502 | 0.94431 |

| State of material  | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|--------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                    | $C_0$                                   | C        | $n_3$   | $n_4$    |                            |
| solution treatment | 50. . .55                               | 46.74840 | 0.03523 | −8.18961 | <80                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

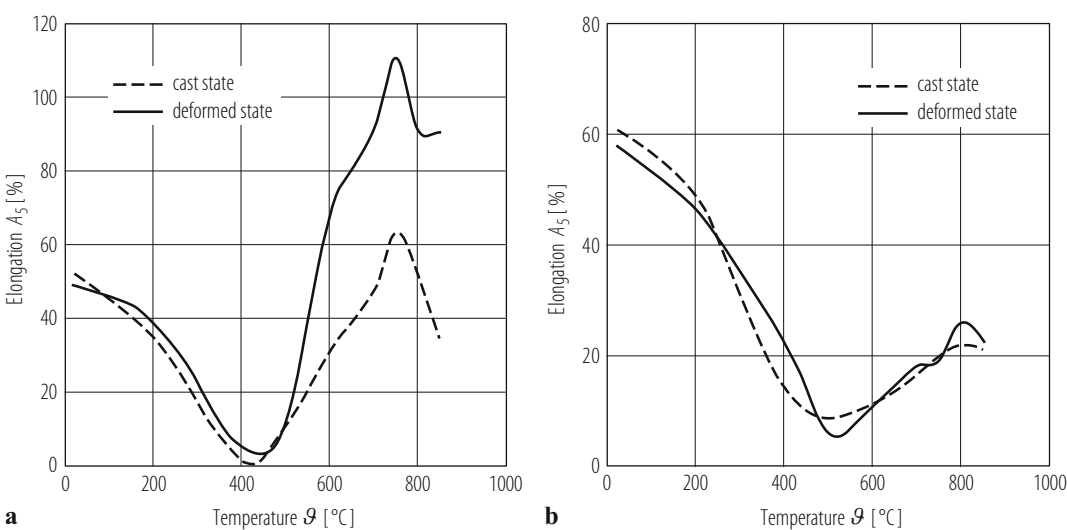


Fig. 5.14 Hot plasticity of CuBe<sub>2</sub> as a function of the temperature. (a) Initial test: static. (b) Initial test: dynamic.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>−6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 104.2                | 404.0              | 16.00                                   | 8300.2                      | 135.0           |
| 100              | 113.1                | 408.0              | 16.52                                   | 8280.3                      |                 |
| 200              | 124.2                | 413.0              | 17.17                                   | 8253.7                      |                 |
| 300              | 135.3                | 418.1              | 17.82                                   | 8225.1                      |                 |
| 400              | 146.4                | 423.1              | 18.47                                   | 8194.6                      |                 |
| 500              | 157.5                | 428.1              | 19.12                                   | 8162.1                      |                 |
| 600              | 168.6                | 433.1              | 19.77                                   | 8127.7                      |                 |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 700              | 179.7                | 438.1              | 20.42                                   | 8091.4                      |                 |
| 800              | 190.8                | 443.1              | 21.07                                   | 8053.1                      |                 |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |
| AMS                 | American measurement standard                                         |
| SAE                 | society of automotive engineers                                       |

# Flow stress, mechanical and physical properties of CuFe<sub>2</sub>P

## 5.2 Copper- and Copper alloys

### 5.2.1 Pure Copper and low alloyed Copper

#### Designation

|             |               |               |               |              |               |
|-------------|---------------|---------------|---------------|--------------|---------------|
| UNS number: | <b>C19400</b> | Chem. symbol: | <b>CuFe2P</b> | (EN number): | <b>CW107C</b> |
|-------------|---------------|---------------|---------------|--------------|---------------|

#### Composition (EN) [Weight-%]

| Cu     | Fe          | P            | Zn          | Pb    | Others |
|--------|-------------|--------------|-------------|-------|--------|
| >96.50 | 2.10...2.50 | 0.015...0.15 | 0.05...0.20 | <0.03 | <0.50  |

#### International comparison of standards

|                       |              |
|-----------------------|--------------|
| Euronorm              | ISO          |
| EN 12449 : 1999       | EN 1654      |
| EN 13148              | EN 1758      |
| EN 14436              |              |
| Material number (DIN) | DIN          |
| 2.1310                | DIN 17666    |
| Japan                 | Russia       |
| JIS H 3100            |              |
| USA                   |              |
| ASTM and ASME         | UNS standard |
| ASTM B 465            | ASTM B 543   |
| ASTM B 888            | ASTM B 694   |
| ASME SB 543           |              |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                  | Hot deformation |                | Cold deformation     |                    |                 |
|------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                    | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                |                 | 110.71         |                      | 294.11             |                 |
| A                                  |                 | 3286.13        |                      | 517.115            |                 |
| Effect of temperature $K_{\theta}$ |                 |                |                      |                    |                 |
| $m_1$                              |                 | −0.00418       |                      | −0.00136           |                 |
| Effect of strain $K_{\phi}$        |                 |                |                      |                    |                 |
| $m_2$                              |                 | 0.26281        |                      | 0.24544            |                 |
| $m_4$                              |                 | 0.00188        |                      | −0.00117           |                 |
| $m_5$                              |                 | −0.00104       |                      |                    |                 |
| $m_7$                              |                 | 0.00253        |                      |                    |                 |

(continued)



| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 | 0.000118       |                      | 0.01681            |                 |
| $m_8$                                  |                 |                |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                       |                 | 650...1000     |                      | 20 ... 300         |                 |
| $\varphi$                              |                 | 0.03 ... 1.50  |                      | 0.03 ... 2.50      |                 |
| $\dot{\varphi}$ [1/s]                  |                 | <100           |                      | <100               |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

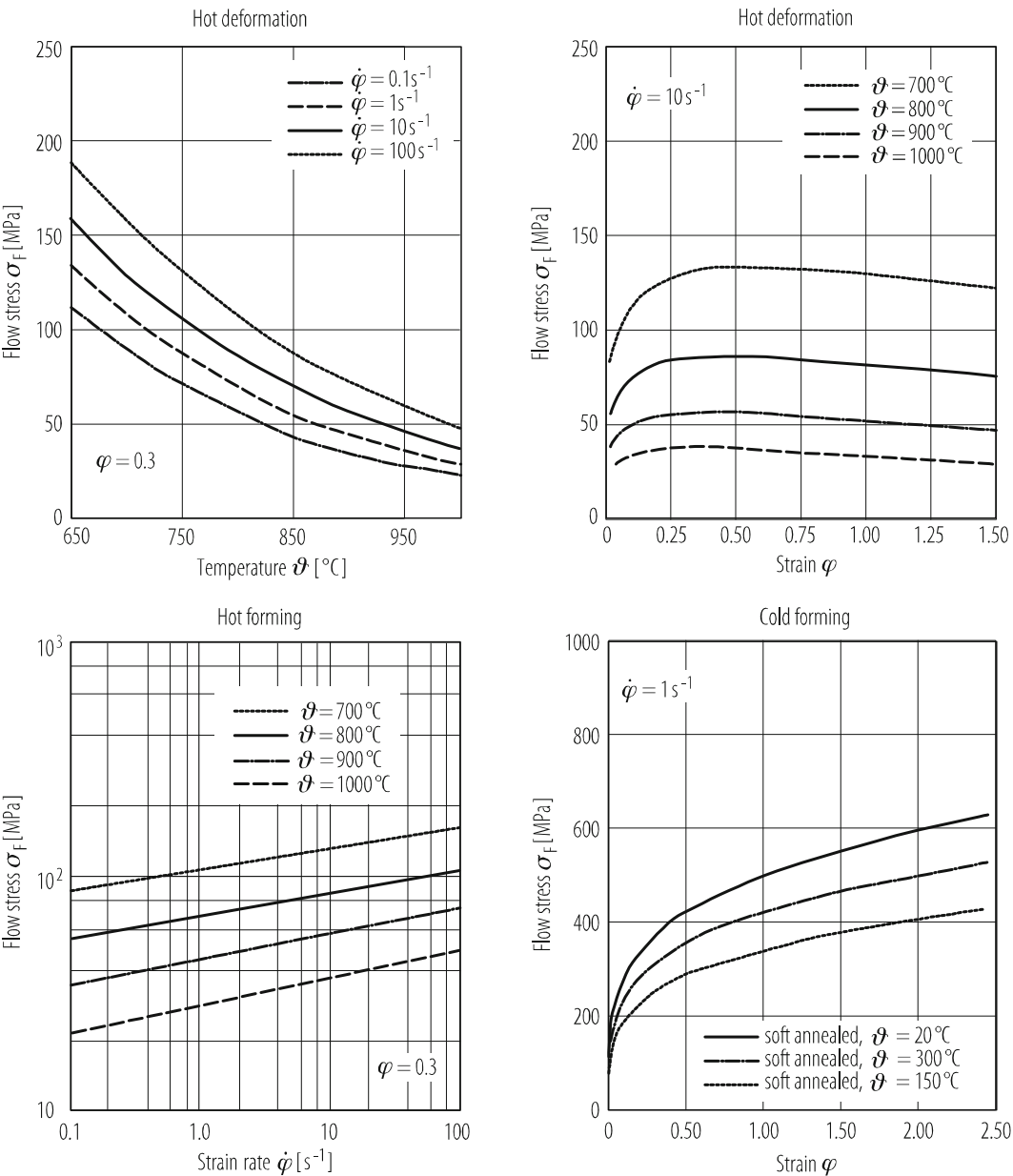


Fig. 5.15 Flow stress curves of CuFe<sub>2</sub>P by hot and cold forming.

### Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| semi hard         | 200...240                       | 48.81414 | 0.47385 | 340...390                           | 3.54051 | 0.93777 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| semi hard         | 25...30                                 | 21.43253 | 0.06554 | −5.50529 | <80                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

### Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 260.1                | 378.8              | 15.06                                   | 8780.2                      | 123.0           |
| 100              | 270.2                | 387.4              | 15.42                                   | 8760.6                      | 120.0           |
| 200              | 274.7                | 391.0              | 15.87                                   | 8734.8                      | 114.0           |
| 300              | 277.3                | 393.1              | 16.32                                   | 8707.6                      |                 |
| 400              | 279.2                | 394.6              | 16.77                                   | 8678.9                      |                 |
| 500              | 280.7                | 395.7              | 17.22                                   | 8648.9                      |                 |
| 600              | 281.9                | 396.7              | 17.67                                   | 8617.4                      |                 |
| 700              | 283.0                | 397.5              | 18.12                                   | 8584.5                      |                 |
| 800              | 283.9                | 398.2              | 18.57                                   | 8550.1                      |                 |
| 900              | 284.7                | 398.9              | 19.02                                   | 8514.4                      |                 |
| 950              | 285.0                | 399.2              | 19.24                                   | 8495.9                      |                 |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |

(continued)

| Short form     | Full form                               |
|----------------|-----------------------------------------|
| $R_m$          | tensile strength                        |
| $R_p$          | yield stress                            |
| $T, \vartheta$ | temperature                             |
| UNS            | unified numbering system                |
| $\alpha_m$     | average coefficient of linear expansion |
| $\lambda$      | thermal conductivity                    |
| $\rho$         | density                                 |

# Flow stress, mechanical and physical properties of CuZn<sub>5</sub>

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |                |               |              |            |               |
|-------------|----------------|---------------|--------------|------------|---------------|
| UNS number: | <b>C 21000</b> | Chem. symbol: | <b>CuZn5</b> | EN number: | <b>CW500L</b> |
|-------------|----------------|---------------|--------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Zn    | Al     | Fe    | Ni    | Pb    | Sn    | Others |
|-------------|-------|--------|-------|-------|-------|-------|--------|
| 94.0...96.0 | >3.50 | <0.020 | <0.05 | <0.20 | <0.05 | <0.05 | <0.10  |

#### International comparison of standards

|                       |                 |                  |                 |
|-----------------------|-----------------|------------------|-----------------|
| Euronorm              |                 | ISO              |                 |
| EN 1652: 1997         | EN 13148        | ISO 426–1 : 1983 | ISO 1634-1      |
| EN 14436              | EN 12449        |                  |                 |
| EN 12163              |                 |                  |                 |
| Material number (DIN) |                 | DIN              |                 |
| 2.0220                |                 | DIN 17660 : 1983 |                 |
| Japan                 |                 | Russia           |                 |
| JIS H 3100            | JIS 3100 : 1992 | L96              | GOST 15527 – 70 |
|                       | JIS H 3260      | GOST 11383       | GOST 20900      |
|                       |                 | GOST 617         |                 |
| USA                   |                 |                  |                 |
| ASTM and SAE          |                 | UNS standard     |                 |
| ASTM B 36             | ASTM B 95 M     | C21000           |                 |
| ASTM B 587            | ASTM B 642      |                  |                 |
| ASTM B 927            |                 |                  |                 |
| SAE J463              | SAE J461        |                  |                 |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

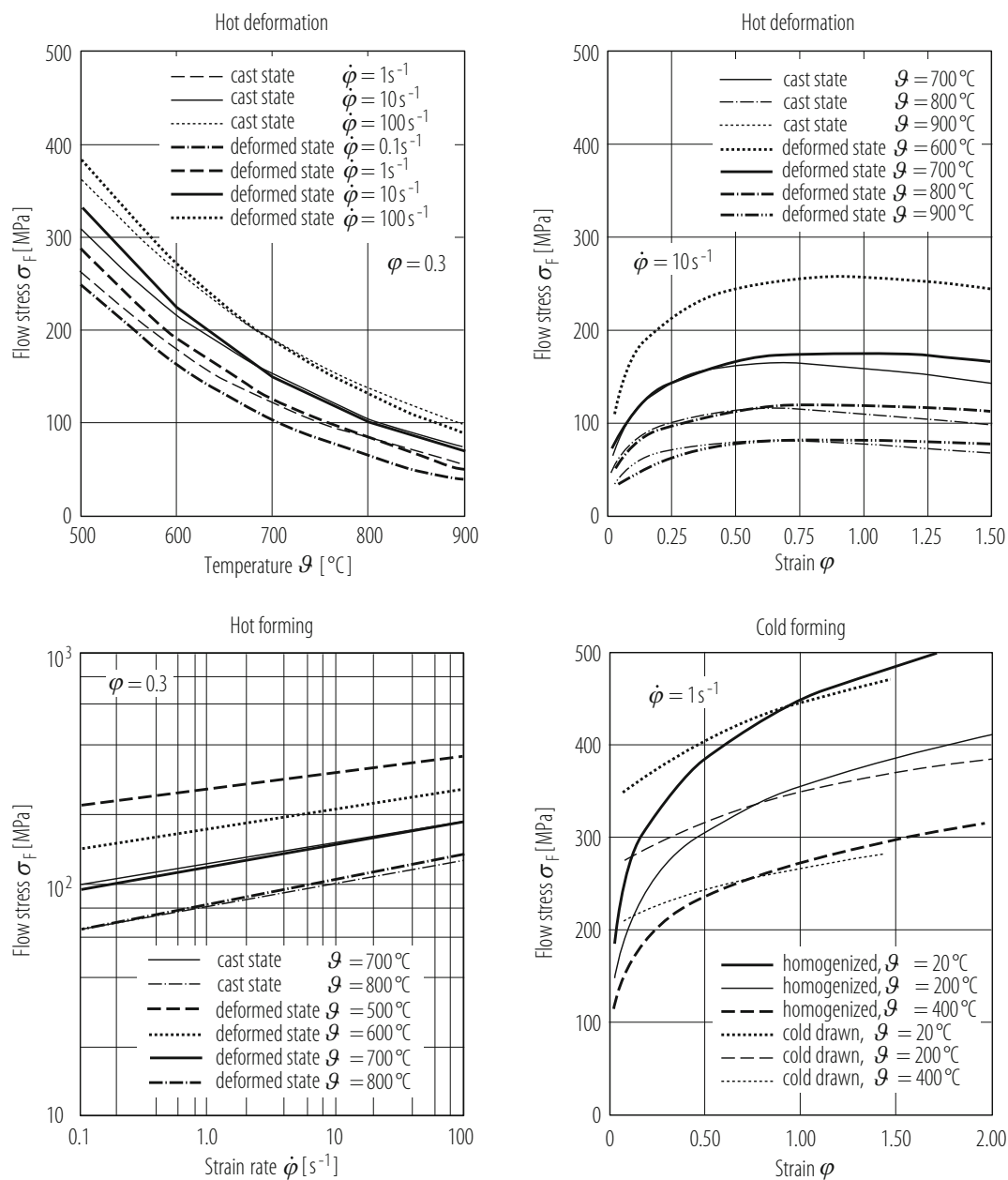
#### Flow curves

| State of material           | Hot deformation |                | Cold deformation |                 |
|-----------------------------|-----------------|----------------|------------------|-----------------|
|                             | cast state      | deformed state | homogenized(hom) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]         | 111.9           | 113.0          | 274.8            | 362.0           |
| A                           | 3304.760        | 4012.769       | 461.118          | 452.564         |
| Effect of temperature $K_8$ |                 |                |                  |                 |
| $m_1$                       | −0.00384        | −0.00433       | −0.00130         | −0.00135        |
| Effect of strain $K_\phi$   |                 |                |                  |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|
|                                        | cast state      | deformed state | homogenized(hom) | cold drawn (cd) |
| m <sub>2</sub>                         | 0.3749          | 0.31402        | 0.20767          | 0.14835         |
| m <sub>4</sub>                         | 0.00013         | 0.00051        | −0.00463         | 0.01116         |
| m <sub>5</sub>                         | −0.0002         | 0.0003         |                  |                 |
| m <sub>7</sub>                         | −0.46305        | −0.44814       |                  |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |
| m <sub>3</sub>                         |                 |                | 0.01390          | 0.01455         |
| m <sub>8</sub>                         | 0.000138        | 0.000126       |                  |                 |
| Range of validity                      |                 |                |                  |                 |
| $\vartheta$ [°C]                       | 500 ... 900     | 500 ... 900    | 20 ... 400       | 20 ... 400      |
| $\varphi$                              | 0.03 ... 1.50   | 0.03 ... 1.50  | 0.03 ... 2.00    | 0.03 ... 2.00   |
| $\dot{\varphi}$ [1/s]                  | <100            | <100           | <100             | <100            |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |



**Fig. 5.16** Flow stress curves of CuZn<sub>5</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |     |       | Tensile strength $\Delta R_m$ [MPa] |          |         |
|-------------------|---------------------------------|-----|-------|-------------------------------------|----------|---------|
|                   | $A_0$                           | $A$ | $n_1$ | $B_0$                               | $B$      | $n_2$   |
| soft annealed     |                                 |     |       | 230...270                           | 16.38195 | 0.63795 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| soft annealed     | 43...48                                 | 18.64485 | 0.22704 | -4.81474 | <70                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

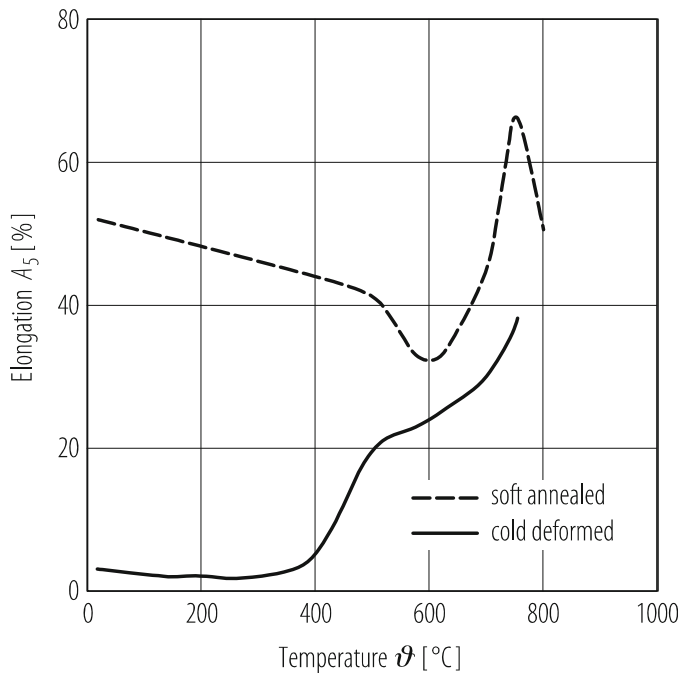


Fig. 5.17 Plasticity of CuZn<sub>5</sub> as a function of the temperature



## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 243.9                | 381.1              | 16.73                                   | 8854.7                      | 127.0           |
| 100              | 246.5                | 385.8              | 17.06                                   | 8832.8                      |                 |
| 200              | 249.7                | 391.6              | 17.47                                   | 8804.3                      |                 |
| 300              | 252.9                | 397.5              | 17.89                                   | 8774.4                      |                 |
| 400              | 256.1                | 403.3              | 18.30                                   | 8743.3                      |                 |
| 500              | 259.4                | 409.2              | 18.71                                   | 8710.8                      |                 |
| 600              | 262.6                | 415.1              | 19.12                                   | 8677.0                      |                 |
| 700              | 265.8                | 420.9              | 19.53                                   | 8641.9                      |                 |
| 800              | 269.0                | 426.8              | 19.95                                   | 8605.5                      |                 |
| 900              | 272.2                | 432.6              | 20.36                                   | 8567.8                      |                 |
| 950              | 273.8                | 435.6              | 20.56                                   | 8548.4                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese Industrial Standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| SAE                 | society of automotive engineers                                       |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuZn<sub>10</sub>

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |               |               |               |            |               |
|-------------|---------------|---------------|---------------|------------|---------------|
| UNS number: | <b>C22000</b> | Chem. symbol: | <b>CuZn10</b> | EN number: | <b>CW501L</b> |
|-------------|---------------|---------------|---------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Zn    | Al     | Fe    | Ni    | Pb    | Sn    | Others |
|-------------|-------|--------|-------|-------|-------|-------|--------|
| 89.0...91.0 | >8.50 | <0.020 | <0.05 | <0.20 | <0.05 | <0.05 | <0.10  |

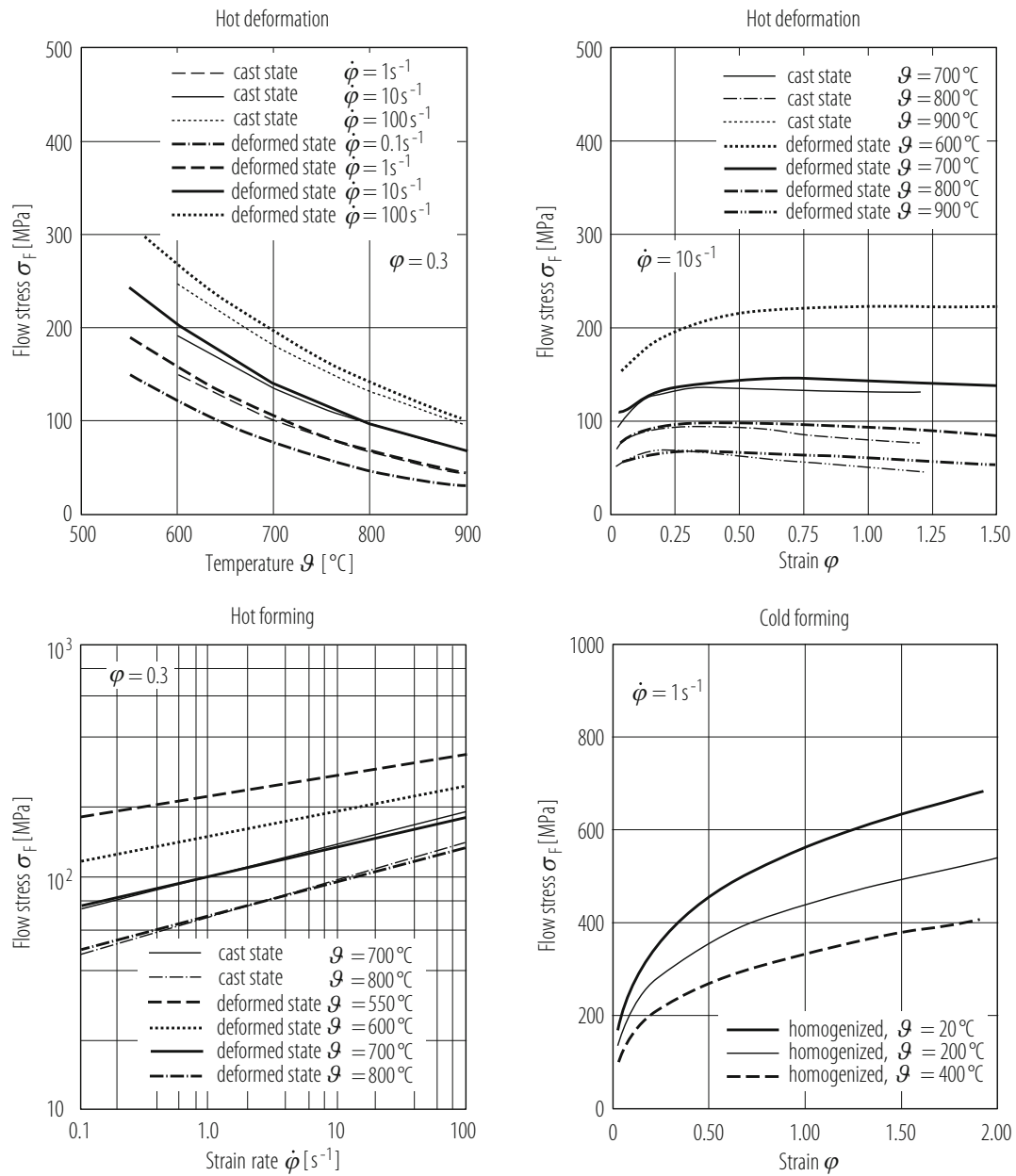
#### International comparison of standards

|                       |            |                  |                 |
|-----------------------|------------|------------------|-----------------|
| Euronorm              |            | ISO              |                 |
| EN 1652 : 199         | EN 12166   | ISO 426-1 : 1983 | ISO 1634-1      |
| EN 12163              | EN 12449   |                  |                 |
| EN 13148              | EN 14436,  |                  |                 |
| Material number (DIN) |            | DIN              |                 |
| 2.0230                |            | DIN 17660 : 1983 | DIN 17670-1     |
|                       |            | DIN 17670-1      |                 |
| Japan                 |            | Russia           |                 |
| JIS 3100 : 1992       | JIS H 3300 | L 90             | GOST 15527 - 70 |
|                       | JIS H 3260 | GOST 2208        | GOST 931        |
| USA                   |            |                  |                 |
| ASTM                  |            | UNS standard     |                 |
| ASTM B36 / 36M        | MIL-W-6712 | C22000           |                 |
| ASTM B130             | ASTM B131  |                  |                 |
| ASTM B230             | ASTM B587  |                  |                 |
| ASTM B604             | ASTM B927  |                  |                 |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

Flow curves

|                                                                                                                                                                                |                 |                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|----------------|------------------------------------------------------------------------------------------------------------|
|                                                                                                                                                                                | Hot deformation |                | Cold deformation                                                                                           |
| State of material                                                                                                                                                              | cast state      | deformed state | homogenized (hom)                                                                                          |
| $\sigma_{F0}$ [MPa]                                                                                                                                                            | 117.2           | 119.2          | 283.2                                                                                                      |
| A                                                                                                                                                                              | 2002.781        | 2724.000       | 583.856                                                                                                    |
| Effect of temperature $K_{\vartheta}$                                                                                                                                          |                 |                |                                                                                                            |
| $m_1$                                                                                                                                                                          | −0.00321        | −0.00373       | −0.00137                                                                                                   |
| Effect of strain $K_{\varphi}$                                                                                                                                                 |                 |                |                                                                                                            |
| $m_2$                                                                                                                                                                          | 0.34125         | 0.38518        | 0.29274                                                                                                    |
| $m_4$                                                                                                                                                                          | 0.00408         | 0.01492        | −0.00521                                                                                                   |
| $m_5$                                                                                                                                                                          | −0.00293        | −0.00164       |                                                                                                            |
| $m_7$                                                                                                                                                                          | 0.64382         | 0.12807        |                                                                                                            |
| Effect of strain rate $K_{\dot{\varphi}}$                                                                                                                                      |                 |                |                                                                                                            |
| $m_3$                                                                                                                                                                          |                 |                | 0.01244                                                                                                    |
| $m_8$                                                                                                                                                                          | 0.000179        | 0.000196       |                                                                                                            |
| Range of validity                                                                                                                                                              |                 |                |                                                                                                            |
| $\vartheta$ [°C]                                                                                                                                                               | 600 ... 900     | 550 ... 900    | 20 ... 400                                                                                                 |
| $\varphi$                                                                                                                                                                      | 0.03 ... 1.20   | 0.03 ... 1.50  | 0.03 ... 2.00                                                                                              |
| $\dot{\varphi}$ [1/s]                                                                                                                                                          | <100            | <100           | <100                                                                                                       |
| Hot deformation:                                                                                                                                                               |                 |                | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |                 |                | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |                 |                | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     |                 |                | [DOI: 978-3-642-14174-4_2]                                                                                 |



**Fig. 5.18** Flow stress curves of CuZn<sub>10</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material     | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-----------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                       | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| grain size 0.070 [mm] | 100...140                       | 32.55529 | 0.48785 | 240...290                           | 5.23455 | 0.92709 |

| State of material     | Elongation to fracture $\Delta A_5$ [%] |          |          |          | Validity $\varepsilon$ [%] |
|-----------------------|-----------------------------------------|----------|----------|----------|----------------------------|
|                       | $C_0$                                   | $C$      | $n_3$    | $n_4$    |                            |
| grain size 0.070 [mm] | 45...50                                 | 66.13843 | −0.07079 | −9.52462 | <70                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

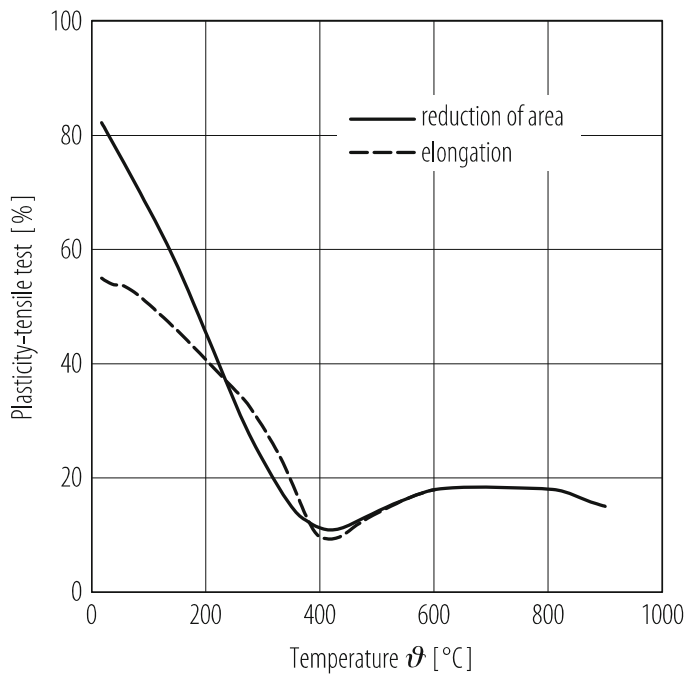


Fig. 5.19 Plasticity of CuZn10 as a function of the temperature.

**Physical properties**

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}/K$ ]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 182.2                | 377.7              | 16.91                                   | 8784.6                      | 124.0           |
| 100              | 185.3                | 383.1              | 17.26                                   | 8762.7                      | 123.0           |
| 200              | 189.3                | 389.8              | 17.71                                   | 8734.0                      | 118.0           |
| 300              | 193.2                | 396.6              | 18.15                                   | 8703.9                      | 113.0           |
| 400              | 197.2                | 403.3              | 18.59                                   | 8672.3                      | 107.0           |
| 500              | 201.1                | 410.0              | 19.04                                   | 8639.4                      | 98.0            |
| 600              | 205.0                | 416.7              | 19.48                                   | 8605.1                      | 88.0            |
| 700              | 209.0                | 423.4              | 19.92                                   | 8569.4                      | 78.0            |
| 800              | 212.9                | 430.2              | 20.36                                   | 8532.2                      |                 |
| 900              | 216.9                | 436.9              | 20.81                                   | 8493.7                      |                 |
| 950              | 218.8                | 440.2              | 21.03                                   | 8473.9                      |                 |

**Symbols and abbreviations**

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese Industrial Standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuZn<sub>15</sub>

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |               |               |               |            |               |
|-------------|---------------|---------------|---------------|------------|---------------|
| UNS number: | <b>C23000</b> | Chem. symbol: | <b>CuZn15</b> | EN number: | <b>CW502L</b> |
|-------------|---------------|---------------|---------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu            | Zn    | Al     | Fe    | Ni    | Pb    | Sn    | Others |
|---------------|-------|--------|-------|-------|-------|-------|--------|
| 84.0 . . 86.0 | >13.5 | <0.020 | <0.05 | <0.20 | <0.05 | <0.05 | <0.10  |

#### International comparison of standards

| Euronorm              |            | ISO              |                 |
|-----------------------|------------|------------------|-----------------|
| EN 1652 : 1997        | EN 1654    | ISO 426–1 : 1983 | ISO 1634-1      |
| EN 13148              | EN 14436   | ISO 1634-3       | ISO 1638        |
| EN 1758               | EN 12449   | ISO 1635         |                 |
| Material number (DIN) |            | DIN              |                 |
| 2.0240                |            | DIN 17660 : 1983 | DIN 17677-1     |
|                       |            | DIN 17672-1      |                 |
| Japan                 |            | Russia           |                 |
| JIS H 3100 : 1992     | JIS H 3260 | L 85             | GOST 15527 - 70 |
|                       | JIS H 3300 | GOST 2208        | GOST 931        |
| USA                   |            | UNS standard     |                 |
| ASTM                  |            | C23000           |                 |
| ASTM B36              | ASTM B36 M |                  |                 |
| ASTM B569             | ASTM B694  |                  |                 |
| ASTM B888             | ASTM B927  |                  |                 |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material   | Hot deformation |                | Cold deformation  |                    |
|---------------------|-----------------|----------------|-------------------|--------------------|
|                     | cast state      | deformed state | homogenized (hom) | soft annealed (sa) |
| $\sigma_{F0}$ [MPa] | 125.4           | 124.2          | 287.51            |                    |
| A                   | 3873.873        | 4120.437       | 637.372           |                    |

(continued)

| State of material                         | Hot deformation |                | Cold deformation  |                    |
|-------------------------------------------|-----------------|----------------|-------------------|--------------------|
|                                           | cast state      | deformed state | homogenized (hom) | soft annealed (sa) |
| Effect of temperature $K_\theta$          |                 |                |                   |                    |
| $m_1$                                     | −0.00410        | −0.00383       | −0.00139          |                    |
| Effect of strain $K_\varphi$              |                 |                |                   |                    |
| $m_2$                                     | 0.30438         | 0.38513        | 0.32903           |                    |
| $m_4$                                     | 0.00093         | 0.00133        | −0.00384          |                    |
| $m_5$                                     | −0.00099        | −0.00177       |                   |                    |
| $m_7$                                     | −0.19459        | 0.10107        |                   |                    |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                   |                    |
| $m_3$                                     |                 |                | 0.01139           |                    |
| $m_8$                                     | 0.000134        | 0.000099       |                   |                    |
| Range of validity                         |                 |                |                   |                    |
| $\vartheta$ [°C]                          | 600 ... 900     | 600 ... 900    | 20 ... 400        |                    |
| $\varphi$                                 | 0.03 ... 1.50   | 0.03 ... 1.50  | 0.03 ... 2.00     |                    |
| $\dot{\varphi}$ [1/s]                     | <100            | <100           | <10               |                    |

| Hot deformation:                                                                                                                                                      | Cold deformation                                                                                        |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                  | [Equation (2.25), Chapter 2.3.2.2.2]                                                                    |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                 | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                   |



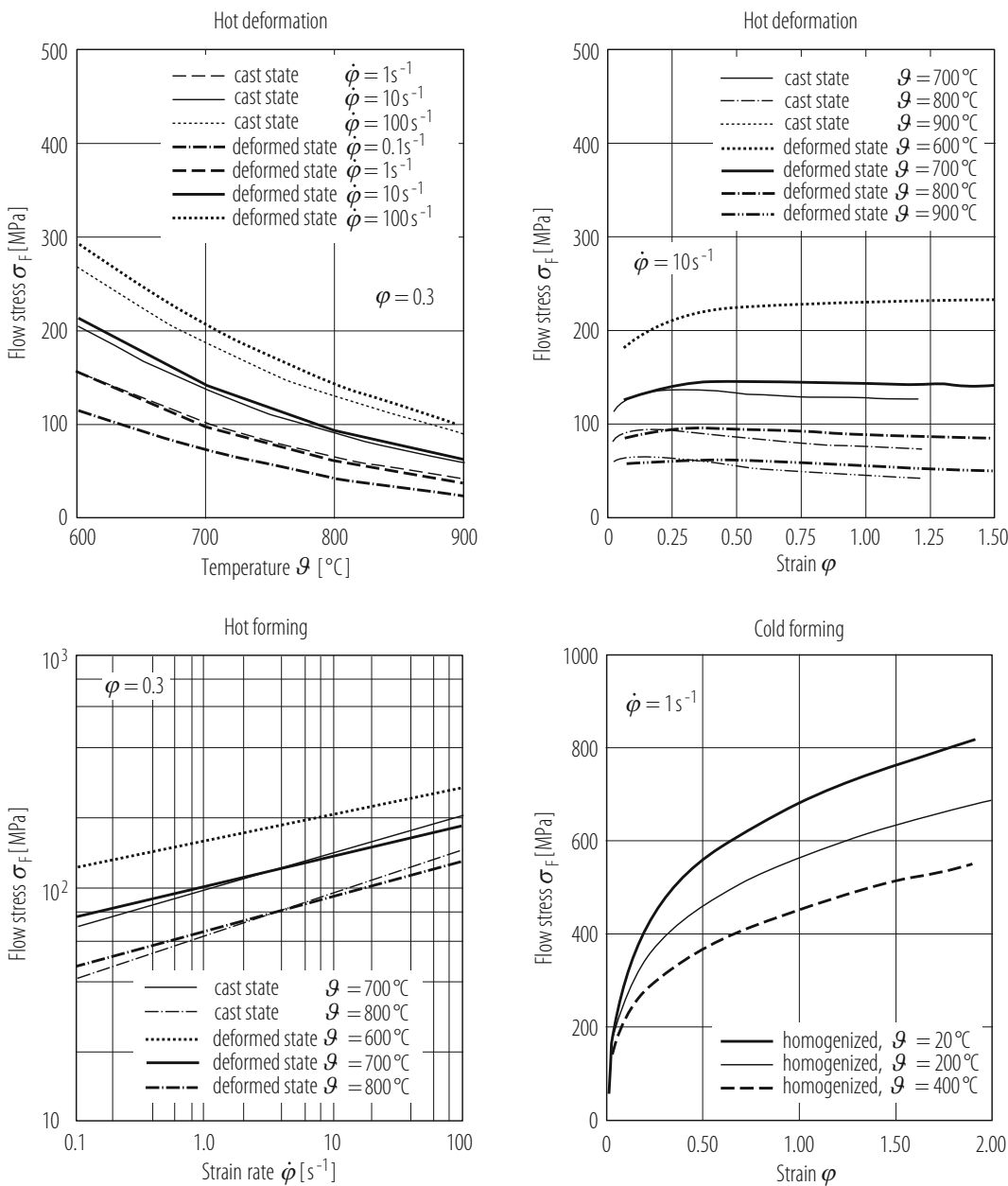


Fig. 5.20 Flow stress curves of CuZn15 by hot and cold forming.

Mechanical properties after cold deformation

| State of material     | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-----------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                       | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| grain size 0.070 [mm] | 80...130                        | 28.89244 | 0.66300 | 260...310                           | 2.58276 | 1.16642 |
| hot extruded          | 80...130                        | 25.13949 | 0.72131 | 260...310                           | 0.95210 | 1.43154 |

| State of material     | Elongation to fracture $\Delta A_5$ [%] |          |         |             | Validity $\epsilon$ [%] |
|-----------------------|-----------------------------------------|----------|---------|-------------|-------------------------|
|                       | $C_0$                                   | $C$      | $n_3$   | $n_4$       |                         |
| grain size 0.070 [mm] | 45...50                                 | 37.47860 | 0.06215 | -7.26244318 | <70                     |
| hot extruded          | 45...50                                 | 15.52730 | 0.32682 | -7.64044    | <60                     |

|                                      |                                      |                                                             |
|--------------------------------------|--------------------------------------|-------------------------------------------------------------|
| Yield stress:                        | Tensile strength:                    | Elongation to fracture                                      |
| $R_p = A_0 + A \cdot \epsilon^{n_1}$ | $R_m = B_0 + B \cdot \epsilon^{n_2}$ | $A_5 = C_0 - C \cdot \epsilon^{n_3} \cdot e^{n_4/\epsilon}$ |
| [Equation (4.1), Chapter 5.1.4]      | [Equation(4.2), Chapter 5.1.4]       | [Equation(4.3), Chapter 5.1.4]                              |
| [DOI: 978-3-642-14174-4_5]           | [DOI: 978-3-642-14174-4_5]           | [DOI: 978-3-642-14174-4_5]                                  |

Plasticity in tensile test

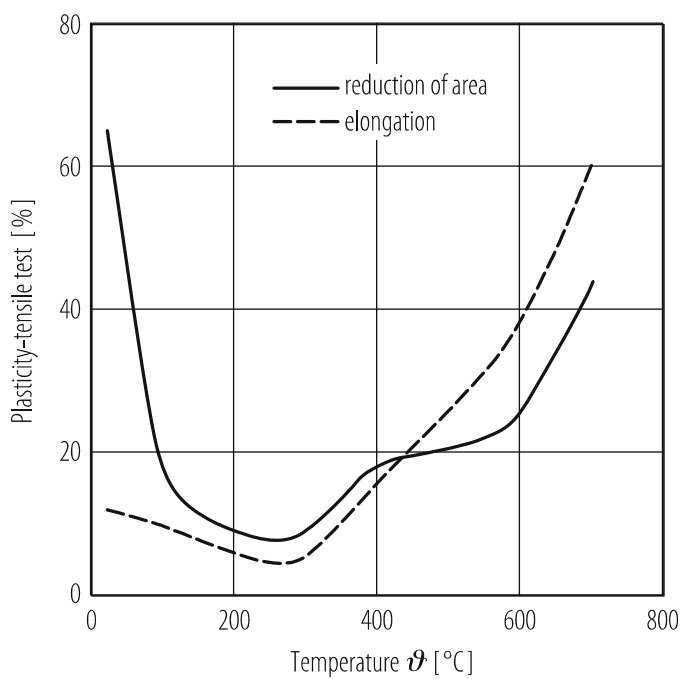


Fig. 5.21 Plasticity of CuZn15 as a function of the temperature.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 161.2                | 380.6              | 17.19                                   | 8744.6                      | 122.0           |
| 100              | 165.2                | 385.5              | 17.61                                   | 8722.3                      | 119.0           |
| 200              | 170.2                | 391.7              | 18.13                                   | 8692.9                      | 114.0           |
| 300              | 175.2                | 397.8              | 18.65                                   | 8661.9                      | 109.0           |
| 400              | 180.2                | 403.9              | 19.17                                   | 8629.2                      | 103.0           |
| 500              | 185.3                | 410.1              | 19.70                                   | 8594.9                      | 94.0            |
| 600              | 190.3                | 416.2              | 20.22                                   | 8559.0                      | 84.0            |
| 700              | 195.3                | 422.3              | 20.74                                   | 8521.4                      | 74.0            |
| 800              | 200.3                | 428.4              | 21.26                                   | 8482.1                      |                 |
| 900              | 205.3                | 434.6              | 21.78                                   | 8441.3                      |                 |
| 950              | 207.8                | 437.6              | 22.04                                   | 8420.2                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| BS                  | British standards                                                     |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese Industrial Standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuZn<sub>20</sub>

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |               |               |               |            |               |
|-------------|---------------|---------------|---------------|------------|---------------|
| UNS number: | <b>C24000</b> | Chem. symbol: | <b>CuZn20</b> | EN number: | <b>CW503L</b> |
|-------------|---------------|---------------|---------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Zn    | Al     | Fe    | Ni    | Pb    | Sn    | Others |
|-------------|-------|--------|-------|-------|-------|-------|--------|
| 79.0...81.0 | >18.5 | <0.020 | <0.05 | <0.20 | <0.05 | <0.05 | <0.10  |

#### International comparison of standards

|                       |            |                  |                 |
|-----------------------|------------|------------------|-----------------|
| Euronorm              |            | ISO              |                 |
| EN 1652 : 1997        | EN 12163   | ISO 426–1 : 1983 | ISO 1634-1      |
| EN 1314               | EN 12449   | ISO 1638         |                 |
| EN 14436              | EN 12166   |                  |                 |
| Material number (DIN) |            | DIN              |                 |
| 2.0250                |            | DIN 17660 : 1983 | DIN 17670-1     |
|                       |            | DIN 17677-1      |                 |
| Japan                 |            | Russia           |                 |
| JIS H 3100 : 1992     |            | L 80             | GOST 15527 - 70 |
| JIS H 3260            |            | GOST 14436       | GOST 931        |
|                       |            | GOST 2208        |                 |
| USA                   |            |                  |                 |
| ASTM                  |            | UNS standard     |                 |
| ASTM B36              | ASTM B36 M | C24000           |                 |
| ASTM B134             | ASTM B134M |                  |                 |
| ASTM B 927            |            |                  |                 |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

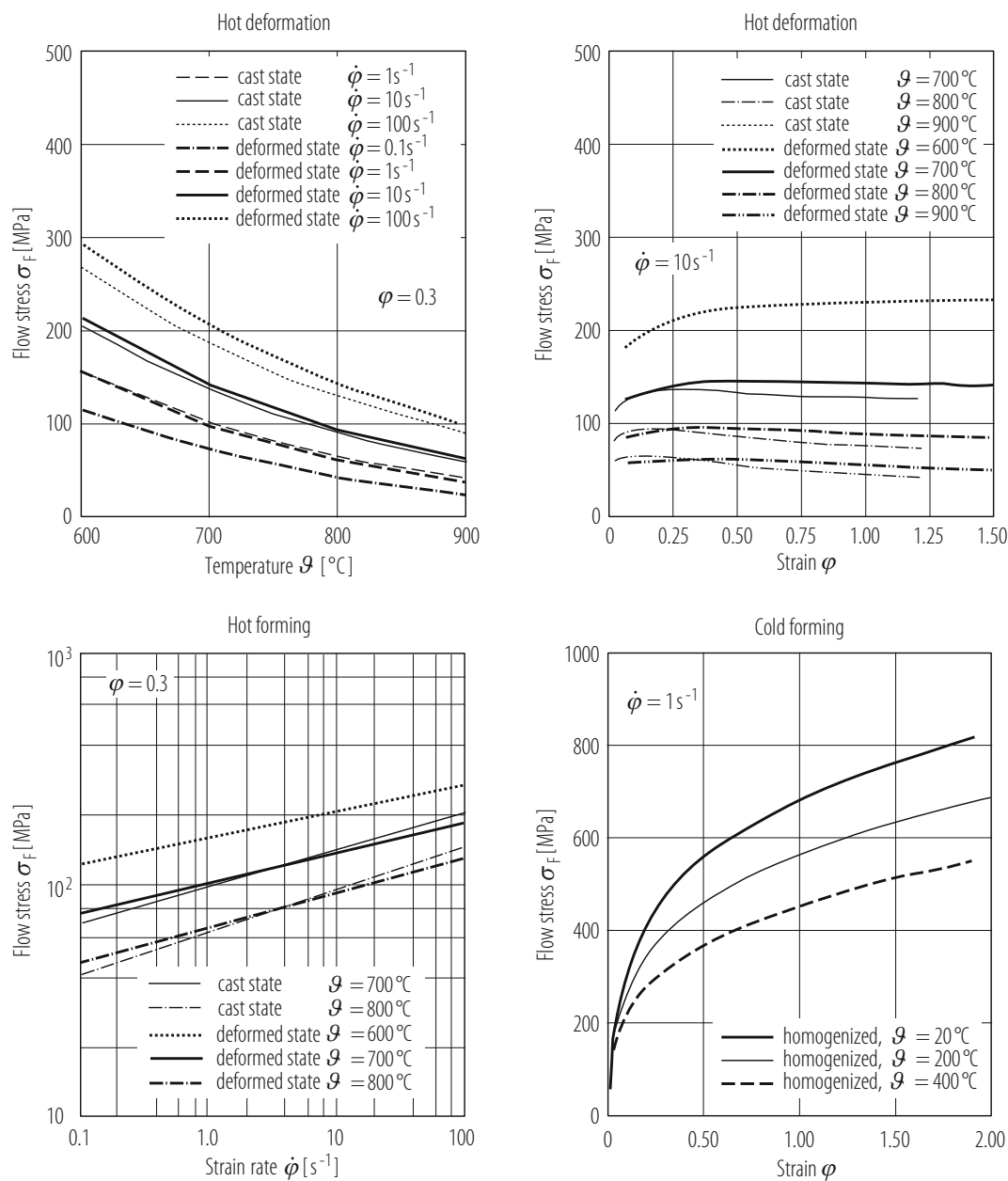
#### Flow curves

| State of material            | Hot deformation |                | Cold deformation  |                    |
|------------------------------|-----------------|----------------|-------------------|--------------------|
|                              | cast state      | deformed state | homogenized (hom) | soft annealed (sa) |
| $\sigma_{F0}$ [MPa]          | 131.6           | 128.7          | 331.28            |                    |
| A                            | 2049.437        | 3307.499       | 712.147           |                    |
| Effect of temperature $K_8$  |                 |                |                   |                    |
| m <sub>1</sub>               | −0.00377        | −0.00421       | −0.00143          |                    |
| Effect of strain $K_\varphi$ |                 |                |                   |                    |
| m <sub>2</sub>               | 0.21463         | 0.32862        | 0.26745           |                    |
| m <sub>4</sub>               | 0.0024          | 0.01704        | −0.01481          |                    |
| m <sub>5</sub>               | −0.0027         | −0.00151       |                   |                    |
| m <sub>7</sub>               | 0.70361         | 0.16114        |                   |                    |

(continued)

|                                        |                 |                |                   |                    |
|----------------------------------------|-----------------|----------------|-------------------|--------------------|
| State of material                      | Hot deformation |                | Cold deformation  |                    |
|                                        | cast state      | deformed state | homogenized (hom) | soft annealed (sa) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                   |                    |
| m <sub>3</sub>                         |                 |                | 0.01109           |                    |
| m <sub>8</sub>                         | 0.000193        | 0.000230       |                   |                    |
| Range of validity                      |                 |                |                   |                    |
| ϑ [°C]                                 | 600 ... 900     | 600 ... 900    | 20 ... 300        |                    |
| ϕ                                      | 0.03 ... 1.25   | 0.03 ... 1.50  | 0.03 ... 2.00     |                    |
| ϕ̇ [1/s]                               | <100            | <100           | <100              |                    |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                                                 |



**Fig. 5.22** Flow stress curves of CuZn<sub>20</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material     | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |          |         |
|-----------------------|---------------------------------|----------|---------|-------------------------------------|----------|---------|
|                       | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$      | $n_2$   |
| grain size 0.020 [mm] | 80. . . 130                     | 28.89244 | 0.66300 | 270. . . 320                        | 11.93362 | 0.85161 |

| State of material     | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\epsilon$ [%] |
|-----------------------|-----------------------------------------|----------|---------|----------|-------------------------|
|                       | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                         |
| grain size 0.020 [mm] | 45. . . 50                              | 24.14531 | 0.18092 | −4.21977 | <70                     |

| Yield stress:                        | Tensile strength:                    | Elongation to fracture                                      |
|--------------------------------------|--------------------------------------|-------------------------------------------------------------|
| $R_p = A_0 + A \cdot \epsilon^{n_1}$ | $R_m = B_0 + B \cdot \epsilon^{n_2}$ | $A_5 = C_0 - C \cdot \epsilon^{n_3} \cdot e^{n_4/\epsilon}$ |
| [Equation (4.1), Chapter 5.1.4]      | [Equation (4.2), Chapter 5.1.4]      | [Equation (4.3), Chapter 5.1.4]                             |
| [DOI: 978-3-642-14174-4_5]           | [DOI: 978-3-642-14174-4_5]           | [DOI: 978-3-642-14174-4_5]                                  |

Plasticity in tensile test

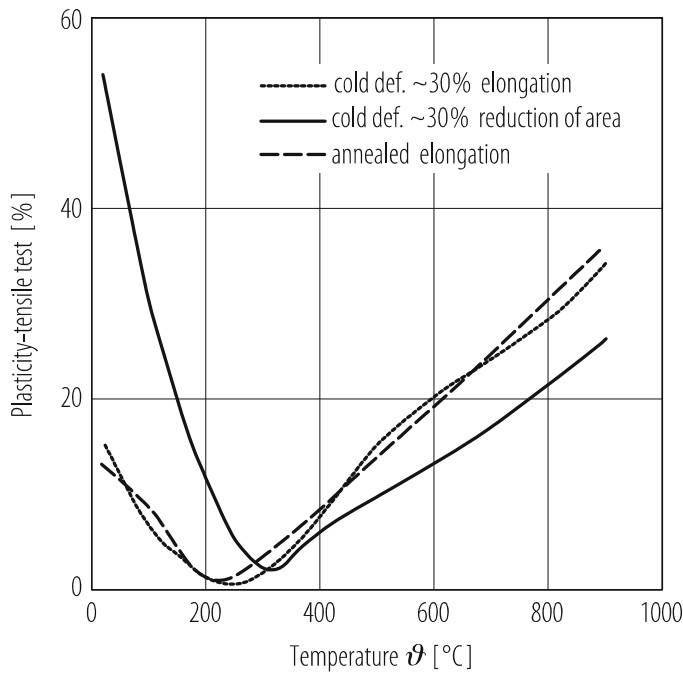


Fig. 5.23 Plasticity of CuZn<sub>20</sub> as a function of the temperature.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 142.0                | 380.6              | 17.50                                   | 8674.5                      | 119.0           |
| 100              | 147.0                | 385.6              | 17.94                                   | 8652.0                      | 116.0           |
| 200              | 153.3                | 391.8              | 18.50                                   | 8622.2                      | 111.0           |
| 300              | 159.5                | 398.1              | 19.05                                   | 8590.7                      | 106.0           |
| 400              | 165.8                | 404.3              | 19.61                                   | 8557.5                      | 100.0           |
| 500              | 172.1                | 410.6              | 20.16                                   | 8522.5                      | 91.0            |
| 600              | 178.4                | 416.9              | 20.71                                   | 8485.8                      | 81.0            |
| 700              | 184.7                | 423.1              | 21.27                                   | 8447.4                      | 71.0            |
| 800              | 190.9                | 429.4              | 21.82                                   | 8407.2                      |                 |
| 900              | 197.2                | 435.6              | 22.38                                   | 8365.4                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese Industrial Standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |



# Flow stress, mechanical and physical properties of CuZn<sub>28</sub>

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |               |               |               |            |               |
|-------------|---------------|---------------|---------------|------------|---------------|
| UNS number: | <b>C25600</b> | Chem. symbol: | <b>CuZn28</b> | EN number: | <b>CW504L</b> |
|-------------|---------------|---------------|---------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Zn    | Al     | Fe    | Ni    | Pb    | Sn    | Others |
|-------------|-------|--------|-------|-------|-------|-------|--------|
| 71.0...73.0 | >26.5 | <0.020 | <0.05 | <0.20 | <0.05 | <0.05 | <0.10  |

#### International comparison of standards

|                       |                            |
|-----------------------|----------------------------|
| Euronorm              | ISO                        |
| EN 12163 : 1998       |                            |
| EN 12166              |                            |
| Material number (DIN) | DIN                        |
| 2.0261                | DIN 17660 : 1983 DIN 17682 |
| USA                   |                            |
| ASTM                  | UNS standard               |
|                       | C25600                     |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation  |                    |
|----------------------------------------|-----------------|----------------|-------------------|--------------------|
|                                        | cast state      | deformed state | homogenized (hom) | soft annealed (sa) |
| $\sigma_{F0}$ [MPa]                    |                 | 123.2          | 318.21            |                    |
| A                                      |                 | 6061.545       | 701.145           |                    |
| Effect of temperature $K_9$            |                 |                |                   |                    |
| $m_1$                                  |                 | −0.00498       | −0.00152          |                    |
| Effect of strain $K_\phi$              |                 |                |                   |                    |
| $m_2$                                  |                 | 0.38706        | 0.30542           |                    |
| $m_4$                                  |                 | 0.01906        | −0.00865          |                    |
| $m_5$                                  |                 | −0.00153       |                   |                    |
| $m_7$                                  |                 | −0.05689       |                   |                    |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                   |                    |
| $m_3$                                  |                 |                | 0.01241           |                    |
| $m_8$                                  |                 | 0.000247       |                   |                    |
| Range of validity                      |                 |                |                   |                    |
| $\vartheta$ [°C]                       |                 | 600 ... 850    | 20 ... 300        |                    |
| $\phi$                                 |                 | 0.03 ... 1.25  | 0.03 ... 2.00     |                    |
| $\dot{\phi}$ [1/s]                     |                 | <100           | <100              |                    |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

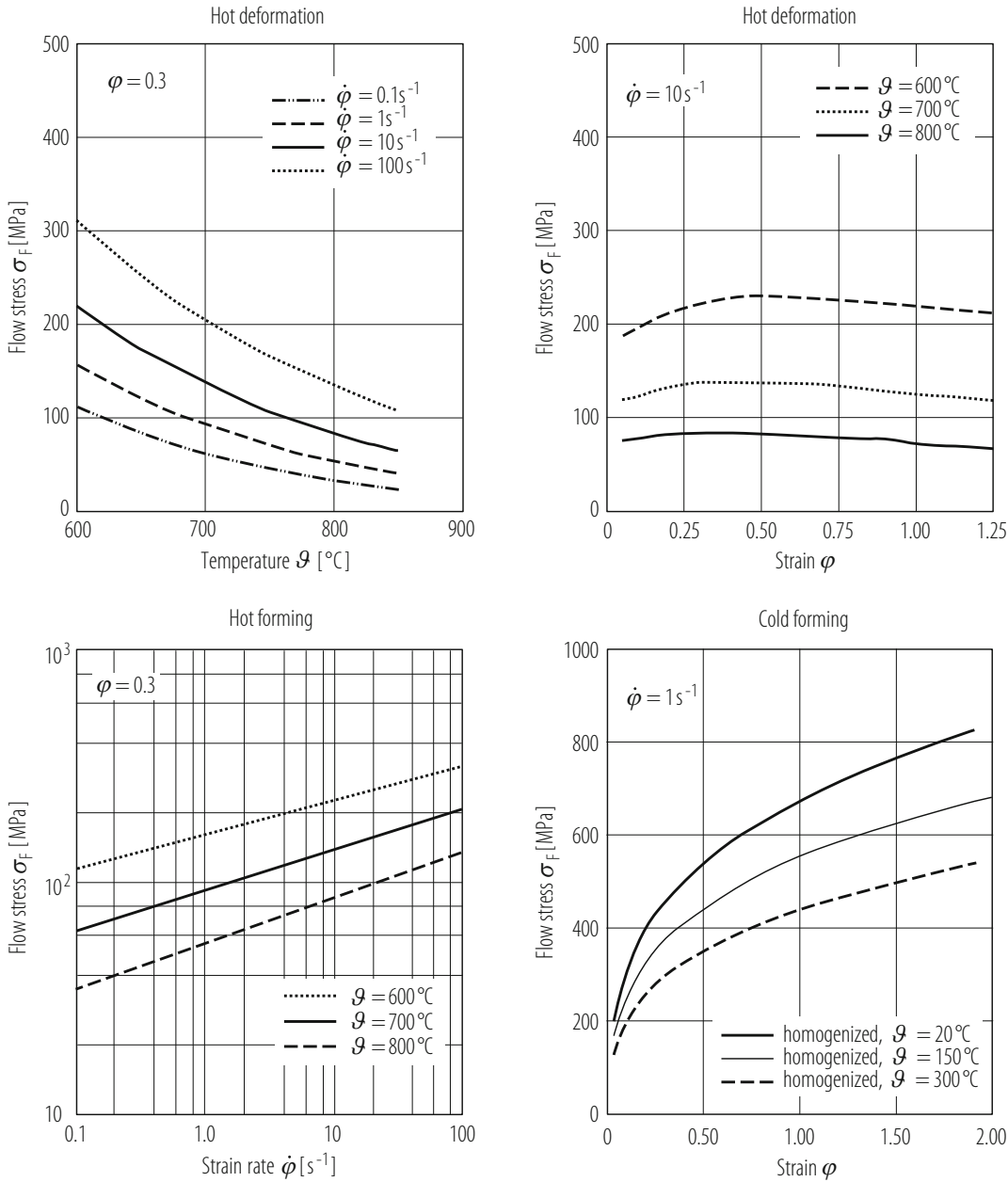


Fig. 5.24 Flow stress curves of CuZn28 by hot and cold forming.

Mechanical properties after cold deformation

| State of material     | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-----------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                       | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| hot rolled            | 100...160                       | 23.52115 | 0.74749 | 270...350                           | 6.95326 | 0.92940 |
| grain size 0.070 [mm] | 100..160                        | 45.96085 | 0.57922 | 270...350                           | 7.54526 | 0.91652 |

| State of material     | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-----------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                       | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| hot rolled            | 40...45                                 | 19.60883 | 0.18232 | -7.61113 | <70                        |
| grain size 0.070 [mm] | 60...65                                 | 37.66571 | 0.15464 | -7.06538 | <70                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

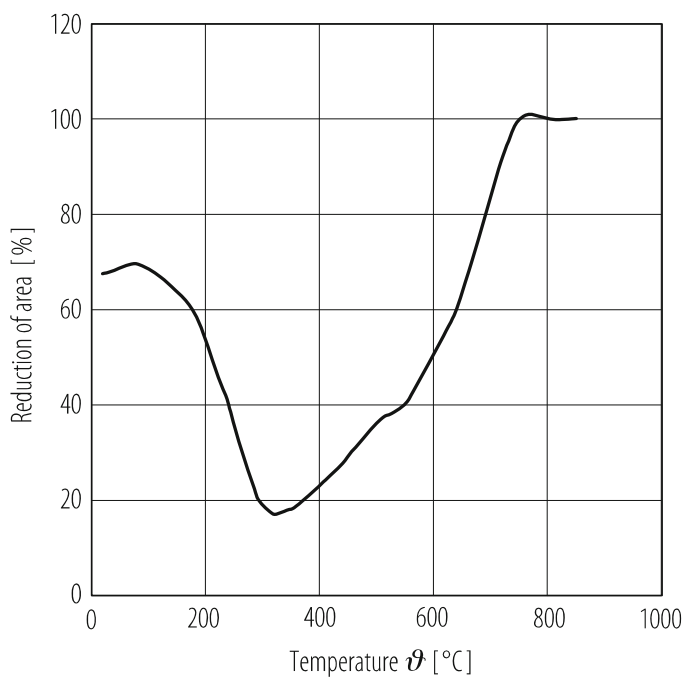


Fig. 5.25 Plasticity of CuZn28 as a function of the temperature.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 126.7                | 378.6              | 17.88                                   | 8554.5                      | 114.0           |
| 100              | 134.1                | 384.9              | 18.38                                   | 8531.7                      |                 |
| 200              | 143.3                | 392.8              | 19.00                                   | 8501.4                      |                 |
| 300              | 152.4                | 400.7              | 19.63                                   | 8469.3                      |                 |
| 400              | 161.6                | 408.6              | 20.25                                   | 8435.2                      |                 |
| 500              | 170.8                | 416.6              | 20.87                                   | 8399.2                      |                 |
| 600              | 180.0                | 424.5              | 21.49                                   | 8361.3                      |                 |
| 700              | 189.2                | 432.4              | 22.11                                   | 8321.5                      |                 |
| 800              | 198.3                | 440.3              | 22.74                                   | 8279.7                      |                 |
| 900              | 207.5                | 448.2              | 23.36                                   | 8236.1                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuZn<sub>30</sub>

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |               |               |               |            |               |
|-------------|---------------|---------------|---------------|------------|---------------|
| UNS number: | <b>C26000</b> | Chem. symbol: | <b>CuZn30</b> | EN number: | <b>CW505L</b> |
|-------------|---------------|---------------|---------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Zn    | Al     | Fe    | Ni    | Pb    | Sn    | Others |
|-------------|-------|--------|-------|-------|-------|-------|--------|
| 69.0...71.0 | >28.5 | <0.020 | <0.05 | <0.20 | <0.05 | <0.05 | <0.10  |

#### International comparison of standards

|                       |                    |              |                 |
|-----------------------|--------------------|--------------|-----------------|
| Euronorm              |                    | ISO          |                 |
| EN 1654 : 1997        | EN 1652            |              |                 |
| EN 13148              | EN 12449           |              |                 |
| EN 14436              | EN 12163           |              |                 |
| Material number (DIN) |                    | DIN          |                 |
| 2.0265                | DIN 17660 : 1983   |              | DIN 1777        |
|                       | DIN 17670-1        |              | DIN 17672-1     |
|                       | DIN 17682          |              | DIN 1785        |
| Japan                 |                    | Russia       |                 |
| JIA 3100              | JIS H 3250         | L 70         | GOST 15527 - 70 |
| JIS H 3260            | JIS H 3320         |              |                 |
| JIS H 3300            |                    |              |                 |
| USA                   |                    |              |                 |
| ASTM                  |                    | UNS standard |                 |
| ASTM B19              | ASTM B 36 / B 36 M | C26000       |                 |
| ASTM B 129            | ASTM B 888         |              |                 |
| ASTM B 569            | ASTM B927          |              |                 |
| AMS 4507              | AMS 4508           |              |                 |
| SAE J463              | SAE J461           |              |                 |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material           | Hot deformation |                | Cold deformation  |                    |
|-----------------------------|-----------------|----------------|-------------------|--------------------|
|                             | cast state      | deformed state | homogenized (hom) | soft annealed (sa) |
| $\sigma_{F0}$ [MPa]         | 122.3           | 124.9          | 323.9             |                    |
| A                           | 3330.106        | 2995.571       | 724.309           |                    |
| Effect of temperature $K_9$ |                 |                |                   |                    |
| $m_1$                       | -0.00505        | -0.00513       | -0.00155          |                    |
| Effect of strain $K_\phi$   |                 |                |                   |                    |
| $m_2$                       | 0.06528         | -0.09319       | 0.38276           |                    |

(continued)

| State of material                      | Hot deformation |                | Cold deformation  |                    |
|----------------------------------------|-----------------|----------------|-------------------|--------------------|
|                                        | cast state      | deformed state | homogenized (hom) | soft annealed (sa) |
| m <sub>4</sub>                         | 0.00096         | −0.02283       | 0.00797           |                    |
| m <sub>5</sub>                         | 0.00052         | 0.00029        |                   |                    |
| m <sub>7</sub>                         | −0.42008        | −0.15023       |                   |                    |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                   |                    |
| m <sub>3</sub>                         |                 |                | 0.01156           |                    |
| m <sub>8</sub>                         | 0.000235        | 0.000262       |                   |                    |
| Range of validity                      |                 |                |                   |                    |
| $\vartheta$ [°C]                       | 600 ... 900     | 600 ... 900    | 20 ... 300        |                    |
| $\varphi$                              | 0.03 ... 1.50   | 0.03 ... 1.50  | 0.03 ... 2.00     |                    |
| $\dot{\varphi}$ [1/s]                  | <100            | <100           | <100              |                    |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

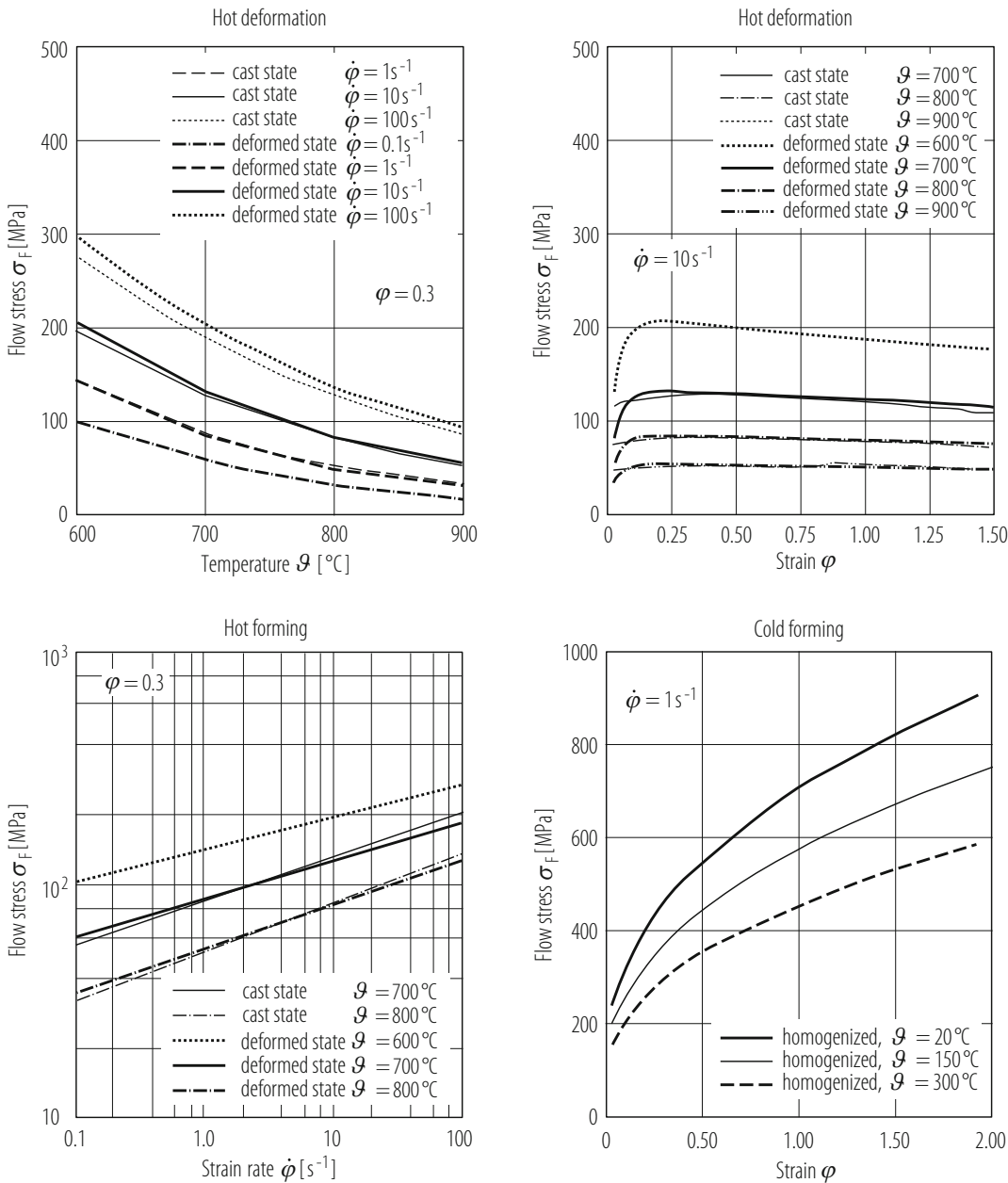


Fig. 5.26 Flow stress curves of CuZn30 by hot and cold forming

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| soft annealed     | 90...140                        | 36.06021 | 0.64111 | 300...350                           | 6.16988 | 0.99767 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |          |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|----------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$    | $n_4$    |                            |
| soft annealed     | 55...65                                 | 84.76562 | -0.03494 | -11.0981 | <60                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

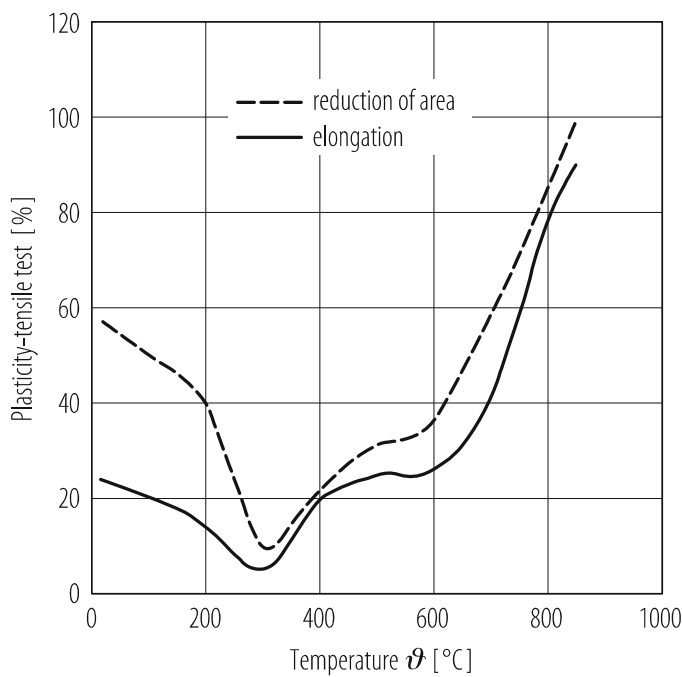


Fig. 5.27 Plasticity of CuZn30 as a function of the temperature.



## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 125.4                | 375.7              | 19.01                                   | 8554.1                      | 115.0           |
| 100              | 132.6                | 382.0              | 19.52                                   | 8529.9                      | 112.0           |
| 200              | 141.6                | 389.9              | 20.16                                   | 8497.9                      | 107.0           |
| 300              | 150.7                | 397.8              | 20.80                                   | 8463.9                      | 103.0           |
| 400              | 159.7                | 405.7              | 21.44                                   | 8427.9                      | 96.0            |
| 500              | 168.7                | 413.7              | 22.08                                   | 8389.9                      | 88.0            |
| 600              | 177.7                | 421.6              | 22.71                                   | 8350.0                      | 77.0            |
| 700              | 186.7                | 429.5              | 23.35                                   | 8308.1                      | 67.0            |
| 800              | 195.7                | 437.4              | 23.99                                   | 8264.3                      |                 |
| 900              | 204.8                | 445.3              | 24.63                                   | 8218.4                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese Industrial Standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| SAE                 | society of automotive engineers                                       |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuZn<sub>33</sub>

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |               |               |               |            |               |
|-------------|---------------|---------------|---------------|------------|---------------|
| UNS number: | <b>C26800</b> | Chem. symbol: | <b>CuZn33</b> | EN number: | <b>CW506L</b> |
|-------------|---------------|---------------|---------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu            | Zn            | Al    | Fe    | Ni    | Pb    | Mn    | Sn    | Sb    | Others |
|---------------|---------------|-------|-------|-------|-------|-------|-------|-------|--------|
| 66.0 ... 69.0 | 31.0 ... 34.0 | <0.10 | <0.10 | <0.50 | <0.10 | <0.10 | <0.10 | <0.01 | <0.10  |

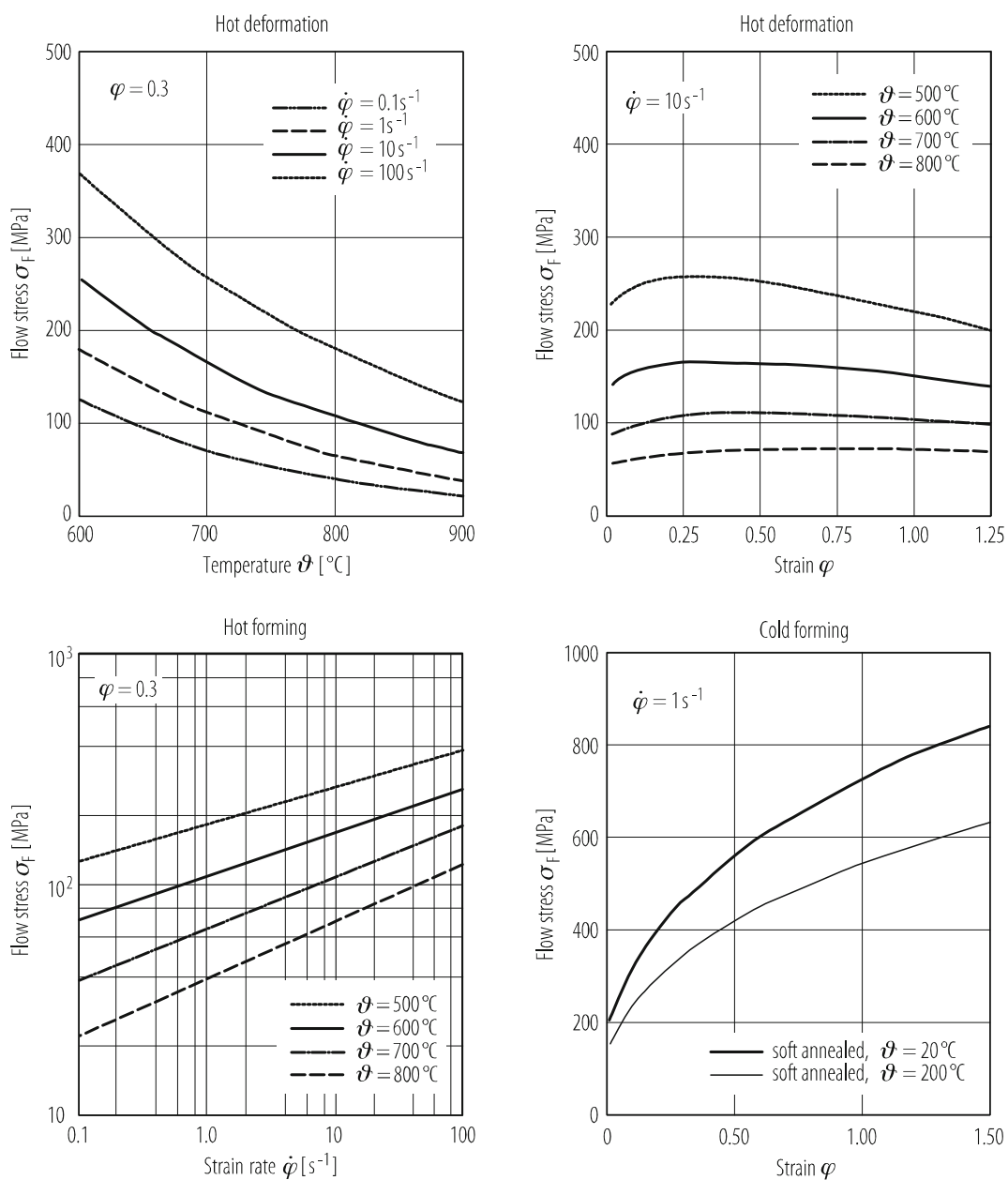
#### International comparison of standards

| Euronorm              |            | ISO              |             |
|-----------------------|------------|------------------|-------------|
| EN 13148 : 2001       | EN 1652    | ISO 426–1 : 1973 | ISO 1634-1  |
| EN 12163              | EN 14436   | ISO 1638         |             |
| Material number (DIN) |            | DIN              |             |
| 2.028                 |            | DIN 17660 : 1983 | DIN 17670-1 |
|                       |            | DIN 17672 (X)    |             |
| Japan                 |            | Russia           |             |
| C 2680                |            |                  |             |
| JIS H 3100 : 1992     | JIS H 3320 |                  |             |
| USA                   |            |                  |             |
| ASTM and SAE          |            | UNS standard     |             |
| ASTM B36              | ASTM B36M  | C26800           |             |
| ASTM B927             | ASTM B587  |                  |             |
| SAE J463              | SAE J461   |                  |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

Flow curves

| State of material                                                                                                                                                              | Hot deformation |                | Cold deformation     |                                                                                                            |                 |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|----------------|----------------------|------------------------------------------------------------------------------------------------------------|-----------------|
|                                                                                                                                                                                | cast state      | deformed state | recrystallized (rec) | soft annealed (sa)                                                                                         | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                                                                                                                                                            |                 | 98.5           |                      | 330.1                                                                                                      |                 |
| A                                                                                                                                                                              |                 | 3125.478       |                      | 746.378                                                                                                    |                 |
| Effect of temperature $K_{\vartheta}$                                                                                                                                          |                 |                |                      |                                                                                                            |                 |
| $m_1$                                                                                                                                                                          |                 | −0.00549       |                      | −0.0016                                                                                                    |                 |
| Effect of strain $K_{\varphi}$                                                                                                                                                 |                 |                |                      |                                                                                                            |                 |
| $m_2$                                                                                                                                                                          |                 | 0.05924        |                      | 0.37577                                                                                                    |                 |
| $m_4$                                                                                                                                                                          |                 | −0.00021       |                      | 0.00495                                                                                                    |                 |
| $m_5$                                                                                                                                                                          |                 | 0.00141        |                      |                                                                                                            |                 |
| $m_7$                                                                                                                                                                          |                 | −0.757925      |                      |                                                                                                            |                 |
| Effect of strain rate $K_{\dot{\varphi}}$                                                                                                                                      |                 |                |                      |                                                                                                            |                 |
| $m_3$                                                                                                                                                                          |                 |                |                      | 0.01333                                                                                                    |                 |
| $m_8$                                                                                                                                                                          |                 | 0.000314       |                      |                                                                                                            |                 |
| Range of validity                                                                                                                                                              |                 |                |                      |                                                                                                            |                 |
| $\vartheta$ [°C]                                                                                                                                                               |                 | 500 ... 800    |                      | 20 ... 250                                                                                                 |                 |
| $\varphi$                                                                                                                                                                      |                 | 0.03 ... 1.25  |                      | 0.03 ... 1.50                                                                                              |                 |
| $\dot{\varphi}$ [1/s]                                                                                                                                                          |                 | <100           |                      | <100                                                                                                       |                 |
|                                                                                                                                                                                |                 |                |                      |                                                                                                            |                 |
| Hot deformation:                                                                                                                                                               |                 |                |                      | Cold deformation                                                                                           |                 |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |                 |                |                      | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |                 |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |                 |                |                      | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |                 |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     |                 |                |                      | [DOI: 978-3-642-14174-4_2]                                                                                 |                 |



**Fig. 5.28** Flow stress curves of CuZn<sub>33</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material     | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |          |         |
|-----------------------|---------------------------------|----------|---------|-------------------------------------|----------|---------|
|                       | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$      | $n_2$   |
| grain size 0.070 [mm] | 90...150                        | 30.97034 | 0.65491 | 290...350                           | 12.11701 | 0.80892 |

| State of material     | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-----------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                       | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| grain size 0.070 [mm] | 50...55                                 | 32.91373 | 0.11239 | -6.07985 | <70                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

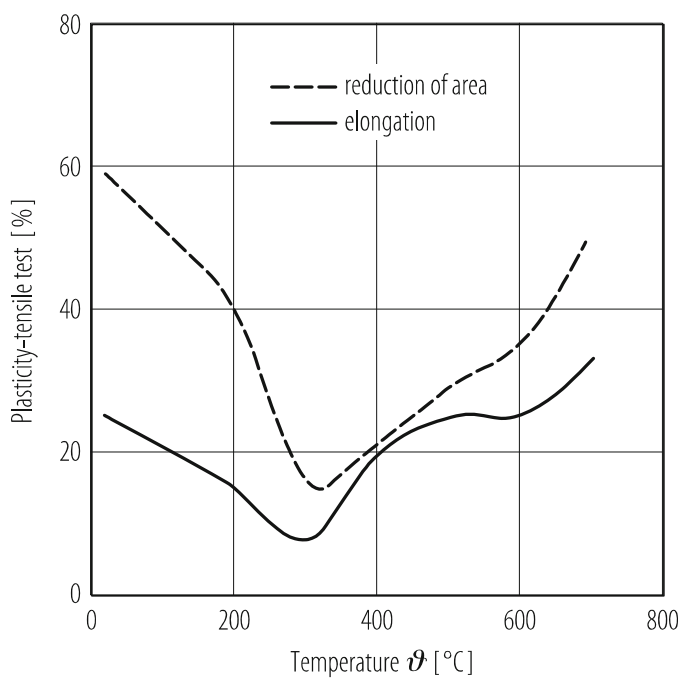


Fig. 5.29 Plasticity of CuZn<sub>33</sub> as a function of the temperature.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 119.8                | 377.3              | 18.10                                   | 8534.4                      | 112.0           |
| 100              | 128.7                | 383.6              | 18.62                                   | 8511.4                      |                 |
| 200              | 139.8                | 391.6              | 19.26                                   | 8480.8                      |                 |

(continued)

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}/K$ ] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 300                             | 150.9                                     | 399.5                                   | 19.91                                                                    | 8448.2                                 |                              |
| 400                             | 162.0                                     | 407.5                                   | 20.56                                                                    | 8413.6                                 |                              |
| 500                             | 173.1                                     | 415.4                                   | 21.21                                                                    | 8377.0                                 |                              |
| 600                             | 184.1                                     | 423.3                                   | 21.85                                                                    | 8338.5                                 |                              |
| 700                             | 195.2                                     | 431.3                                   | 22.50                                                                    | 8297.9                                 |                              |
| 800                             | 206.3                                     | 439.2                                   | 23.15                                                                    | 8255.4                                 |                              |
| 850                             | 211.9                                     | 443.2                                   | 23.47                                                                    | 8233.3                                 |                              |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese Industrial Standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| SAE                 | society of automotive engineers                                       |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuZn<sub>37</sub>

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |               |               |               |            |               |
|-------------|---------------|---------------|---------------|------------|---------------|
| UNS number: | <b>C27400</b> | Chem. symbol: | <b>CuZn37</b> | EN number: | <b>CW508L</b> |
|-------------|---------------|---------------|---------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu            | Zn    | Al     | Fe    | Ni    | Pb    | Sn    | Others |
|---------------|-------|--------|-------|-------|-------|-------|--------|
| 62.0 . . 64.0 | >35.3 | <0.030 | <0.10 | <0.30 | <0.10 | <0.10 | <0.10  |

#### International comparison of standards

| Euronorm              |             | ISO              |                 |
|-----------------------|-------------|------------------|-----------------|
| EN 13148 : 2001       | EN 1652     | ISO 426–1 : 1983 | ISO 1634-3      |
| EN 14436,             | EN 12449    | ISO 1634–1,      | ISO 1637        |
| EN 12163              | EN 12165    | ISO 1638         | ISO 1635        |
| EN 12167              | EN 12166    |                  |                 |
| Material number (DIN) |             | DIN              |                 |
| 2.0321                |             | DIN 17660 : 1983 | DIN 1777        |
|                       |             | DIN 17672-1      | DIN 17682       |
| Japan                 |             | Russia           |                 |
| C 2720                | JIS H 3260  | L 63             | GOST 15527 - 70 |
| JIS H 3100 : 1992     |             | GOST 2208        | GOST 931        |
|                       |             | GOST 2060        | GOST 6688       |
|                       |             | GOST 11383       | GOST 20900      |
| USA                   |             | UNS standard     |                 |
| ASTM                  |             |                  |                 |
| ASTM B135             | ASTM B135 M | C 27400          |                 |
| ASTM B927             |             |                  |                 |

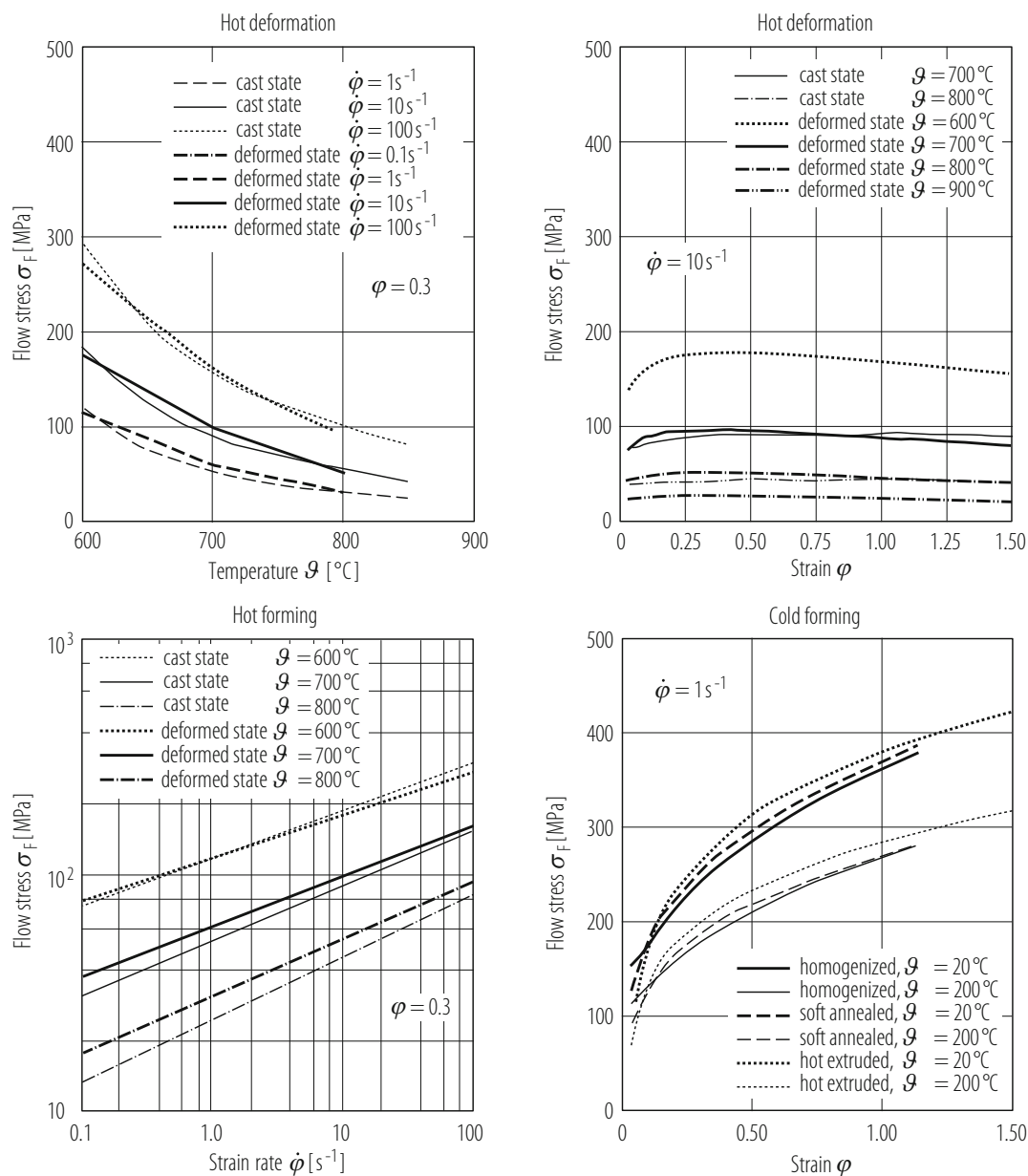
It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

**Flow curves**

| State of material                      | Hot deformation |                | Cold deformation  |                    |                   |
|----------------------------------------|-----------------|----------------|-------------------|--------------------|-------------------|
|                                        | cast state      | deformed state | homogenized (hom) | soft annealed (sa) | hot extruded (he) |
| $\sigma_{F0}$ [MPa]                    | 81.8            | 88.9           | 368.5             | 362.3              | 352.1             |
| A                                      | 17765.687       | 8655.744       | 738.406           | 768.611            | 801.997           |
| Effect of temperature $K_8$            |                 |                |                   |                    |                   |
| $m_1$                                  | −0.00779        | −0.00659       | −0.00168          | −0.00173           | −0.00162          |
| Effect of strain $K_\varphi$           |                 |                |                   |                    |                   |
| $m_2$                                  | 0.2235          | 0.17485        | 0.35694           | 0.30891            | 0.24904           |
| $m_4$                                  | 0.00975         | 0.00043        | 0.01232           | −0.00407           | −0.02490          |
| $m_5$                                  | −0.00067        | −0.00079       |                   |                    |                   |
| $m_7$                                  | −0.03063        | −0.07862       |                   |                    |                   |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                   |                    |                   |
| $m_3$                                  |                 |                | 0.0157            | 0.01436            | 0.01283           |
| $m_8$                                  | 0.000333        | 0.000306       |                   |                    |                   |
| Range of validity                      |                 |                |                   |                    |                   |
| $\vartheta$ [°C]                       | 600 ... 850     | 600 ... 800    | 20 ... 400        | 20 ... 300         | 20 ... 300        |
| $\varphi$                              | 0.03 ... 1.50   | 0.03 ... 1.50  | 0.03 ... 1.20     | 0.03 ... 1.20      | 0.03 ... 2.00     |
| $\dot{\varphi}$ [1/s]                  | <100            | <100           | <100              | <100               | <100              |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |





**Fig. 5.30** Flow stress curves of CuZn<sub>37</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| sheet             | 100...150                       | 23.78702 | 0.76322 | 300...370                           | 6.83625 | 0.95311 |
| wire              | 100...150                       | 17.82586 | 0.78835 | 300...370                           | 1.00695 | 1.39098 |
| bar               | 100...150                       | 18.84693 | 0.77732 | 300...370                           | 2.84306 | 1.17501 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| sheet             | 50...60                                 | 15.70658 | 0.32294 | -5.55654 | <60                        |
| wire              | 60...70                                 | 8.95364  | 0.51119 | -8.38329 | <70                        |
| bar               | 60..70                                  | 13.60109 | 0.32965 | -4.34632 | <60                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

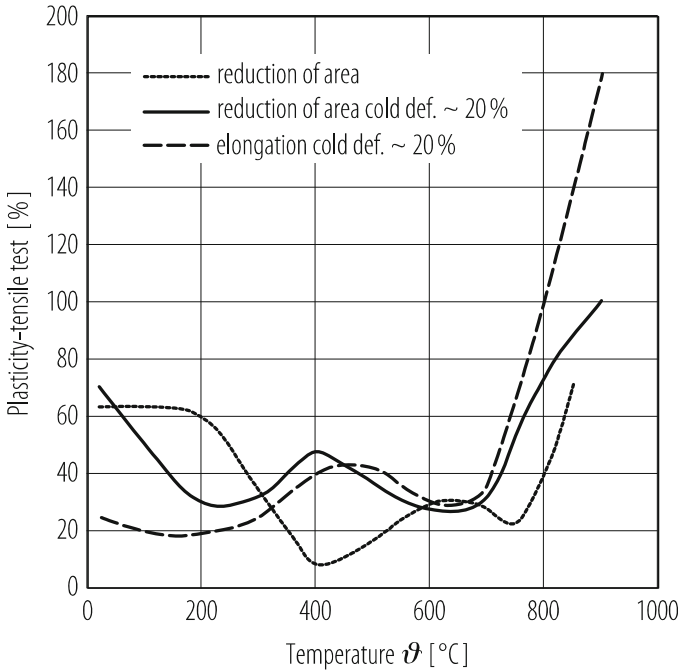


Fig. 5.31 Plasticity of CuZn<sub>37</sub> as a function of the temperature.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 113.8                | 373.8              | 18.39                                   | 8434.4                      | 110.0           |
| 100              | 126.6                | 382.5              | 18.96                                   | 8411.2                      | 106.0           |
| 200              | 142.5                | 393.5              | 19.67                                   | 8380.2                      | 102.0           |
| 300              | 158.5                | 404.4              | 20.37                                   | 8347.1                      | 97.0            |
| 400              | 174.4                | 415.3              | 21.08                                   | 8311.9                      | 89.0            |
| 500              | 190.4                | 426.3              | 21.79                                   | 8274.5                      | 79.0            |
| 600              | 206.3                | 437.2              | 22.50                                   | 8234.9                      | 72.0            |
| 700              | 222.3                | 448.2              | 23.21                                   | 8193.2                      | 72.0            |
| 800              | 238.2                | 459.1              | 23.91                                   | 8149.4                      |                 |
| 900              |                      |                    |                                         |                             |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese Industrial Standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuZn<sub>40</sub>

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |               |               |               |            |               |
|-------------|---------------|---------------|---------------|------------|---------------|
| UNS number: | <b>C28000</b> | Chem. symbol: | <b>CuZn40</b> | EN number: | <b>CW509L</b> |
|-------------|---------------|---------------|---------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Zn    | Al     | Fe    | Ni    | Pb    | Sn    | Others |
|-------------|-------|--------|-------|-------|-------|-------|--------|
| 59.5...61.5 | >37.3 | <0.050 | <0.20 | <0.30 | <0.30 | <0.20 | <0.20  |

#### International comparison of standards

| Euronorm              |             | ISO              |                 |
|-----------------------|-------------|------------------|-----------------|
| EN 12420 : 1999       | EN 1652     | ISO 426–1 : 1983 | ISO 1637        |
| EN 12163              | EN 12165    | ISO 1635         | ISO 1639        |
| EN 12167              | EN 12449    |                  |                 |
| Material number (DIN) |             | DIN              |                 |
| 2.036                 |             | DIN 17660 : 1983 | DIN 17675-1     |
|                       |             | DIN 17672-1      | DIN 17677-      |
| Japan                 |             | Russia           |                 |
| JIS H 3250 : 1992     | JIS H 3260  | L 60             | GOST 15527 - 70 |
|                       | JIS H 3300  | GOST 494         |                 |
| USA                   |             | UNS standard     |                 |
| ASTM and ASME         |             | C28000           |                 |
| ASTM B111             | ASTM B111 M |                  |                 |
| ASTM B36              | ASTM B36M   |                  |                 |
| ASTM B135             | ASTM B135 M |                  |                 |
| ASME SB111            |             |                  |                 |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

**Flow curves**

| State of material                         | Hot deformation |                | Cold deformation  |                    |                   |
|-------------------------------------------|-----------------|----------------|-------------------|--------------------|-------------------|
|                                           | cast state      | deformed state | homogenized (hom) | soft annealed (sa) | hot extruded (he) |
| $\sigma_{F0}$ [MPa]                       | 40.5            | 39.7           | 374               | 364.2              | 404.09            |
| A                                         | 2627.607        | 7050.94        | 853.292           | 898.425            | 939.651           |
| Effect of temperature $K_\theta$          |                 |                |                   |                    |                   |
| $m_1$                                     | −0.00687        | −0.00808       | −0.00207          | −0.00215           | −0.00207          |
| Effect of strain $K_\varphi$              |                 |                |                   |                    |                   |
| $m_2$                                     | −0.05455        | 0.06156        | 0.36924           | 0.36891            | 0.36577           |
| $m_4$                                     | −0.00265        | −0.00016       | 0.00324           | −0.0043            | 0.000495          |
| $m_5$                                     | −0.00054        | −0.00063       |                   |                    |                   |
| $m_7$                                     | 0.21694         | −0.01774       |                   |                    |                   |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                   |                    |                   |
| $m_3$                                     |                 |                | 0.01433           | 0.01339            | 0.01448           |
| $m_8$                                     | 0.000342        | 0.000411       |                   |                    |                   |
| Range of validity                         |                 |                |                   |                    |                   |
| $\vartheta$ [°C]                          | 400 ... 800     | 600 ... 800    | 20 ... 250        | 20 ... 250         | 20 ... 300        |
| $\varphi$                                 | 0.03 ... 1.25   | 0.03 ... 1.25  | 0.03 ... 1.50     | 0.03 ... 1.50      | 0.03 ... 1.50     |
| $\dot{\varphi}$ [1/s]                     | <100            | <100           | <100              | <100               | <100              |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |

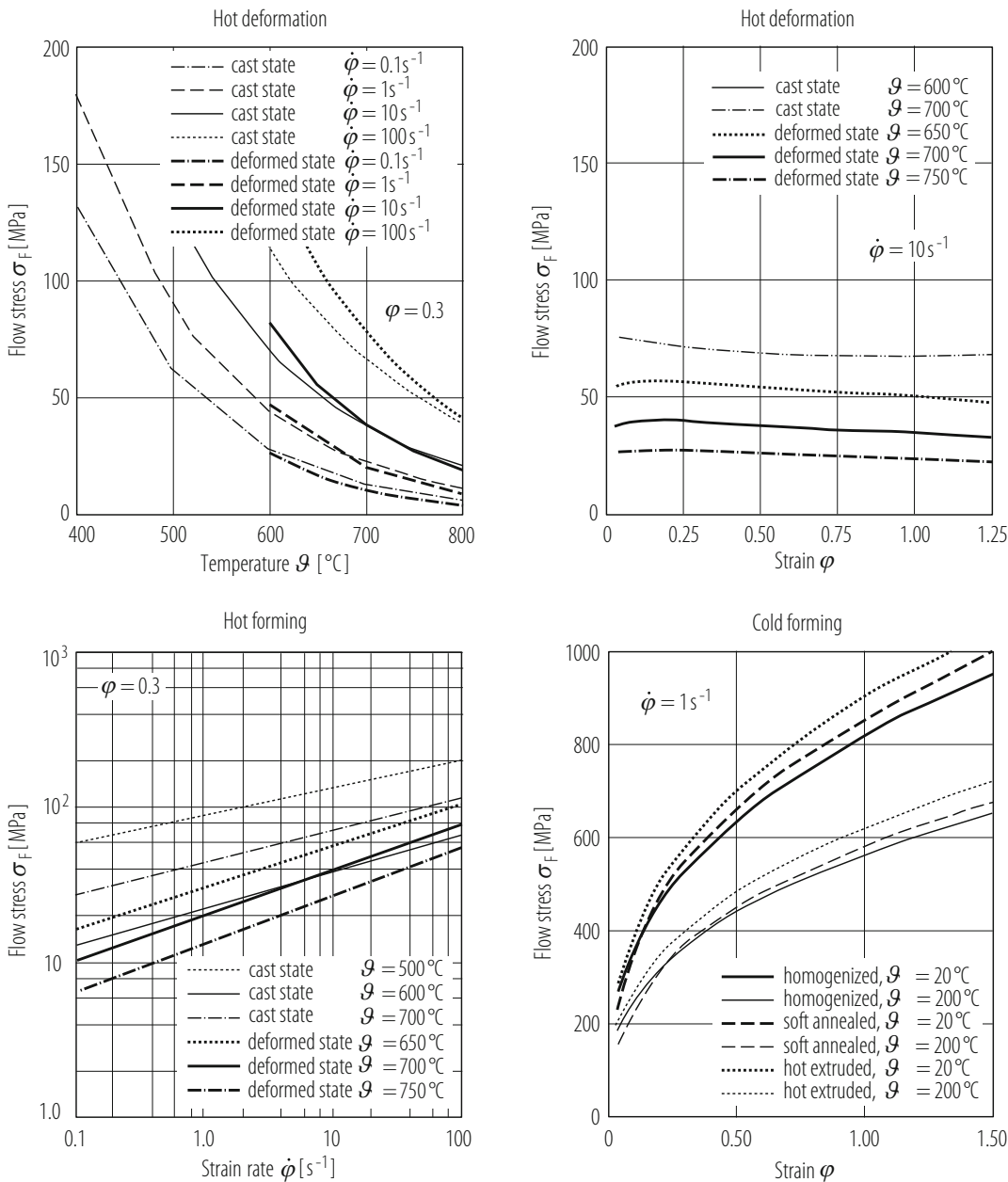


Fig. 5.32 Flow stress curves of CuZn40 by hot and cold forming

Mechanical properties after cold deformation

| State of material     | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-----------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                       | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| grain size 0.015 [mm] | 140. . .200                     | 30.01058 | 0.67236 | 360. . .410                         | 4.16818 | 1.06331 |
| grain size 0.045 [mm] | 140. . .200                     | 43.16500 | 0.59331 | 360. . .410                         | 5.57437 | 0.99229 |

| State of material     | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-----------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                       | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| grain size 0.015 [mm] | 40. . . 50                              | 27.22240 | 0.15617 | −8.50648 | <70                        |
| grain size 0.045 [mm] | 45. . . 55                              | 23.40384 | 0.21322 | −4.56922 | <70                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

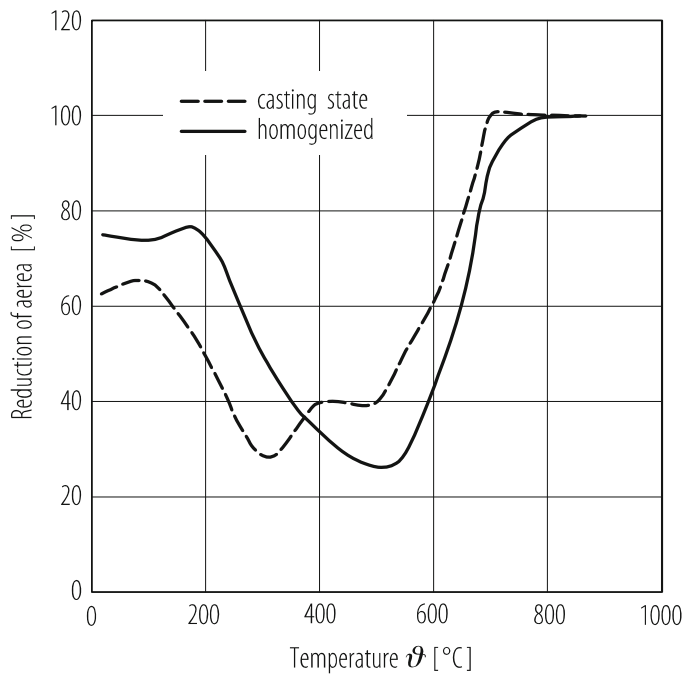


Fig. 5.33 Plasticity of CuZn40 as a function of the temperature.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 106.0                | 377.2              | 18.29                                   | 8444.4                      | 102.0           |
| 100              | 118.9                | 385.9              | 18.83                                   | 8421.4                      | 99.0            |
| 200              | 135.1                | 396.9              | 19.51                                   | 8390.7                      | 94.0            |
| 300              | 151.2                | 407.8              | 20.19                                   | 8357.9                      | 89.0            |
| 400              | 167.4                | 418.8              | 20.87                                   | 8323.1                      | 83.0            |
| 500              | 183.5                | 429.7              | 21.54                                   | 8286.2                      | 74.0            |
| 600              | 199.7                | 440.6              | 22.22                                   | 8247.2                      | 64.0            |
| 700              | 215.8                | 451.6              | 22.90                                   | 8206.2                      | 54.0            |
| 800              | 232.0                | 462.5              | 23.58                                   | 8163.1                      |                 |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 850              | 240.0                | 468.0              | 24.02                                   | 8139.5                      |                 |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese Industrial Standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |



# Flow stress and mechanical properties of CuZn<sub>42</sub>

## 5.2 Copper- and Copper alloys

### 5.2.1 Pure Copper and low alloyed Copper

#### Designation

|             |               |                          |            |               |
|-------------|---------------|--------------------------|------------|---------------|
| UNS number: | Chem. symbol: | <b>CuZn<sub>42</sub></b> | EN number: | <b>CW621N</b> |
|-------------|---------------|--------------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu  | Zn    | Al     | Fe    | Ni    | Pb    | Sn    | Others |
|-----|-------|--------|-------|-------|-------|-------|--------|
| ~58 | ~39.5 | <0.050 | <0.20 | <0.30 | <0.30 | <0.20 | <0.20  |

#### International comparison of standards

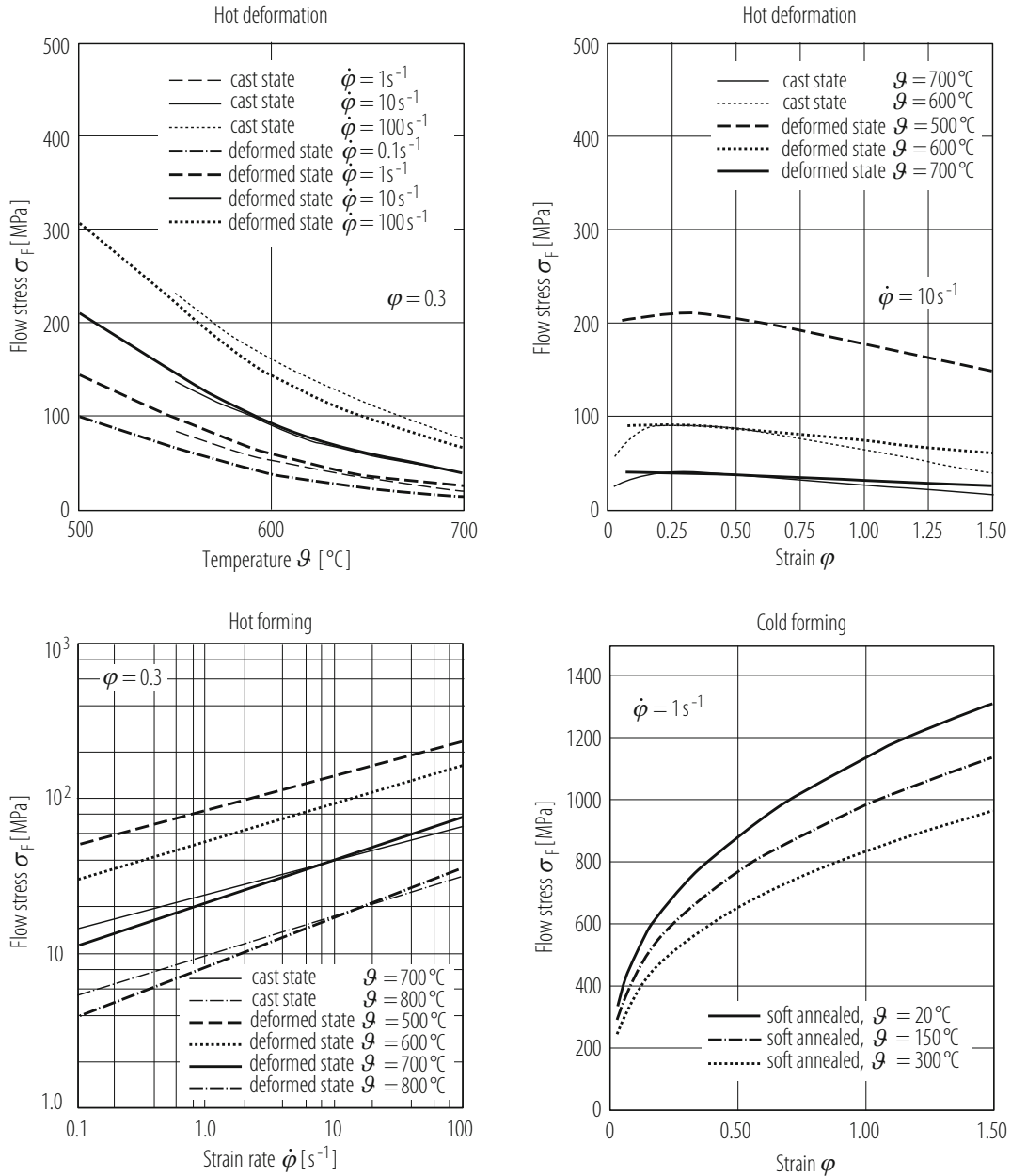
|                       |              |
|-----------------------|--------------|
| Euronorm              | ISO          |
| EN 12167 : 1998       |              |
| Material number (DIN) | DIN          |
| 2.0109                |              |
| USA                   |              |
| ASTM                  | UNS standard |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                    | 33.8            | 39.9           |                      | 524.74             |                 |
| A                                      | 31759.749       | 18289.456      |                      | 1159.235           |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                      |                    |                 |
| $m_1$                                  | -0.00912        | -0.00884       |                      | -0.00109           |                 |
| Effect of strain $K_{\phi}$            |                 |                |                      |                    |                 |
| $m_2$                                  | 0.4352927       | 0.20154        |                      | 0.35665            |                 |
| $m_4$                                  | 0.005204        | 0.00931        |                      | 0.00078            |                 |
| $m_5$                                  | -0.00081        | -0.00089       |                      |                    |                 |
| $m_7$                                  | -0.98683        | -0.29236       |                      |                    |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.01789            |                 |
| $m_8$                                  | 0.000398        | 0.000323       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\theta$ [°C]                          | 500 ... 700     | 550 ... 700    |                      | 20 ... 300         |                 |
| $\phi$                                 | 0.03 ... 1.50   | 0.05 ... 1.50  |                      | 0.03 ... 1.50      |                 |
| $\dot{\phi}$ [1/s]                     | <100            | <100           |                      | <100               |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.34** Flow stress curves of CuZn42 by hot and cold forming.

**Mechanical properties after cold deformation**

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |          |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|----------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$      | $n_2$   |
| soft annealed     | 160. . .200                     | 33.58401 | 0.60043 | 350. . .400                         | 21.11724 | 0.64733 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |           |          |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|-----------|----------|----------|----------------------------|
|                   | $C_0$                                   | $C$       | $n_3$    | $n_4$    |                            |
| soft annealed     | 45. . .55                               | 731.82396 | -0.65552 | -29.9805 | <70                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

**Symbols and abbreviations**

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| UNS                 | unified numbering system                                              |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| ASTM                | American society for testing and materials                            |
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $R_p$               | yield stress                                                          |
| $R_m$               | tensile strength                                                      |
| $A, B, C$ and $n_i$ | constants                                                             |
| $A_5$               | elongation to fracture                                                |
| $T, \vartheta$      | temperature                                                           |

# Flow stress, mechanical and physical properties of CuZn<sub>20</sub>Al<sub>2</sub>As

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |               |               |                    |            |               |
|-------------|---------------|---------------|--------------------|------------|---------------|
| UNS number: | <b>C68700</b> | Chem. symbol: | <b>CuZn20Al2As</b> | EN number: | <b>CW702R</b> |
|-------------|---------------|---------------|--------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Zn    | Al          | Fe    | Ni    | Pb    | As            | Mg     | Mn    | P     | Others |
|-------------|-------|-------------|-------|-------|-------|---------------|--------|-------|-------|--------|
| 76.0...79.0 | >18.2 | 1.80...2.30 | <0.07 | <0.10 | <0.07 | 0.020...0.035 | <0.005 | <0.10 | <0.01 | <0.10  |

#### International comparison of standards

|                       |  |             |                  |  |            |
|-----------------------|--|-------------|------------------|--|------------|
| Euronorm              |  |             | ISO              |  |            |
| EN 12452 : 1999       |  | EN 1652     | ISO 426-1 : 1983 |  | ISO 1634-2 |
| EN 12167              |  | EN 1653     | ISO 1635-2       |  |            |
| EN 12451              |  | EN 12449    |                  |  |            |
| Material number (DIN) |  |             | DIN              |  |            |
| 2.0460                |  |             | DIN 17660 : 1983 |  | DIN 17672- |
|                       |  |             | DIN 17670-1      |  | DIN 17679  |
|                       |  |             | DIN 17673-1      |  | DIN 1785   |
| Japan                 |  |             | Russia           |  |            |
| C 6870                |  | JIS H 3300  | LAMs77-2-0,05    |  | GOST 15527 |
| JIS H 3300 : 1992     |  |             |                  |  |            |
| USA                   |  |             |                  |  |            |
| ASTM                  |  |             | UNS standard     |  |            |
| ASTM B111             |  | ASTM B359 M | C68700           |  |            |
| ASTM B543             |  |             |                  |  |            |
| ASTM B956             |  |             |                  |  |            |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

Flow curves

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                    |                 | 158.2          |                      | 442.1              |                 |
| A                                      |                 | 6096.377       |                      | 868.432            |                 |
| Effect of temperature $K_8$            |                 |                |                      |                    |                 |
| $m_1$                                  |                 | −0.00485       |                      | −0.00141           |                 |
| Effect of strain $K_\varphi$           |                 |                |                      |                    |                 |
| $m_2$                                  |                 | 0.28723        |                      | 0.35672            |                 |
| $m_4$                                  |                 | 0.01266        |                      | 0.01477            |                 |
| $m_5$                                  |                 | −0.00066       |                      |                    |                 |
| $m_7$                                  |                 | −0.30626       |                      |                    |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.01127            |                 |
| $m_8$                                  |                 | 0.000219       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                       |                 | 600 ... 900    |                      | 20 ... 300         |                 |
| $\varphi$                              |                 | 0.03 ... 1.50  |                      | 0.03 ... 1.25      |                 |
| $\dot{\varphi}$ [1/s]                  |                 | <100           |                      | <100               |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

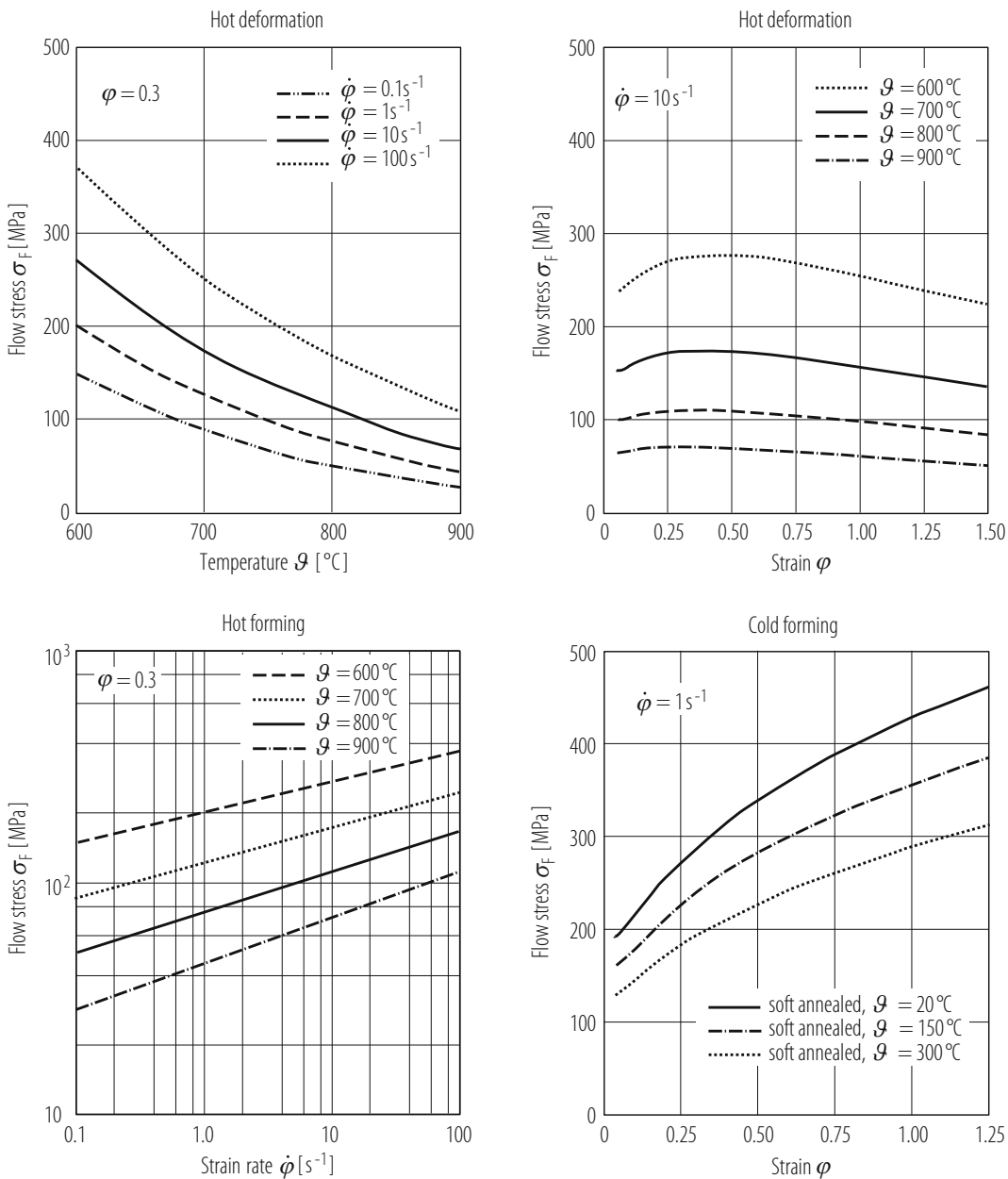


Fig. 5.35 Flow stress curves of CuZn20Al2As by hot and cold forming.

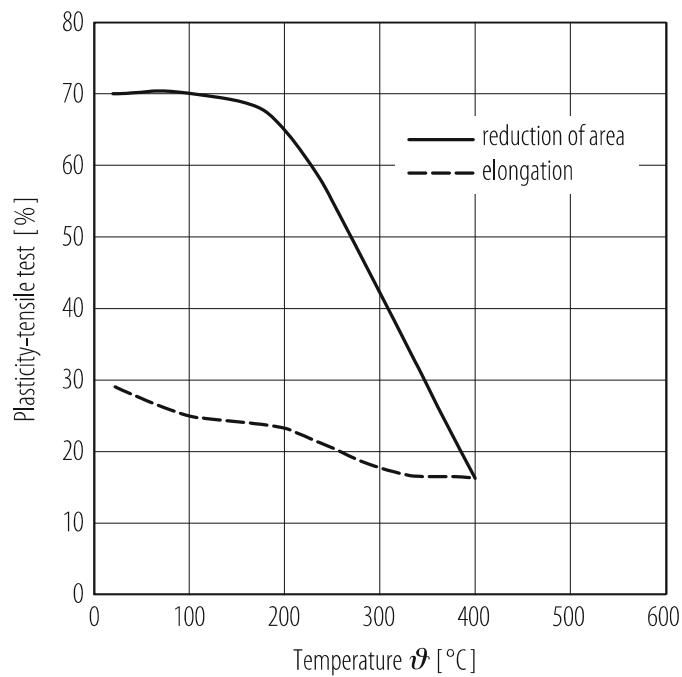
Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |          |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|----------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$      | $n_2$   |
| recrystallised    | 180...210                       | 56.94125 | 0.56798 | 380...420                           | 10.73844 | 0.85176 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| recrystallised    | 50...55                                 | 21.20867 | 0.22922 | -5.67951 | <60                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

## Plasticity in tensile test



**Fig. 5.36** Plasticity of CuZn<sub>20</sub>Al<sub>2</sub>As as a function of the temperature.

## Physical properties

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [10 <sup>-6</sup> /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                              | 102.5                                     | 373.5                                   | 16.84                                                                          | 8354.9                                 | 110.0                        |
| 100                             | 112.6                                     | 379.5                                   | 17.46                                                                          | 8333.7                                 | 107.0                        |
| 200                             | 125.1                                     | 387.0                                   | 18.24                                                                          | 8305.1                                 | 94.0                         |
| 300                             | 137.7                                     | 394.5                                   | 19.03                                                                          | 8274.1                                 | 79.0                         |
| 400                             | 150.3                                     | 402.0                                   | 19.81                                                                          | 8240.8                                 | 59.0                         |
| 500                             | 162.9                                     | 409.5                                   | 20.59                                                                          | 8205.1                                 |                              |
| 600                             | 175.4                                     | 416.9                                   | 21.37                                                                          | 8167.0                                 |                              |
| 700                             | 188.0                                     | 424.4                                   | 22.15                                                                          | 8126.6                                 |                              |
| 800                             | 200.6                                     | 431.9                                   | 22.94                                                                          | 8083.9                                 |                              |
| 900                             | 213.1                                     | 439.4                                   | 23.72                                                                          | 8038.8                                 |                              |

## Symbols and Abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |

(continued)



# Flow stress and physical properties of CuZn<sub>28</sub>Sn<sub>1</sub>As

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |               |               |                    |            |               |
|-------------|---------------|---------------|--------------------|------------|---------------|
| UNS number: | <b>C44300</b> | Chem. symbol: | <b>CuZn28Sn1As</b> | EN number: | <b>CW706R</b> |
|-------------|---------------|---------------|--------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Zn   | Sn        | Fe    | Ni    | Pb    | As            | Mg     | P     | Others |
|-------------|------|-----------|-------|-------|-------|---------------|--------|-------|--------|
| 70.0...72.5 | Bal. | 1.0...2.0 | <0.07 | <0.10 | <0.05 | 0.020...0.060 | <0.005 | <0.01 | <0.10  |

#### International comparison of standards

| Euronorm              |              | ISO              |             |
|-----------------------|--------------|------------------|-------------|
| EN 12451 : 1999       | EN 1652      | ISO 426-1 : 1983 | ISO 1635-2  |
|                       |              | ISO 1634-2       |             |
| Material number (DIN) |              | DIN              |             |
| 2.0470                |              | DIN 17660 : 1983 | DIN 17670-1 |
|                       |              | DIN 17679        | DIN 1785    |
| Japan                 |              | Russia           |             |
| C 4430                | JIS H 3300   | LO62-1           | GOST 15527  |
| JIS H 3320 : 1992     | JIS H 3100   |                  |             |
| JIS H 3320            |              |                  |             |
| USA                   |              | UNS standard     |             |
| ASTM                  |              | C44300           |             |
| ASTM B 111            | ASTM B 111 M |                  |             |
| ASTM B 171            | ASTM B 171 M |                  |             |
| ASTM B 432            | ASTM B 135 M |                  |             |
| ASTM B 359 M          | ASTM B 395 M |                  |             |
| ASTM B 543 M          | ASTM B 956   |                  |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

Flow curves

| State of material                         | Hot deformation |                | Cold deformation   |                 |
|-------------------------------------------|-----------------|----------------|--------------------|-----------------|
|                                           | cast state      | deformed state | soft annealed (sa) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 140.4          |                    | 384.6           |
| A                                         |                 | 4028.503       |                    | 753.459         |
| Effect of temperature $K_{\vartheta}$     |                 |                |                    |                 |
| $m_1$                                     |                 | −0.00629       |                    | −0.00154        |
| Effect of strain $K_{\varphi}$            |                 |                |                    |                 |
| $m_2$                                     |                 | −0.29515       |                    | 0.28571         |
| $m_4$                                     |                 | −0.02223       |                    | −0.00081        |
| $m_5$                                     |                 | 0.0049         |                    |                 |
| $m_7$                                     |                 | −1.61775       |                    |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                    |                 |
| $m_3$                                     |                 |                |                    | 0.010074        |
| $m_8$                                     |                 | 0.000263       |                    |                 |
| Range of validity                         |                 |                |                    |                 |
| $\vartheta$ [°C]                          |                 | 600 ... 900    |                    | 20 ... 300      |
| $\varphi$                                 |                 | 0.03 ... 1.00  |                    | 0.03 ... 2.00   |
| $\dot{\varphi}$ [1/s]                     |                 | <100           |                    | <100            |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

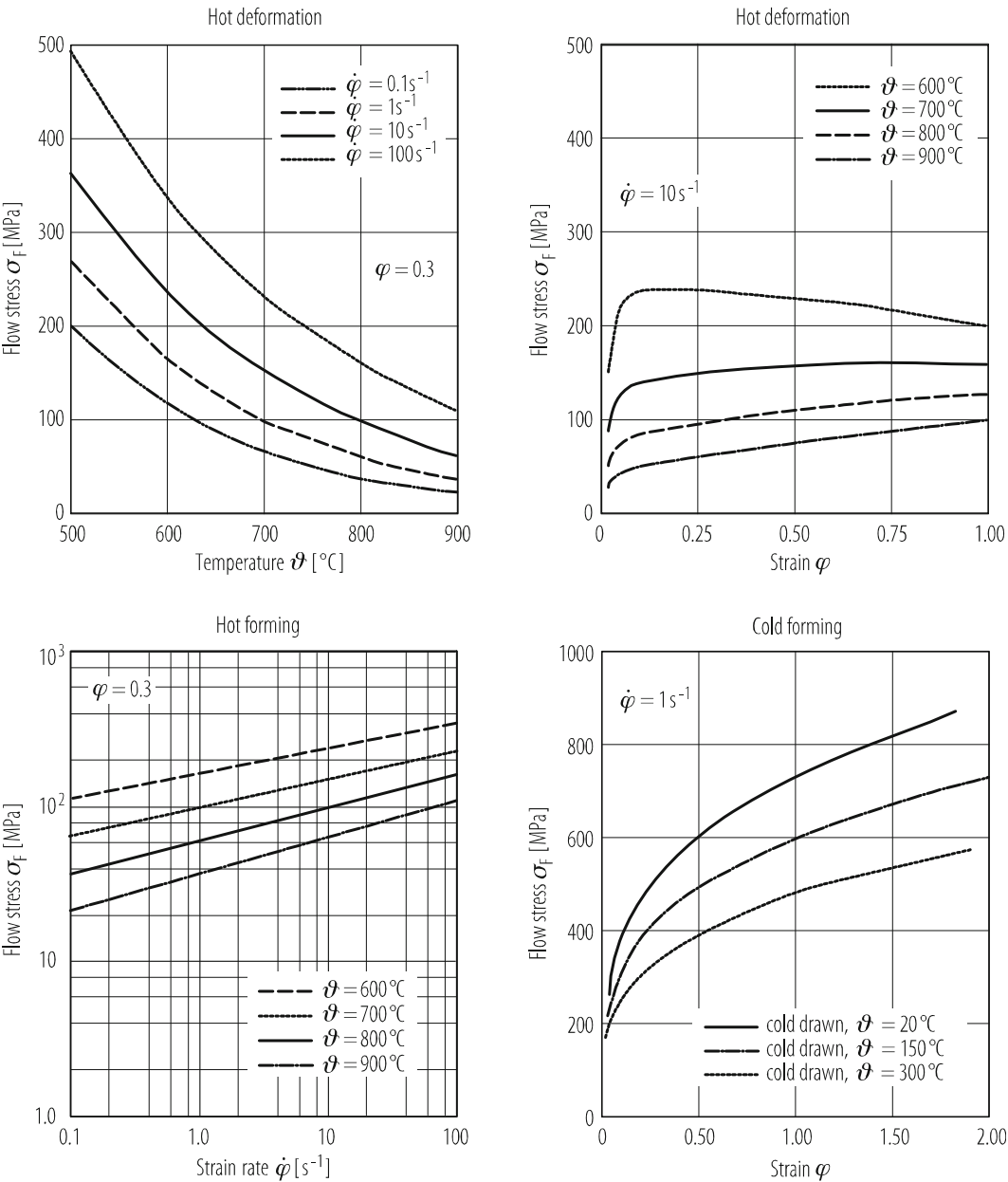
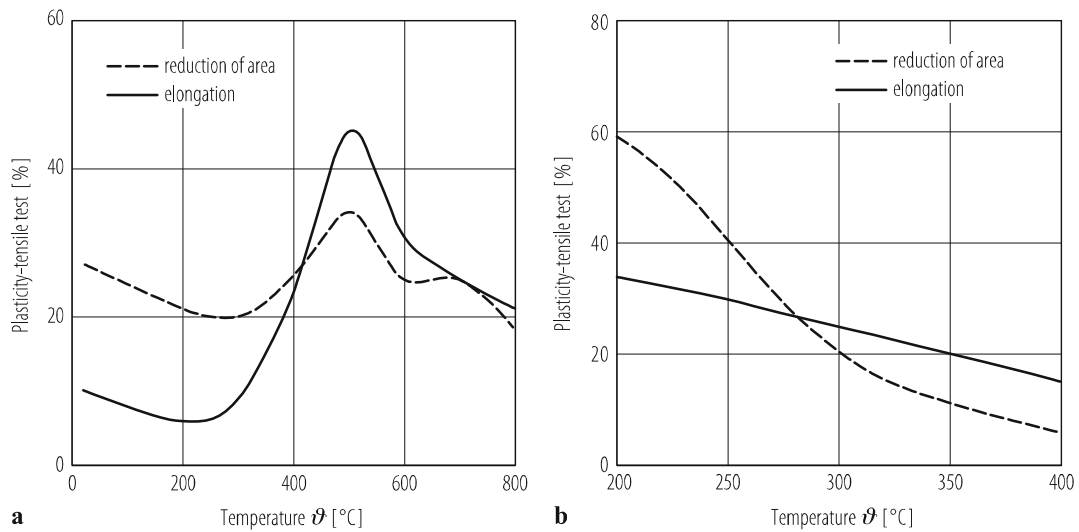


Fig. 5.37 Flow stress curves of CuZn<sub>28</sub>Sn<sub>1</sub>As by hot and cold forming.

### Plasticity in tensile test



**Fig. 5.38** Plasticity of  $\text{CuZn}_{28}\text{Sn}_1\text{As}$  as a function of the temperature. a.) Plasticity by cold and hot forming b.) Plasticity at middle temperature

### Physical properties

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}/\text{K}$ ] | Density<br>$\rho$ [ $\text{kg}/\text{m}^3$ ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|---------------------------------------------------------------------------------|----------------------------------------------|------------------------------|
| 20                              | 110.8                                     | 376.5                                   | 17.81                                                                           | 8494.5                                       | 110.0                        |
| 100                             | 118.2                                     | 382.5                                   | 18.31                                                                           | 8472.0                                       | 107.0                        |
| 200                             | 127.4                                     | 390.0                                   | 18.93                                                                           | 8442.1                                       | 94.0                         |
| 300                             | 136.5                                     | 397.5                                   | 19.56                                                                           | 8410.2                                       | 79.0                         |
| 400                             | 145.7                                     | 405.0                                   | 20.18                                                                           | 8376.5                                       | 59.0                         |
| 500                             | 154.9                                     | 412.5                                   | 20.80                                                                           | 8340.9                                       |                              |
| 600                             | 164.1                                     | 419.9                                   | 21.42                                                                           | 8303.3                                       |                              |
| 700                             | 173.3                                     | 427.4                                   | 22.04                                                                           | 8263.9                                       |                              |
| 800                             | 182.4                                     | 434.9                                   | 22.67                                                                           | 8222.6                                       |                              |
| 900                             | 191.6                                     | 442.4                                   | 23.29                                                                           | 8179.3                                       |                              |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| GOST            | gosudarstvennyy standart (state standard)                             |
| ISO             | international organisation for standardization                        |
| JIS             | Japanese Industrial Standards                                         |
| $T, \vartheta$  | Temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, mechanical and physical properties of CuZn<sub>38</sub>Pb<sub>2</sub>

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |               |                  |            |               |
|-------------|---------------|------------------|------------|---------------|
| UNS number: | Chem. symbol: | <b>CuZn38Pb2</b> | EN number: | <b>CW608N</b> |
|-------------|---------------|------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Zn    | Pb          | Al    | Fe    | Ni    | Sn    | Others |
|-------------|-------|-------------|-------|-------|-------|-------|--------|
| 59.5...61.5 | >35.5 | 1.00...2.00 | <0.05 | <0.30 | <0.30 | <0.20 | <0.20  |

#### International comparison of standards

| Euronorm              |          | ISO              |                 |
|-----------------------|----------|------------------|-----------------|
| EN 12168 : 1998       | EN 1652  | CuZn37Pb2        | ISO 1634-1      |
| EN 12164              | EN 12165 | ISO 426-2 : 1983 | ISO 1637        |
| EN 12167              | EN 12168 | ISO 1638         | ISO 1639        |
| EN 12166              | EN 12449 | ISO 1635         | ISO 1640        |
| Material number (DIN) |          | DIN              |                 |
| 2.0371                |          | DIN 17660 : 1983 | DIN 17670-1     |
|                       |          | DIN 17672-1      | DIN 17677-1     |
| Japan                 |          | Russia           |                 |
|                       |          | LS60-2           | GOST 15527 - 70 |
| USA                   |          |                  |                 |
| ASTM                  |          | UNS standard     |                 |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material           | Hot deformation |                | Cold deformation     |                    |                 |
|-----------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                             | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]         |                 | 31.89          |                      | 368.0              |                 |
| A                           |                 | 4012.010       |                      | 748.070            |                 |
| Effect of temperature $K_9$ |                 |                |                      |                    |                 |
| $m_1$                       |                 | -0.00678       |                      | -0.00163           |                 |
| Effect of strain $K_q$      |                 |                |                      |                    |                 |
| $m_2$                       |                 | 0.32862        |                      | 0.35631            |                 |
| $m_4$                       |                 | 0.01704        |                      | 0.0112             |                 |
| $m_5$                       |                 | -0.00151       |                      |                    |                 |
| $m_7$                       |                 | 0.16114        |                      |                    |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.01326            |                 |
| $m_8$                                  |                 | 0.000361       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                       |                 | 600 ... 850    |                      | 20 ... 350         |                 |
| $\varphi$                              |                 | 0.03 ... 1.25  |                      | 0.03 ... 2,0       |                 |
| $\dot{\varphi}$ [1/s]                  |                 | <100           |                      | <100               |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

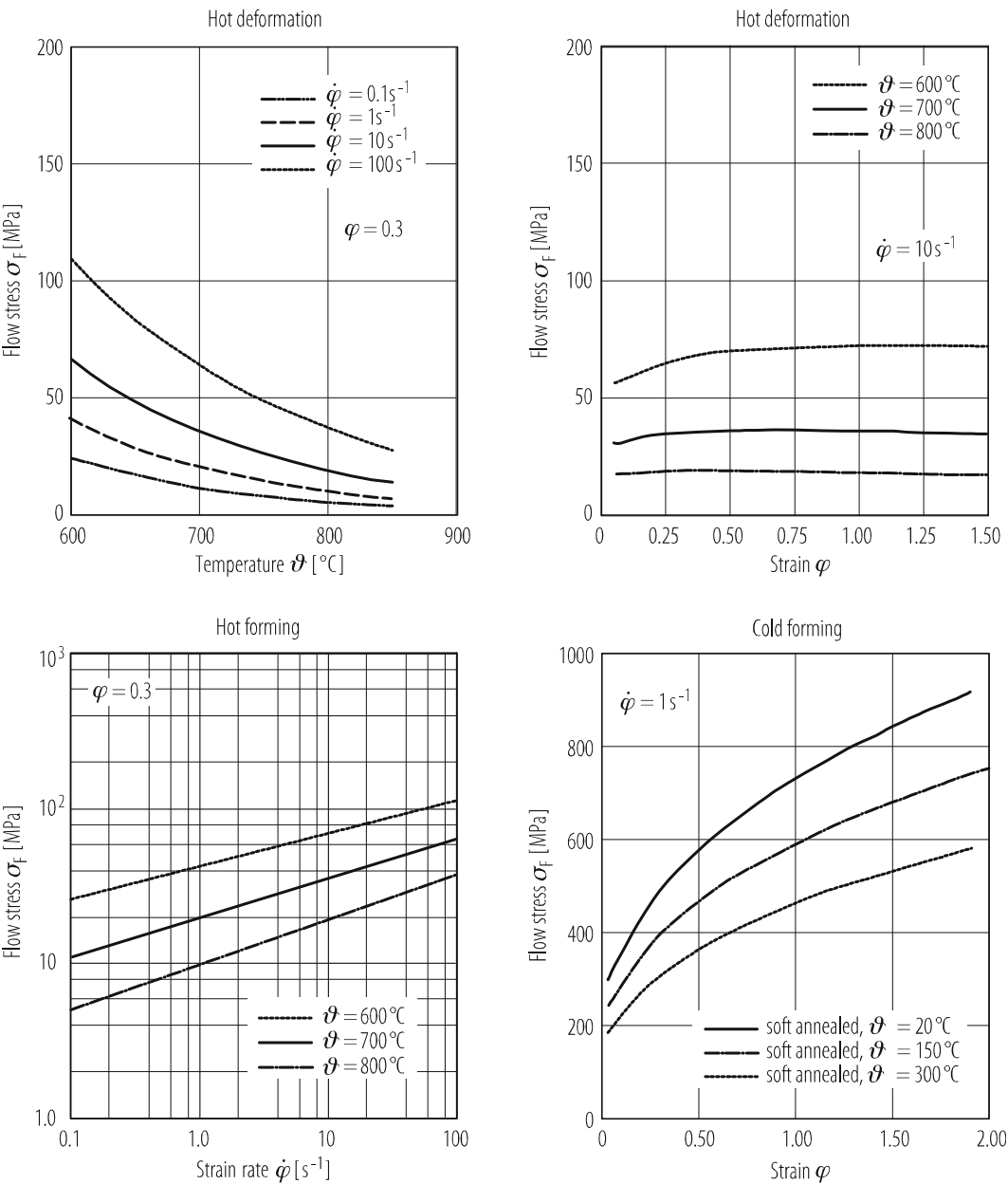


Fig. 5.39 Flow stress curves of CuZn38Pb2 by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |          |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|----------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$      | $n_2$   |
| soft annealed     | 150...200                       | 63.19214 | 0.50661 | 340...380                           | 12.26047 | 0.80682 |

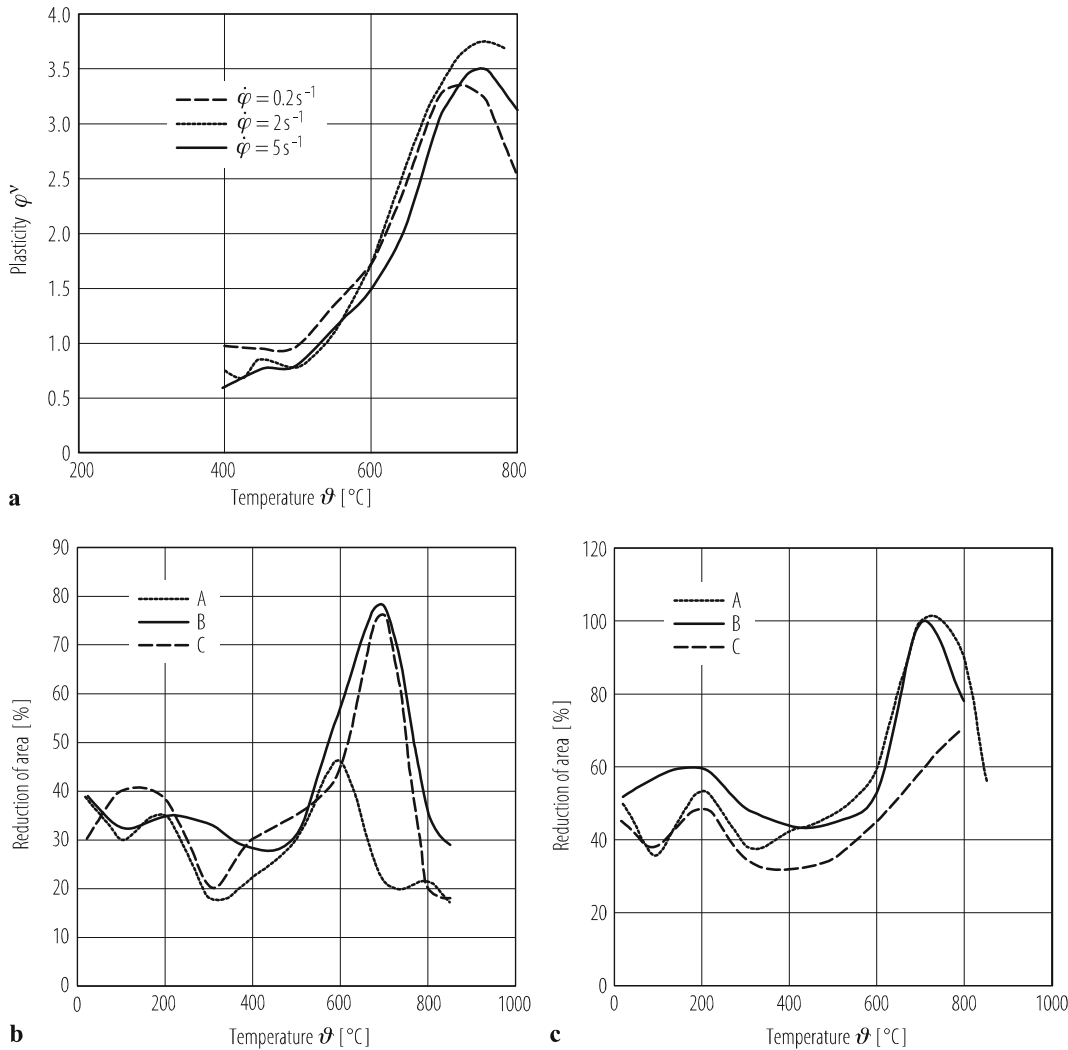
  

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| soft annealed     | 45...50                                 | 33.10916 | 0.13052 | -8.61935 | <70                        |



| Yield stress:                        | Tensile strength:                    | Elongation to fracture                                      |
|--------------------------------------|--------------------------------------|-------------------------------------------------------------|
| $R_p = A_0 + A \cdot \epsilon^{n_1}$ | $R_m = B_0 + B \cdot \epsilon^{n_2}$ | $A_5 = C_0 - C \cdot \epsilon^{n_3} \cdot e^{n_4/\epsilon}$ |
| [Equation (4.1), Chapter 5.1.4]      | [Equation (4.2), Chapter 5.1.4]      | [Equation (4.3), Chapter 5.1.4]                             |
| [DOI: 978-3-642-14174-4_5]           | [DOI: 978-3-642-14174-4_5]           | [DOI: 978-3-642-14174-4_5]                                  |

Plasticity in torsion and tensile test



**Fig. 5.40** Plasticity of CuZn<sub>38</sub>Pb<sub>2</sub> as a function of the temperature. Charge A: 1.2 [%] Pb; Charge B: 1.16 [%] Pb, 0.34 [%] Ni; 0.12 [%] Si, 0.11 [%] Mn; Charge C: 1.11 [%] Pb, 0.25 [%] Ni, 0.01 [%] Si. (a) Initial test: cast. (b) Initial test: cast. (c) Initial test: deformed.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 108.6                | 377.5              | 19.31                                   | 8434.1                      | 102.0           |
| 100              | 119.2                | 383.5              | 19.81                                   | 8409.9                      | 96.0            |
| 200              | 132.3                | 391.0              | 20.43                                   | 8377.9                      | 83.0            |
| 300              | 145.5                | 398.5              | 21.06                                   | 8344.0                      | 69.0            |
| 400              | 158.7                | 406.0              | 21.68                                   | 8308.3                      |                 |
| 500              | 171.8                | 413.5              | 22.30                                   | 8270.6                      |                 |
| 600              | 185.0                | 420.9              | 22.92                                   | 8231.1                      |                 |
| 700              | 198.2                | 428.4              | 23.54                                   | 8189.6                      |                 |
| 800              | 211.3                | 435.9              | 24.17                                   | 8146.3                      |                 |

## Symbols and Abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuZn<sub>39</sub>Pb<sub>2</sub>

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |               |                  |            |               |
|-------------|---------------|------------------|------------|---------------|
| UNS number: | Chem. symbol: | <b>CuZn39Pb2</b> | EN number: | <b>CW612N</b> |
|-------------|---------------|------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Zn    | Pb          | Al    | Fe    | Ni    | Sn    | Others |
|-------------|-------|-------------|-------|-------|-------|-------|--------|
| 58.5...60.0 | >36.3 | 1.50...2.50 | <0.10 | <0.40 | <0.30 | <0.20 | <0.20  |

#### International comparison of standards

| Euronorm              |          | ISO              |
|-----------------------|----------|------------------|
| EN 12164 : 1998       | EN 1652  |                  |
| EN 12165              | EN 12167 |                  |
| EN 12166              |          |                  |
| Material number (DIN) |          | DIN              |
| 2.0380                |          | DIN 17660 : 1983 |
|                       |          | DIN 17672-1      |
|                       |          | DIN 17673-1      |
| Japan                 |          | Russia           |
| USA                   |          |                  |
| ASTM                  |          | UNS standard     |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material           | Hot deformation |                | Cold deformation   |                 |
|-----------------------------|-----------------|----------------|--------------------|-----------------|
|                             | cast state      | deformed state | soft annealed (sa) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]         |                 | 35.7           | 370.2              | 424.4           |
| A                           |                 | 530.270        | 766.171            | 804.423         |
| Effect of temperature $K_9$ |                 |                |                    |                 |
| $m_1$                       |                 | −0.00475       | −0.00153           | −0.00163        |
| Effect of strain $K_\phi$   |                 |                |                    |                 |
| $m_2$                       |                 | −0.06368       | 0.29912            | 0.29721         |
| $m_4$                       |                 | −0.00637       | −0.00349           | 0.00481         |
| $m_5$                       |                 | −0.00037       |                    |                 |
| $m_7$                       |                 | 0.10204        |                    |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation   |                 |
|----------------------------------------|-----------------|----------------|--------------------|-----------------|
|                                        | cast state      | deformed state | soft annealed (sa) | cold drawn (cd) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                    |                 |
| $m_3$                                  |                 |                | 0.01109            | 0.01236         |
| $m_8$                                  |                 | 0.000347       |                    |                 |
| Range of validity                      |                 |                |                    |                 |
| $\vartheta$ [°C]                       |                 | 500 ... 850    | 20 ... 300         | 20 ... 300      |
| $\varphi$                              |                 | 0.03 ... 1.50  | 0.03 ... 2.00      | 0.03 ... 2.00   |
| $\dot{\varphi}$ [1/s]                  |                 | <10            | <100               | <100            |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

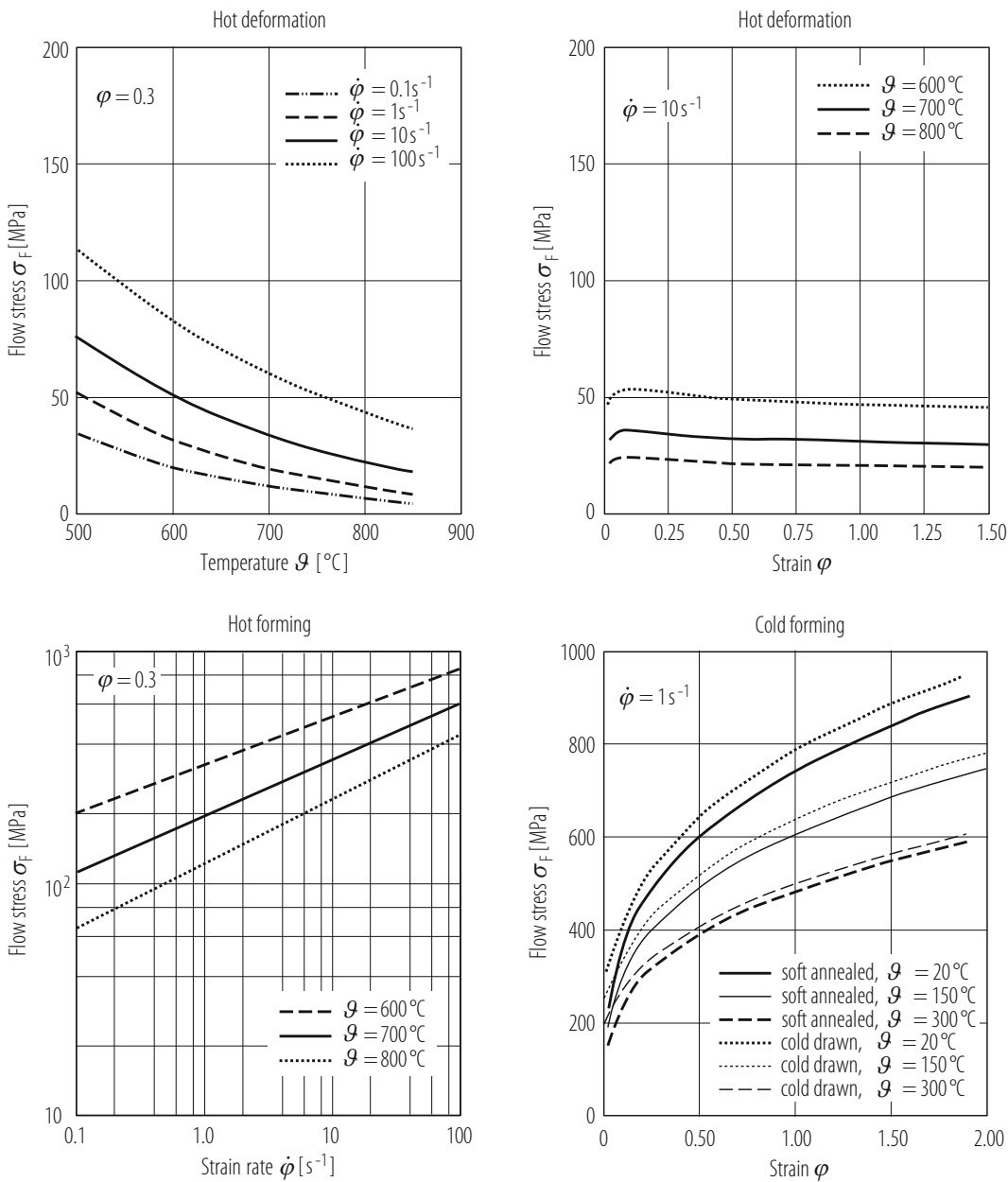


Fig. 5.41 Flow stress curves of CuZn39Pb2 by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| soft annealed     | 180...240                       | 23.13670 | 0.74065 | 360...400                           | 5.23036 | 1.01548 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |        |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|--------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$  | $n_4$   |                            |
| soft annealed     | 35...45                                 | 9.83149 | 0.3601 | -4.6797 | <60                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                                      |
|-----------------------------------------|-----------------------------------------|-----------------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot \varepsilon^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                             |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                                  |

Plasticity in tensile test

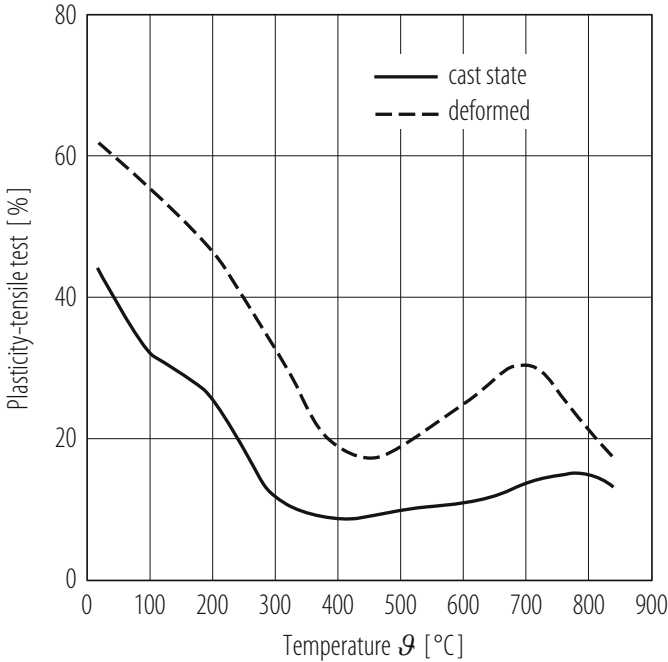


Fig. 5.42 Plasticity of CuZn<sub>39</sub>Pb<sub>2</sub> as a function of the temperature.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 115.6                | 377.1              | 19.28                                   | 8439.1                      | 102.0           |
| 100              | 134.4                | 383.3              | 19.78                                   | 8414.9                      |                 |
| 200              | 143.3                | 391.2              | 20.40                                   | 8383.0                      |                 |
| 300              | 148.9                | 399.0              | 21.03                                   | 8349.1                      |                 |
| 400              | 152.9                | 406.9              | 21.65                                   | 8313.4                      |                 |
| 500              | 156.1                | 414.7              | 22.27                                   | 8275.7                      |                 |
| 600              | 158.8                | 422.5              | 22.89                                   | 8236.2                      |                 |
| 700              | 161.1                | 430.4              | 23.51                                   | 8194.8                      |                 |
| 800              | 163.1                | 438.2              | 24.14                                   | 8151.5                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| UNS                 | unified numbering system                                              |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| ASTM                | American society for testing and materials                            |
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $R_p$               | yield stress                                                          |
| $R_m$               | tensile strength                                                      |
| $\lambda$           | thermal conductivity                                                  |
| $c_{pm}$            | mean specific heat                                                    |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\rho$              | density                                                               |
| $E$                 | Young's modulus                                                       |
| $A, B, C$ and $n_i$ | constants                                                             |
| $A_5$               | elongation to fracture                                                |
| $T, \vartheta$      | temperature                                                           |

# Flow stress, mechanical and physical properties of CuZn<sub>39</sub>Pb<sub>3</sub>

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|             |               |               |                  |            |               |
|-------------|---------------|---------------|------------------|------------|---------------|
| UNS number: | <b>C38500</b> | Chem. symbol: | <b>CuZn39Pb3</b> | EN number: | <b>CW614N</b> |
|-------------|---------------|---------------|------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Zn    | Pb          | Al    | Fe    | Ni    | Sn    | Others |
|-------------|-------|-------------|-------|-------|-------|-------|--------|
| 57.0...59.0 | >35.8 | 2.50...3.50 | <0.10 | <0.50 | <0.50 | <0.20 | <0.20  |

#### International comparison of standards

| Euronorm              |           | ISO              |             |
|-----------------------|-----------|------------------|-------------|
| EN 12164 : 1998       | EN 12165  | ISO 426-2 : 1983 | ISO 1635    |
| EN 12167              | EN 12168  | ISO 1637         | ISO 1638    |
| EN 12449              | EN 12166  | ISO 1639         | ISO 1640    |
| Material number (DIN) |           | DIN              |             |
| 2.0401                |           | DIN 17660 : 1983 | DIN 17671-  |
|                       |           | DIN 17672-1      | DIN 17677-1 |
|                       |           | DIN 17674-1      | DIN 17678-1 |
| Japan                 |           | Russia           |             |
| USA                   |           |                  |             |
| ASTM                  |           | UNS standard     |             |
| ASTM B455             | ASTM B981 | C38500           |             |
| ASTM B249             |           |                  |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

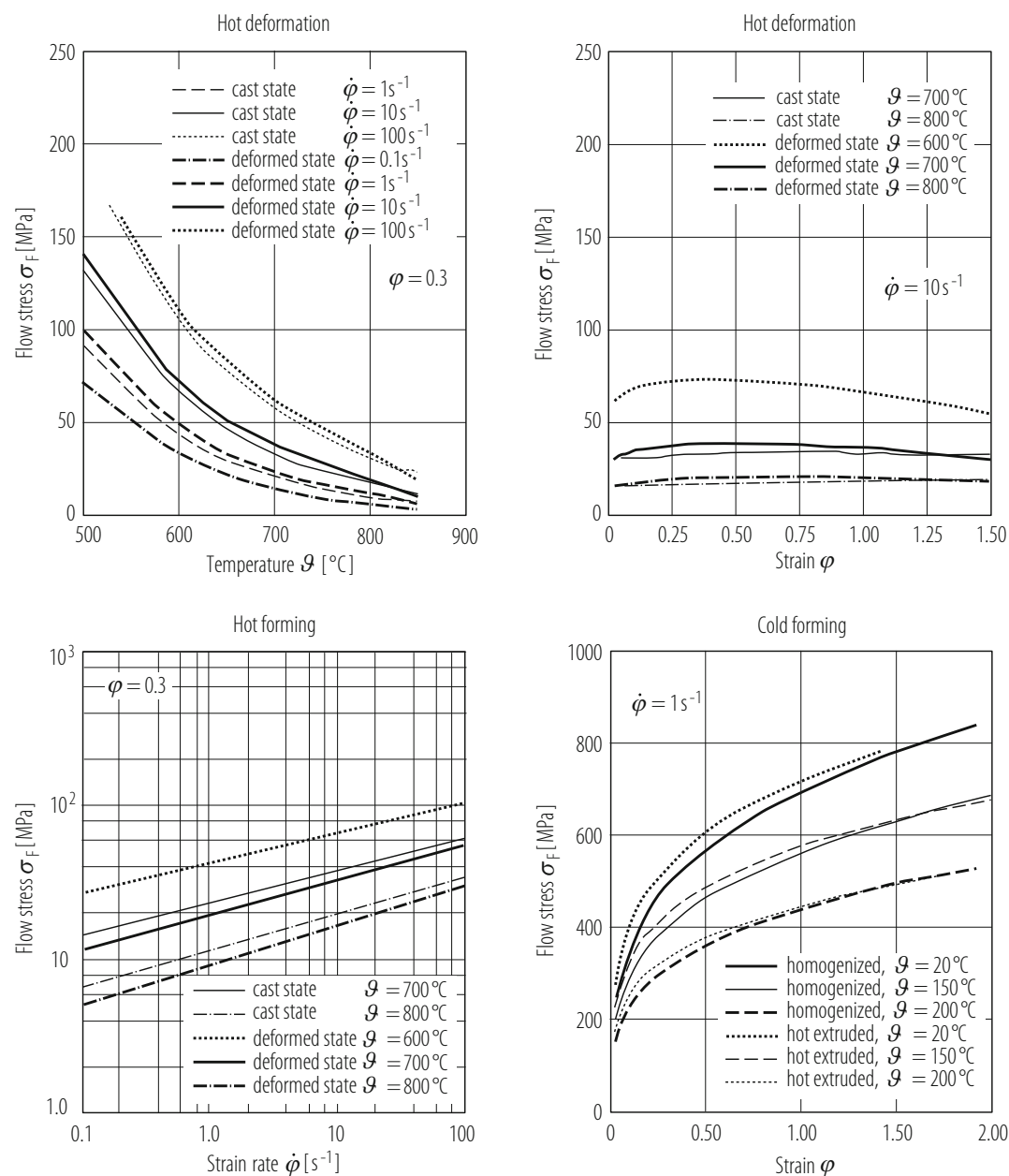
| State of material           | Hot deformation |                | Cold deformation  |                   |
|-----------------------------|-----------------|----------------|-------------------|-------------------|
|                             | cast state      | deformed state | homogenized (hom) | hot extruded (he) |
| $\sigma_{F0}$ [MPa]         | 31.7            | 34.3           | 364.9             | 419.4             |
| A                           | 5256.095        | 5304.702       | 717.15            | 741.347           |
| Effect of temperature $K_8$ |                 |                |                   |                   |
| $m_1$                       | -0.00826        | -0.00772       | -0.00161          | -0.00168          |
| Effect of strain $K_\phi$   |                 |                |                   |                   |
| $m_2$                       | -0.03498        | 0.05924        | 0.28476           | 0.23918           |
| $m_4$                       | 0.00062         | -0.00021       | -0.00116          | -0.00326          |
| $m_5$                       | 0.00229         | 0.00141        |                   |                   |
| $m_7$                       | -0.903916       | -0.87925       |                   |                   |

(continued)



| State of material                      | Hot deformation |                | Cold deformation  |                   |
|----------------------------------------|-----------------|----------------|-------------------|-------------------|
|                                        | cast state      | deformed state | homogenized (hom) | hot extruded (he) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                   |                   |
| $m_3$                                  |                 |                | 0.00987           | 0.01004           |
| $m_8$                                  | 0.000324        | 0.000295       |                   |                   |
| Range of validity                      |                 |                |                   |                   |
| $\vartheta$ [°C]                       | 500 ... 850     | 500 ... 850    | 20 ... 300        | 20 ... 300        |
| $\varphi$                              | 0.03 ... 1.50   | 0.03 ... 1.50  | 0.03 ... 2.00     | 0.03 ... 1.50     |
| $\dot{\varphi}$ [1/s]                  | <100            | <100           | <100              | <100              |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |



**Fig. 5.43** Flow stress curves of CuZn<sub>39</sub>Pb<sub>3</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| soft annealed     | 180...240                       | 75.58441 | 0.34712 | 360...400                           | 6.73825 | 0.93816 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |        | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|--------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$  |                            |
| soft annealed     | 40...45                                 | 15.11821 | 0.28734 | -7.369 | <70                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in torsion test

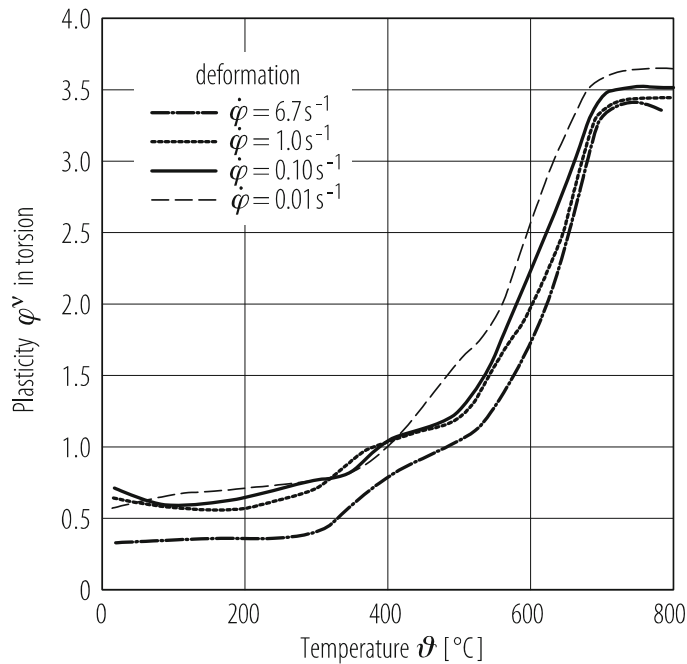


Fig. 5.44 Plasticity of CuZn<sub>39</sub>Pb<sub>3</sub> as a function of the temperature

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 107.1                | 377.1              | 19.19                                   | 8504.1                      | 111.0           |
| 100              | 122.4                | 383.3              | 19.76                                   | 8479.7                      | 108.0           |
| 200              | 129.7                | 391.2              | 20.47                                   | 8447.3                      | 104.0           |
| 300              | 134.2                | 399.0              | 21.17                                   | 8412.7                      | 99.0            |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 400              | 137.4                | 406.9              | 21.88                                   | 8375.9                      |                 |
| 500              | 140.0                | 414.7              | 22.59                                   | 8337.0                      |                 |
| 600              | 142.2                | 422.5              | 23.30                                   | 8295.9                      |                 |
| 700              | 144.0                | 430.4              | 24.01                                   | 8252.6                      |                 |
| 800              | 145.6                | 438.2              | 24.71                                   | 8207.1                      |                 |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| UNS                 | unified numbering system                                              |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| ASTM                | American society for testing and materials                            |
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $R_p$               | yield stress                                                          |
| $R_m$               | tensile strength                                                      |
| $\lambda$           | thermal conductivity                                                  |
| $c_{pm}$            | mean specific heat                                                    |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\rho$              | density                                                               |
| $E$                 | Young's modulus                                                       |
| $A, B, C$ and $n_i$ | constants                                                             |
| $A_5$               | elongation to fracture                                                |
| $T, \vartheta$      | temperature                                                           |

# Flow stress and physical properties of CuZn<sub>35</sub>Ni<sub>3</sub>Mn<sub>2</sub>AlPb

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|            |               |                         |            |               |
|------------|---------------|-------------------------|------------|---------------|
| UNS number | Chem. symbol: | <b>CuZn35Ni3Mn2AlPb</b> | EN number: | <b>CW710R</b> |
|------------|---------------|-------------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Zn           | Ni          | Al          | Fe    | Mn          | Pb    | Sn    |
|-------------|--------------|-------------|-------------|-------|-------------|-------|-------|
| 57.0...62.0 | 33.50...35.0 | 2.80...3.20 | 0.30...1.50 | <0.50 | 1.50...2.50 | <0.80 | <0.50 |

#### International comparison of standards

| Euronorm              |          | ISO              |
|-----------------------|----------|------------------|
| CEN/TS 13388 : 2003   | EN 12163 |                  |
| EN 12165              | EN 12420 |                  |
| EN 12167              | EN 12449 |                  |
| Material number (DIN) |          | DIN              |
| 2.0540                |          | DIN 17660 : 1983 |
|                       |          | DIN 17671-1      |
|                       |          | DIN 17673-1      |
| Japan                 |          | Russia           |
| USA                   |          |                  |
| ASTM                  |          | UNS standard     |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

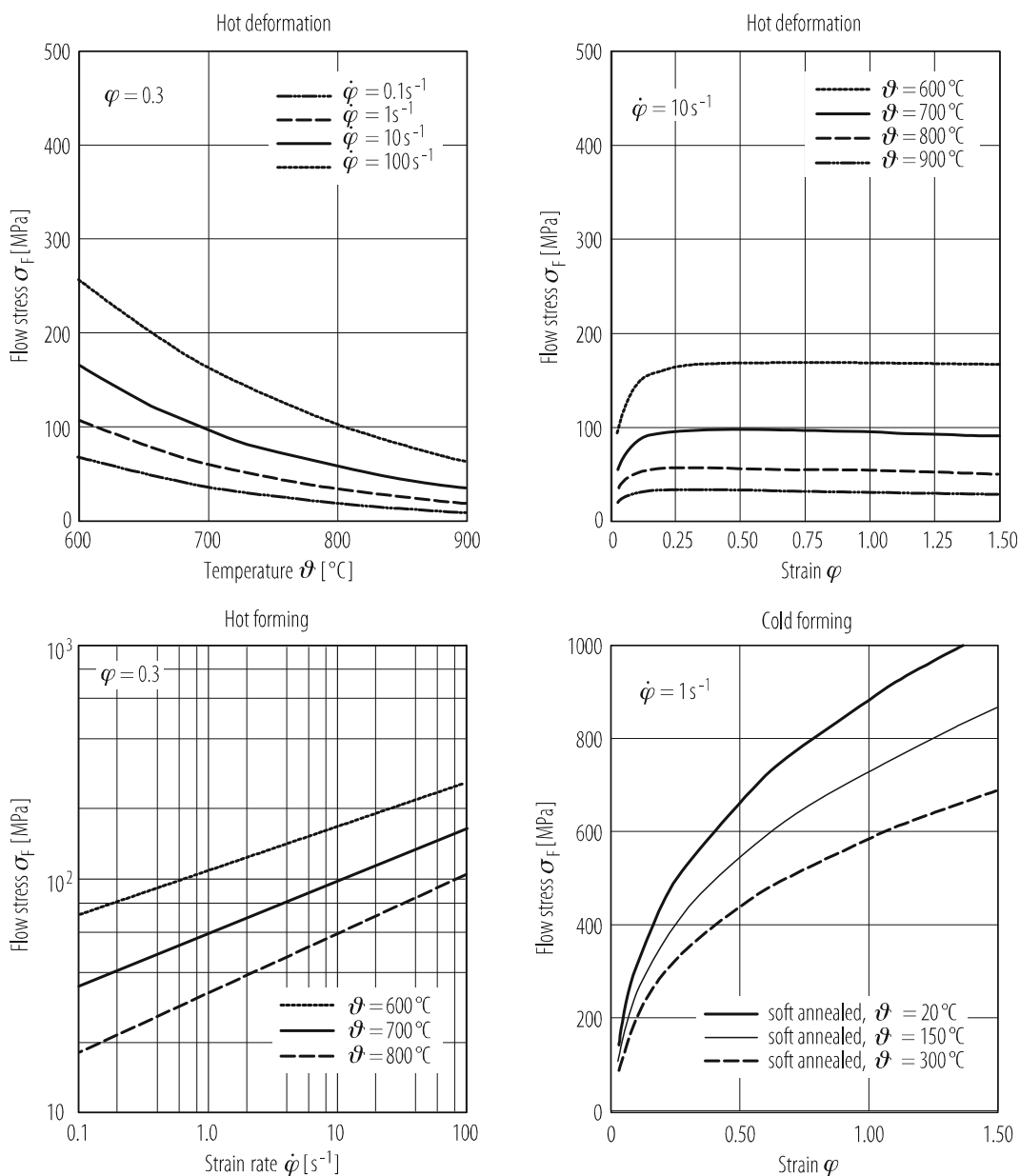
#### Flow curves

| State of material                | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                  | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]              |                 | 86.8           |                      | 324.1              |                 |
| A                                |                 | 4512.157       |                      | 923.970            |                 |
| Effect of temperature $K_\theta$ |                 |                |                      |                    |                 |
| $m_1$                            |                 | −0.0058        |                      | −0.00146           |                 |
| Effect of strain $K_\varphi$     |                 |                |                      |                    |                 |
| $m_2$                            |                 | 0.08916        |                      | 0.3926             |                 |
| $m_4$                            |                 | −0.01487       |                      | −0.01395           |                 |
| $m_5$                            |                 | −0.00084       |                      |                    |                 |
| $m_7$                            |                 | 0.11993        |                      |                    |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| m <sub>3</sub>                         |                 |                |                      | 0.00995            |                 |
| m <sub>8</sub>                         |                 | 0.000314       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| θ [°C]                                 |                 | 600 ... 900    |                      | 20 ... 300         |                 |
| φ                                      |                 | 0.03 ... 1.50  |                      | 0.03 ... 1.50      |                 |
| $\dot{\varphi}$ [1/s]                  |                 | <100           |                      | <100               |                 |

|                                                                                                                                                                       |                                                                                                         |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                      | Cold deformation                                                                                        |
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                  | [Equation (2.25), Chapter 2.3.2.2.2]                                                                    |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                            | [DOI: 978-3-642-14174-4_2]                                                                              |



**Fig. 5.45** Flow stress curves of CuZn<sub>35</sub>Ni<sub>3</sub>Mn<sub>2</sub>AlPb by hot and cold forming.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 87.8                 | 376.6              | 18.82                                   | 8284.4                      |                 |
| 100              | 97.1                 | 382.8              | 19.36                                   | 8261.1                      |                 |
| 200              | 108.7                | 390.7              | 20.03                                   | 8230.2                      |                 |
| 300              | 120.3                | 398.5              | 20.69                                   | 8197.4                      |                 |
| 400              | 131.9                | 406.4              | 21.36                                   | 8162.5                      |                 |
| 500              | 143.5                | 414.2              | 22.03                                   | 8125.6                      |                 |
| 600              | 155.1                | 422.0              | 22.70                                   | 8086.8                      |                 |
| 700              | 166.7                | 429.9              | 23.37                                   | 8045.9                      |                 |
| 800              | 178.3                | 437.7              | 24.03                                   | 8003.1                      |                 |
| 850              | 184.1                | 441.6              | 24.37                                   | 7980.9                      |                 |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | Temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |



# Flow stress and physical properties of CuZn<sub>23</sub>Al<sub>6</sub>Mn<sub>4</sub>Fe<sub>3</sub>

## 5.2 Copper- and Copper alloys

### 5.2.2 Copper – Zinc - alloys

#### Designation

|            |               |               |                        |            |               |
|------------|---------------|---------------|------------------------|------------|---------------|
| UNS number | <b>C67000</b> | Chem. symbol: | <b>CuZn23Al6Mn4Fe3</b> | EN number: | <b>CW704R</b> |
|------------|---------------|---------------|------------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Zn    | Pb          | Al        | Fe          | Ni    | Mn        | Sn    | Others |
|-------------|-------|-------------|-----------|-------------|-------|-----------|-------|--------|
| 63.5...65.5 | >19.2 | 0.20...1.00 | 4.5...6.5 | 2.00...3.00 | <0.50 | 3.0...5.0 | <0.25 | <0.10  |

#### International comparison of standards

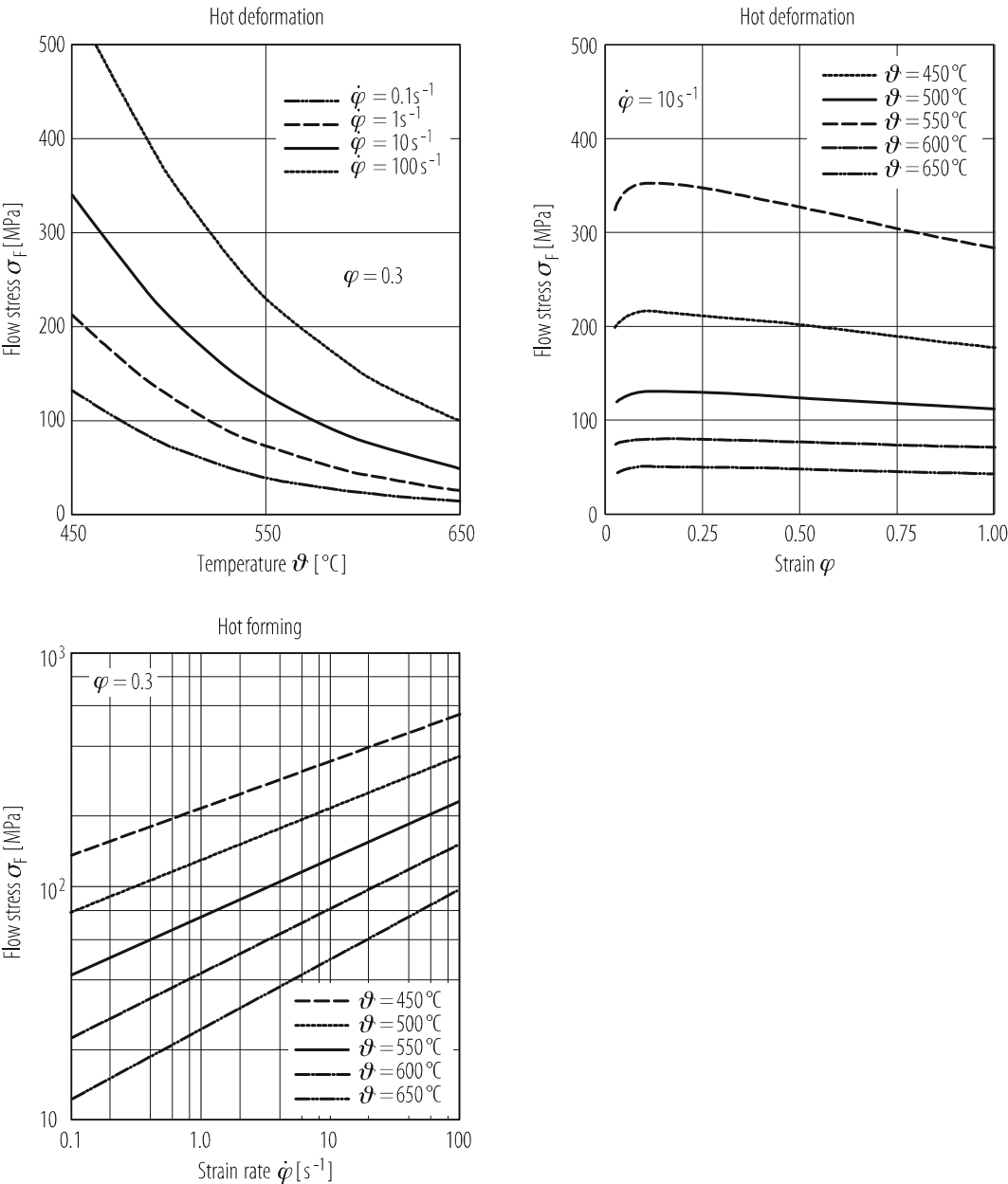
|                       |                  |             |
|-----------------------|------------------|-------------|
| Euronorm              | ISO              |             |
| EN 12165 : 1998       | EN 12163         |             |
| EN 12420              |                  |             |
| Material number (DIN) | DIN              |             |
| 2.0500                | DIN 17660 : 1983 | DIN 17671-1 |
|                       | DIN 17672-1      | DIN 17673-1 |
| Japan                 | Russia           |             |
| USA                   |                  |             |
| ASTM and SAE          | UNS standard     |             |
| ASTM B138             | ASTM B138 M      | C67000      |
| SAE J461              | SAE J463         |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

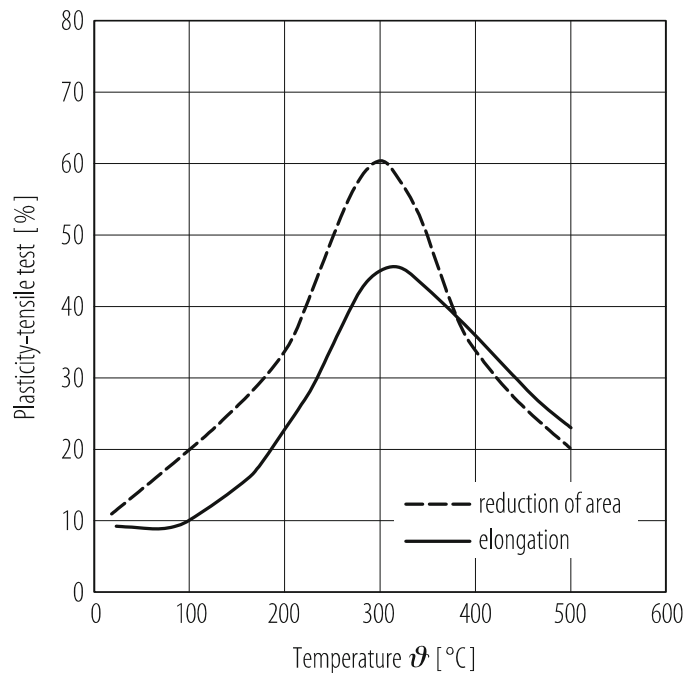
| State of material                         | Hot deformation |                | Cold deformation     |                    |                 |
|-------------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                           | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                       |                 | (29.9)         |                      |                    |                 |
| A                                         |                 | 30393.985      |                      |                    |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                      |                    |                 |
| $m_1$                                     |                 | -0.010977      |                      |                    |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                      |                    |                 |
| $m_2$                                     |                 | -0.02732       |                      |                    |                 |
| $m_4$                                     |                 | -0.00494       |                      |                    |                 |
| $m_5$                                     |                 | 0.0007         |                      |                    |                 |
| $m_7$                                     |                 | -0.42688       |                      |                    |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                      |                    |                 |
| $m_3$                                     |                 |                |                      |                    |                 |
| $m_8$                                     |                 | 0.00046        |                      |                    |                 |
| Range of validity                         |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                          |                 | 450 ... 600    |                      |                    |                 |
| $\varphi$                                 |                 | 0.03 ... 1.0   |                      |                    |                 |
| $\dot{\varphi}$ [1/s]                     |                 | <100           |                      |                    |                 |

|                                                                                                                                                                                |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          |



**Fig. 5.46** Flow stress curves of  $\text{CuZn}_{20}\text{Al}_6\text{Mn}_4\text{Fe}$  by hot and cold forming.

## Plasticity in tensile test



**Fig. 5.47** Cold plasticity of CuZn20Al6Mn4Fe3 as a function of the temperature.

## Physical properties

| Temperature<br>$\theta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                           | 33.5                                      | 377.1                                   | 18.51                                                                    | 7799.8                                 | 105.0                        |
| 100                          |                                           | 383.3                                   | 19.01                                                                    | 7778.3                                 |                              |
| 200                          |                                           | 391.2                                   | 19.63                                                                    | 7749.8                                 |                              |
| 300                          |                                           | 399.0                                   | 20.26                                                                    | 7719.6                                 |                              |
| 400                          |                                           | 406.9                                   | 20.88                                                                    | 7687.7                                 |                              |
| 500                          |                                           | 414.7                                   | 21.50                                                                    | 7654.0                                 |                              |
| 600                          |                                           | 422.5                                   | 22.12                                                                    | 7618.5                                 |                              |
| 700                          |                                           | 430.4                                   | 22.74                                                                    | 7581.3                                 |                              |
| 800                          |                                           | 438.2                                   | 23.37                                                                    | 7542.4                                 |                              |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| EN             | Euronorm                                       |
| ISO            | international organisation for standardization |
| SAE            | society of automotive engineers                |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |

# Flow stress, mechanical and physical properties of CuZn<sub>37</sub>Mn<sub>3</sub>Al<sub>2</sub>PbSi

## 5.2 Copper- and Copper alloys

### 5.2.1 Pure Copper and low alloyed Copper

#### Designation

|            |               |                         |            |               |
|------------|---------------|-------------------------|------------|---------------|
| UNS number | Chem. symbol: | <b>CuZn37Mn3Al2PbSi</b> | EN number: | <b>CW713R</b> |
|------------|---------------|-------------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu            | Zn            | Mn            | Al            | Fe   | Pb            | Si            | Sn    | Ni   | Others |
|---------------|---------------|---------------|---------------|------|---------------|---------------|-------|------|--------|
| 57.0 ... 59.0 | 36.0 ... 38.0 | 1.50 ... 3.00 | 1.30 ... 2.30 | <1.0 | 0.20 ... 0.80 | 0.30 ... 1.30 | <0.40 | <1.0 | <0.30  |

#### International comparison of standards

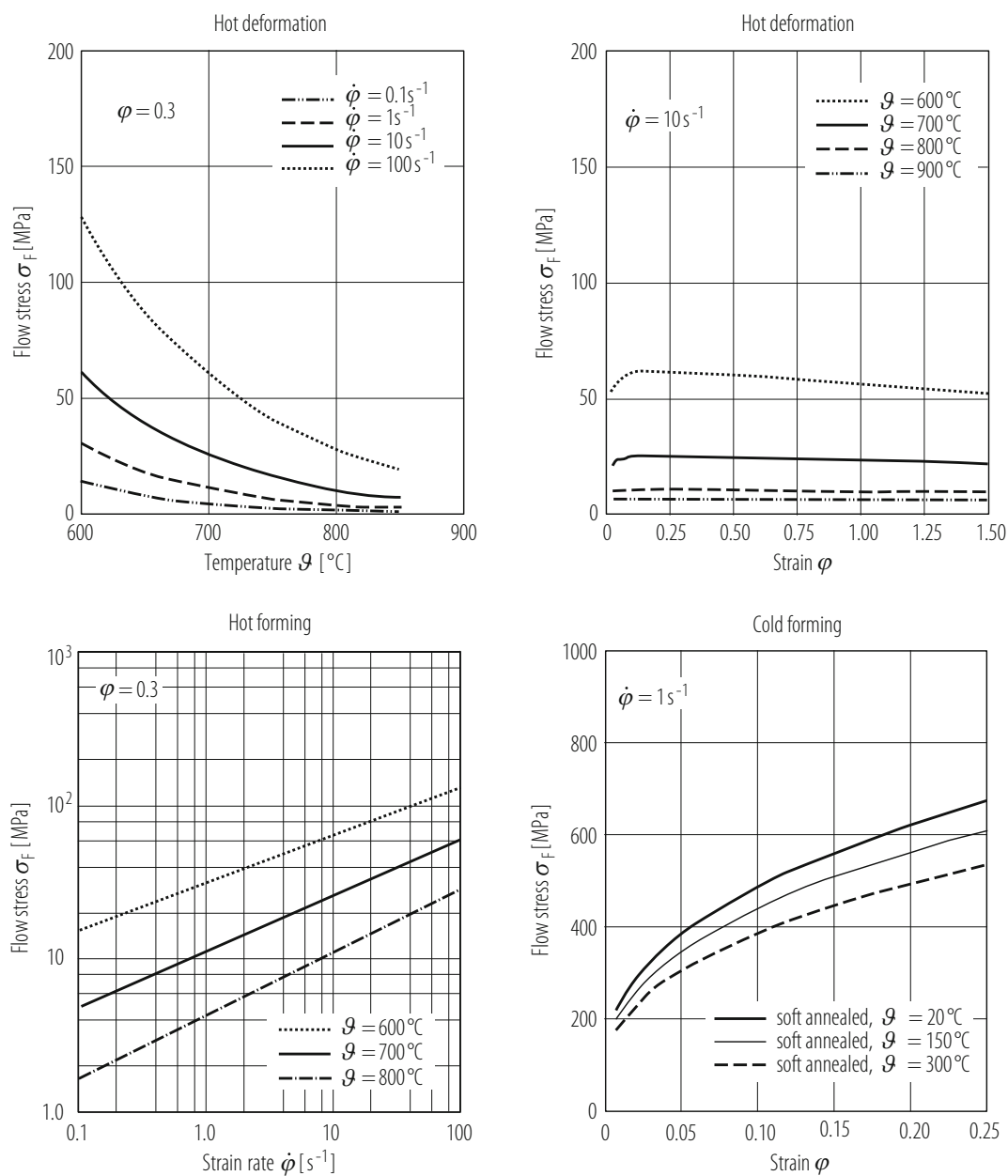
| Euronorm              |          | ISO              |                  |
|-----------------------|----------|------------------|------------------|
| CEN/TS 13388 : 2003   | EN 12164 | CuZn37Mn3Al2Si   | ISO 426-1 : 1983 |
| EN 12167              | EN 12168 | ISO 1639         |                  |
| EN 12420              | EN 12449 |                  |                  |
| Material number (DIN) |          | DIN              |                  |
| 2.0550                |          | DIN 17660 : 1983 | DIN 17672-1      |
|                       |          | DIN 17671-1      | DIN 17674-1      |
|                       |          | DIN 17673-1      | DIN 17678-1      |
| Japan                 |          | Russia           |                  |
| USA                   |          |                  |                  |
| ASTM                  |          | UNS standard     |                  |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

Flow curves

| State of material                         | Hot deformation |                | Cold deformation     |                    |                 |
|-------------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                           | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                       |                 | 25.5           |                      | 501.5              |                 |
| A                                         |                 | 12217.810      |                      | 1139.027           |                 |
| Effect of temperature $K_8$               |                 |                |                      |                    |                 |
| $m_1$                                     |                 | −0.00993       |                      | −0.00132           |                 |
| Effect of strain $K_\varphi$              |                 |                |                      |                    |                 |
| $m_2$                                     |                 | −0.01161       |                      | 0.36132            |                 |
| $m_4$                                     |                 | −0.00727       |                      | 0.00141            |                 |
| $m_5$                                     |                 | 0.00017        |                      |                    |                 |
| $m_7$                                     |                 | −0.19833       |                      |                    |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                      |                    |                 |
| $m_3$                                     |                 |                |                      | 0.00975            |                 |
| $m_8$                                     |                 | 0.000518       |                      |                    |                 |
| Range of validity                         |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                          |                 | 650 ... 850    |                      | 20 ... 200         |                 |
| $\varphi$                                 |                 | 0.03 ... 1.50  |                      | 0.03 ... 0.25      |                 |
| $\dot{\varphi}$ [1/s]                     |                 | <100           |                      | <100               |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                                                 |



**Fig. 5.48** Flow stress curves of CuZn<sub>37</sub>Mn<sub>3</sub>Al<sub>2</sub>PbSi by hot and cold forming.

## Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| soft annealed     | 180...240                       | 75.58441 | 0.34712 | 360...400                           | 6.73825 | 0.93816 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |        | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|--------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$  |                            |
| soft annealed     | 40...45                                 | 15.11821 | 0.28734 | -7.369 | <70                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | [GPa]           |
| 20               | 66.0                 | 377.1              | 18.72                                   | 8119.5                      | 93.0            |
| 100              | 73.5                 | 383.3              | 19.22                                   | 8096.9                      |                 |
| 200              | 77.0                 | 391.2              | 19.84                                   | 8067.0                      |                 |
| 300              | 79.1                 | 399.0              | 20.47                                   | 8035.2                      |                 |
| 400              | 80.7                 | 406.9              | 21.09                                   | 8001.6                      |                 |
| 500              | 81.9                 | 414.7              | 21.71                                   | 7966.2                      |                 |
| 600              | 82.9                 | 422.5              | 22.33                                   | 7929.0                      |                 |
| 700              | 83.8                 | 430.4              | 22.95                                   | 7890.0                      |                 |
| 800              | 84.5                 | 438.2              | 23.58                                   | 7849.2                      |                 |

## Symbols and Abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| UNS                 | unified numbering system                                              |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| ASTM                | American society for testing and materials                            |
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $R_p$               | yield stress                                                          |
| $R_m$               | tensile strength                                                      |
| $\lambda$           | thermal conductivity                                                  |
| $c_{pm}$            | mean specific heat                                                    |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\rho$              | density                                                               |
| $A, B, C$ and $n_i$ | constants                                                             |
| $A_5$               | elongation to fracture                                                |
| $T, \vartheta$      | temperature                                                           |



# Flow stress, mechanical and physical properties of CuSn<sub>2</sub>

## 5.2 Copper- and Copper alloys

### 5.2.3 Copper – Tin - alloys

#### Designation

|             |               |              |            |
|-------------|---------------|--------------|------------|
| UNS number: | Chem. symbol: | <b>CuSn2</b> | EN number: |
|-------------|---------------|--------------|------------|

#### Composition (DIN) [Weight-%]

| Cu   | Sn          | P     | Zn    | Pb    | Others |
|------|-------------|-------|-------|-------|--------|
| Bal. | 1.00...2.00 | <0.10 | <0.30 | <0.05 | <0.20  |

#### International comparison of standards

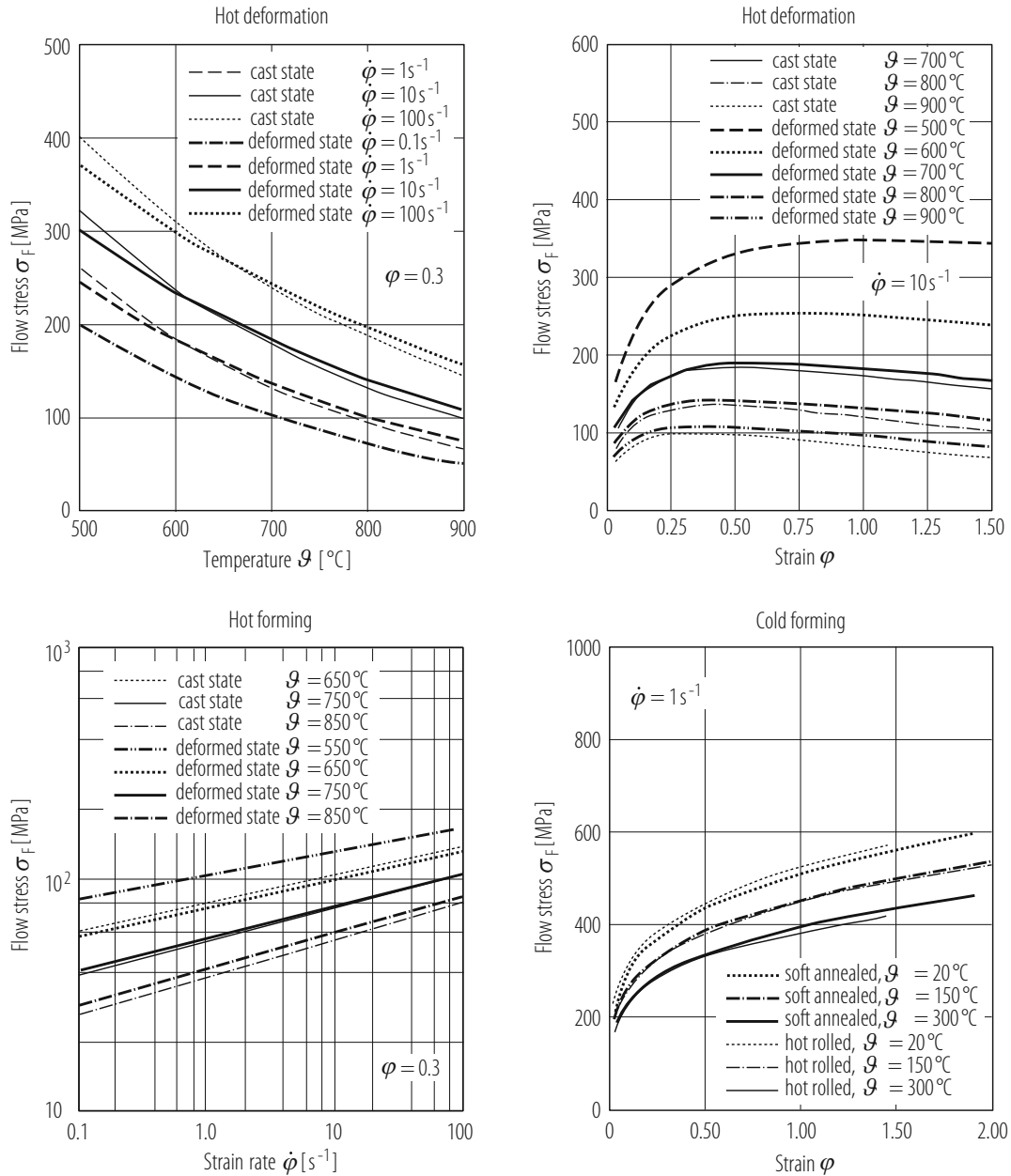
|                       |                      |
|-----------------------|----------------------|
| Euronorm              | ISO                  |
|                       | ISO 427 : 1983       |
| Material number (DIN) | DIN                  |
| 2.1010                | [[DIN 17662 : 1974]] |
| Japan                 | Russia               |
|                       | BrOF2-0.25           |
|                       | GOST 05017           |
| USA                   |                      |
| ASTM                  | UNS standard         |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                    | Hot deformation |                | Cold deformation     |                    |                 |
|--------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                      | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                  | 139.5           | 142.4          |                      | 306.7              | 322.3           |
| A                                    | 2305.20         | 1782.69        |                      | 521.845            | 534.309         |
| Effect of temperature $K_\theta$     |                 |                |                      |                    |                 |
| $m_1$                                | −0.00286        | −0.00258       |                      | −0.00091           | −0.00108        |
| Effect of strain $K_\phi$            |                 |                |                      |                    |                 |
| $m_2$                                | 0.43478         | 0.41552        |                      | 0.23519            | 0.22426         |
| $m_4$                                | 0.00188         | 0.00562        |                      | −0.00109           | −0.00122        |
| $m_5$                                | −0.00196        | −0.00152       |                      |                    |                 |
| $m_7$                                | 0.06344         | −0.0237        |                      |                    |                 |
| Effect of strain rate $K_\dot{\phi}$ |                 |                |                      |                    |                 |
| $m_3$                                |                 |                |                      | 0.01659            | 0.01899         |
| $m_8$                                | 0.000188        | 0.000176       |                      |                    |                 |
| Range of validity                    |                 |                |                      |                    |                 |
| $\theta$ [°C]                        | 500 ... 900     | 500 ... 900    |                      | 20 ... 300         | 20 ... 300      |
| $\phi$                               | 0.03 ... 1.50   | 0.03 ... 1.50  |                      | 0.03 ... 2.00      | 0.03 ... 2.00   |
| $\dot{\phi}$ [1/s]                   | <100            | <100           |                      | <100               | <100            |

| Hot deformation:                                                                                                                                                      | Cold deformation                                                                                        |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                  | [Equation (2.25), Chapter 2.3.2.2.2]                                                                    |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                            | [DOI: 978-3-642-14174-4_2]                                                                              |



**Fig. 5.49** Flow stress curves of CuSn<sub>2</sub> by hot and cold forming.

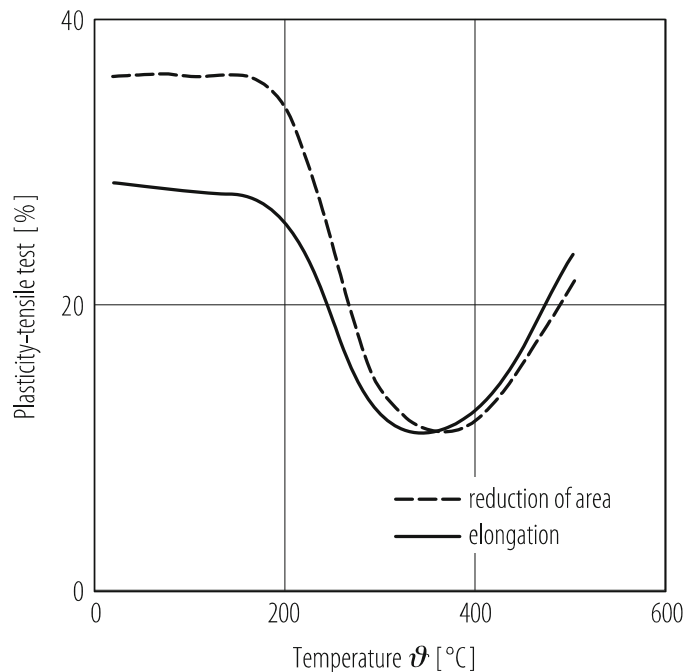
## Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |         |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|---------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$     | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| soft annealed     | 80...140                        | 9.04281 | 0.93906 | 260...300                           | 7.11873 | 0.90271 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| soft annealed     | 50...55                                 | 41.08980 | 0.06373 | -6.02854 | <70                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

## Plasticity in tensile test



**Fig. 5.50** Cold plasticity of CuSn<sub>2</sub> as a function of the temperature.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 163.14               | 377.3              | 16.15                                   | 8894.8                      | 127.0           |
| 100              | 176.9                | 383.6              | 16.63                                   | 8873.4                      | 126.0           |
| 200              | 194.1                | 391.6              | 17.23                                   | 8844.8                      | 122.0           |
| 300              | 211.3                | 399.5              | 17.83                                   | 8814.3                      | 117.0           |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 400              | 228.5                | 407.5              | 18.43                                   | 8781.9                      | 113.0           |
| 500              | 245.7                | 415.4              | 19.03                                   | 8747.5                      | 105.0           |
| 600              | 262.9                | 423.3              | 19.63                                   | 8711.3                      | 94.0            |
| 700              | 280.1                | 431.3              | 20.23                                   | 8673.1                      |                 |
| 800              | 297.3                | 439.2              | 20.83                                   | 8633.0                      |                 |
| 900              | 314.5                |                    |                                         |                             |                 |
| 950              | 323.1                |                    |                                         |                             |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvenny standart (state standard)                              |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuSn<sub>4</sub>

## 5.2 Copper- and Copper alloys

### 5.2.3 Copper – Tin - alloys

#### Designation

|             |               |               |              |            |               |
|-------------|---------------|---------------|--------------|------------|---------------|
| UNS number: | <b>C51100</b> | Chem. symbol: | <b>CuSn4</b> | EN number: | <b>CW450K</b> |
|-------------|---------------|---------------|--------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu    | Sn          | P           | Fe    | Ni    | Pb    | Zn    | Others |
|-------|-------------|-------------|-------|-------|-------|-------|--------|
| >94.2 | 3.50...4.50 | 0.01...0.35 | <0.10 | <0.30 | <0.05 | <0.30 | <0.20  |

#### International comparison of standards

| Euronorm              |              | ISO                  |                |
|-----------------------|--------------|----------------------|----------------|
| EN 1654 : 1997        | EN 1652      | ISO 427 : 1983       | ISO 1634-3     |
| EN 12166              | EN 14436     | ISO 1634-1           |                |
| EN 13148              |              |                      |                |
| Material number (DIN) |              | DIN                  |                |
| 2.1016                |              | [[DIN 17662 : 1983]] | DIN 17670-1    |
|                       |              | DIN 1777             |                |
| Japan                 |              | Russia               |                |
| C 5111                | JIS H 3110   | BrOF4-0.26           | GOST 5017 – 74 |
| JIS H 3270            |              |                      |                |
| USA                   |              | UNS standard         |                |
| ASTM                  |              |                      |                |
| ASTM B 103            | ASTM B 103 M | C 51100              |                |
| ASTM B 888            | ASTM B 100   |                      |                |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

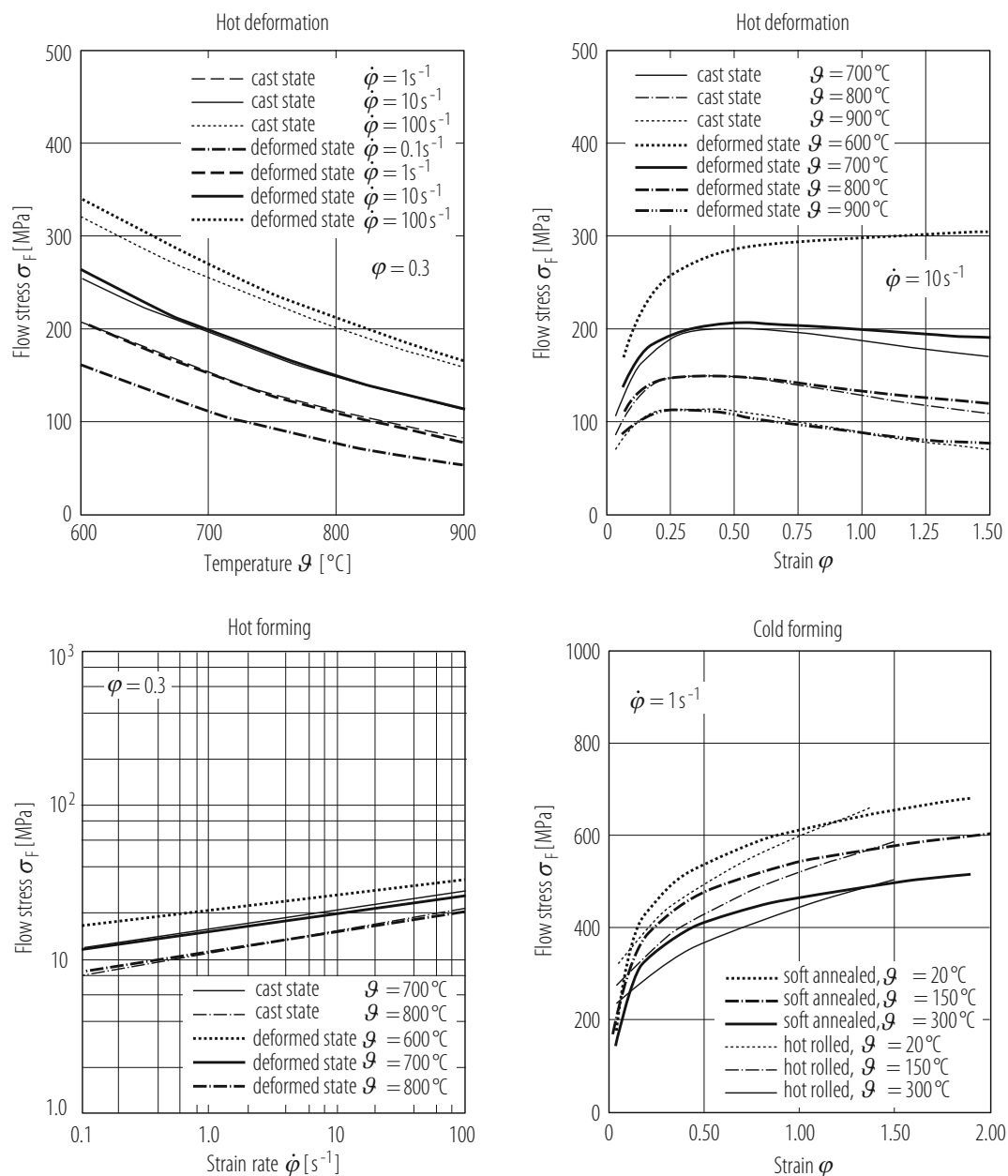
#### Flow curves

| State of material           | Hot deformation |                | Cold deformation     |                    |                 |
|-----------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                             | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]         | 150.3           | 156.2          |                      | 330.6              | 342.7           |
| A                           | 2198.20         | 2220.40        |                      | 645.177            | 603.911         |
| Effect of temperature $K_g$ |                 |                |                      |                    |                 |
| $m_1$                       | –0.00241        | –0.00255       |                      | –0.00097           | –0.00107        |

(continued)

| State of material                         | Hot deformation |                | Cold deformation     |                    |                 |
|-------------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                           | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| Effect of strain $K_\varphi$              |                 |                |                      |                    |                 |
| $m_2$                                     | 0.48888         | 0.44981        |                      | 0.13297            | 0.29734         |
| $m_4$                                     | 0.00174         | 0.00145        |                      | −0.03355           | 0.0135          |
| $m_5$                                     | −0.00255        | −0.00276       |                      |                    |                 |
| $m_7$                                     | 0.20331         | 0.41851        |                      |                    |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                      |                    |                 |
| $m_3$                                     |                 |                |                      | −0.00406           | 0.00168         |
| $m_8$                                     | 0.000162        | 0.000182       |                      |                    |                 |
| Range of validity                         |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                          | 600 ... 900     | 600 ... 900    |                      | 20 ... 300         | 20 ... 300      |
| $\varphi$                                 | 0.03 ... 1.50   | 0.03 ... 1.50  |                      | 0.03 ... 2.00      | 0.03 ... 1.50   |
| $\dot{\varphi}$ [1/s]                     | <100            | <100           |                      | <100               | <100            |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |



**Fig. 5.51** Flow stress curves of CuSn4 by hot and cold forming.

Mechanical properties after cold deformation

| State of material     | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-----------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                       | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| grain size 0.015 [mm] | 190...230                       | 31.55304 | 0.67390 | 290...330                           | 9.76876 | 0.88902 |
| grain size 0.070 [mm] | 115...150                       | 30.25193 | 0.67748 | 330...370                           | 4.78808 | 1.01698 |

| State of material     | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-----------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                       | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| grain size 0.015 [mm] | 45...50                                 | 32.16053 | 0.10083 | −8.55548 | <70                        |
| grain size 0.070 [mm] | 45...50                                 | 20.80431 | 0.2242  | −5.59755 | <70                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

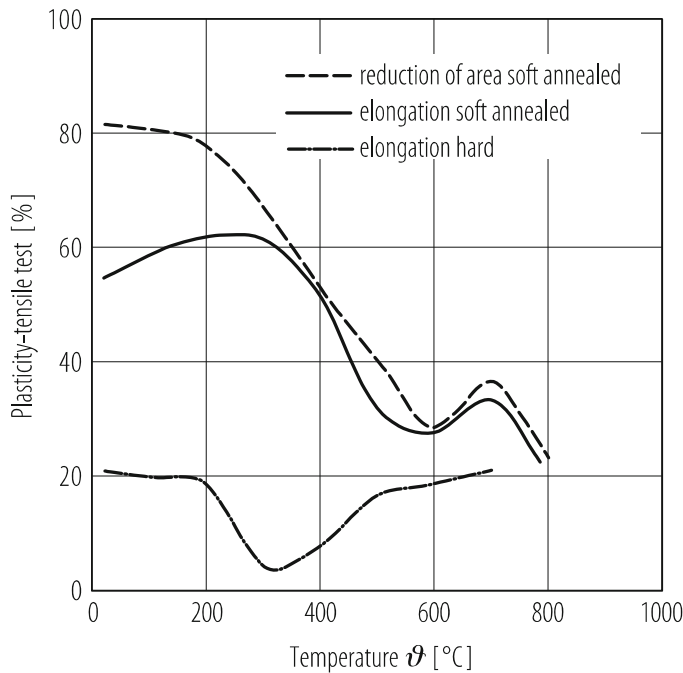


Fig. 5.52 Plasticity of CuSn<sub>4</sub> as a function of the temperature.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>−6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 87.1                 | 377.3              | 16.71                                   | 8854.7                      | 120.0           |
| 100              | 100.9                | 383.6              | 17.23                                   | 8832.5                      | 118.0           |
| 200              | 118.1                | 391.6              | 17.88                                   | 8803.0                      | 115.0           |

(continued)



| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 300                             | 135.3                                     | 399.5                                   | 18.53                                                                    | 8771.3                                 | 110.0                        |
| 400                             | 152.5                                     | 407.5                                   | 19.18                                                                    | 8737.6                                 | 105.0                        |
| 500                             | 169.7                                     | 415.4                                   | 19.83                                                                    | 8701.9                                 | 98.0                         |
| 600                             | 186.9                                     | 423.3                                   | 20.48                                                                    | 8664.0                                 | 87.0                         |
| 700                             | 204.1                                     | 431.3                                   | 21.13                                                                    | 8624.1                                 |                              |
| 800                             | 221.3                                     | 439.2                                   | 21.78                                                                    | 8582.1                                 |                              |
| 900                             | 238.5                                     |                                         | 22.43                                                                    | 8538.1                                 |                              |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese Industrial Standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuSn<sub>6</sub>

## 5.2 Copper- and Copper alloys

### 5.2.3 Copper – Tin - alloys

#### Designation

|             |               |               |              |            |               |
|-------------|---------------|---------------|--------------|------------|---------------|
| UNS number: | <b>C51900</b> | Chem. symbol: | <b>CuSn6</b> | EN number: | <b>CW452K</b> |
|-------------|---------------|---------------|--------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu    | Sn          | P           | Fe    | Ni    | Pb    | Zn    | Others |
|-------|-------------|-------------|-------|-------|-------|-------|--------|
| >91.7 | 5.50...7.00 | 0.01...0.35 | <0.10 | <0.30 | <0.05 | <0.30 | <0.20  |

#### International comparison of standards

| Euronorm              |                   | ISO                  |                |
|-----------------------|-------------------|----------------------|----------------|
| EN 1654 : 1997        | EN1652            | ISO 427 : 1983       | ISO 1634-3     |
| EN 1654, ,            | EN 12467          | ISO 1634-1,          | ISO 1638       |
| EN 13148              | EN 12166          | ISO 1637             |                |
| Material number (DIN) |                   | DIN                  |                |
| 2.1020                |                   | [[DIN 17662 : 1983]] | DIN 1777       |
|                       |                   | DIN 17670-1          | DIN 17672-1    |
|                       |                   | DIN 17682            | DIN 17671-1    |
| Japan                 |                   | Russia               |                |
| JIS H 3270            | JIS H 3110 : 1992 | BrOF 6.5–0.15        | GOST 5017 – 74 |
| USA                   |                   | UNS standard         |                |
| ASTM                  |                   | C51900               |                |
| ASTM B 103 M          |                   |                      |                |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

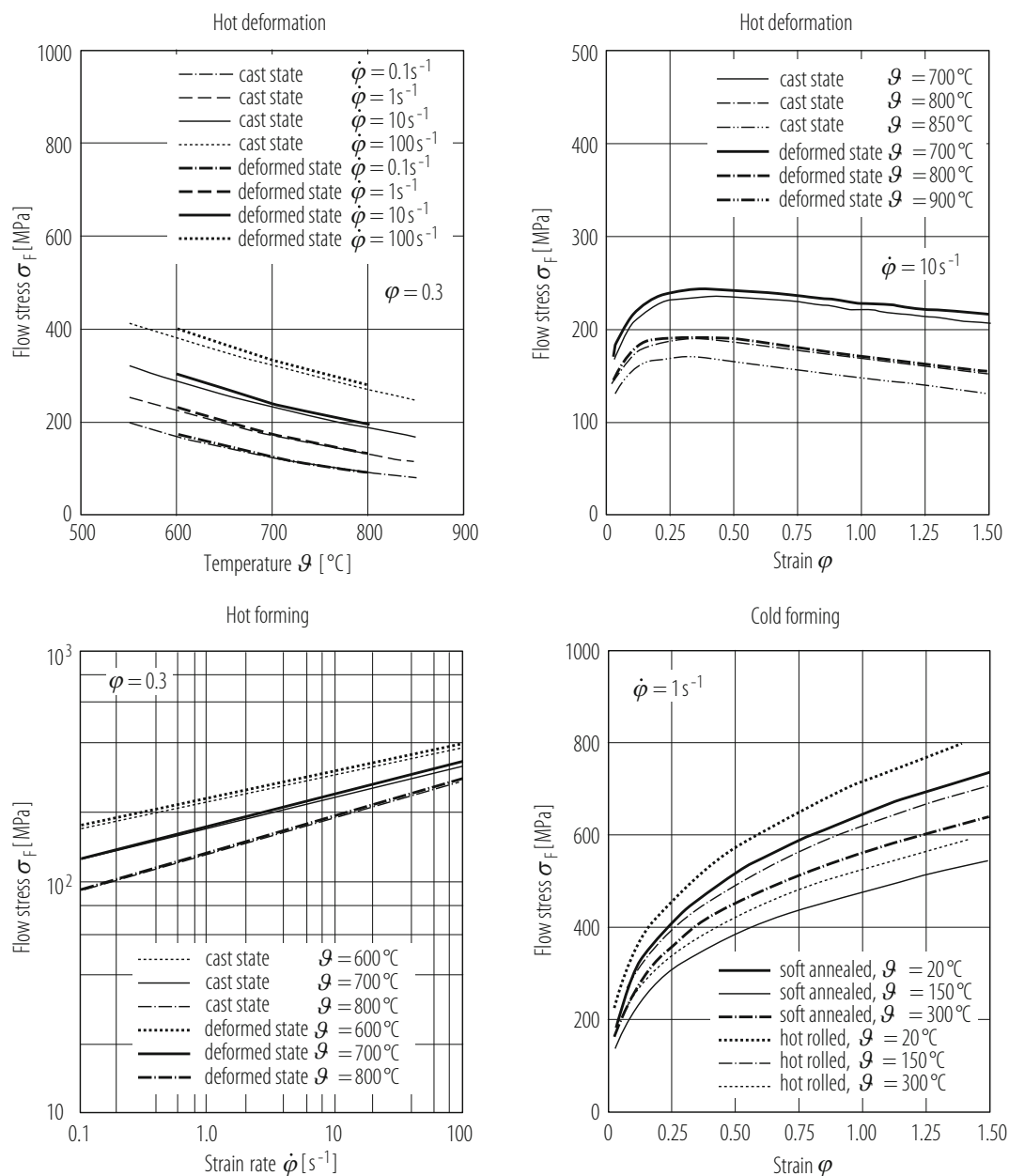
#### Flow curves

| State of material                  | Hot deformation |                | Cold deformation     |                    |                 |
|------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                    | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                | 206.8           | 215.4          |                      | 313.4              | 354.4           |
| A                                  | 1377.14         | 1484.25        |                      | 661.033            | 731.876         |
| Effect of temperature $K_{\theta}$ |                 |                |                      |                    |                 |
| $m_1$                              | –0.00224        | –0.00231       |                      | –0.00106           | –0.0011         |

(continued)

| State of material                         | Hot deformation |                | Cold deformation     |                    |                 |
|-------------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                           | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| Effect of strain $K_\varphi$              |                 |                |                      |                    |                 |
| $m_2$                                     | 0.2446          | 0.24161        |                      | 0.31015            | 0.32402         |
| $m_4$                                     | 0.00063         | 0.00059        |                      | −0.00497           | −0.0003         |
| $m_5$                                     | −0.00134        | −0.00153       |                      |                    |                 |
| $m_7$                                     | 0.08112         | 0.16492        |                      |                    |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                      |                    |                 |
| $m_3$                                     |                 |                |                      | 0.01625            | 0.0193          |
| $m_8$                                     | 0.000192        | 0.0002         |                      |                    |                 |
| Range of validity                         |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                          | 600 ... 900     | 600 ... 800    |                      | 20 ... 300         | 20 ... 300      |
| $\varphi$                                 | 0.03 ... 1.50   | 0.03 ... 1.50  |                      | 0.03 ... 1.50      | 0.03 ... 1.50   |
| $\dot{\varphi}$ [1/s]                     | <100            | <100           |                      | <100               | <100            |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.53** Flow stress curves of CuSn6 by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| soft annealed     | 190...250                       | 15.39480 | 0.83896 | 340...400                           | 5.63276 | 1.00473 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |        |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|--------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$  | $n_4$    |                            |
| soft annealed     | 50...55                                 | 11.07145 | 0.3286 | -5.53945 | <60                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

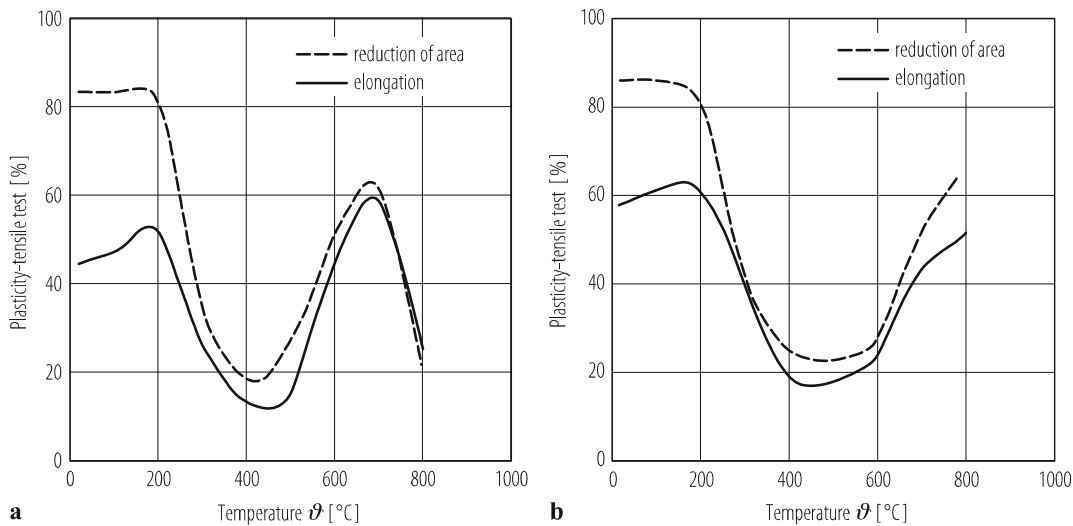


Fig. 5.54 Plasticity of CuSn6 as a function of the temperature. (a) Initial test: soft annealed; 14 mm Ø. (b) Initial test: soft annealed; 16 mm Ø.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 74.7                 | 377.3              | 17.54                                   | 8824.4                      | 114.0           |
| 100              | 85.3                 | 383.6              | 18.03                                   | 8801.3                      | 108.0           |
| 200              | 98.6                 | 391.6              | 18.65                                   | 8770.7                      | 105.0           |
| 300              | 111.9                | 399.5              | 19.27                                   | 8738.1                      | 98.0            |
| 400              | 125.2                | 407.5              | 19.89                                   | 8703.5                      |                 |
| 500              | 138.5                | 415.4              | 20.51                                   | 8667.0                      |                 |
| 600              | 151.8                | 423.3              | 21.13                                   | 8628.5                      |                 |
| 700              | 165.1                | 431.3              | 21.75                                   | 8588.0                      |                 |
| 800              | 178.4                | 439.2              | 22.37                                   | 8545.5                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese Industrial Standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuSn<sub>8</sub>

## 5.2 Copper- and Copper alloys

### 5.2.3 Copper – Tin - alloys

#### Designation

|             |               |               |              |            |               |
|-------------|---------------|---------------|--------------|------------|---------------|
| UNS number: | <b>C52100</b> | Chem. symbol: | <b>CuSn8</b> | EN number: | <b>CW453K</b> |
|-------------|---------------|---------------|--------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu    | Sn          | P           | Fe    | Ni    | Pb    | Zn    | Others |
|-------|-------------|-------------|-------|-------|-------|-------|--------|
| >90.2 | 7.50...8.50 | 0.01...0.35 | <0.10 | <0.30 | <0.05 | <0.30 | <0.20  |

#### International comparison of standards

| Euronorm              |              | ISO                  |                |
|-----------------------|--------------|----------------------|----------------|
| EN 12449 : 1999       | EN 1652      | ISO 427 : 1983       | ISO 1634-3     |
| EN 1654               | EN12166      | ISO 1634-1           | ISO 1638       |
| EN 13148              | EN 14436     | ISO 1637             |                |
| EN 12163              |              | ISO 1635             |                |
| Material number (DIN) |              | DIN                  |                |
| 2.1030                |              | [[DIN 17662 : 1983]] | DIN 17670-1    |
|                       |              | DIN 1777             | DIN 17672-1    |
| Japan                 |              | Russia               |                |
| C 5210                |              | BrOF7-0.2            | GOST 5017 – 74 |
| JIS H 3130 : 1992     |              |                      |                |
| USA                   |              |                      |                |
| ASTM, SAE and AWS     |              | UNS standard         |                |
| ASTM B 103            | ASTM B 103 M | C 52100              |                |
| ASTM B 888            | ASTM B 139   |                      |                |
| ASTM B 159            | ASTM B 159 M |                      |                |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

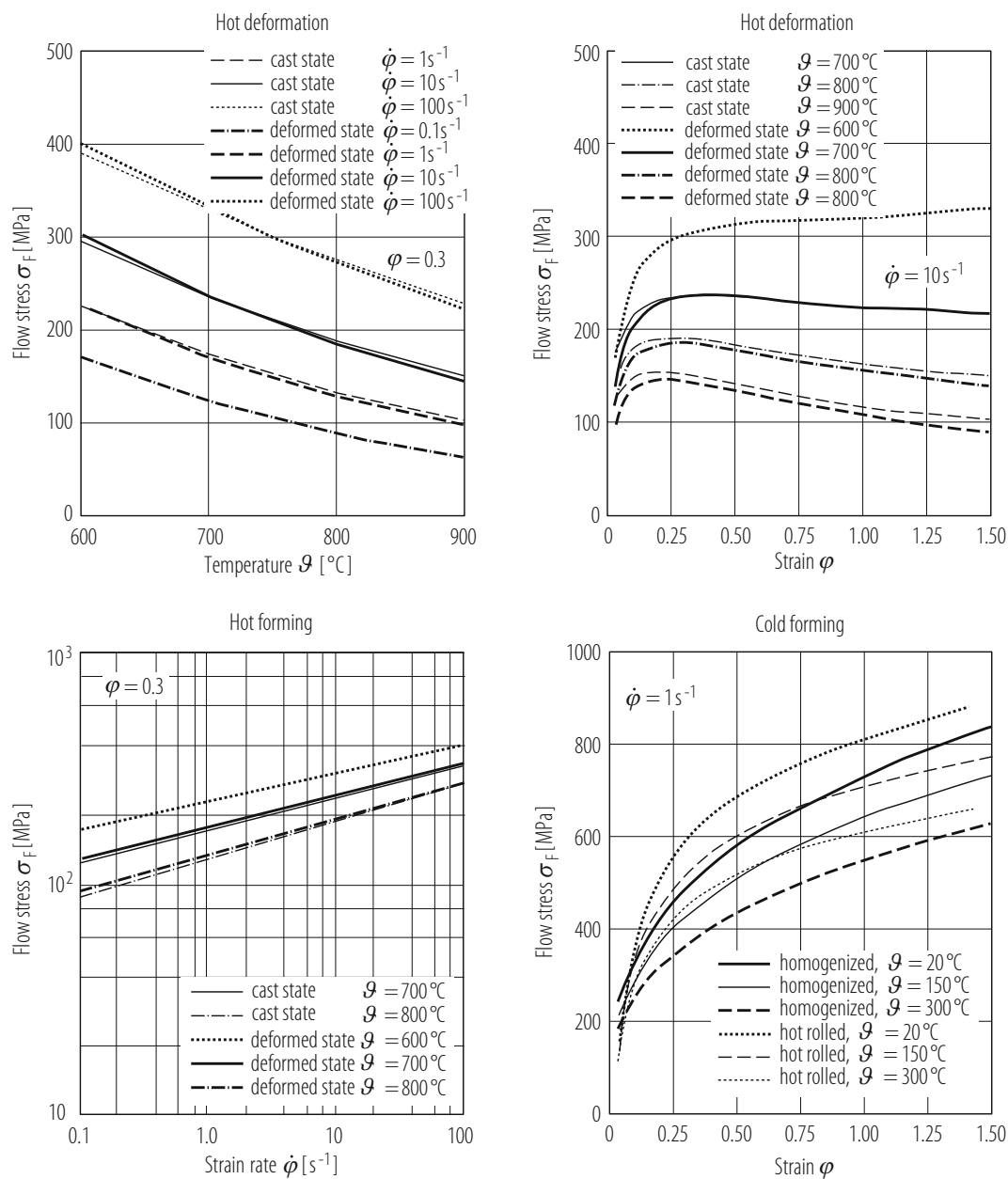
#### Flow curves

| State of material           | Hot deformation |                | Cold deformation     |                    |                 |
|-----------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                             | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]         | 213.5           | 204,5          |                      | 345.7              | 374.0           |
| A                           | 1342.43         | 1558.47        |                      | 747.945            | 866.827         |
| Effect of temperature $K_9$ |                 |                |                      |                    |                 |
| $m_1$                       | −0.00206        | −0.00215       |                      | −0.00102           | −0.00102        |

(continued)

| State of material                                                                                                                                                              | Hot deformation |                | Cold deformation     |                                                                                                            |                 |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|----------------|----------------------|------------------------------------------------------------------------------------------------------------|-----------------|
|                                                                                                                                                                                | cast state      | deformed state | recrystallized (rec) | soft annealed (sa)                                                                                         | hot rolled (hr) |
| Effect of strain $K_\varphi$                                                                                                                                                   |                 |                |                      |                                                                                                            |                 |
| $m_2$                                                                                                                                                                          | 0.26405         | 0.29612        |                      | 0.33341                                                                                                    | 0.1723          |
| $m_4$                                                                                                                                                                          | 0.000198        | −0.00476       |                      | −0.00109                                                                                                   | −0.04502        |
| $m_5$                                                                                                                                                                          | −0.00242        | −0.00282       |                      |                                                                                                            |                 |
| $m_7$                                                                                                                                                                          | 0.51015         | 0.60366        |                      |                                                                                                            |                 |
| Effect of strain rate $K\dot{\varphi}$                                                                                                                                         |                 |                |                      |                                                                                                            |                 |
| $m_3$                                                                                                                                                                          |                 |                |                      | 0.01124                                                                                                    | 0.01057         |
| $m_8$                                                                                                                                                                          | 0.000198        | 0.000205       |                      |                                                                                                            |                 |
| Range of validity                                                                                                                                                              |                 |                |                      |                                                                                                            |                 |
| $\vartheta$ [°C]                                                                                                                                                               | 600 ... 900     | 600 ... 900    |                      | 20 ... 300                                                                                                 | 20 ... 300      |
| $\varphi$                                                                                                                                                                      | 0.03 ... 1.50   | 0.03 ... 1.50  |                      | 0.03 ... 1.50                                                                                              | 0.03 ... 1.50   |
| $\dot{\varphi}$ [1/s]                                                                                                                                                          | <100            | <100           |                      | <100                                                                                                       | <100            |
|                                                                                                                                                                                |                 |                |                      |                                                                                                            |                 |
| Hot deformation:                                                                                                                                                               |                 |                |                      | Cold deformation                                                                                           |                 |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |                 |                |                      | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |                 |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |                 |                |                      | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |                 |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    |                 |                |                      | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |                 |





**Fig. 5.55** Flow stress curves of CuSn<sub>8</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| soft annealed     | 190...260                       | 21.68693 | 0.82628 | 370...430                           | 9.66547 | 0.93708 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| soft annealed     | 70...75                                 | 29.35227 | 0.22459 | −4.94689 | <60                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

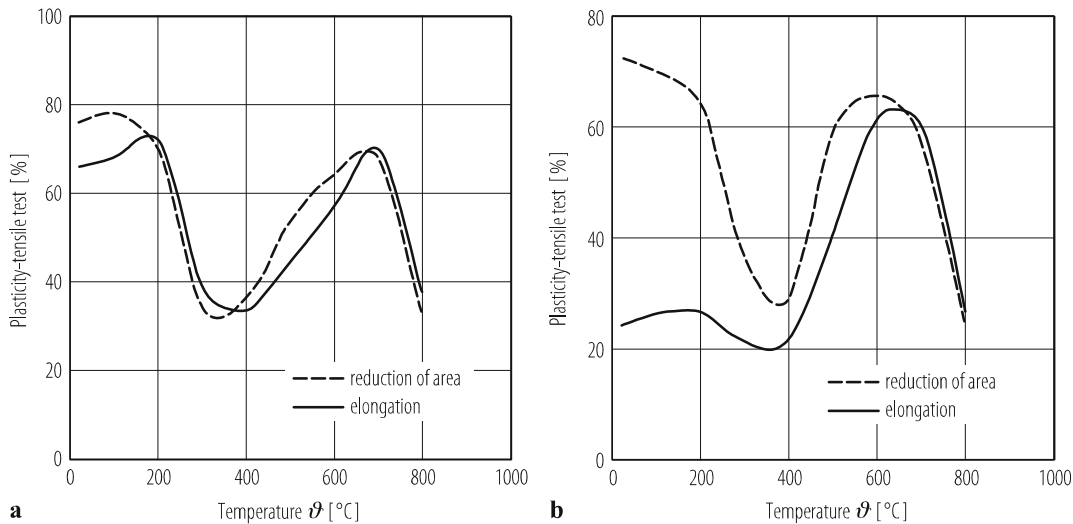


Fig. 5.56 Plasticity of CuSn<sub>8</sub> as a function of the temperature. (a) Initial test: soft annealed. (b) Initial test: hard.

Physical properties

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [10 <sup>−6</sup> /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                              | 59.0                                      | 377.3                                   | 17.05                                                                          | 8794.6                                 | 111.0                        |
| 100                             | 67.0                                      | 383.6                                   | 17.53                                                                          | 8772.2                                 | 108.5                        |
| 200                             | 77.0                                      | 391.6                                   | 18.13                                                                          | 8742.6                                 | 104.0                        |
| 300                             | 87.0                                      | 399.5                                   | 18.73                                                                          | 8711.0                                 | 100.0                        |
| 400                             | 97.0                                      | 407.5                                   | 19.33                                                                          | 8677.5                                 | 95.0                         |
| 500                             | 107.0                                     | 415.4                                   | 19.93                                                                          | 8642.1                                 | 86.5                         |
| 600                             | 117.0                                     | 423.3                                   | 20.53                                                                          | 8604.9                                 | 76.0                         |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 700              | 127.0                | 431.3              | 21.13                                   | 8565.7                      |                 |
| 800              | 137.0                | 439.2              | 21.73                                   | 8524.6                      |                 |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| AWS                 | American welding society                                              |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese Industrial Standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| SAE                 | society of automotive engineers                                       |
| $T, \vartheta$      | Temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress and physical properties of CuSn<sub>10</sub>-C

## 5.2 Copper- and Copper alloys

### 5.2.3 Copper – Tin - alloys

#### Designation

|             |               |               |                 |            |               |
|-------------|---------------|---------------|-----------------|------------|---------------|
| UNS number: | <b>C90700</b> | Chem. symbol: | <b>CuSn10-C</b> | EN number: | <b>CC480K</b> |
|-------------|---------------|---------------|-----------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Sn          | P     | Fe    | Ni   | Pb    | Zn    | Others |
|-------------|-------------|-------|-------|------|-------|-------|--------|
| 88.0...90.0 | 9.0...11.50 | <0.20 | <0.20 | <2.0 | <1.00 | <0.50 | <0.70  |

#### International comparison of standards

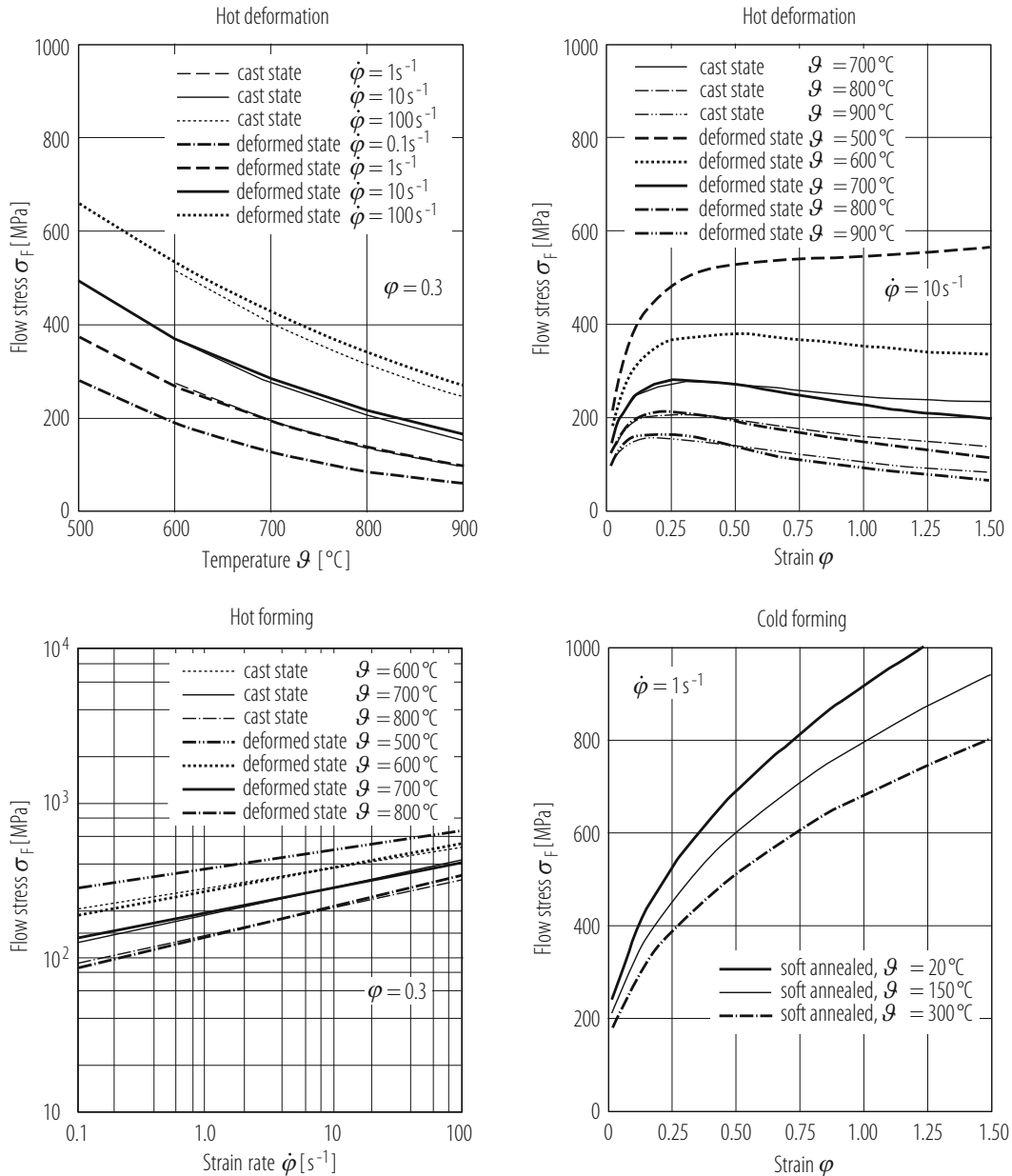
| Euronorm              | ISO             |                    |
|-----------------------|-----------------|--------------------|
| EN 1982 : 1998        | CuSn10          | CuSn10-B           |
|                       | CuSn10-GB       | ISO 1338 : 1977    |
| Material number (DIN) | DIN             |                    |
| 2.1050                | DIN 1705 : 1981 | DIN 1705 : 1981-11 |
| Japan                 | Russia          |                    |
| USA                   |                 |                    |
| ASTM                  | UNS standard    |                    |
| ASTM B 427-09         | C90700          |                    |
| ASTM B 505 : 1996     |                 |                    |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                    | 240.6           | 243.5          |                      | 383.1              |                 |
| A                                      | 2924.25         | 2900.07        |                      | 933.326            |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                      |                    |                 |
| $m_1$                                  | -0.00263        | -0.00241       |                      | -0.00109           |                 |
| Effect of strain $K_{\phi}$            |                 |                |                      |                    |                 |
| $m_2$                                  | 0.37786         | 0.43743        |                      | 0.41573            |                 |
| $m_4$                                  | 0.0004          | 0.00089        |                      | 0.00639            |                 |
| $m_5$                                  | -0.00327        | -0.00365       |                      |                    |                 |
| $m_7$                                  | 0.59326         | 0.52252        |                      |                    |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.01014            |                 |
| $m_8$                                  | 0.000228        | 0.000247       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\theta$ [°C]                          | 600 ... 900     | 500 ... 900    |                      | 20 ... 300         |                 |
| $\phi$                                 | 0.03 ... 1.50   | 0.03 ... 1.50  |                      | 0.03 ... 1.50      |                 |
| $\dot{\phi}$ [1/s]                     | <100            | <100           |                      | <100               |                 |

| Hot deformation:                                                                                                                                                            | Cold deformation                                                                                              |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \dot{\varphi}^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \dot{\varphi}^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                        | [Equation (2.25), Chapter 2.3.2.2.2]                                                                          |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                  | [DOI: 978-3-642-14174-4_2]                                                                                    |



**Fig. 5.57** Flow stress curves of CuSn10C by hot and cold forming.

**Physical properties**

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 50.3                 | 377.3              | 17.41                                   | 8744.5                      |                 |
| 100              | 58.5                 | 383.6              | 17.93                                   | 8721.8                      |                 |
| 200              | 68.8                 | 391.6              | 18.58                                   | 8691.5                      |                 |
| 300              | 79.1                 | 399.5              | 19.23                                   | 8659.1                      |                 |
| 400              | 89.4                 | 407.5              | 19.88                                   | 8624.8                      |                 |
| 500              | 99.7                 | 415.4              | 20.53                                   | 8588.3                      |                 |
| 600              | 110.0                | 423.3              | 21.18                                   | 8549.8                      |                 |
| 700              | 120.3                | 431.3              | 21.83                                   | 8509.3                      |                 |
| 800              | 130.6                | 439.2              | 22.48                                   | 8466.8                      |                 |
| 900              | 140.9                | 447.2              | 23.13                                   | 8422.1                      |                 |

**Symbols and abbreviations**

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress and physical properties of G–CuSn<sub>12</sub>

## 5.2 Copper- and Copper alloys

### 5.2.3 Copper – Tin - alloys

#### Designation

|             |               |               |                 |            |               |
|-------------|---------------|---------------|-----------------|------------|---------------|
| UNS number: | <b>C90800</b> | Chem. symbol: | <b>G–CuSn12</b> | EN number: | <b>CC483K</b> |
|-------------|---------------|---------------|-----------------|------------|---------------|

#### Composition (EN) [Weight-%]

|      |     |   |    |      |    |
|------|-----|---|----|------|----|
| Cu   | Sn  | P | Fe | Ni   | Pb |
| Bal. | ~12 |   |    | <1.5 |    |

#### International comparison of standards

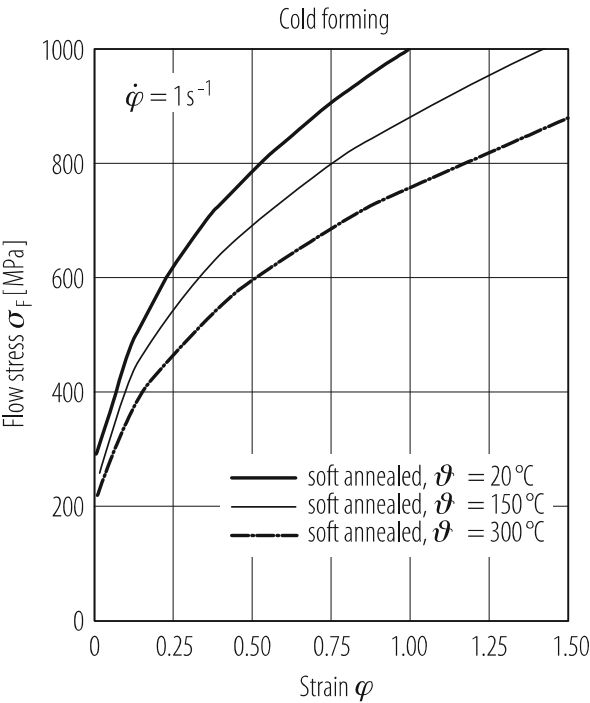
|                       |                  |                    |
|-----------------------|------------------|--------------------|
| Euronorm              | ISO              |                    |
| EN 1982 : 1998        | CuSn12           | ISO 1338 : 1977    |
|                       | CuSn12-B         |                    |
| Material number (DIN) | DIN              |                    |
| 2.1052                | DIN 01705 : 1981 | DIN 1705 : 1981-11 |
| Japan                 | Russia           |                    |
| USA                   |                  |                    |
| ASTM                  | UNS standard     |                    |
| ASTM B 427            | C90800           |                    |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                    |                 |                |                      | 471.1              |                 |
| A                                      |                 |                |                      | 1018.930           |                 |
| Effect of temperature $K_\theta$       |                 |                |                      |                    |                 |
| $m_1$                                  |                 |                |                      | –0.00098           |                 |
| Effect of strain $K_\varphi$           |                 |                |                      |                    |                 |
| $m_2$                                  |                 |                |                      | 0.35151            |                 |
| $m_4$                                  |                 |                |                      | 0.00364            |                 |
| $m_5$                                  |                 |                |                      |                    |                 |
| $m_7$                                  |                 |                |                      |                    |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.00863            |                 |
| $m_8$                                  |                 |                |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                       |                 |                |                      | 20 ... 300         |                 |
| $\varphi$                              |                 |                |                      | 0.03 ... 1.50      |                 |
| $\dot{\varphi}$ [1/s]                  |                 |                |                      | <100               |                 |

|                                                                                                            |
|------------------------------------------------------------------------------------------------------------|
| Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                 |



**Fig. 5.57** Flow stress curves of CuSn12 - C by cold forming.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ GPa]        |
| 20               | 40.8                 | 377.3              | 17.41                                   | 8769.5                      | 100             |
| 100              | 49.0                 | 383.6              | 17.93                                   | 8746.7                      |                 |
| 200              | 59.3                 | 391.6              | 18.58                                   | 8716.3                      |                 |
| 300              | 69.6                 | 399.5              | 19.23                                   | 8683.9                      |                 |
| 400              | 79.9                 | 407.5              | 19.88                                   | 8649.4                      |                 |
| 500              | 90.2                 | 415.4              | 20.53                                   | 8612.9                      |                 |
| 600              | 100.5                | 423.3              | 21.18                                   | 8574.3                      |                 |
| 700              | 110.8                | 431.3              | 21.83                                   | 8533.6                      |                 |
| 800              | 121.1                | 439.2              | 22.48                                   | 8490.9                      |                 |

Symbols and abbreviations

| Short form      | Full form                                  |
|-----------------|--------------------------------------------|
| $\sigma_F$      | flow stress                                |
| $\varphi$       | strain                                     |
| $\dot{\varphi}$ | strain rate                                |
| ASTM            | American society for testing and materials |
| $c_{pm}$        | mean specific heat                         |

(continued)



| Short form     | Full form                                                             |
|----------------|-----------------------------------------------------------------------|
| DIN            | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$            | Young's modulus                                                       |
| EN             | Euronorm                                                              |
| ISO            | international organisation for standardization                        |
| $T, \vartheta$ | Temperature                                                           |
| UNS            | unified numbering system                                              |
| $\alpha_m$     | average coefficient of linear expansion                               |
| $\lambda$      | thermal conductivity                                                  |
| $\rho$         | density                                                               |

# Flow stress and physical properties of G-CuSn<sub>14</sub>

## 5.2 Copper- and Copper alloys

### 5.2.3 Copper – Tin - alloys

#### Designation

|             |               |                 |            |
|-------------|---------------|-----------------|------------|
| UNS number: | Chem. symbol: | <b>G-CuSn14</b> | EN number: |
|-------------|---------------|-----------------|------------|

#### Composition (ISO) [Weight-%]

| Cu          | Sn          | P | Sb    | Ni    | Pb    |
|-------------|-------------|---|-------|-------|-------|
| 85.0...87.0 | 14.0...15.8 |   | <0.25 | <1.00 | <1.00 |

#### International comparison of standards

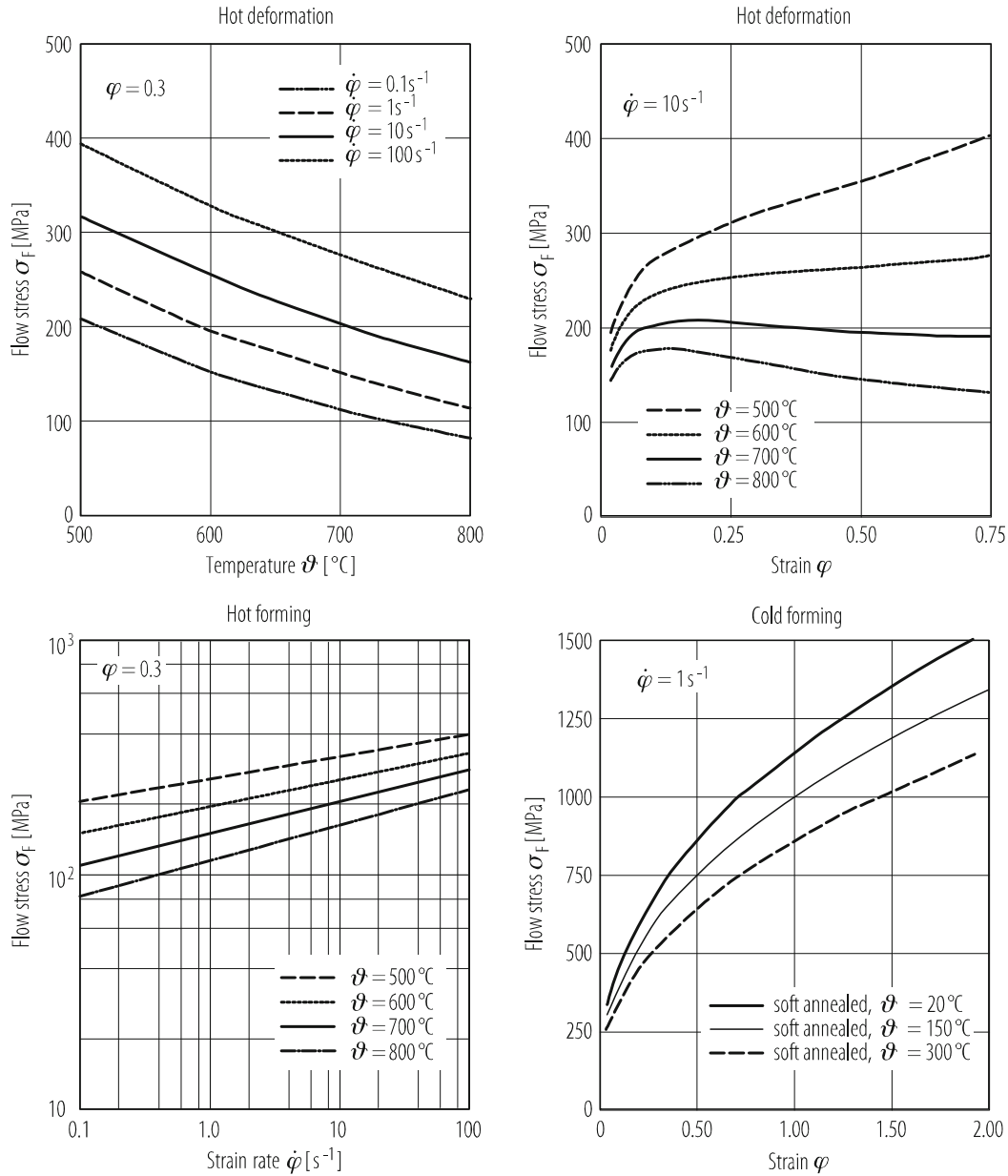
|                       |         |                    |             |
|-----------------------|---------|--------------------|-------------|
| Euronorm              |         | ISO                |             |
|                       |         | ISO/TS16949        |             |
| Material number (DIN) |         | DIN                |             |
| Japan                 |         | France             |             |
| JIS H 5120            | CAC503A | NF A 53-707 : 1987 | NF A 53-707 |
| USA                   |         |                    |             |
| ASTM                  |         | UNS standard       |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                    |                 | 200.7          |                      | 471.2              |                 |
| A                                      |                 | 778.6700       |                      | 1160.838           |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                      |                    |                 |
| $m_1$                                  |                 | -0.00134       |                      | -0.00102           |                 |
| Effect of strain $K_{\phi}$            |                 |                |                      |                    |                 |
| $m_2$                                  |                 | 0.2383         |                      | 0.42166            |                 |
| $m_4$                                  |                 | -0.00019       |                      | 0.00648            |                 |
| $m_5$                                  |                 | -0.0051        |                      |                    |                 |
| $m_7$                                  |                 | 1.71274        |                      |                    |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.01022            |                 |
| $m_8$                                  |                 | 0.000187       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\theta$ [°C]                          |                 | 500...800      |                      | 20...300           |                 |
| $\phi$                                 |                 | 0.03...0.75    |                      | 0.03...0.50        |                 |
| $\dot{\phi}$ [1/s]                     |                 | <50            |                      | <50                |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.59** Flow stress curves of G-CuSn<sub>14</sub> by hot and cold forming.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 35.8                 | 377.3              | 17.41                                   | 8834.5                      | 92              |
| 100              | 43.1                 | 383.6              | 17.93                                   | 8811.5                      |                 |
| 200              | 52.2                 | 391.6              | 18.58                                   | 8780.9                      |                 |
| 300              | 61.3                 | 399.5              | 19.23                                   | 8748.2                      |                 |
| 400              | 70.4                 | 407.5              | 19.88                                   | 8713.5                      |                 |
| 500              | 79.5                 | 415.4              | 20.53                                   | 8676.7                      |                 |
| 600              | 88.6                 | 423.3              | 21.18                                   | 8637.8                      |                 |
| 700              | 97.7                 | 431.3              | 21.83                                   | 8596.8                      |                 |
| 800              | 102.3                | 435.3              | 22.16                                   | 8575.6                      |                 |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| JIS             | Japanese Industrial Standards                                         |
| NF              | France normalisation                                                  |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, mechanical and physical properties of CuSn<sub>4</sub>Zn<sub>3</sub>

## 5.2 Copper- and Copper alloys

### 5.2.3 Copper – Tin - alloys

#### Designation

|             |               |                                       |            |
|-------------|---------------|---------------------------------------|------------|
| UNS number: | Chem. symbol: | <b>CuSn<sub>4</sub>Zn<sub>3</sub></b> | EN number: |
|-------------|---------------|---------------------------------------|------------|

#### Composition [Weight-%]

|      |                 |                  |   |
|------|-----------------|------------------|---|
| Cu   | Sn              | Zn               | O |
| Bal. | 3.50 . . . 4.50 | 2.70 . . . 4.00o |   |

#### International comparison of standards

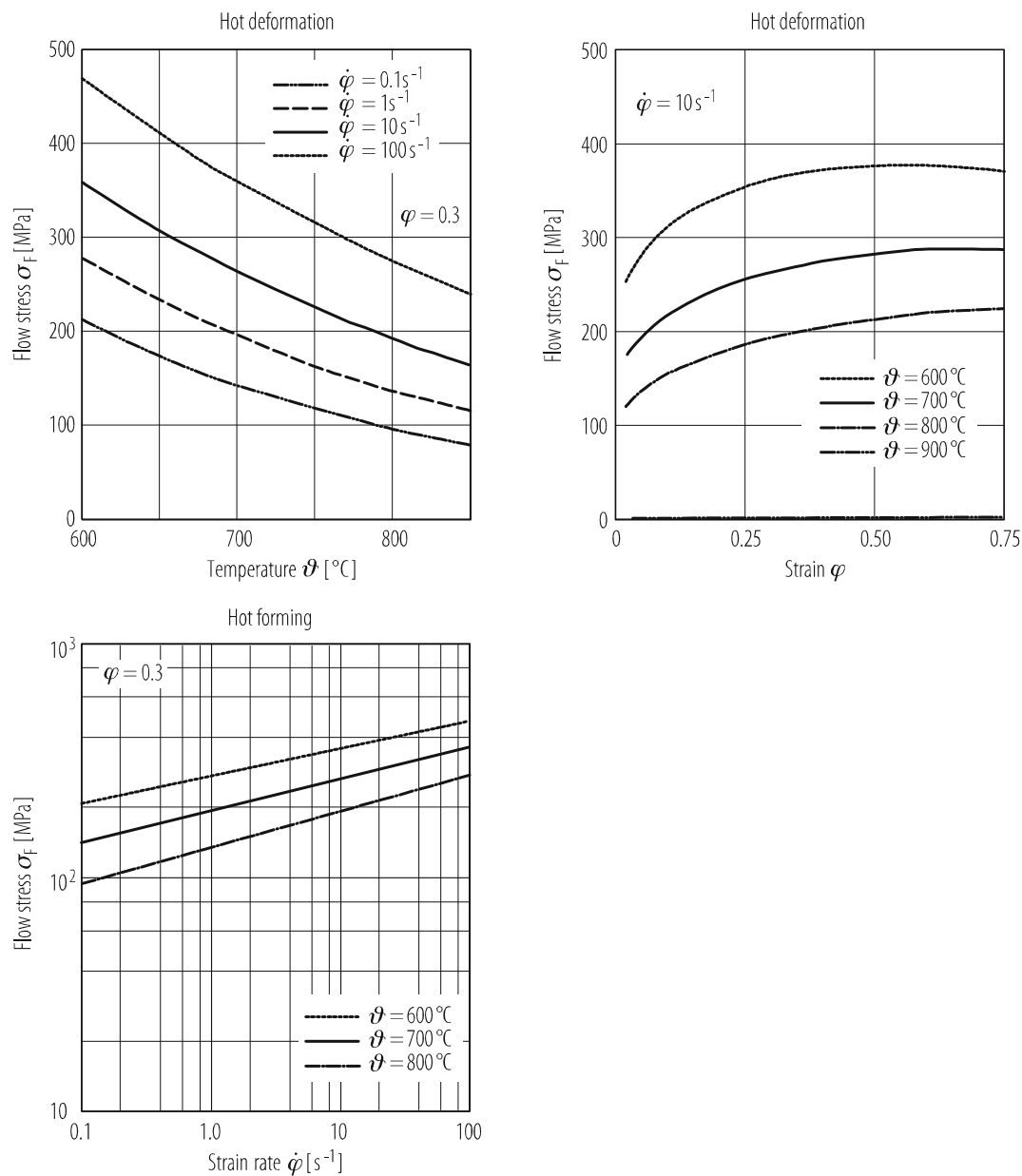
|                       |              |              |  |
|-----------------------|--------------|--------------|--|
| Euronorm              | ISO          |              |  |
| Material number (DIN) | DIN          |              |  |
| Japan                 | Russia       |              |  |
|                       | BrOC4-3      | GOST 5017-74 |  |
| USA                   |              |              |  |
| ASTM                  | UNS standard |              |  |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                 | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|-----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state  | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                    |                 | 217.9           |                      |                    |                 |
| A                                      |                 | 3936.46         |                      |                    |                 |
| Effect of temperature $K_{\theta}$     |                 |                 |                      |                    |                 |
| $m_1$                                  |                 | −0.00413        |                      |                    |                 |
| Effect of strain $K_{\phi}$            |                 |                 |                      |                    |                 |
| $m_2$                                  |                 | 0.15408         |                      |                    |                 |
| $m_4$                                  |                 | 0.00113         |                      |                    |                 |
| $m_5$                                  |                 | 0.00114         |                      |                    |                 |
| $m_7$                                  |                 | −1.10918        |                      |                    |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                 |                      |                    |                 |
| $m_3$                                  |                 |                 |                      |                    |                 |
| $m_8$                                  |                 | 0.000191        |                      |                    |                 |
| Range of validity                      |                 |                 |                      |                    |                 |
| $\theta$ [°C]                          |                 | 600 . . . 850   |                      |                    |                 |
| $\phi$                                 |                 | 0.03 . . . 0.75 |                      |                    |                 |
| $\dot{\phi}$ [1/s]                     |                 | <100            |                      |                    |                 |

|                                                                                                                                                                                |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          |



**Fig. 5.60** Flow stress curves of CuSn<sub>4</sub>Zn<sub>3</sub> by hot forming.

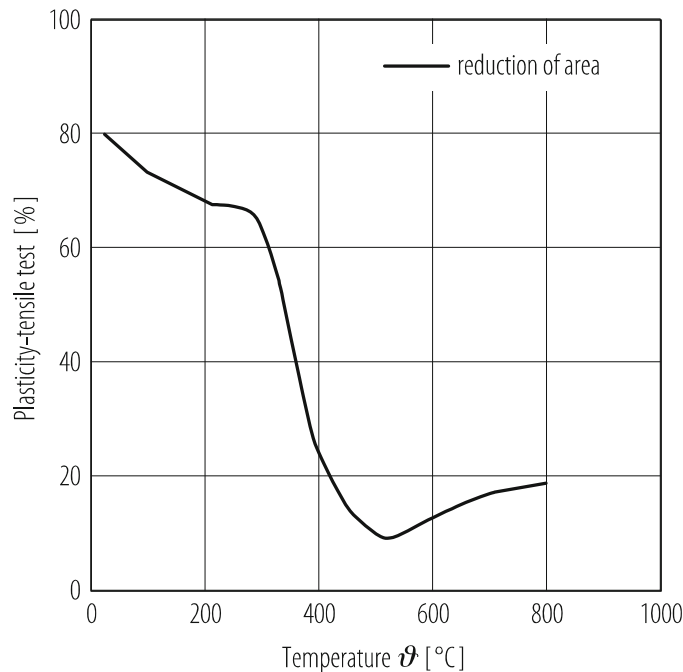
### Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |     |       | Tensile strength $\Delta R_m$ [MPa] |          |         |
|-------------------|---------------------------------|-----|-------|-------------------------------------|----------|---------|
|                   | $A_0$                           | $A$ | $n_1$ | $B_0$                               | $B$      | $n_2$   |
| soft annealed     |                                 |     |       | 350. . . 400                        | 11.11172 | 0.87249 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |          |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|----------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$    | $n_4$    |                            |
| soft annealed     | 50. . . 55                              | 58.31970 | −0.00548 | −10.5667 | <70                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

### Plasticity in tensile test



**Fig. 5.61** Plasticity of CuSn<sub>4</sub>Zn<sub>3</sub> as a function of the temperature.

### Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 72.1                 | 377.3              | 16.21                                   | 8894.8                      | 105             |
| 100              | 76.2                 | 383.6              | 16.73                                   | 8873.2                      |                 |
| 200              | 81.3                 | 391.6              | 17.38                                   | 8844.3                      |                 |
| 300              | 86.4                 | 399.5              | 18.03                                   | 8813.3                      |                 |
| 400              | 91.5                 | 407.5              | 18.68                                   | 8780.3                      |                 |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 500              | 96.6                 | 415.4              | 19.33                                   | 8745.2                      |                 |
| 600              | 101.7                | 423.3              | 19.98                                   | 8708.0                      |                 |
| 700              | 106.8                | 431.3              | 20.63                                   | 8668.7                      |                 |
| 800              | 111.9                | 439.2              | 21.28                                   | 8627.3                      |                 |

## Symbols and Abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |



# Flow stress, mechanical and physical properties of CuNi<sub>3</sub>Si<sub>1</sub>

## 5.2 Copper- and Copper alloys

### 5.2.4 Copper - Nickel - alloys

#### Designation

|             |               |               |                 |            |               |
|-------------|---------------|---------------|-----------------|------------|---------------|
| UNS number: | <b>C70250</b> | Chem. symbol: | <b>CuNi3Si1</b> | EN number: | <b>CW112C</b> |
|-------------|---------------|---------------|-----------------|------------|---------------|

#### Composition (EN) [Weight-%]

|       |             |              |       |       |       |
|-------|-------------|--------------|-------|-------|-------|
| Cu    | Ni          | Si           | Mn    | Pb    | Fe    |
| >93.6 | 2.60...4.50 | ~0.80...1.30 | <0.10 | <0.02 | <0.20 |

#### International comparison of standards

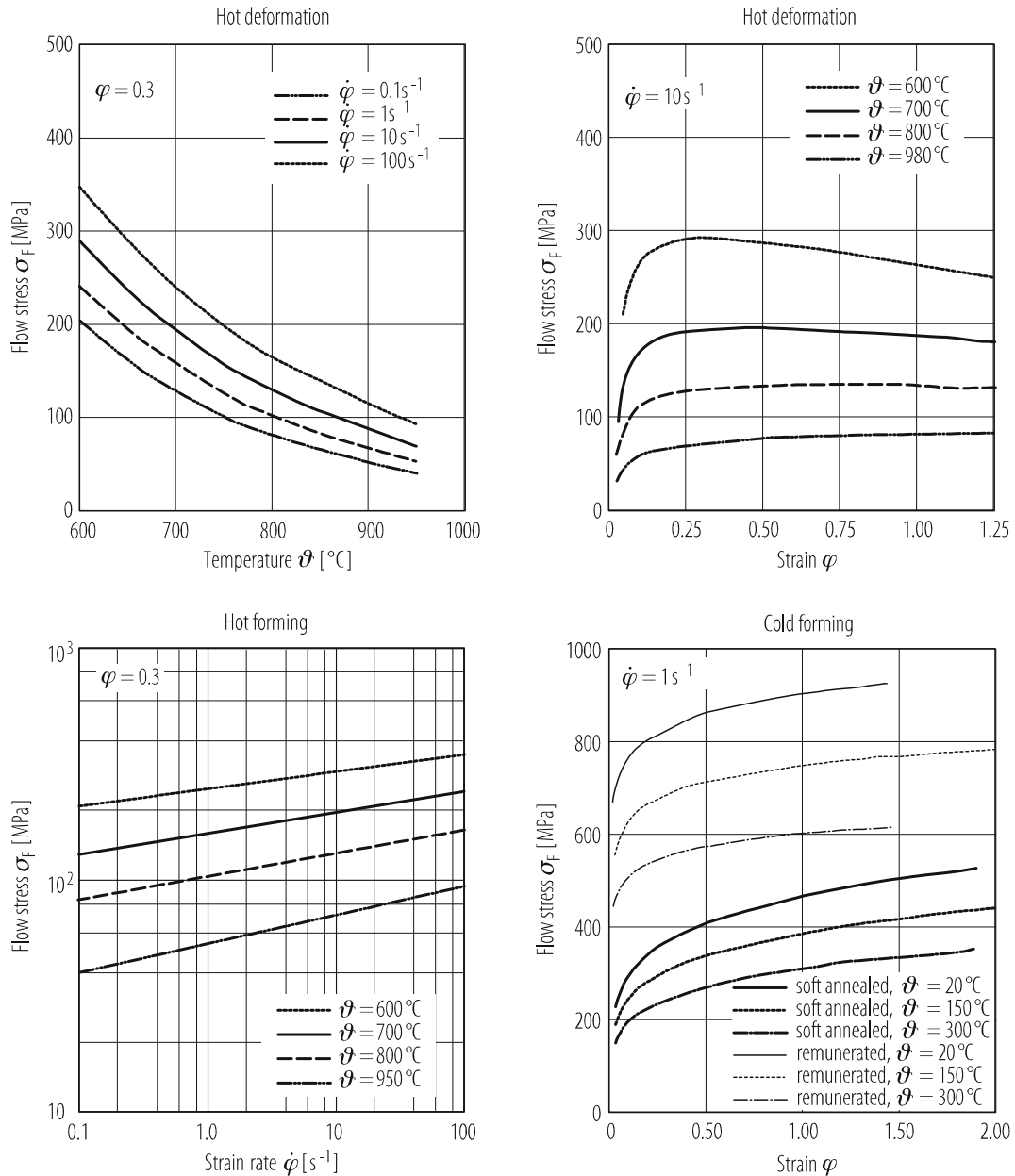
|                       |              |             |
|-----------------------|--------------|-------------|
| Euronorm              | ISO          |             |
| EN 12420 : 1999       | EN 12163     |             |
| EN 12165              |              |             |
| Material number (DIN) | DIN          |             |
| 2.0857                | DIN 17666    | DIN 17672-1 |
| Japan                 | Russia       |             |
|                       | BrKN1-3      | GOST 18175  |
| USA                   |              |             |
| ASTM                  | UNS standard |             |
| ASTM B 422            | ASTM B 888   | C70250      |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation   |                   |
|----------------------------------------|-----------------|----------------|--------------------|-------------------|
|                                        | cast state      | deformed state | soft annealed (sa) | remunerated (rem) |
| $\sigma_{F0}$ [MPa]                    |                 | 170.9          | 305.2              | 785.1             |
| A                                      |                 | 3682.179       | 480.025            | 928.447           |
| Effect of temperature $K_\theta$       |                 |                |                    |                   |
| $m_1$                                  |                 | −0.00476       | −0.00147           | −0.00145          |
| Effect of strain $K_\varphi$           |                 |                |                    |                   |
| $m_2$                                  |                 | −0.14219       | 0.18953            | 0.06979           |
| $m_4$                                  |                 | −0.03225       | −0.00186           | −0.00081          |
| $m_5$                                  |                 | 0.00152        |                    |                   |
| $m_7$                                  |                 | −0.56297       |                    |                   |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                    |                   |
| $m_3$                                  |                 |                | 0.01327            | 0.01294           |
| $m_8$                                  |                 | 0.000131       |                    |                   |
| Range of validity                      |                 |                |                    |                   |
| $\vartheta$ [°C]                       |                 | 600 ... 950    | 20 ... 300         | 20 ... 300        |
| $\varphi$                              |                 | 0.03 ... 1.25  | 0.03 ... 2.00      | 0.03 ... 1.50     |
| $\dot{\varphi}$ [1/s]                  |                 | <100           | <100               | <100              |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



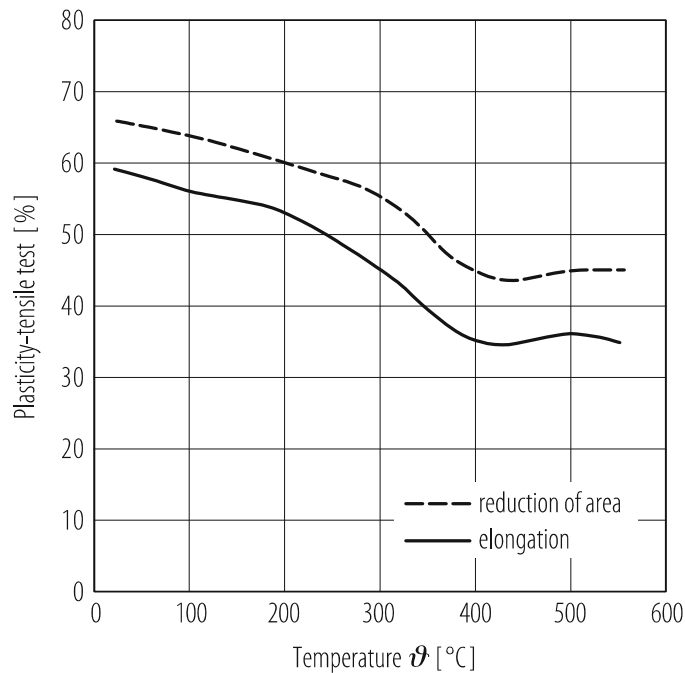
**Fig. 5.62** Flow stress curves of CuNi<sub>3</sub>Si<sub>1</sub> by hot and cold forming.

**Mechanical properties after cold deformation**

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| 850°C/0.5h/water  | 120...160                       | 20.00776 | 0.76001 | 270...330                           | 7.66159 | 0.87595 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| 850°C/0.5h/water  | 28...33                                 | 17.94031 | 0.09455 | −6.37674 | <80                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

**Plasticity in tensile test****Fig. 5.63** Cold plasticity of CuNi<sub>3</sub>Si<sub>1</sub> as a function of the temperature.**Physical properties**

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 119.1                | 376.4              | 14.75                                   | 8920.3                      | 143.0           |
| 100              | 139.3                | 384.1              | 15.13                                   | 8900.7                      |                 |
| 200              | 149.1                | 393.8              | 15.59                                   | 8874.9                      |                 |
| 300              | 155.1                | 403.4              | 16.06                                   | 8847.6                      |                 |
| 400              | 159.5                | 413.1              | 16.52                                   | 8818.8                      |                 |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}/\text{K}$ ]       | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 500              | 163.0                | 422.7              | 16.99                                   | 8788.6                      |                 |
| 600              | 165.9                | 432.3              | 17.45                                   | 8756.8                      |                 |
| 700              | 168.4                | 442.0              | 17.92                                   | 8723.5                      |                 |
| 800              | 170.6                | 451.6              | 18.38                                   | 8688.8                      |                 |
| 900              | 172.6                | 461.3              | 18.85                                   | 8652.5                      |                 |
| 950              | 173.5                | 466.1              | 19.08                                   | 8633.8                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress and physical properties of CuNi<sub>5</sub>Fe

## 5.2 Copper- and Copper alloys

### 5.2.4 Copper - Nickel - alloys

#### Designation

|             |               |               |                |            |
|-------------|---------------|---------------|----------------|------------|
| UNS number: | <b>C70400</b> | Chem. symbol: | <b>CuNi5Fe</b> | EN number: |
|-------------|---------------|---------------|----------------|------------|

#### Composition (DIN) [Weight-%]

| Cu   | Ni          | Fe          | Mn          | Zn    | Pb     | S     | C     | Co    | Others |
|------|-------------|-------------|-------------|-------|--------|-------|-------|-------|--------|
| Bal. | 4.50...6.00 | 1.00...1.50 | 0.30...0.80 | <0.30 | <0.005 | <0.03 | <0.03 | <0.10 | <0.50  |

#### International comparison of standards

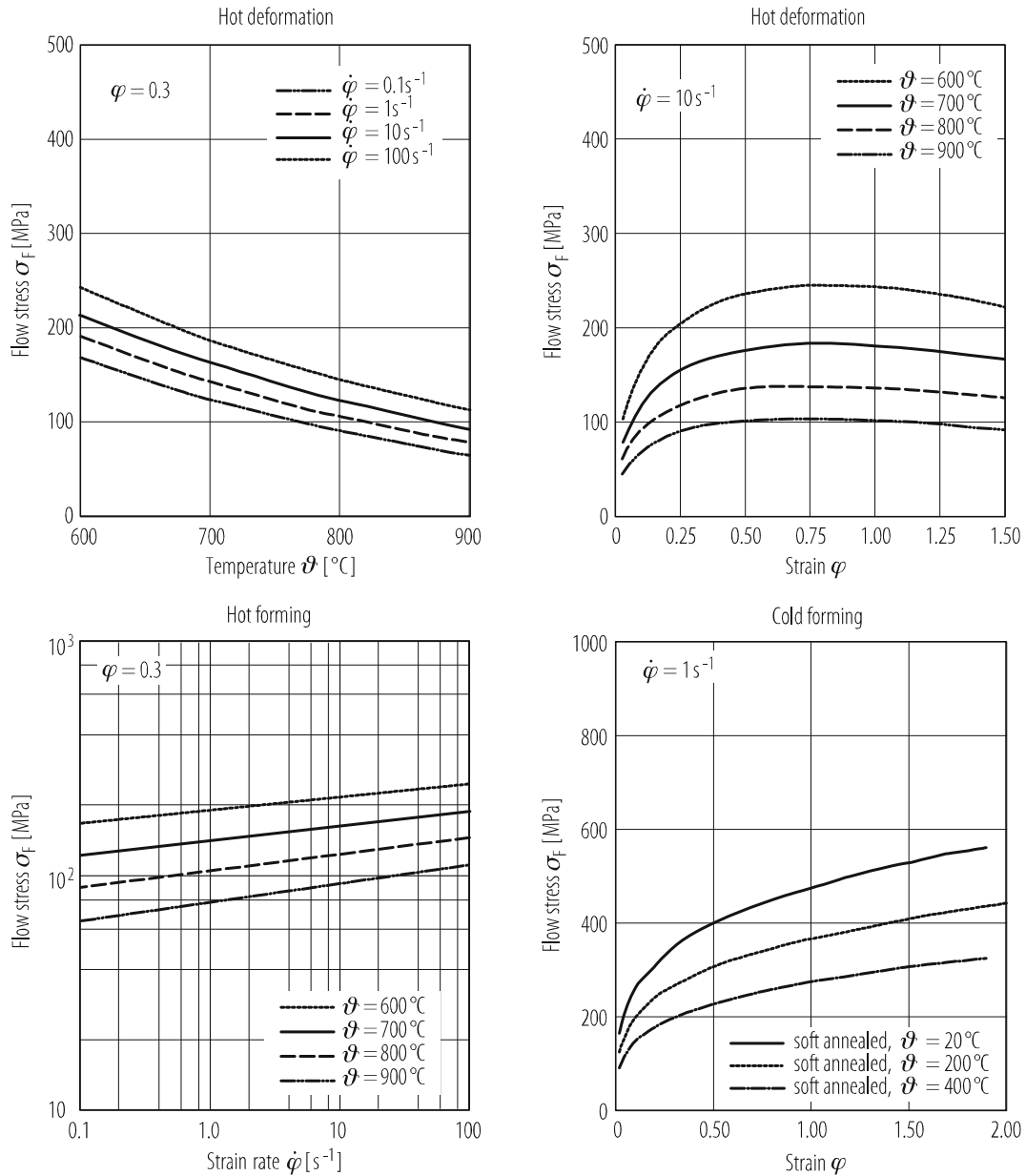
|                       |                      |            |
|-----------------------|----------------------|------------|
| Euronorm              | ISO                  |            |
|                       | ISO 429 : 1973       |            |
| Material number (DIN) | DIN                  |            |
| 2.0862                | [DIN 17664 : 1967]]  |            |
| Japan                 | Russia               |            |
|                       | MNZ5-1               | GOST 00492 |
| USA                   |                      |            |
| ASTM                  | UNS standard         |            |
| ASTM B 111 / B 111 M  | ASTM B 359 / B 359 M | C70400     |
| ASTM B 395 / B 395 M  | ASTM B 466 / B 466 M |            |
| ASTM B 543 / B 543 M  | ASTM B 956           |            |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                    |                 | 118.6          |                      | 270.2              |                 |
| A                                      |                 | 2062.383       |                      | 492.060            |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                      |                    |                 |
| $m_1$                                  |                 | −0.00294       |                      | −0.00146           |                 |
| Effect of strain $K_{\phi}$            |                 |                |                      |                    |                 |
| $m_2$                                  |                 | 0.38567        |                      | 0.25618            |                 |
| $m_4$                                  |                 | 0.00043        |                      | −0.00182           |                 |
| $m_5$                                  |                 | −0.00024       |                      |                    |                 |
| $m_7$                                  |                 | −0.40004       |                      |                    |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.01595            |                 |
| $m_8$                                  |                 | 0.000087       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\theta$ [°C]                          |                 | 600 ... 900    |                      | 20 ... 400         |                 |
| $\phi$                                 |                 | 0.03 ... 1.50  |                      | 0.03 ... 2.00      |                 |
| $\dot{\phi}$ [1/s]                     |                 | <100           |                      | <100               |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.64** Flow stress curves of CuNi<sub>5</sub>Fe by hot and cold forming.

Plasticity in tensile test

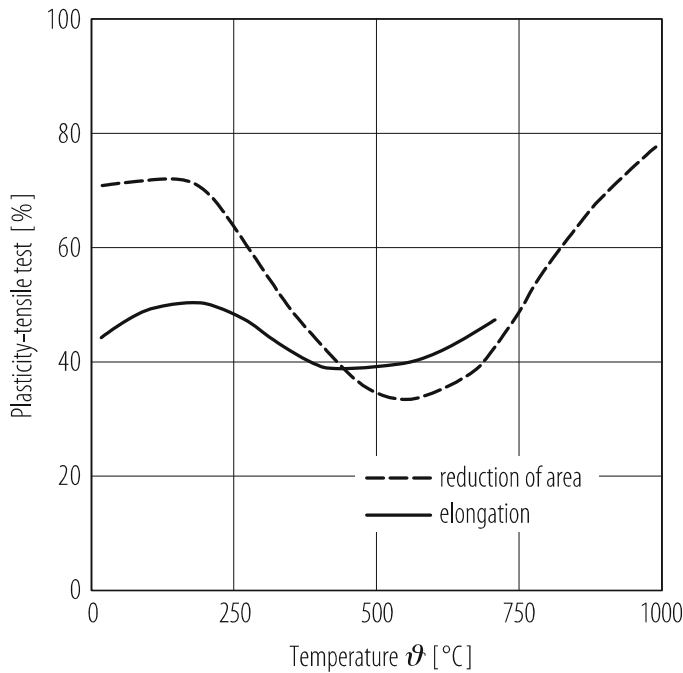


Fig. 5.65 Plasticity of CuNi<sub>5</sub>Fe as a function of the temperature.

Physical properties

| Temperature<br>Θ [°C] | Thermal conductivity<br>λ [W/m·K] | Mean specific heat<br>c <sub>pm</sub> [J/kg·K] | Average coefficient<br>of linear expansion<br>α <sub>m</sub> [10 <sup>-6</sup> /K] | Density<br>ρ [kg/m <sup>3</sup> ] | Young's-modulus<br>E [GPa] |
|-----------------------|-----------------------------------|------------------------------------------------|------------------------------------------------------------------------------------|-----------------------------------|----------------------------|
| 20                    | 44.8                              | 376.4                                          | 15.05                                                                              | 8920.2                            | 126.0                      |
| 100                   | 58.7                              | 384.1                                          | 15.43                                                                              | 8900.2                            |                            |
| 200                   | 65.9                              | 393.8                                          | 15.89                                                                              | 8873.9                            |                            |
| 300                   | 70.6                              | 403.4                                          | 16.36                                                                              | 8846.2                            |                            |
| 400                   | 74.1                              | 413.1                                          | 16.82                                                                              | 8816.9                            |                            |
| 500                   | 76.9                              | 422.7                                          | 17.29                                                                              | 8786.2                            |                            |
| 600                   | 79.3                              | 432.3                                          | 17.75                                                                              | 8753.9                            |                            |
| 700                   | 81.4                              | 442.0                                          | 18.22                                                                              | 8720.2                            |                            |
| 800                   | 83.2                              | 451.6                                          | 18.68                                                                              | 8684.9                            |                            |
| 900                   | 84.9                              | 461.3                                          | 19.15                                                                              | 8648.2                            |                            |
| 950                   | 85.7                              | 466.1                                          | 19.38                                                                              | 8629.3                            |                            |

Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| σ <sub>F</sub>  | flow stress                                                           |
| φ               | strain                                                                |
| φ̇              | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| c <sub>pm</sub> | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| E               | Young's modulus                                                       |
| EN              | Euronorm                                                              |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| GOST           | gosudarstvennyy standart (state standard)      |
| ISO            | international organisation for standardization |
| $T, \vartheta$ | Temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |



# Flow stress and physical properties of CuNi<sub>10</sub>Fe<sub>1</sub>Mn

## 5.2 Copper- and Copper alloys

### 5.2.4 Copper - Nickel - alloys

#### Designation

|             |               |               |                    |            |               |
|-------------|---------------|---------------|--------------------|------------|---------------|
| UNS number: | <b>C70600</b> | Chem. symbol: | <b>CuNi10Fe1Mn</b> | EN number: | <b>CW352H</b> |
|-------------|---------------|---------------|--------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu    | Ni         | Sn    | Mn         | Pb    | Fe          | Zn    | C     | Co    | S     |
|-------|------------|-------|------------|-------|-------------|-------|-------|-------|-------|
| >85.1 | 9.0...11.0 | <0.30 | 0.50...1.0 | <0.03 | 1.00...2.00 | <0.30 | <0.05 | <0.10 | <0.05 |

#### International comparison of standards

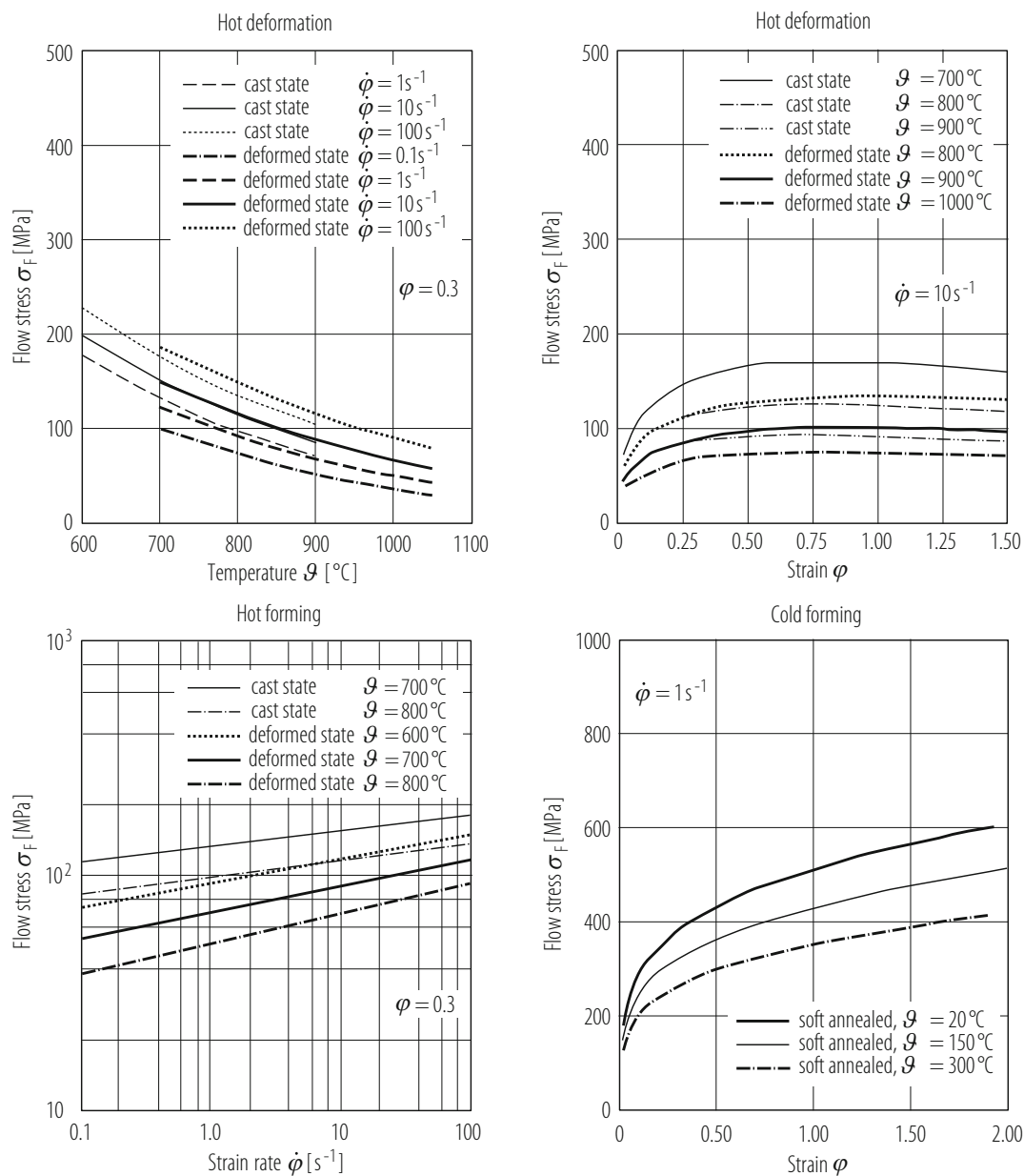
| Euronorm              |                     | ISO                  |                |
|-----------------------|---------------------|----------------------|----------------|
| EN 1653 : 1997        | EN 1652             | CuNi10Fe1Mn          | ISO 429 : 1983 |
| EN 12163              | EN 12165            | ISO 1634-2           | ISO 1635-2     |
| EN 12449,             | EN 12420            |                      |                |
| Material number (DIN) |                     | DIN                  |                |
| 2.0872                |                     | [[DIN 17664 : 1983]] | DIN 17670-1    |
|                       |                     | DIN 17675-1          | DIN 17672-1    |
|                       |                     | DIN 17671-1,         | DIN 17679,     |
| Japan                 |                     | Russia               |                |
| C 7060                | JIS H 3100 : 1992   | MNZMc10-1-           | GOST 00492     |
| JIS H 3300            | JIS H 3320          |                      |                |
| USA                   |                     | UNS standard         |                |
| ASTM                  |                     | C 70600              |                |
| ASTM B 122 / B 122 M  | ASTM B 111/ B 111 M |                      |                |
| ASTM B 171 / B 171 M  | ASTM B 151/ B 151 M |                      |                |
| ASTM B 467 / B 467 M  | ASTM B 552          |                      |                |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

**Flow curves**

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                    | 115.9           | 116.1          |                      | 295.8              |                 |
| A                                      | 1788.439        | 1564.028       |                      | 529.131            |                 |
| Effect of temperature $K_\theta$       |                 |                |                      |                    |                 |
| $m_1$                                  | −0.00287        | −0.00285       |                      | −0.00134           |                 |
| Effect of strain $K_\varphi$           |                 |                |                      |                    |                 |
| $m_2$                                  | 0.3606          | 0.34278        |                      | 0.23929            |                 |
| $m_4$                                  | 0.00123         | 0.002199       |                      | −0.00279           |                 |
| $m_5$                                  | −0.00054        | −0.00043       |                      |                    |                 |
| $m_7$                                  | −0.23114        | −0.16911       |                      |                    |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.01004            |                 |
| $m_8$                                  | 0.000092        | 0.000128       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                       | 600 ... 900     | 700 ... 1050   |                      | 20 ... 300         |                 |
| $\varphi$                              | 0.03 ... 1.50   | 0.03 ... 1.50  |                      | 0.03 ... 2.00      |                 |
| $\dot{\varphi}$ [1/s]                  | <100            | <100           |                      | <100               |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.66** Flow stress curves of CuNi<sub>10</sub>Fe<sub>1</sub>Mn by hot and cold forming

Plasticity in tensile test

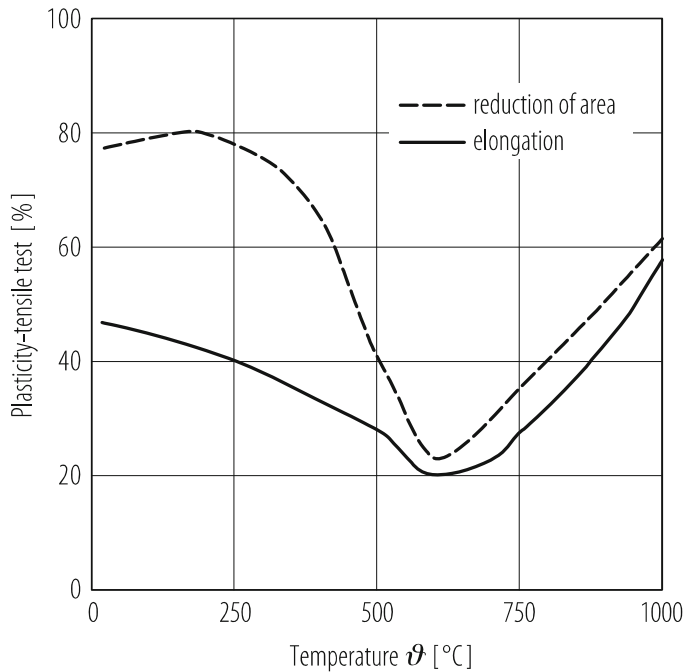


Fig. 5.67 Plasticity of CuNi10Fe1Mn as a function of the temperature

Physical properties

| Temperature | Thermal conductivity | Mean specific heat       | Average coefficient of linear expansion | Density                | Young's-modulus |
|-------------|----------------------|--------------------------|-----------------------------------------|------------------------|-----------------|
| Θ [°C]      | λ [W/m·K]            | c <sub>pm</sub> [J/kg·K] | α <sub>m</sub> [10 <sup>-6</sup> /K]    | ρ [kg/m <sup>3</sup> ] | E [GPa]         |
| 20          | 49.7                 | 368.0                    | 15.85                                   | 8914.9                 | 124.0           |
| 100         | 65.2                 | 375.7                    | 16.23                                   | 8893.9                 | 118.0           |
| 200         | 73.2                 | 385.4                    | 16.69                                   | 8866.4                 | 112.0           |
| 300         | 78.4                 | 395.0                    | 17.16                                   | 8837.4                 | 106.0           |
| 400         | 82.3                 | 404.7                    | 17.62                                   | 8806.8                 | 100.0           |
| 500         | 85.4                 | 414.3                    | 18.09                                   | 8774.8                 |                 |
| 600         | 88.1                 | 429.8                    | 18.55                                   | 8741.3                 |                 |
| 700         | 90.4                 | 426.1                    | 19.02                                   | 8706.3                 |                 |
| 800         | 92.5                 | 422.4                    | 19.48                                   | 8669.8                 |                 |
| 900         | 94.3                 | 418.7                    | 19.95                                   | 8631.8                 |                 |
| 950         | 95.2                 | 416.9                    | 20.18                                   | 8612.2                 |                 |

Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| σ <sub>F</sub>  | flow stress                                                           |
| φ               | strain                                                                |
| φ̇              | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| c <sub>pm</sub> | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| $E$            | Young's modulus                                |
| EN             | Euronorm                                       |
| GOST           | gosudarstvennyy standart (state standard)      |
| ISO            | international organisation for standardization |
| JIS            | Japanese Industrial Standards                  |
| $T, \vartheta$ | Temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |

# Flow stress, mechanical and physical properties of CuNi<sub>9</sub>Sn<sub>2</sub>

## 5.2 Copper- and Copper alloys

### 5.2.4 Copper - Nickel - alloys

#### Designation

|             |               |               |                 |            |               |
|-------------|---------------|---------------|-----------------|------------|---------------|
| UNS number: | <b>C72500</b> | Chem. symbol: | <b>CuNi9Sn2</b> | EN number: | <b>CW351H</b> |
|-------------|---------------|---------------|-----------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu   | Ni           | Sn          | Mn    | Pb    | Fe    | Zn    | Others |
|------|--------------|-------------|-------|-------|-------|-------|--------|
| Bal. | 8.50...10.50 | 1.80...2.80 | <0.30 | <0.03 | <0.30 | <0.10 | <0.10  |

#### International comparison of standards

| Euronorm              |                 | ISO                  |             |
|-----------------------|-----------------|----------------------|-------------|
| EN 1652               | EN 14436 : 2002 | ISO 429 : 1983       |             |
| EN 13148              | EN 1654         | ISO 1634-3           |             |
| Material number (DIN) |                 | DIN                  |             |
| 2.0875                |                 | [[DIN 17664 : 1983]] | DIN 17670-1 |
|                       |                 |                      | DIN 1777    |
| Japan                 |                 | Russia               |             |
| C 7250                | JIS H 3100      |                      |             |
| USA                   |                 | UNS standard         |             |
| ASTM                  |                 | C72500               |             |
| ASTM B 122 / B 122 M  |                 |                      |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material           | Hot deformation |                | Cold deformation     |                    |                 |
|-----------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                             | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]         |                 | 150.3          |                      | 287.4              |                 |
| A                           |                 | 2476.854       |                      | 554.048            |                 |
| Effect of temperature $K_9$ |                 |                |                      |                    |                 |
| $m_1$                       |                 | -0.00287       |                      | -0.00139           |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| Effect of strain $K_\varphi$           |                 |                |                      |                    |                 |
| $m_2$                                  |                 | 0.3606         |                      | 0.17035            |                 |
| $m_4$                                  |                 | 0.00123        |                      | −0.0206            |                 |
| $m_5$                                  |                 | −0.00054       |                      |                    |                 |
| $m_7$                                  |                 | −0.23114       |                      |                    |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | −0.01332           |                 |
| $m_8$                                  |                 | 0.000052       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                       |                 | 600 ... 900    |                      | 20 ... 300         |                 |
| $\varphi$                              |                 | 0.03 ... 1.50  |                      | 0.03 ... 2.00      |                 |
| $\dot{\varphi}$ [1/s]                  |                 | <100           |                      | <100               |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

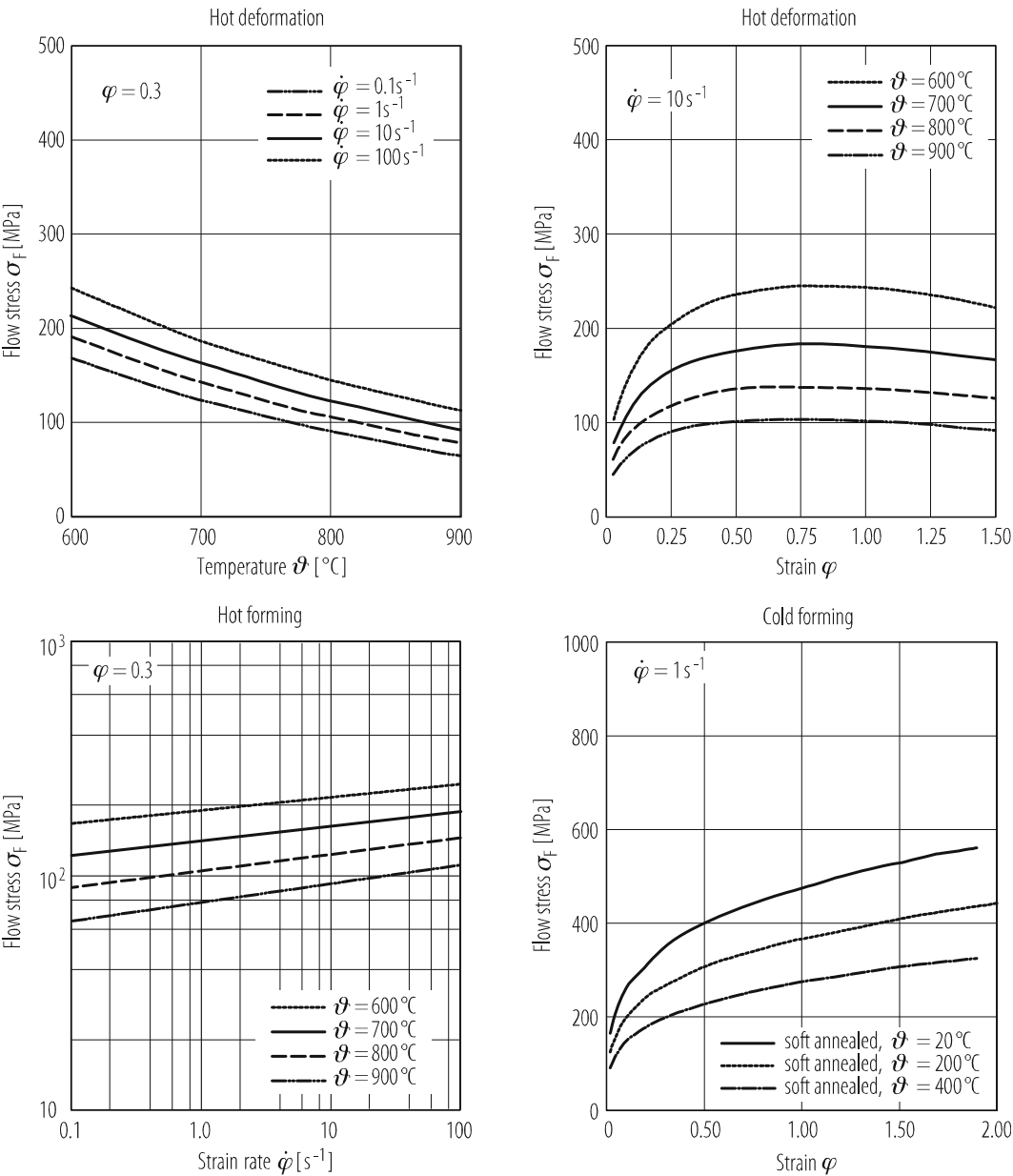


Fig. 5.68 Flow stress curves of CuNi<sub>9</sub>Sn<sub>2</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |        | Tensile strength $\Delta R_m$ [MPa] |        |         |
|-------------------|---------------------------------|----------|--------|-------------------------------------|--------|---------|
|                   | $A_0$                           | $A$      | $n_1$  | $B_0$                               | $B$    | $n_2$   |
| soft annealed     | 180. . . 220                    | 35.98852 | 0.5932 | 340. . . 410                        | 3.9304 | 0.99545 |



| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| soft annealed     | 35...40                                 | 11.11283 | 0.24748 | -2.34592 | <90                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 46.6                 | 371.6              | 15.01                                   | 8885.2                      | 140.0           |
| 100              | 60.2                 | 380.5              | 15.45                                   | 8865.3                      | 136.0           |
| 200              | 67.1                 | 391.6              | 16.00                                   | 8838.8                      | 132.0           |
| 300              | 71.6                 | 402.7              | 16.55                                   | 8810.6                      | 127.0           |
| 400              | 74.9                 | 413.8              | 17.10                                   | 8780.5                      |                 |
| 500              | 77.6                 | 425.0              | 17.65                                   | 8748.8                      |                 |
| 600              | 79.9                 | 436.1              | 18.20                                   | 8715.3                      |                 |
| 700              | 81.9                 | 447.2              | 18.75                                   | 8680.0                      |                 |
| 800              | 83.6                 | 458.3              | 19.30                                   | 8642.9                      |                 |
| 900              | 85.2                 | 469.4              | 19.85                                   | 8604.1                      |                 |
| 950              | 85.9                 | 474.9              | 20.13                                   | 8584.1                      |                 |

## Symbols and Abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese industrial standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuNi<sub>20</sub>

## 5.2 Copper- and Copper alloys

### 5.2.4 Copper - Nickel - alloys

#### Designation

|             |               |               |               |              |
|-------------|---------------|---------------|---------------|--------------|
| UNS number: | <b>C71000</b> | Chem. symbol: | <b>CuNi20</b> | (EN number): |
|-------------|---------------|---------------|---------------|--------------|

#### Composition (DIN) [Weight-%]

| Cu   | Ni          | Zn    | Mn         | Pb     | Fe    | S     | C     |
|------|-------------|-------|------------|--------|-------|-------|-------|
| Bal. | 18.0...20.0 | <0.30 | 0.10..0.50 | <0.005 | <0.30 | 0.010 | <0.05 |

#### International comparison of standards

|                       |                      |                  |
|-----------------------|----------------------|------------------|
| Euronorm              |                      | ISO              |
|                       |                      | ISO 429 : 1973   |
| Material number (DIN) |                      | DIN              |
| 2.0878                |                      | DIN 17664 : 1974 |
| Japan                 |                      | Russia           |
| C 7100                | JIS H 3300 : 1992    |                  |
| JIS H 3300            |                      |                  |
| USA                   |                      |                  |
| ASTM                  |                      | UNS standard     |
| ASTM B 122 / B 122 M  | ASTM B 694           | C71000           |
| ASTM B 206 / B 206 M  | ASTM B 466 / B 466 M |                  |
| ASTM B 111 / B 111 M  | ASTM B 543/ B 543 M  |                  |
| ASTM B 359 / B 359 M  | ASTM B 956           |                  |
| ASTM B 395 / B 395 M  |                      |                  |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

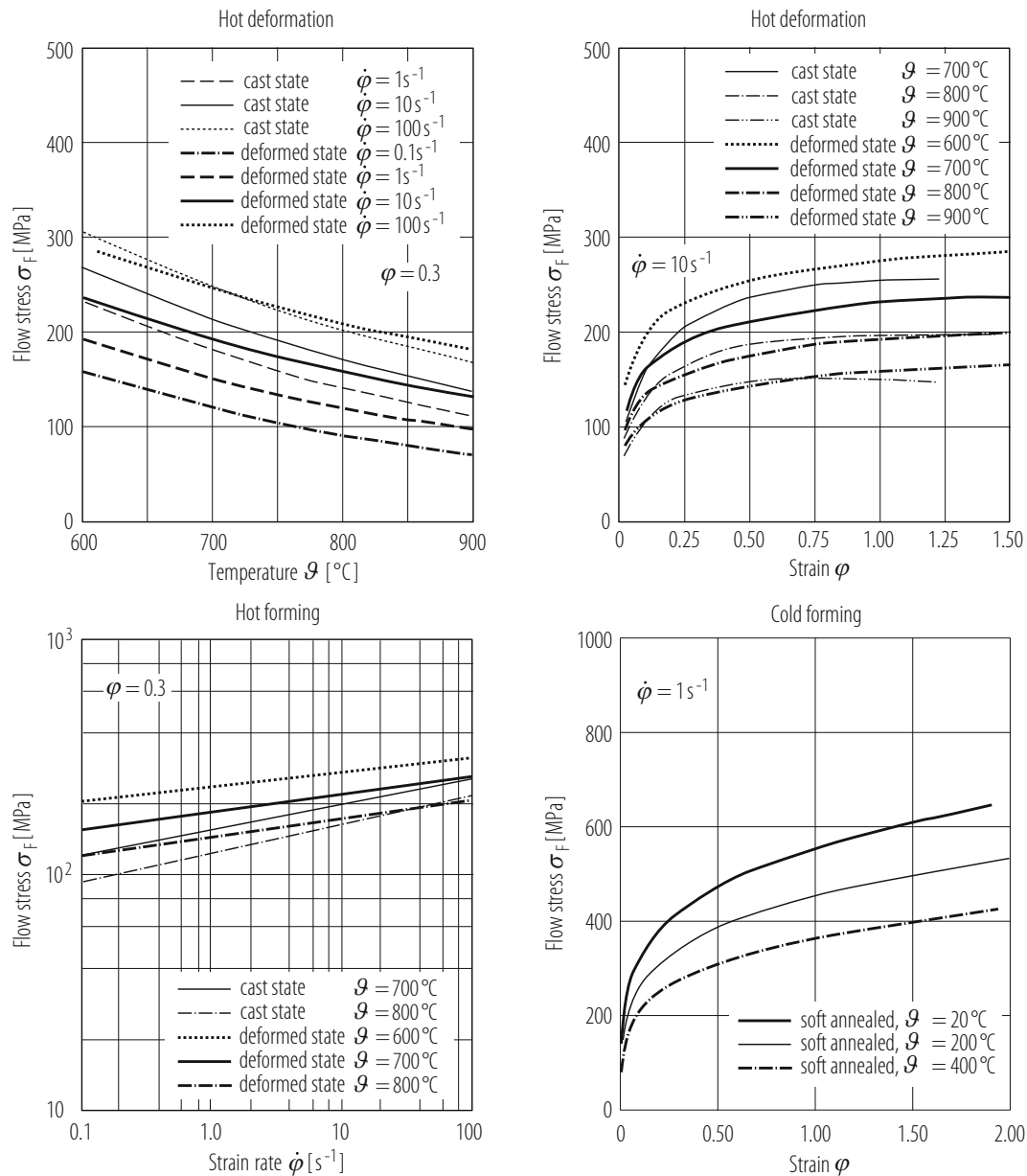
#### Flow curves

| State of material           | Hot deformation |                | Cold deformation     |                    |                 |
|-----------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                             | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]         | 157.23          | 160.9          |                      | 331.0              |                 |
| A                           | 1622.462        | 934.814        |                      | 570.737            |                 |
| Effect of temperature $K_9$ |                 |                |                      |                    |                 |
| $m_1$                       | -0.00218        | -0.002316      |                      | -0.00112           |                 |
| Effect of strain $K_\phi$   |                 |                |                      |                    |                 |
| $m_2$                       | 0.39963         | 0.13997        |                      | 0.22727            |                 |
| $m_4$                       | 0.00196         | -0.00598       |                      | -0.00205           |                 |
| $m_5$                       | -0.001          | 0.00022        |                      |                    |                 |
| $m_7$                       | 0.00062         | -0.11886       |                      |                    |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| m <sub>3</sub>                         |                 |                |                      | 0.0089             |                 |
| m <sub>8</sub>                         | 0.000098        | 0.000149       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| θ [°C]                                 | 600 ... 900     | 600 ... 900    |                      | 20 ... 400         |                 |
| φ                                      | 0.03 ... 1.25   | 0.03 ... 1.50  |                      | 0.03 ... 2.00      |                 |
| $\dot{\varphi}$ [1/s]                  | <100            | <100           |                      | <100               |                 |

|                                                                                                                                                                       |                                                                                                         |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                      | Cold deformation                                                                                        |
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                  | [Equation (2.25), Chapter 2.3.2.2.2]                                                                    |



**Fig. 5.69** Flow stress curves of CuNi20 by hot and cold forming.

### Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         | Validity $\varepsilon$ [%] |
|-------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|----------------------------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |                            |
| soft annealed     | 120...160                       | 20.00776 | 0.76001 | 310...350                           | 8.69128 | 0.75053 | <60                        |

Yield stress:

$$R_p = A_0 + A \cdot \varepsilon^{n_1}$$

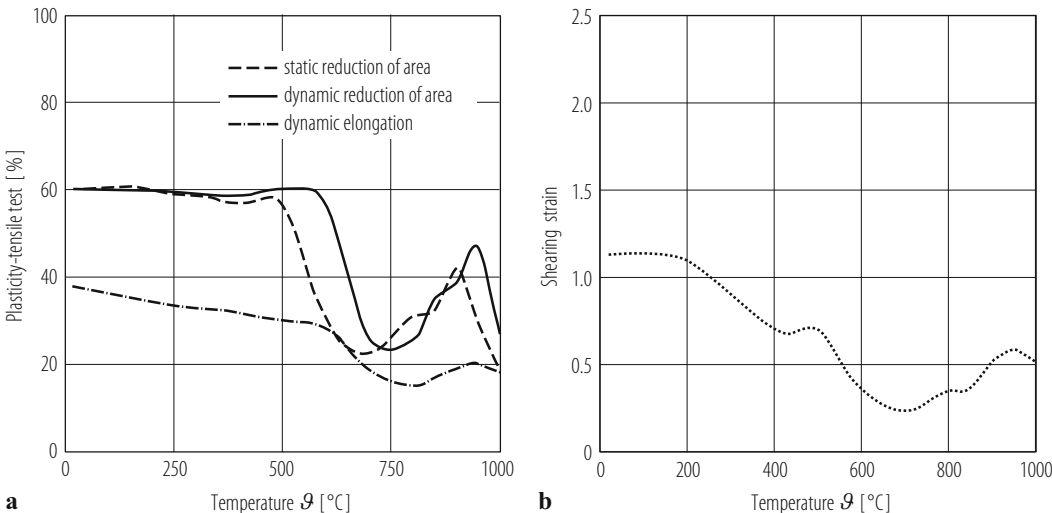
[Equation (4.1), Chapter 5.1.4]

Tensile strength:

$$R_m = B_0 + B \cdot \varepsilon^{n_2}$$

[Equation (4.2), Chapter 5.1.4]

Plasticity in tensile test



**Fig. 5.70** Plasticity of CuNi20 as a function of the temperature. **(a)** Initial test: annealed at 800 °C/2 h. **(b)** Initial test: annealed at 800 °C/2 h.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 32.9                 | 368.4              | 14.61                                   | 8890.3                      | 140.0           |
| 100              | 43.1                 | 376.1              | 15.05                                   | 8870.9                      |                 |
| 200              | 48.4                 | 385.8              | 15.60                                   | 8845.0                      |                 |
| 300              | 51.8                 | 395.4              | 16.15                                   | 8817.4                      |                 |
| 400              | 54.3                 | 405.1              | 16.70                                   | 8788.0                      |                 |
| 500              | 56.4                 | 414.7              | 17.25                                   | 8756.9                      |                 |
| 600              | 58.1                 | 424.3              | 17.80                                   | 8724.0                      |                 |
| 700              | 59.7                 | 434.0              | 18.35                                   | 8689.3                      |                 |
| 800              | 61.0                 | 443.6              | 18.90                                   | 8652.9                      |                 |
| 900              | 62.2                 | 453.3              | 19.45                                   | 8614.7                      |                 |
| 950              | 62.8                 | 458.1              | 19.73                                   | 8595.0                      |                 |

Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| ISO            | international organisation for standardization |
| JIS            | Japanese industrial standards                  |
| $R_m$          | tensile strength                               |
| $R_p$          | yield stress                                   |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |

# Flow stress, mechanical and physical properties of CuNi<sub>25</sub>

## 5.2 Copper- and Copper alloys

### 5.2.4 Copper - Nickel - alloys

#### Designation

|             |               |               |               |            |               |
|-------------|---------------|---------------|---------------|------------|---------------|
| UNS number: | <b>C71300</b> | Chem. symbol: | <b>CuNi25</b> | EN number: | <b>CW350H</b> |
|-------------|---------------|---------------|---------------|------------|---------------|

#### Composition (EN) [Weight-%]

|      |             |       |            |        |       |       |       |
|------|-------------|-------|------------|--------|-------|-------|-------|
| Cu   | Ni          | Zn    | Mn         | Pb     | Fe    | S     | C     |
| Bal. | 24.0...26.0 | <0.30 | 0.10..0.50 | <0.005 | <0.30 | 0.010 | <0.05 |

#### International comparison of standards

|                       |                      |
|-----------------------|----------------------|
| Euronorm              | ISO                  |
| EN 1652 : 1997        | ISO 429 : 1983       |
|                       | ISO 1634-1           |
| Material number (DIN) | DIN                  |
| 2.083                 | [[DIN 17664 : 1983]] |
| Japan                 | Russia               |
|                       | MN25                 |
|                       | GOST 00492           |
| USA                   |                      |
| ASTM                  | UNS standard         |
|                       | C71300               |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                   | Hot deformation |                | Cold deformation     |                    |                 |
|-------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                     | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                 |                 | 171.3          |                      | 353.8              |                 |
| A                                   |                 | 1026.532       |                      | 569.279            |                 |
| Effect of temperature $K_\theta$    |                 |                |                      |                    |                 |
| $m_1$                               |                 | -0.00253       |                      | -0.00108           |                 |
| Effect of strain $K_\phi$           |                 |                |                      |                    |                 |
| $m_2$                               |                 | 0.12106        |                      | 0.23607            |                 |
| $m_4$                               |                 | 0.0057         |                      | 0.00665            |                 |
| $m_5$                               |                 | -0.00003       |                      |                    |                 |
| $m_7$                               |                 | -0.21405       |                      |                    |                 |
| Effect of strain rate $K\dot{\phi}$ |                 |                |                      |                    |                 |
| $m_3$                               |                 |                |                      | 0.00975            |                 |
| $m_8$                               |                 | 0.00014        |                      |                    |                 |
| Range of validity                   |                 |                |                      |                    |                 |
| $\theta$ [°C]                       |                 | 600 ... 1000   |                      | 20 ... 300         |                 |
| $\phi$                              |                 | 0.05 ... 1.50  |                      | 0.03 ... 2.00      |                 |
| $\dot{\phi}$ [1/s]                  |                 | <100           |                      | <100               |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                                                 |

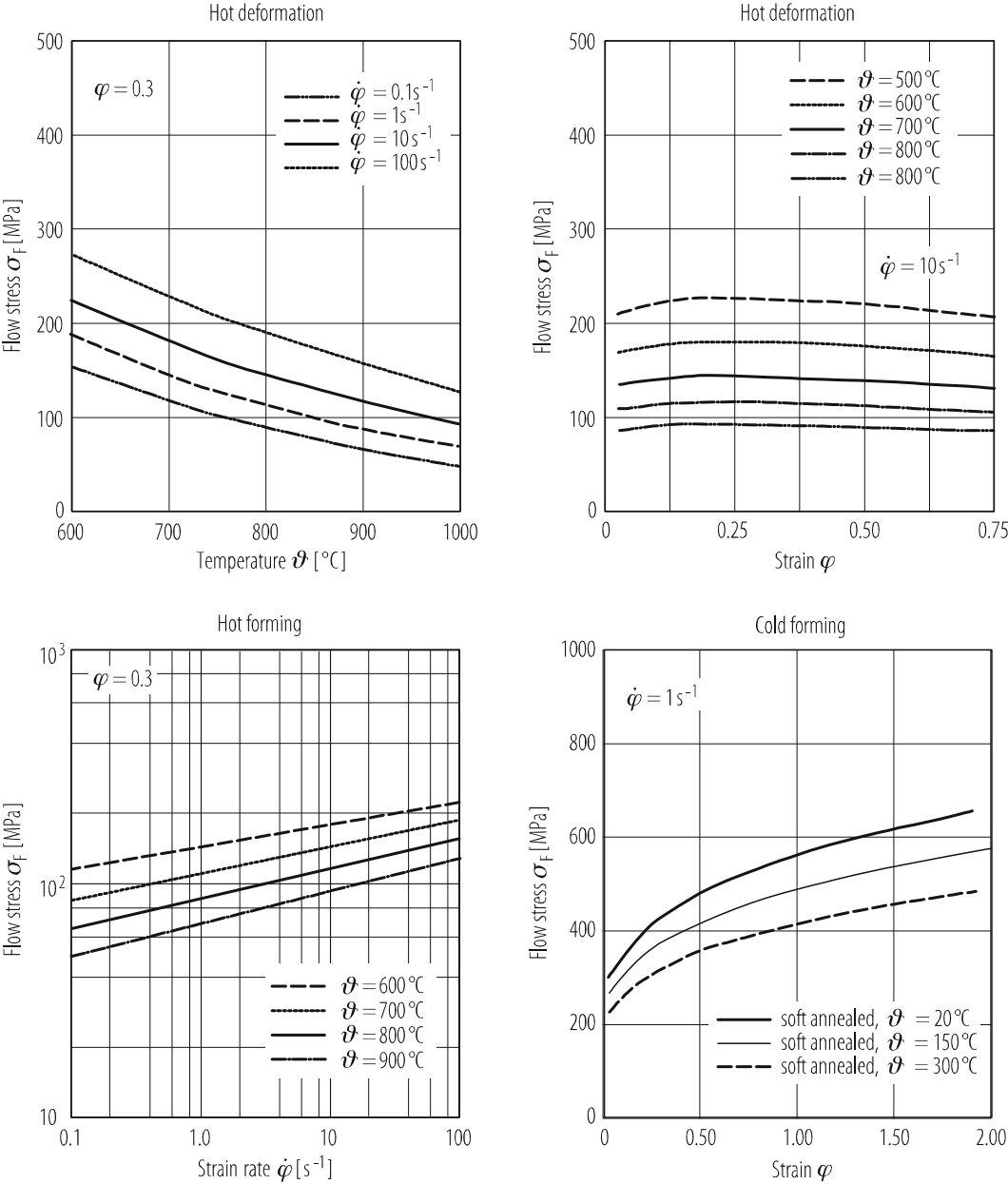


Fig. 5.71 Flow stress curves of CuNi25 by hot and cold forming.



## Mechanical properties after cold deformation

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| soft annealed     | 35...40                                 | 24.92173 | 0.10254 | -5.13813 | <80                        |

Elongation to fracture

$$A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$$

[Equation (4.3), Chapter 5.1.4]

[DOI: [978-3-642-14174-4\\_5](https://doi.org/10.1007/978-3-642-14174-4_5)]

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 29.2                 | 368.4              | 14.01                                   | 8935.5                      | 145.0           |
| 100              | 38.0                 | 376.1              | 14.45                                   | 8916.7                      |                 |
| 200              | 42.6                 | 385.8              | 15.00                                   | 8891.7                      |                 |
| 300              | 45.5                 | 395.4              | 15.55                                   | 8864.9                      |                 |
| 400              | 47.7                 | 405.1              | 16.10                                   | 8836.4                      |                 |
| 500              | 49.5                 | 414.7              | 16.65                                   | 8806.0                      |                 |
| 600              | 51.0                 | 424.3              | 17.20                                   | 8773.9                      |                 |
| 700              | 52.3                 | 434.0              | 17.75                                   | 8740.1                      |                 |
| 800              | 53.4                 | 443.6              | 18.30                                   | 8704.4                      |                 |
| 900              | 54.4                 | 453.3              | 18.85                                   | 8667.0                      |                 |
| 950              | 54.9                 | 458.1              | 19.13                                   | 8647.6                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuNi<sub>12</sub>Zn<sub>24</sub>

## 5.2 Copper- and Copper alloys

### 5.2.4 Copper - Nickel - alloys

#### Designation

|             |               |               |                   |            |               |
|-------------|---------------|---------------|-------------------|------------|---------------|
| UNS number: | <b>C75700</b> | Chem. symbol: | <b>CuNi12Zn24</b> | EN number: | <b>CW403J</b> |
|-------------|---------------|---------------|-------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Ni          | Zn    | Mn    | Pb    | Fe    |
|-------------|-------------|-------|-------|-------|-------|
| 63.0...66.0 | 11.0...13.0 | >19.3 | <0.50 | <0.03 | <0.30 |
| Sn          | Others      |       |       |       |       |
| <0.03       | <0.20       |       |       |       |       |

#### International comparison of standards

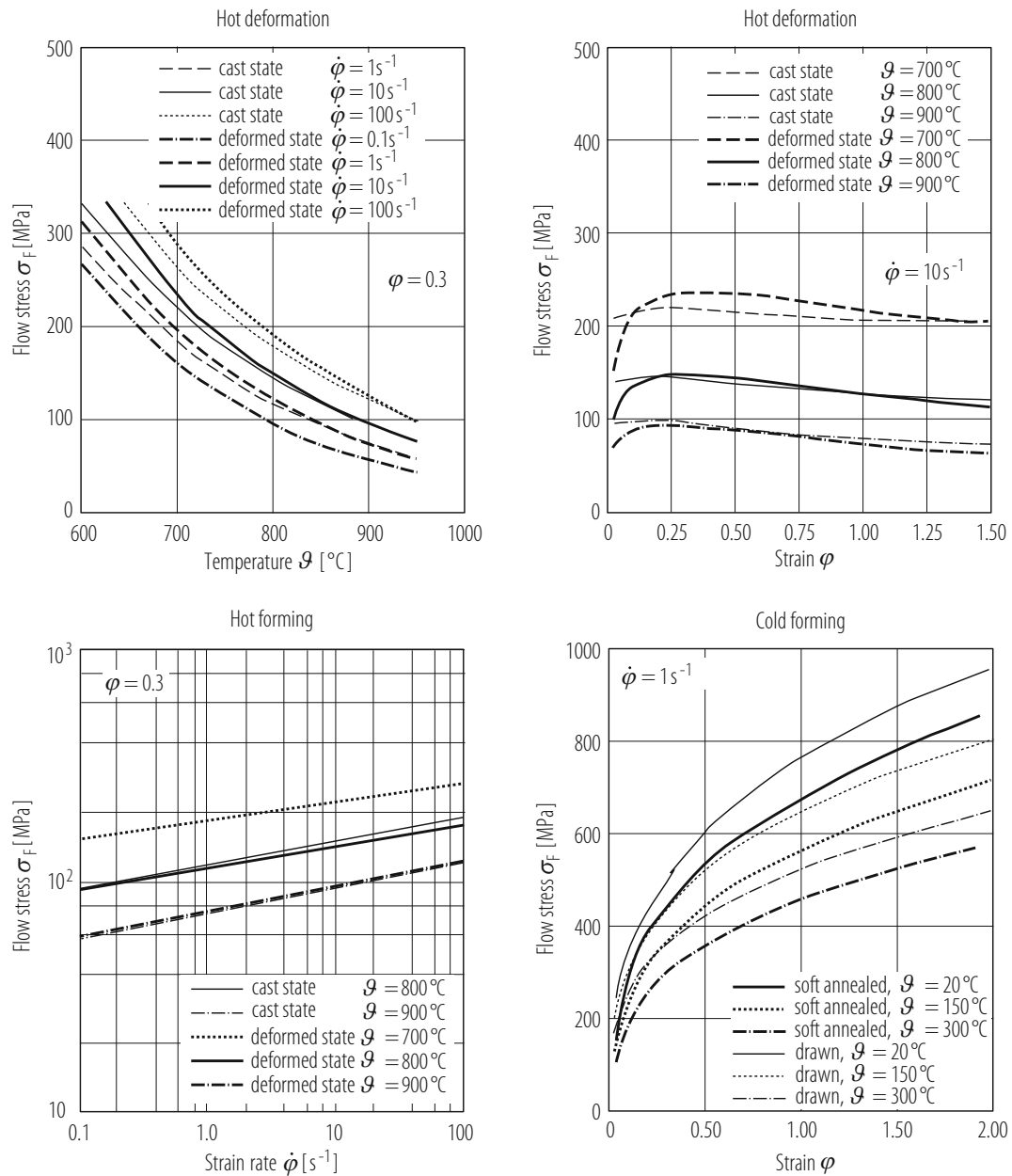
| Euronorm              |                 | ISO                  |             |
|-----------------------|-----------------|----------------------|-------------|
| EN 1652               | EN 12167 : 1998 | ISO 430 : 1983       | ISO 1634-3  |
| EN 1654               | EN 12449        | ISO 1634-1           | ISO 1635    |
| EN 12163              |                 | ISO 1638             |             |
| EN 12166              |                 |                      |             |
| Material number (DIN) |                 | DIN                  |             |
| 2.0730                |                 | [[DIN 17663 : 1983]] | DIN 17670-1 |
|                       |                 | DIN 1777             | DIN 17672-1 |
|                       |                 | DIN 17671-1          |             |
| Japan                 |                 | Russia               |             |
|                       |                 | MNC12-24             | GOST 492-73 |
| USA                   |                 | UNS standard         |             |
| ASTM                  |                 |                      |             |
| ASTM B 206 / B 206 M  |                 | C75700               |             |
| ASTM B 151/ B 151 M   |                 |                      |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

Flow curves

| State of material                         | Hot deformation |                | Cold deformation   |               |
|-------------------------------------------|-----------------|----------------|--------------------|---------------|
|                                           | cast state      | deformed state | soft annealed (sa) | drawn (dr)    |
| $\sigma_{F0}$ [MPa]                       | 215.4           | 208.3          | 297.9              | 396.0         |
| A                                         | 4376.659        | 7586.648       | 706.491            | 813.636       |
| Effect of temperature $K_{\vartheta}$     |                 |                |                    |               |
| $m_1$                                     | −0.00404        | −0.00435       | −0.00142           | −0.00146      |
| Effect of strain $K_{\varphi}$            |                 |                |                    |               |
| $m_2$                                     | 0.14656         | 0.28116        | 0.33497            | 0.29912       |
| $m_4$                                     | 0.00398         | 0.00076        | −0.00949           | −0.00349      |
| $m_5$                                     | −0.0016         | −0.00188       |                    |               |
| $m_7$                                     | 0.369144        | 0.2111         |                    |               |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                    |               |
| $m_3$                                     |                 |                | 0.01269            | 0.01364       |
| $m_8$                                     | 0.000114        | 0.000120       |                    |               |
| Range of validity                         |                 |                |                    |               |
| $\vartheta$ [°C]                          | 600 ... 950     | 600 ... 950    | 20 ... 300         | 20 ... 300    |
| $\varphi$                                 | 0.03 ... 1.50   | 0.03 ... 1.50  | 0.03 ... 2.00      | 0.03 ... 2.00 |
| $\dot{\varphi}$ [1/s]                     | <100            | <100           | <100               | <100          |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |



**Fig. 5.72** 2. Flow stress curves of CuNi<sub>12</sub>Zn<sub>24</sub> by hot and cold forming.

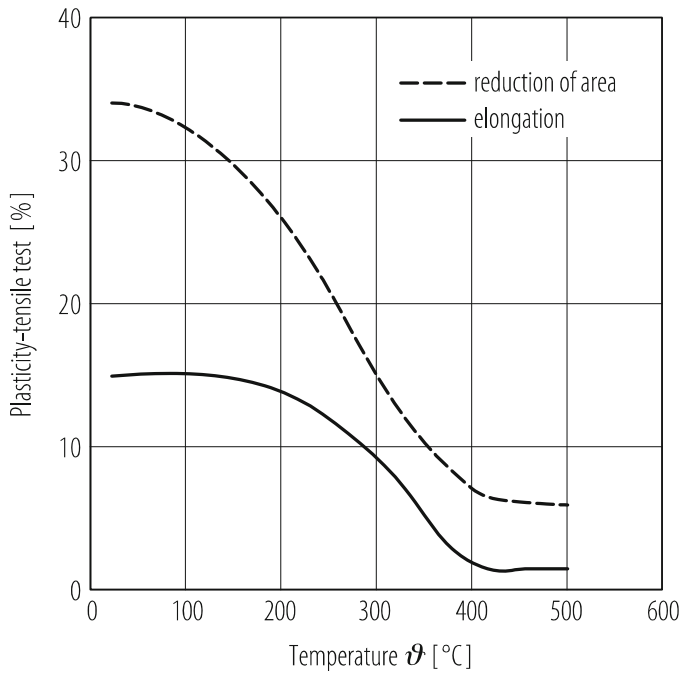
Mechanical properties after cold deformation

| State of material                   | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                                     | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| grain size 0.015 [mm], hot extruded | 250...290                       | 26.75951 | 0.67705 | 360...430                           | 8.01889 | 0.87328 |

| State of material                   | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                                     | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| grain size 0.015 [mm], hot extruded | 50...55                                 | 29.90961 | 0.13543 | -6.27055 | <70                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test



**Fig. 5.73** Cold plasticity of CuNi<sub>12</sub>Zn<sub>24</sub> as a function of the temperature. Initial test: cold drawn.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 43.5                 | 418.8              | 14.79                                   | 8670.4                      | 127.0           |
| 100              | 62.4                 | 422.2              | 15.27                                   | 8651.2                      |                 |
| 200              | 72.9                 | 426.3              | 15.87                                   | 8625.4                      |                 |

(continued)

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 300                             | 79.9                                      | 430.5                                   | 16.47                                                                    | 8597.9                                 |                              |
| 400                             | 85.3                                      | 434.6                                   | 17.07                                                                    | 8568.4                                 |                              |
| 500                             | 89.6                                      | 438.8                                   | 17.67                                                                    | 8537.1                                 |                              |
| 600                             | 93.4                                      | 443.0                                   | 18.27                                                                    | 8503.9                                 |                              |
| 700                             | 96.7                                      | 447.1                                   | 18.87                                                                    | 8468.8                                 |                              |
| 800                             | 99.6                                      | 451.3                                   | 19.47                                                                    | 8431.8                                 |                              |
| 900                             | 102.3                                     | 455.4                                   | 20.07                                                                    | 8393.0                                 |                              |
| 950                             | 103.6                                     | 457.5                                   | 20.37                                                                    | 8372.9                                 |                              |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuNi<sub>15</sub>Zn<sub>21</sub>

## 5.2 Copper- and Copper alloys

### 5.2.4 Copper - Nickel - alloys

#### Designation

|             |               |               |                   |              |
|-------------|---------------|---------------|-------------------|--------------|
| UNS number: | <b>C75400</b> | Chem. symbol: | <b>CuNi15Zn21</b> | (EN number): |
|-------------|---------------|---------------|-------------------|--------------|

#### Composition (ISO) [Weight-%]

| Cu          | Ni          | Zn   | Mn    | Pb    | Fe    | Sn    | Al    | Others |
|-------------|-------------|------|-------|-------|-------|-------|-------|--------|
| 63.0...66.5 | 13.5...16.5 | Bal. | <0.20 | <0.10 | <0.20 | <0.10 | <0.10 | <0.90  |

#### International comparison of standards

|                       |                |
|-----------------------|----------------|
| Euronorm              | ISO            |
|                       | ISO 430 : 1983 |
|                       | ISO 1634-1     |
| Material number (DIN) | DIN            |
| Japan                 | Russia         |
|                       | MNC 15-20      |
| USA                   | GOST 00492     |
| ASTM                  | UNS standard   |
|                       | C75400         |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material           | Hot deformation |                | Cold deformation     |                    |                 |
|-----------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                             | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]         |                 | 230.7          |                      | 419.5              |                 |
| A                           |                 | 6795.287       |                      | 747.820            |                 |
| Effect of temperature $K_0$ |                 |                |                      |                    |                 |
| $m_1$                       |                 | -0.00493       |                      | -0.00122           |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| Effect of strain $K_\varphi$           |                 |                |                      |                    |                 |
| $m_2$                                  |                 | 0.10378        |                      | 0.22933            |                 |
| $m_4$                                  |                 | 0.00561        |                      | −0.00267           |                 |
| $m_5$                                  |                 | −0.000024      |                      |                    |                 |
| $m_7$                                  |                 | −0.13191       |                      |                    |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.01146            |                 |
| $m_8$                                  |                 | 0.000165       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                       |                 | 600 ... 950    |                      | 20 ... 300         |                 |
| $\varphi$                              |                 | 0.04 ... 1.50  |                      | 0.03 ... 2.00      |                 |
| $\dot{\varphi}$ [1/s]                  |                 | <100           |                      | <100               |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |



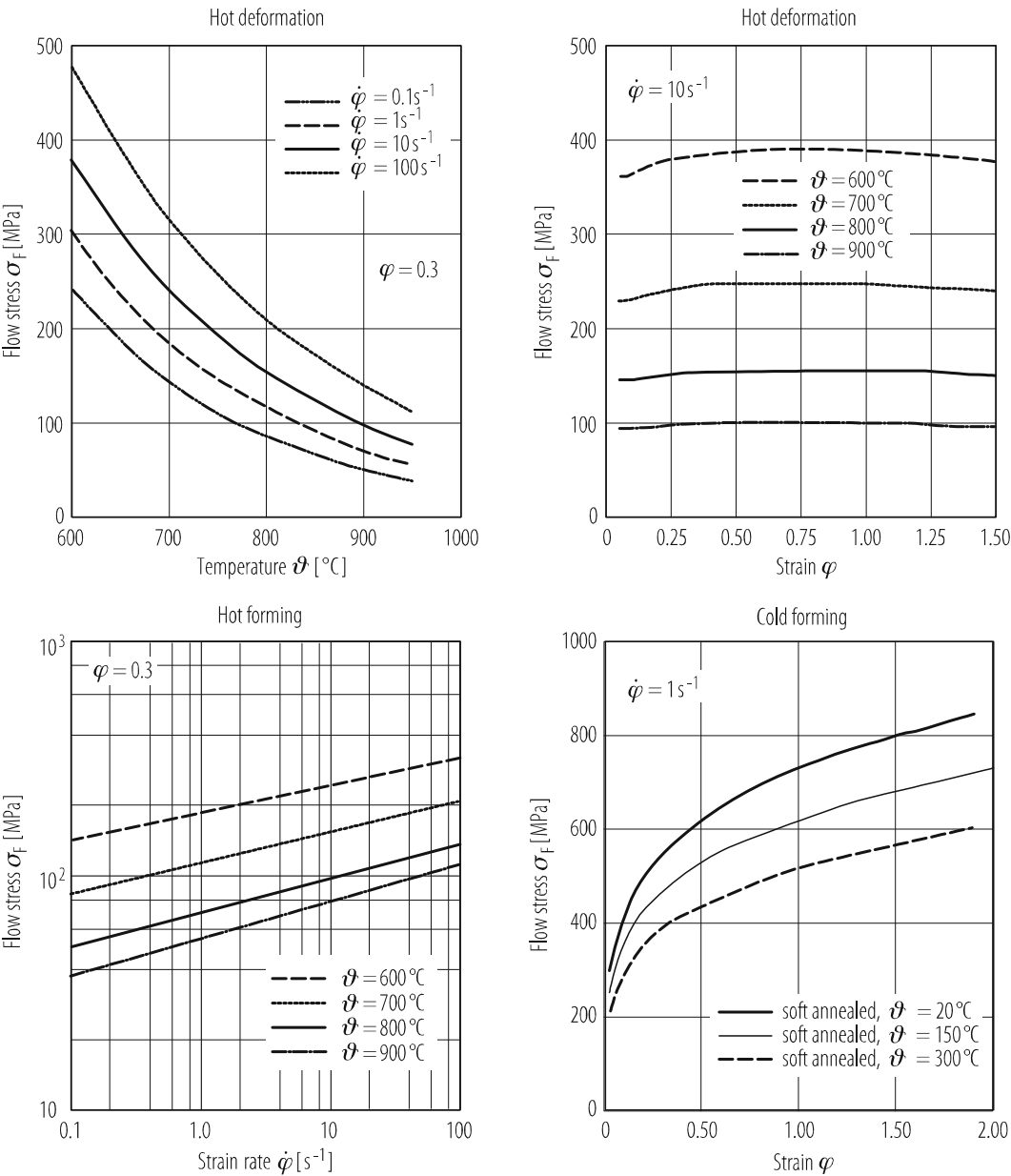


Fig. 5.74 CuNi15Zn21. Flow stress curves of CuNi15Zn21 by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| soft annealed     | 35...40                                 | 11.73939 | 0.27582 | -4.42231 | <70                        |

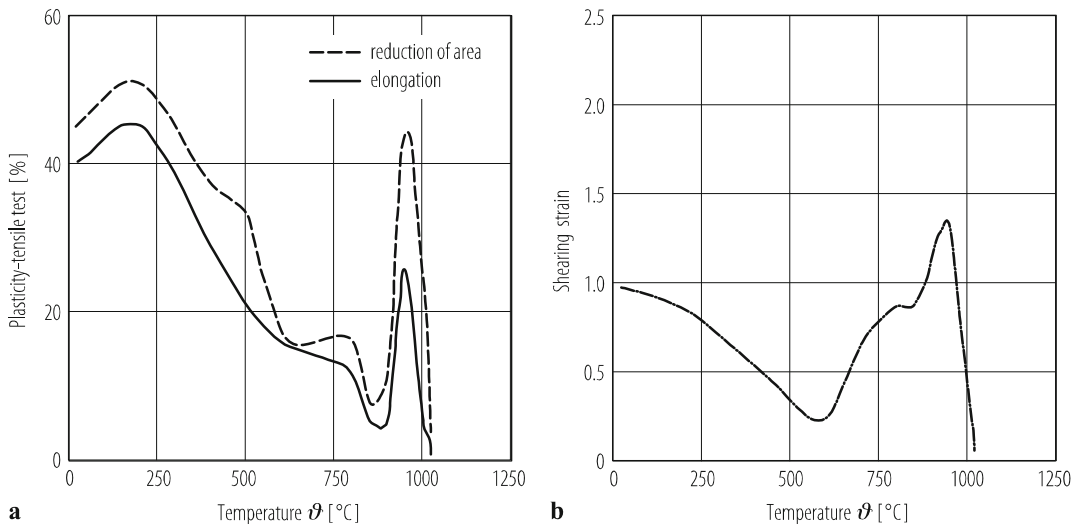
Elongation to fracture

$A_5 = C_0 - C \cdot e^{n_3} \cdot e^{n_4/\varepsilon}$

[Equation (4.3), Chapter 5.1.4]

[DOI: [978-3-642-14174-4\\_5](https://doi.org/10.1007/978-3-642-14174-4_5)]

Plasticity in tensile and torsion test



**Fig. 5.75** Hot plasticity of CuNi<sub>15</sub>Zn<sub>21</sub> as a function of the temperature. a.) Compare elongation and reduction of area b.) shearing strain as a function of the temperature

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 23.8                 | 422.8              | 14.49                                   | 8700.5                      | 124.0           |
| 100              | 34.2                 | 426.2              | 14.97                                   | 8681.5                      |                 |
| 200              | 40.0                 | 430.3              | 15.57                                   | 8656.2                      |                 |
| 300              | 43.8                 | 434.5              | 16.17                                   | 8629.0                      |                 |
| 400              | 46.8                 | 438.6              | 16.77                                   | 8599.9                      |                 |
| 500              | 49.2                 | 442.8              | 17.37                                   | 8568.9                      |                 |
| 600              | 51.2                 | 447.0              | 17.97                                   | 8536.1                      |                 |
| 700              | 53.0                 | 451.1              | 18.57                                   | 8501.4                      |                 |
| 800              | 54.7                 | 455.3              | 19.17                                   | 8464.7                      |                 |
| 900              | 56.1                 | 459.4              | 19.77                                   | 8426.2                      |                 |
| 950              | 56.8                 | 461.5              | 20.07                                   | 8406.3                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuNi<sub>18</sub>Zn<sub>20</sub>

## 5.2 Copper- and Copper alloys

### 5.2.4 Copper - Nickel - alloys

#### Designation

|             |               |               |                   |            |               |
|-------------|---------------|---------------|-------------------|------------|---------------|
| UNS number: | <b>C75200</b> | Chem. symbol: | <b>CuNi18Zn20</b> | EN number: | <b>CW409J</b> |
|-------------|---------------|---------------|-------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Ni          | Zn    | Mn    | Pb    | Fe    | Sn    | Others |
|-------------|-------------|-------|-------|-------|-------|-------|--------|
| 60.0...63.0 | 17.0...19.0 | >16.9 | <0.50 | <0.03 | <0.30 | <0.03 | <0.20  |

#### International comparison of standards

| Euronorm              |                      | ISO                  |             |
|-----------------------|----------------------|----------------------|-------------|
| EN 1652               | EN 12167             | ISO 430 : 1983       | ISO 1634-3  |
| EN 1654 : 1997        | EN 12449             | ISO 1634-1           |             |
| EN 12166              |                      | ISO 1638             |             |
| Material number (DIN) |                      | DIN                  |             |
| 2.0740                |                      | [[DIN 17663 : 1983]] | DIN 17670-1 |
|                       |                      | DIN 1777             | DIN 17672-  |
|                       |                      | DIN 17682            |             |
| Japan                 |                      | Russia               |             |
| JIS H 3270 : 1992     |                      | MNC18-20             | GOST 0492   |
| JIS H 3270            |                      |                      |             |
| USA                   |                      | UNS standard         |             |
| ASTM                  |                      |                      |             |
| ASTM B 122 / B 122 M  | ASTM B 888           | C75200               |             |
| ASTM B 151 / B 151 M  | ASTM B 206 / B 206 M |                      |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material           | Hot deformation |                | Cold deformation   |            |
|-----------------------------|-----------------|----------------|--------------------|------------|
|                             | cast state      | deformed state | soft annealed (sa) | drawn (dr) |
| $\sigma_{F0}$ [MPa]         | 213.98          | 228.1          | 355.2              | 480.8      |
| A                           | 8296.6          | 6095.06        | 767.747            | 780.671    |
| Effect of temperature $K_9$ |                 |                |                    |            |
| $m_1$                       | -0.00461        | -0.00449       | -0.00122           | -0.00129   |

(continued)

| State of material                      | Hot deformation |                | Cold deformation   |               |
|----------------------------------------|-----------------|----------------|--------------------|---------------|
|                                        | cast state      | deformed state | soft annealed (sa) | drawn (dr)    |
| Effect of strain $K_\varphi$           |                 |                |                    |               |
| $m_2$                                  | 0.28116         | 0.18022        | 0.30909            | 0.19941       |
| $m_4$                                  | 0.00076         | 0.00058        | −0.00361           | −0.00233      |
| $m_5$                                  | −0.00188        | −0.00151       |                    |               |
| $m_7$                                  | 0.2111          | 0.28551        |                    |               |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                    |               |
| $m_3$                                  |                 |                | 0.01041            | 0.00987       |
| $m_8$                                  | 0.000194        | 0.000210       |                    |               |
| Range of validity                      |                 |                |                    |               |
| $\vartheta$ [°C]                       | 600 ... 1000    | 600 ... 1000   | 20 ... 300         | 20 ... 300    |
| $\varphi$                              | 0.03 ... 1.25   | 0.03 ... 1.25  | 0.03 ... 1.25      | 0.03 ... 1.25 |
| $\dot{\varphi}$ [1/s]                  | <100            | <100           | <100               | <100          |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |

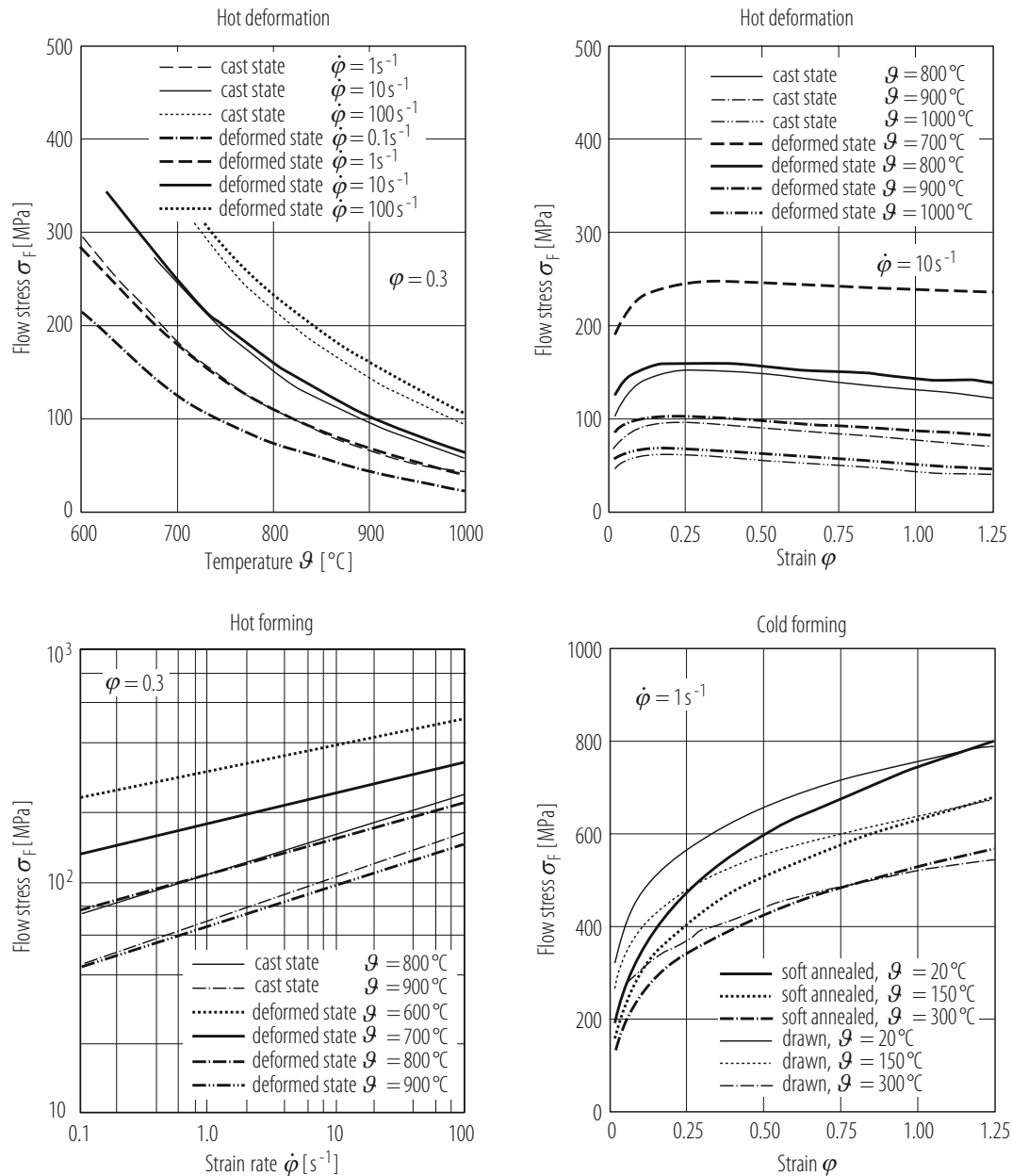


Fig. 5.76 Flow stress curves of CuNi<sub>18</sub>Zn<sub>20</sub> by hot and cold forming.

### Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |                | Tensile strength $\Delta R_m$ [MPa] |         |                |
|-------------------|---------------------------------|----------|----------------|-------------------------------------|---------|----------------|
|                   | A <sub>0</sub>                  | A        | n <sub>1</sub> | B <sub>0</sub>                      | B       | n <sub>2</sub> |
| hot extruded      | 160...200                       | 12.34832 | 0.95915        | 380...450                           | 4.27532 | 1.06242        |
| soft annealed     | 140...180                       | 34.86871 | 0.65076        | 380...450                           | 3.74331 | 1.06867        |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| hot extruded      | 43...48                                 | 16.55056 | 0.2607  | -8.24784 | <60                        |
| soft annealed     | 60...65                                 | 40.19449 | 0.14161 | -5.79268 | <70                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

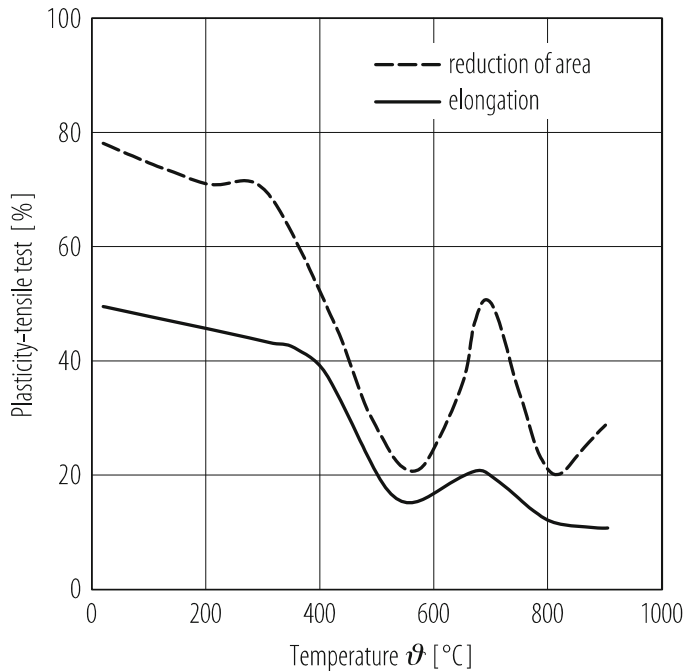


Fig. 5.77 Plasticity of CuNi18Zn20 as a function of the temperature.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 33.6                 | 432.4              | 14.79                                   | 8730.4                      | 127.0           |
| 100              | 48.3                 | 432.6              | 15.27                                   | 8711.0                      |                 |
| 200              | 56.5                 | 432.7              | 15.87                                   | 8685.1                      |                 |
| 300              | 61.9                 | 432.9              | 16.47                                   | 8657.3                      |                 |
| 400              | 66.0                 | 433.1              | 17.07                                   | 8627.7                      |                 |
| 500              | 69.4                 | 433.3              | 17.67                                   | 8596.1                      |                 |
| 600              | 72.3                 | 433.4              | 18.27                                   | 8562.7                      |                 |
| 700              | 74.9                 | 433.6              | 18.87                                   | 8527.4                      |                 |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 800              | 77.2                 | 433.8              | 19.47                                   | 8490.1                      |                 |
| 900              | 79.2                 | 433.9              | 20.07                                   | 8451.0                      |                 |
| 950              | 80.2                 | 434.0              | 20.37                                   | 8430.8                      |                 |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese industrial standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |



# Flow stress and physical properties of CuNi<sub>20</sub>Mn<sub>20</sub>

## 5.2 Copper- and Copper alloys

### 5.2.4 Copper - Nickel - alloys

#### Designation

|             |               |                   |              |
|-------------|---------------|-------------------|--------------|
| UNS number: | Chem. symbol: | <b>CuNi20Mn20</b> | (EN number): |
|-------------|---------------|-------------------|--------------|

#### Composition [Weight-%]

|     |     |    |     |    |    |
|-----|-----|----|-----|----|----|
| Cu  | Ni  | Zn | Mn  | Pb | Fe |
| ~60 | ~20 |    | ~20 |    |    |

#### International comparison of standards

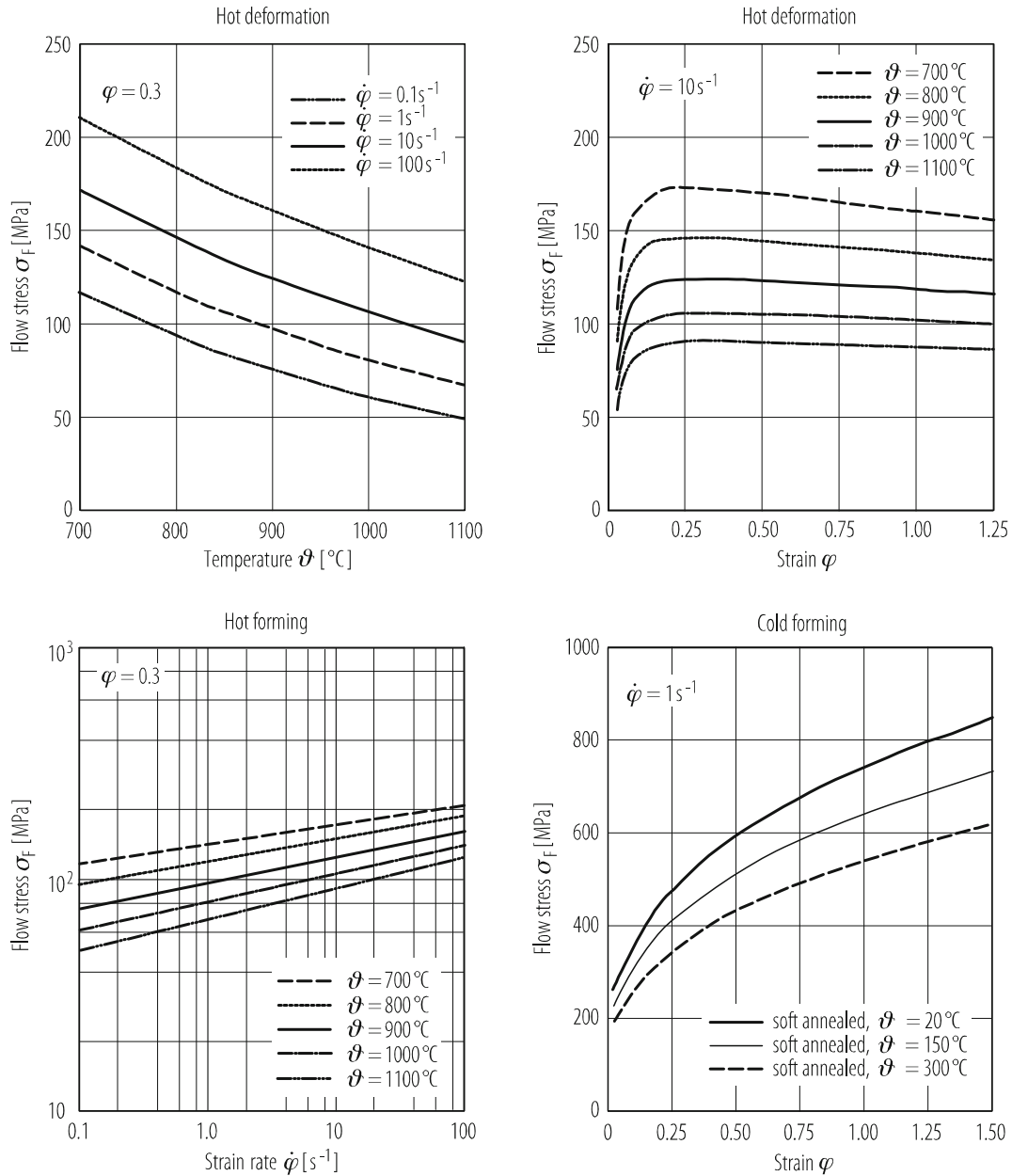
|                       |              |
|-----------------------|--------------|
| Euronorm              | ISO          |
| Material number (DIN) | DIN          |
| Japan                 | Russia       |
|                       | GOST 6689.20 |
| USA                   |              |
| ASTM                  | UNS standard |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                    |                 | 163.2          |                      | 372.1              |                 |
| A                                      |                 | 542.193        |                      | 753.998            |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                      |                    |                 |
| $m_1$                                  |                 | -0.00198       |                      | -0.00112           |                 |
| Effect of strain $K_{\phi}$            |                 |                |                      |                    |                 |
| $m_2$                                  |                 | -0.09319       |                      | 0.33096            |                 |
| $m_4$                                  |                 | -0.02283       |                      | 0.00533            |                 |
| $m_5$                                  |                 | 0.00029        |                      |                    |                 |
| $m_7$                                  |                 | -0.15023       |                      |                    |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.01083            |                 |
| $m_8$                                  |                 | 0.000121       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\theta$ [°C]                          |                 | 700 ... 1100   |                      | 20 ... 300         |                 |
| $\phi$                                 |                 | 0.03 ... 1.25  |                      | 0.03 ... 1.50      |                 |
| $\dot{\phi}$ [1/s]                     |                 | <100           |                      | <100               |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.78** CuNi<sub>20</sub>Mn<sub>20</sub>. Flow stress curves of CuNi<sub>20</sub>Mn<sub>20</sub> by hot and cold forming.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               |                      |                    |                                         | 8500                        |                 |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| GOST            | gosudarstvennyy standart (state standard)                             |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, mechanical and physical properties of CuNi<sub>30</sub>Mn<sub>1</sub>Fe

## 5.2 Copper- and Copper alloys

### 5.2.4 Copper - Nickel - alloys

#### Designation

|             |               |               |                    |            |               |
|-------------|---------------|---------------|--------------------|------------|---------------|
| UNS number: | <b>C71500</b> | Chem. symbol: | <b>CuNi30Mn1Fe</b> | EN number: | <b>CW354H</b> |
|-------------|---------------|---------------|--------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu    | Ni          | Zn    | Mn          | Pb    | Fe          | C     | S     | Pb    | Others |
|-------|-------------|-------|-------------|-------|-------------|-------|-------|-------|--------|
| >64.6 | 30.0...32.0 | <0.50 | 0.50...1.00 | <0.03 | 0.40...1.00 | <0.05 | <0.05 | <0.03 | <0.30  |

#### International comparison of standards

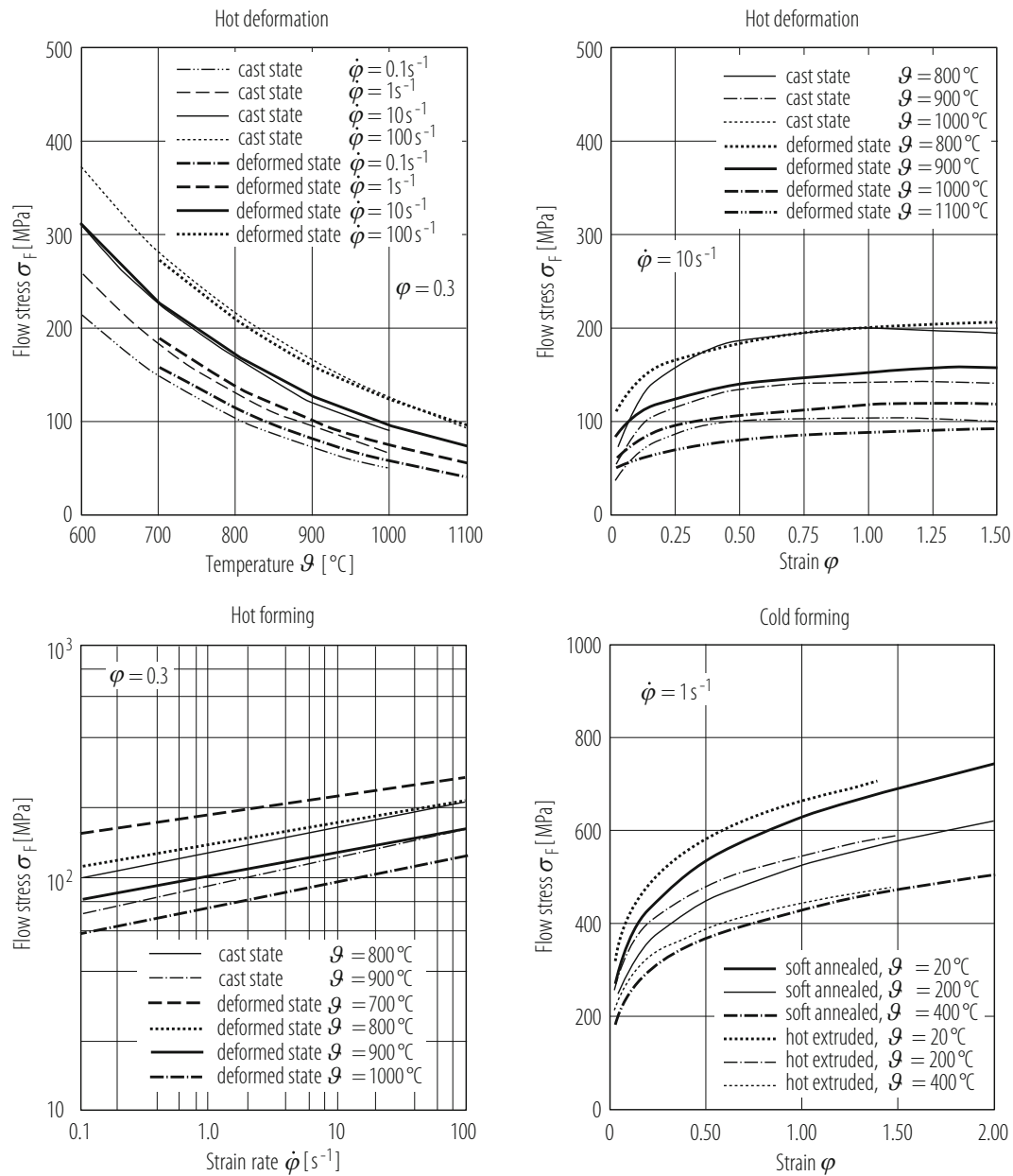
|                       |                      |                      |                |
|-----------------------|----------------------|----------------------|----------------|
| Euronorm              |                      | ISO                  |                |
| EN 12451 : 1999       | EN 12164             | ISO 1634-1           | ISO 429 : 1983 |
| EN 12449              | EN 12420             | ISO 1634-2           |                |
| EN 1652               | EN 12452             | ISO 1635-2           |                |
| EN 12165              |                      | ISO 1637             |                |
| Material number (DIN) |                      | DIN                  |                |
| 2.0882                |                      | [[DIN 17664 : 1983]] | DIN 17670-1    |
|                       |                      | DIN 17672-1          | DIN 17672-5    |
|                       |                      | DIN 17671-1          | DIN 17679,     |
| Japan                 |                      | Russia               |                |
| C 7150                | JIS H 3320 : 1992    | MNZMc30-1-1          | GOST 00492     |
| JIS H 3100            | JIS H 3320           |                      |                |
| USA                   |                      | UNS standard         |                |
| ASTM                  |                      | C71500               |                |
| ASTM B 122 / B 122 M  | ASTM B 151/ B 151 M  |                      |                |
| ASTM B 171/ B 171 M   | ASTM B 359 / B 359 M |                      |                |
| ASTM B 111/ B 111 M   | ASTM B 466 / B 466 M |                      |                |
| ASTM B 395 / B 395 M  | ASTM B 543           |                      |                |
| ASTM B 467 / B 467 M  | ASTM B 956           |                      |                |
| ASTM B 552            |                      |                      |                |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

**Flow curves**

| State of material                      | Hot deformation |                | Cold deformation   |                   |
|----------------------------------------|-----------------|----------------|--------------------|-------------------|
|                                        | cast state      | deformed state | soft annealed (sa) | hot extruded (he) |
| $\sigma_{F0}$ [MPa]                    | 158.2           | 187.1          | 365.4              | 423.4             |
| A                                      | 3385.278        | 2046.97        | 641.815            | 676.467           |
| Effect of temperature $K_8$            |                 |                |                    |                   |
| $m_1$                                  | −0.00325        | −0.00314       | −0.00100           | −0.00106          |
| Effect of strain $K_\varphi$           |                 |                |                    |                   |
| $m_2$                                  | 0.4040          | 0.15539        | 0.23479            | 0.18941           |
| $m_4$                                  | −0.00213        | −0.00208       | −0.00097           | −0.00233          |
| $m_5$                                  | −0.00056        | 0.00029        |                    |                   |
| $m_7$                                  | −0.16735        | −0.18061       |                    |                   |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                    |                   |
| $m_3$                                  |                 |                | 0.00376            | 0.00483           |
| $m_8$                                  | 0.000134        | 0.000113       |                    |                   |
| Range of validity                      |                 |                |                    |                   |
| $\vartheta$ [°C]                       | 600 ... 1000    | 700 ... 1100   | 20 ... 400         | 20 ... 400        |
| $\varphi$                              | 0.03 ... 1.50   | 0.03 ... 1.50  | 0.03 ... 2.00      | 0.03 ... 1.50     |
| $\dot{\varphi}$ [1/s]                  | <100            | <100           | <10                | <10               |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.79** Flow stress curves of CuNi<sub>30</sub>Mn<sub>1</sub>Fe by hot and cold forming.

## Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |     |       | Tensile strength $\Delta R_m$ [MPa] |          |         |
|-------------------|---------------------------------|-----|-------|-------------------------------------|----------|---------|
|                   | $A_0$                           | $A$ | $n_1$ | $B_0$                               | $B$      | $n_2$   |
| soft annealed     |                                 |     |       | 370...420                           | 10.24551 | 0.78806 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| soft annealed     | 40...45                                 | 36.82180 | 0.04608 | -7.37029 | <80                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                                      |
|-----------------------------------------|-----------------------------------------|-----------------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot \varepsilon^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                             |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                                  |

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 27.0                 | 383.9              | 14.31                                   | 8925.4                      | 153.0           |
| 100              | 30.4                 | 390.0              | 14.68                                   | 8906.4                      | 148.0           |
| 200              | 34.7                 | 397.6              | 15.13                                   | 8881.3                      | 143.0           |
| 300              | 39.0                 | 405.2              | 15.59                                   | 8854.8                      | 137.0           |
| 400              | 43.2                 | 412.8              | 16.05                                   | 8826.8                      | 130.0           |
| 500              | 47.5                 | 420.5              | 16.51                                   | 8797.3                      | 121.0           |
| 600              | 51.8                 | 428.1              | 16.96                                   | 8766.4                      |                 |
| 700              | 56.0                 | 435.7              | 17.42                                   | 8734.0                      |                 |
| 800              | 60.3                 | 443.3              | 17.88                                   | 8700.1                      |                 |
| 900              | 64.6                 | 450.9              | 18.33                                   | 8664.8                      |                 |
| 950              | 66.7                 | 454.7              | 18.56                                   | 8646.6                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese industrial standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |

(continued)

| Short form     | Full form                               |
|----------------|-----------------------------------------|
| $T, \vartheta$ | temperature                             |
| UNS            | unified numbering system                |
| $\alpha_m$     | average coefficient of linear expansion |
| $\lambda$      | thermal conductivity                    |
| $\rho$         | density                                 |



# Flow stress, mechanical and physical properties of CuNi<sub>44</sub>Mn<sub>1</sub>

## 5.2 Copper- and Copper alloys

### 5.2.4 Copper - Nickel - alloys

#### Designation

|             |               |               |                  |              |
|-------------|---------------|---------------|------------------|--------------|
| UNS number: | <b>C72150</b> | Chem. symbol: | <b>CuNi44Mn1</b> | (EN number): |
|-------------|---------------|---------------|------------------|--------------|

#### Composition (DIN) [Weight-%]

| Cu    | Ni            | Zn    | Mn            | Pb    | Fe    | C     | S    | Others |
|-------|---------------|-------|---------------|-------|-------|-------|------|--------|
| >52.1 | 43.0 . . 45.0 | <0.20 | 0.50 . . 2.00 | <0.01 | <0.50 | <0.05 | 0.02 | <0.30  |

#### International comparison of standards

|                       |                 |
|-----------------------|-----------------|
| Euronorm              | ISO             |
|                       | ISO 429 : 1983  |
| Material number (DIN) | DIN             |
| 2.0842                | DIN 17471: 1983 |
| Japan                 | Russia          |
|                       | MNMc43-0,5      |
|                       | GOST 00492      |
| USA                   |                 |
| ASTM                  | UNS standard    |
|                       | C72150          |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                  | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]              | 180.9           |                |                      | 471.2              |                 |
| A                                | 1369.863        |                |                      | 789.495            |                 |
| Effect of temperature $K_\theta$ |                 |                |                      |                    |                 |
| $m_1$                            | −0.00129        |                |                      | −0.00097           |                 |
| Effect of strain $K_\phi$        |                 |                |                      |                    |                 |
| $m_2$                            | 0.49487         |                |                      | 0.20938            |                 |
| $m_4$                            | 0.00295         |                |                      | −0.00244           |                 |
| $m_5$                            | −0.00295        |                |                      |                    |                 |
| $m_7$                            | 0.50674         |                |                      |                    |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.00389            |                 |
| $m_8$                                  | 0.000083        |                |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                       | 600 ... 1000    |                |                      | 20 ... 400         |                 |
| $\varphi$                              | 0.03 ... 1.25   |                |                      | 0.03 ... 2.00      |                 |
| $\dot{\varphi}$ [1/s]                  | <100            |                |                      | <100               |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                                                 |

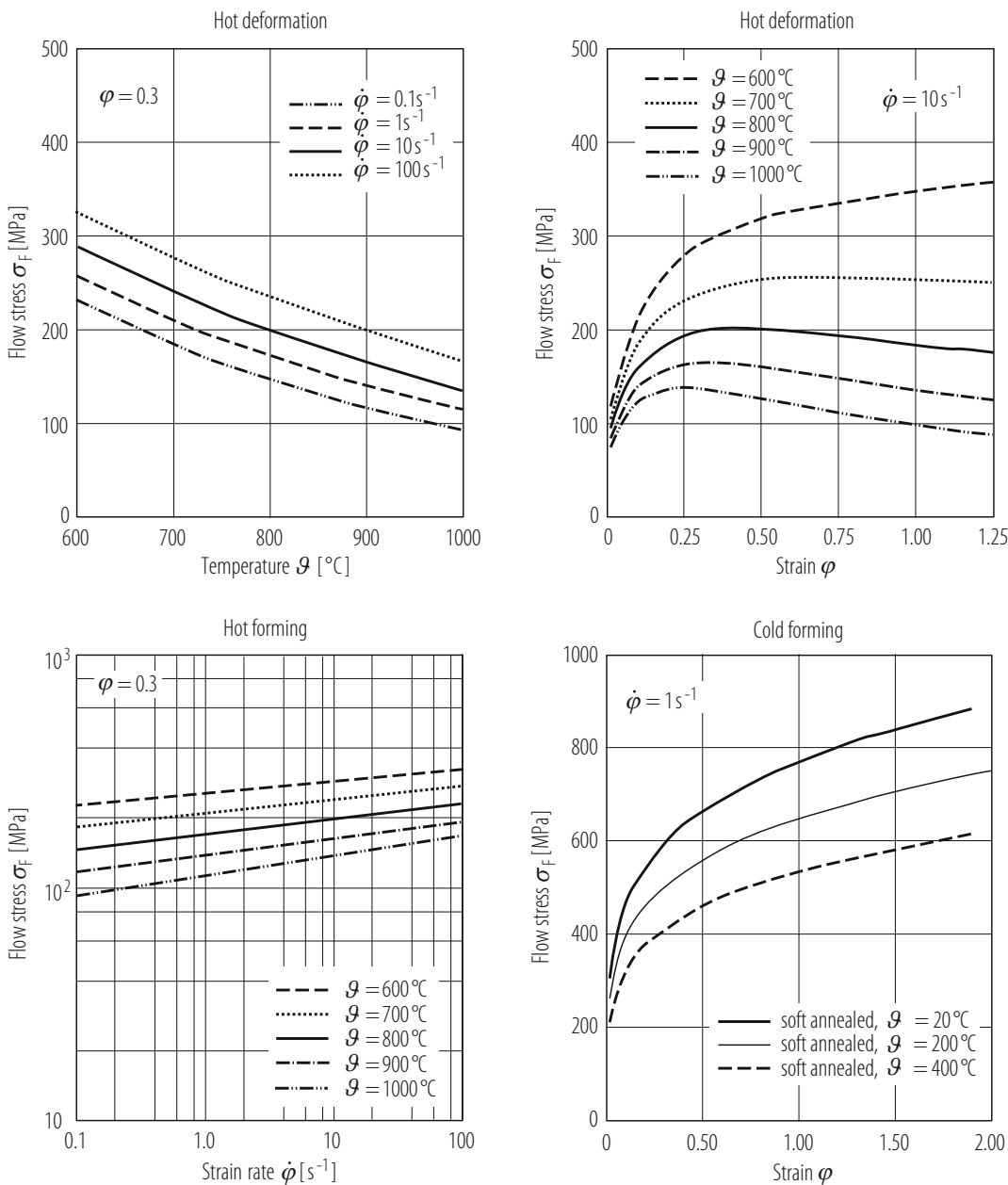


Fig. 5.80 Flow stress curves of CuNi<sub>44</sub>Mn<sub>1</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |     |       | Tensile strength $\Delta R_m$ [MPa] |          |         |
|-------------------|---------------------------------|-----|-------|-------------------------------------|----------|---------|
|                   | $A_0$                           | $A$ | $n_1$ | $B_0$                               | $B$      | $n_2$   |
| soft annealed     |                                 |     |       | 380. . 420                          | 22.00325 | 0.60043 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| soft annealed     | 35...40                                 | 27.33287 | 0.07095 | -6.43613 | <75                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 21.5                 | 408.8              | 13.1                                    | 8900.8                      | 163             |
| 100              | 29.2                 | 412.2              | 13.5                                    | 8883.4                      |                 |
| 200              | 33.3                 | 416.3              | 14.0                                    | 8860.1                      |                 |
| 300              | 36.0                 | 420.5              | 14.5                                    | 8835.3                      |                 |
| 400              | 38.0                 | 424.6              | 15.0                                    | 8808.8                      |                 |
| 500              | 39.6                 | 428.8              | 15.5                                    | 8780.8                      |                 |
| 600              | 41.0                 | 433.0              | 16.0                                    | 8751.1                      |                 |
| 700              | 42.3                 | 437.1              | 16.5                                    | 8719.9                      |                 |
| 800              | 43.3                 | 441.3              | 17.0                                    | 8687.0                      |                 |
| 900              | 44.3                 | 445.4              | 17.5                                    | 8652.5                      |                 |
| 950              | 44.8                 | 447.5              | 17.8                                    | 8634.7                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuAl<sub>5</sub>As

## 5.2 Copper- and Copper alloys

### 5.2.5 Copper – Aluminium - alloys

#### Designation

|             |               |               |                |            |               |
|-------------|---------------|---------------|----------------|------------|---------------|
| UNS number: | <b>C60800</b> | Chem. symbol: | <b>CuAl5As</b> | EN number: | <b>CW300G</b> |
|-------------|---------------|---------------|----------------|------------|---------------|

#### Composition (EN) [Weight-%]

|      |           |             |       |       |       |       |       |       |
|------|-----------|-------------|-------|-------|-------|-------|-------|-------|
| Cu   | Al        | As          | Fe    | Ni    | Zn    | Mn    | Pb    | Sn    |
| Bal. | 4.0...6.5 | 0.10...0.40 | <0.20 | <0.20 | <0.30 | <0.20 | <0.02 | <0.05 |

#### International comparison of standards

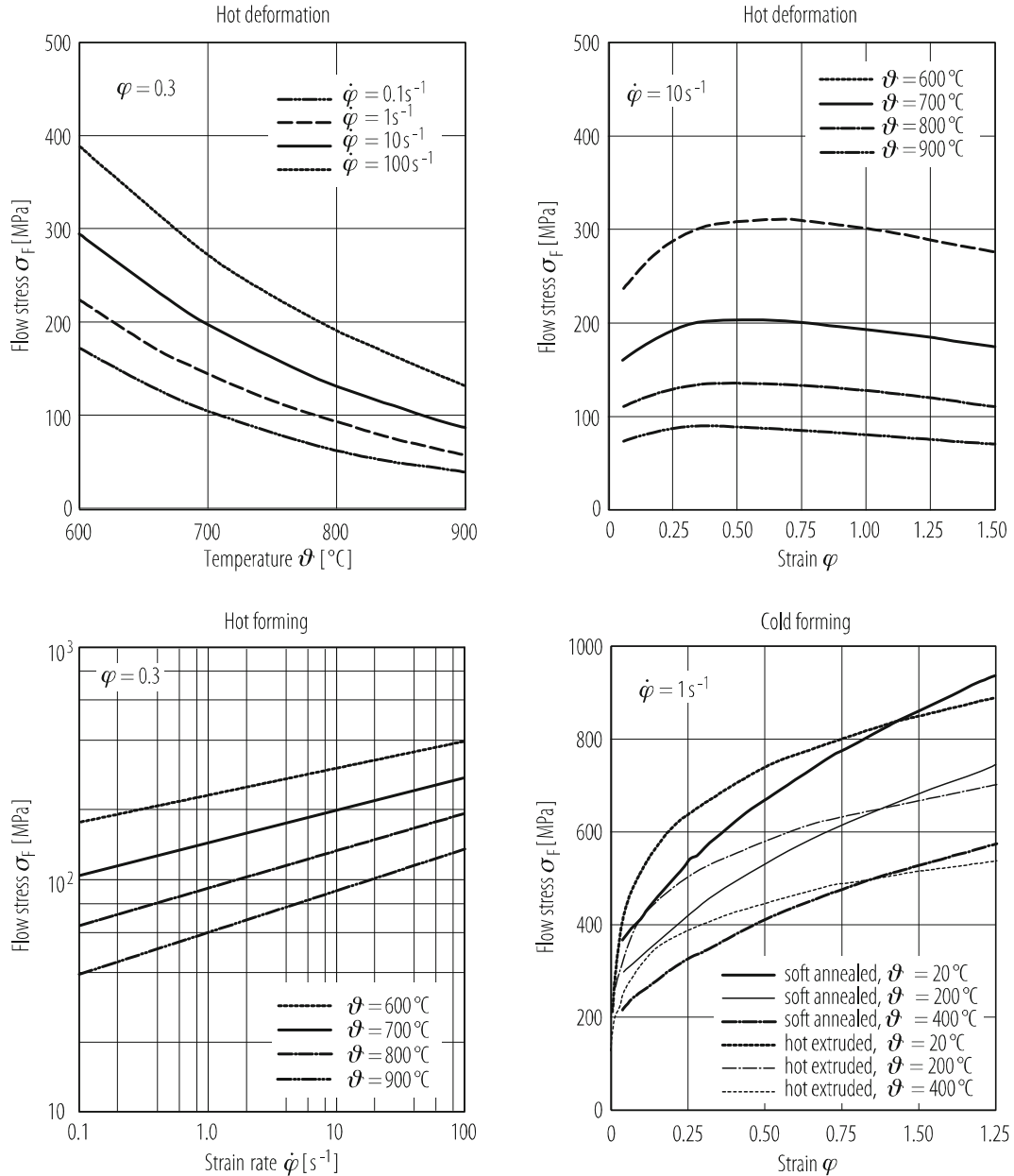
|                       |                      |                      |                |
|-----------------------|----------------------|----------------------|----------------|
| Euronorm              |                      | ISO                  |                |
| EN 12451; 1999        |                      | CuAl5                | ISO 428 : 1983 |
|                       |                      | ISO 1634-1           | ISO 1635       |
| Material number (DIN) |                      | DIN                  |                |
| 2.0918                |                      | [[DIN 17665 : 1983]] | DIN 1785       |
| Japan                 |                      | Russia               |                |
|                       |                      | BrA5                 | GOST 18175–78  |
| USA                   |                      |                      |                |
| ASTM                  |                      | UNS standard         |                |
| ASTM B 111/B 111 M    | ASTM B 395 / B 395 M | C60800               |                |
| ASTM B 359 / B 359 M  |                      |                      |                |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation   |                   |
|----------------------------------------|-----------------|----------------|--------------------|-------------------|
|                                        | cast state      | deformed state | soft annealed (sa) | hot extruded (he) |
| $\sigma_{F0}$ [MPa]                    |                 | 169.4          | 429.0              | 537.4             |
| A                                      |                 | 5301.485       | 865.900            | 873.610           |
| Effect of temperature $K_\theta$       |                 |                |                    |                   |
| $m_1$                                  |                 | −0.00430       | −0.00128           | −0.00132          |
| Effect of strain $K_\varphi$           |                 |                |                    |                   |
| $m_2$                                  |                 | 0.36039        | 0.38763            | 0.19941           |
| $m_4$                                  |                 | 0.01534        | 0.01945            | −0.00233          |
| $m_5$                                  |                 | −0.00079       |                    |                   |
| $m_7$                                  |                 | −0.25409       |                    |                   |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                    |                   |
| $m_3$                                  |                 |                | 0.00895            | 0.00957           |
| $m_8$                                  |                 | 0.000199       |                    |                   |
| Range of validity                      |                 |                |                    |                   |
| $\theta$ [°C]                          |                 | 600 ... 900    | 20 ... 400         | 20 ... 400        |
| $\varphi$                              |                 | 0.03 ... 1.50  | 0.03 ... 1.25      | 0.03 ... 1.25     |
| $\dot{\varphi}$ [1/s]                  |                 | <100           | <10                | <10               |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.81** Flow stress curves of CuAl<sub>5</sub>As by hot and cold forming.

Mechanical properties after cold deformation

| State of material                     | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|---------------------------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                                       | $A_0$                           | $A$      | $n_l$   | $B_0$                               | $B$     | $n_2$   |
| recrystallised, grain size 0.025 [mm] | 135...175                       | 16.50164 | 0.86619 | 370...420                           | 7.46294 | 0.99642 |

| State of material                     | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|---------------------------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                                       | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| recrystallised, grain size 0.025 [mm] | 60...65                                 | 38.08384 | 0.08487 | −7.03569 | <80                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_l}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

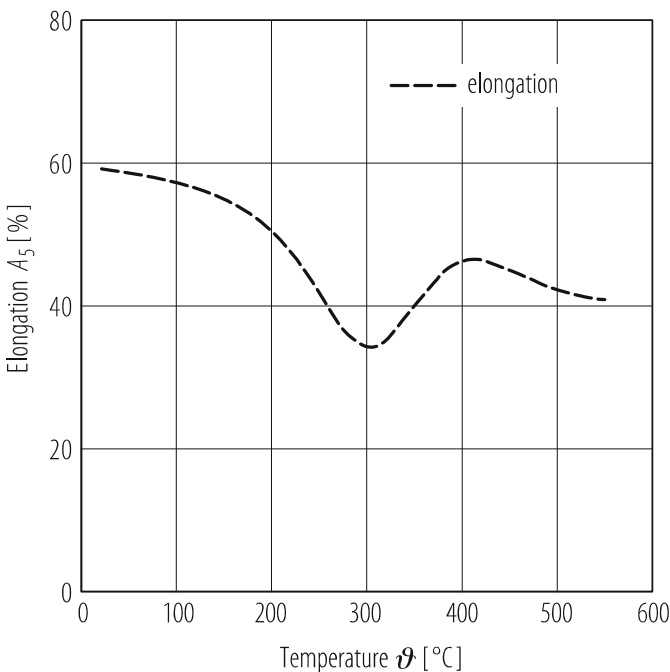


Fig. 5.82 Cold plasticity of CuAl<sub>5</sub>As as a function of the temperature. Initial test: Cold formed and tress relieved.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>−6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 77.2                 | 399.1              | 15.10                                   | 8145.6                      | 123.0           |
| 100              | 83.8                 | 403.4              | 15.87                                   | 8126.7                      |                 |
| 200              | 91.9                 | 408.7              | 16.83                                   | 8100.6                      |                 |
| 300              | 100.1                | 414.1              | 17.79                                   | 8071.7                      |                 |
| 400              | 108.2                | 419.4              | 18.75                                   | 8040.0                      |                 |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}/K$ ]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 500              | 116.4                | 424.8              | 19.72                                   | 8005.4                      |                 |
| 600              | 124.5                | 430.1              | 20.68                                   | 7968.0                      |                 |
| 700              | 132.7                | 435.5              | 21.64                                   | 7927.8                      |                 |
| 800              | 140.8                | 440.9              | 22.60                                   | 7884.8                      |                 |
| 900              | 149.0                | 446.2              | 23.56                                   | 7839.0                      |                 |
| 950              | 153.0                | 448.9              | 24.04                                   | 7815.0                      |                 |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |



# Flow stress, mechanical and physical properties of CuAl<sub>8</sub>

## 5.2 Copper- and Copper alloys

### 5.2.5 Copper – Aluminium - alloys

#### Designation

|             |               |              |            |
|-------------|---------------|--------------|------------|
| UNS number: | Chem. symbol: | <b>CuAl8</b> | EN number: |
|-------------|---------------|--------------|------------|

#### Composition (DIN) [Weight-%]

| Cu    | Al        | Mn    | Fe    | Ni    | Zn    | Si    | Pb    | Others |
|-------|-----------|-------|-------|-------|-------|-------|-------|--------|
| >87.9 | 7.0...9.0 | <0.80 | <0.50 | <0.80 | <0.50 | <0.20 | <0.02 | <0.30  |

#### International comparison of standards

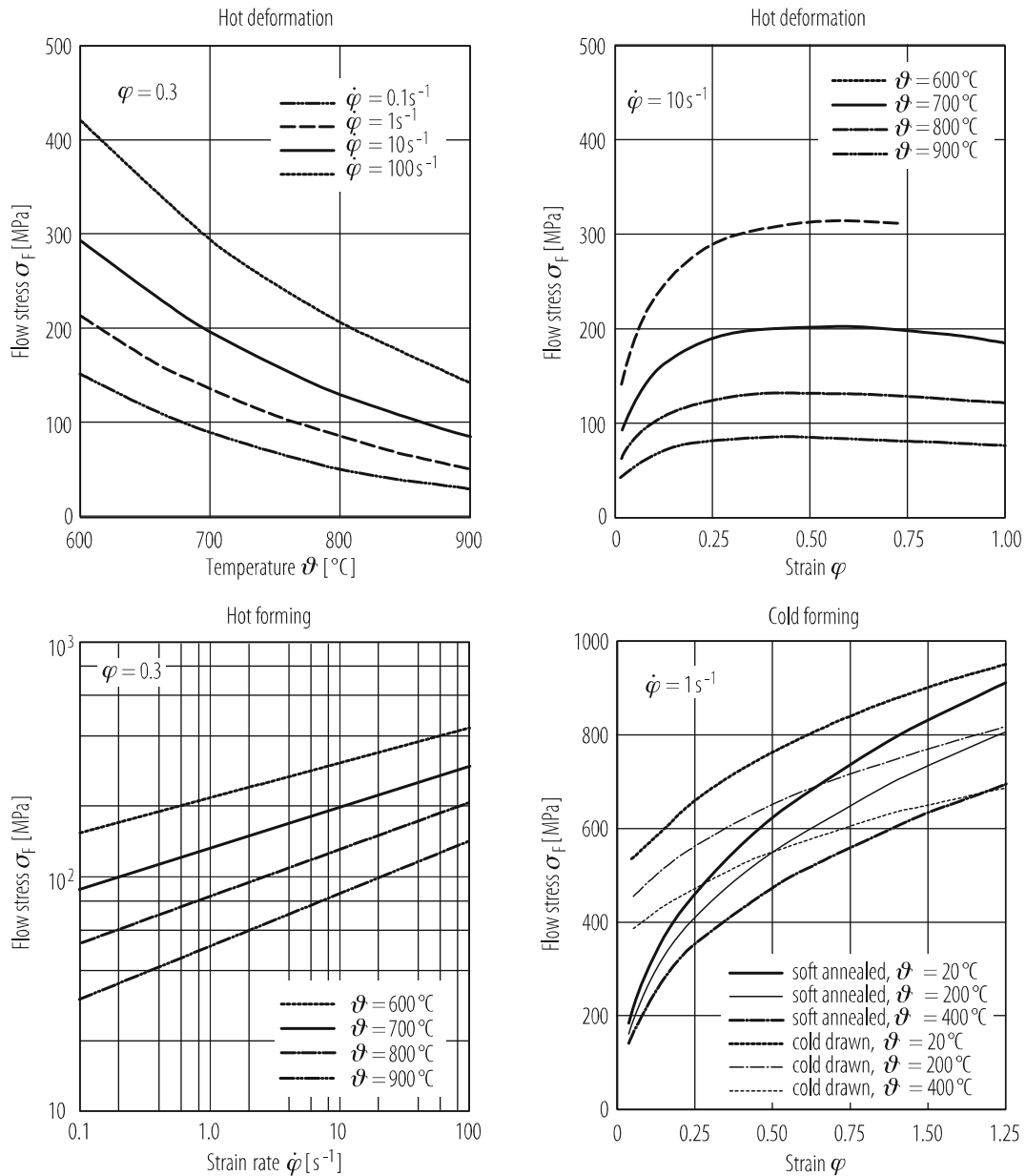
|                       |                      |  |               |
|-----------------------|----------------------|--|---------------|
| Euronorm              | ISO                  |  |               |
|                       | ISO 428 : 1983       |  |               |
|                       | ISO 1634-1           |  | ISO 1634-2    |
| Material number (DIN) | DIN                  |  |               |
| 2.0920                | [[DIN 17665 : 1983]] |  | DIN 17670-1   |
|                       | DIN 17672-1          |  | DIN 17673-1   |
|                       | DIN 17678-1          |  |               |
| Japan                 | Russia               |  |               |
|                       | BrA8                 |  | GOST 18175–78 |
| USA                   |                      |  |               |
| ASTM                  | UNS standard         |  |               |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                   | Hot deformation |                | Cold deformation   |                 |
|-------------------------------------|-----------------|----------------|--------------------|-----------------|
|                                     | cast state      | deformed state | soft annealed (sa) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                 |                 | 152.96         | 349.0              | 590.9           |
| A                                   |                 | 6535.218       | 933.452            | 958.381         |
| Effect of temperature $K_\theta$    |                 |                |                    |                 |
| $m_1$                               |                 | −0.00457       | −0.00073           | −0.00086        |
| Effect of strain $K_\phi$           |                 |                |                    |                 |
| $m_2$                               |                 | 0.38283        | 0.4088             | 0.25534         |
| $m_4$                               |                 | 0.00117        | −0.00477           | 0.01021         |
| $m_5$                               |                 | −0.00079       |                    |                 |
| $m_7$                               |                 | −0.37409       |                    |                 |
| Effect of strain rate $K\dot{\phi}$ |                 |                |                    |                 |
| $m_3$                               |                 |                | 0.00776            | 0.00815         |
| $m_8$                               |                 | 0.00025        |                    |                 |
| Range of validity                   |                 |                |                    |                 |
| $\theta$ [°C]                       |                 | 600 ... 900    | 20 ... 400         | 20 ... 400      |
| $\phi$                              |                 | 0.03 ... 1.00  | 0.03 ... 1.00      | 0.04 ... 1.00   |
| $\dot{\phi}$ [1/s]                  |                 | <100           | <10                | <10             |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                                                 |



**Fig. 5.83** Flow stress curves of CuAl<sub>8</sub> by hot and cold forming.

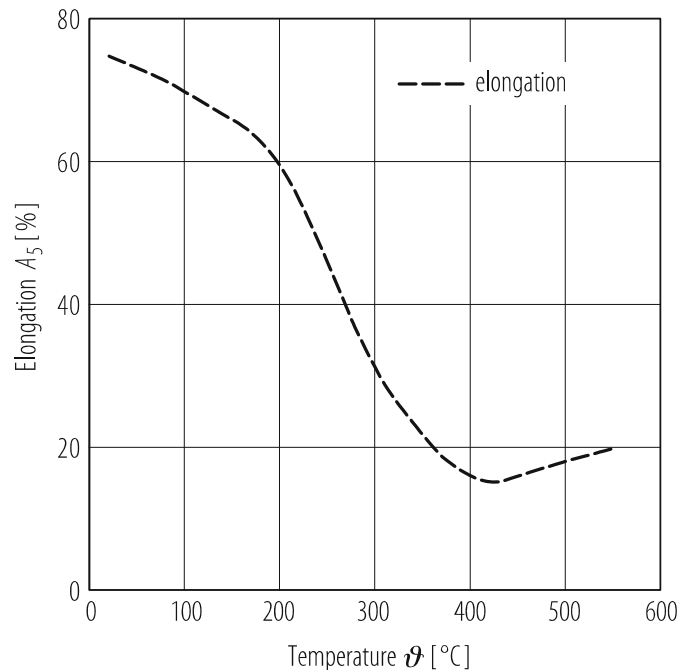
## Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| semi hard         | >170                            | 27.98700 | 0.81046 | 460...530                           | 6.13844 | 1.02097 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |          |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|----------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$    | $n_4$    |                            |
| soft annealed     | 60...65                                 | 10.59190 | 0.44402  | -4.79857 | <60                        |
| soft annealed     | 60...65                                 | 62.65416 | -0.01777 | -12.6665 | <60                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

## Plasticity in tensile test



**Fig. 5.84** Cold plasticity of CuAl8 as a function of the temperature. Initial test: soft annealed.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 68.5                 | 436.1              | 15.10                                   | 7720.8                      | 122.0           |
| 100              | 74.4                 | 440.4              | 15.87                                   | 7702.9                      | 118.0           |
| 200              | 81.9                 | 445.7              | 16.83                                   | 7678.2                      | 110.0           |
| 300              | 89.3                 | 451.1              | 17.79                                   | 7650.8                      | 94.0            |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 400              | 96.8                 | 456.4              | 18.75                                   | 7620.7                      | 68.0            |
| 500              | 104.2                | 461.8              | 19.72                                   | 7587.9                      | 52.0            |
| 600              | 111.6                | 467.1              | 20.68                                   | 7552.5                      | 44.0            |
| 700              | 119.1                | 472.5              | 21.64                                   | 7514.4                      |                 |
| 800              | 126.5                | 477.9              | 22.60                                   | 7473.6                      |                 |
| 900              | 134.0                | 483.2              | 23.56                                   | 7430.2                      |                 |
| 950              | 137.7                | 485.9              | 24.04                                   | 7407.4                      |                 |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuAl<sub>8</sub>Fe<sub>3</sub>

## 5.2 Copper- and Copper alloys

### 5.2.5 Copper – Aluminium - alloys

#### Designation

|             |               |               |                                       |              |               |
|-------------|---------------|---------------|---------------------------------------|--------------|---------------|
| UNS number: | <b>C61400</b> | Chem. symbol: | <b>CuAl<sub>8</sub>Fe<sub>3</sub></b> | (EN number): | <b>CW303G</b> |
|-------------|---------------|---------------|---------------------------------------|--------------|---------------|

#### Composition (EN) [Weight-%]

| Cu   | Al          | Mn        | Fe          | Ni        | Zn        | Pb         | Si        | Sn        |
|------|-------------|-----------|-------------|-----------|-----------|------------|-----------|-----------|
| Bal. | 6.5 ... 8.5 | 0 ... 1.0 | 1.5 ... 3.5 | 0 ... 1.0 | 0 ... 0.5 | 0 ... 0.05 | 0 ... 0.2 | 0 ... 0.1 |

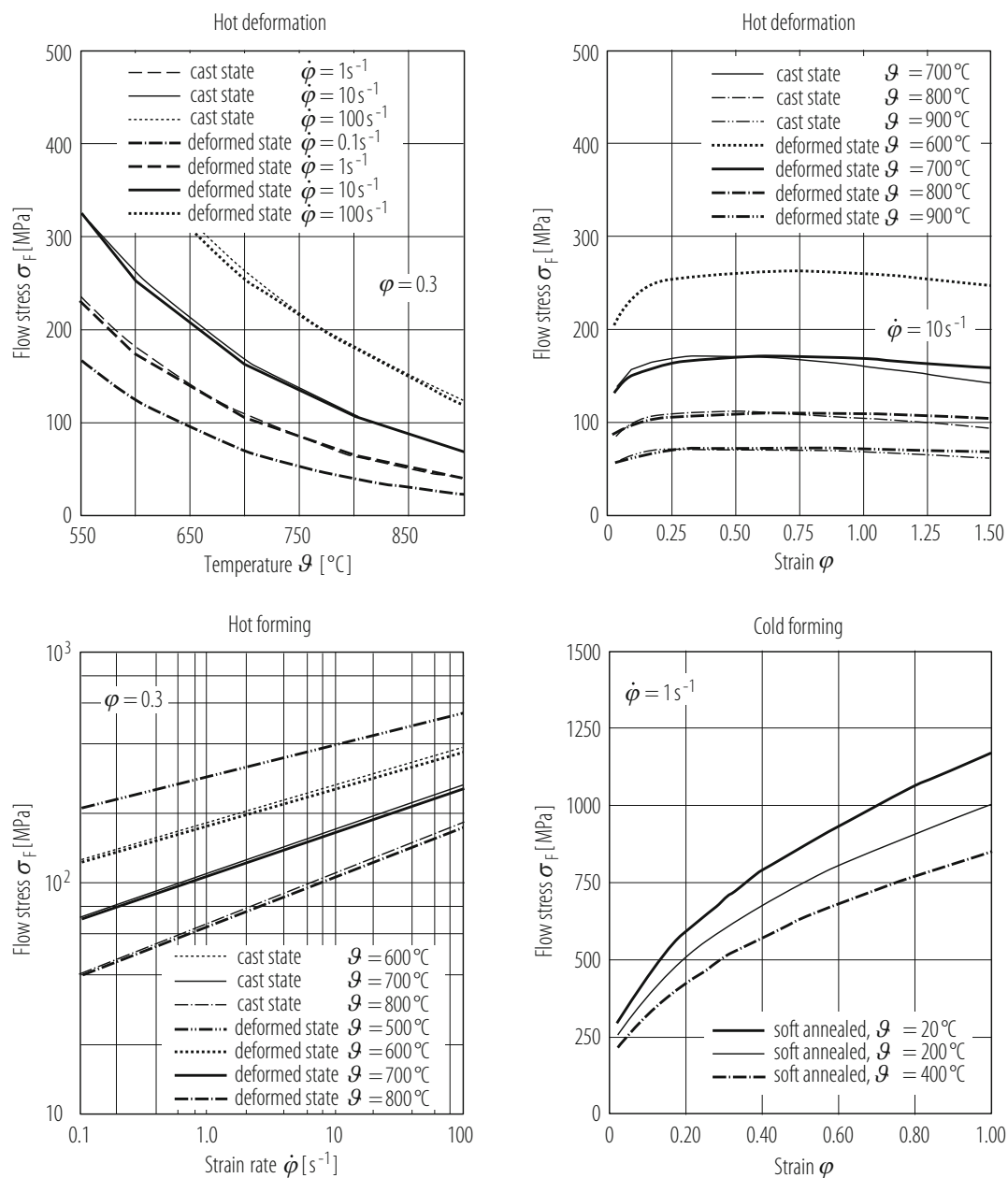
#### International comparison of standards

| Euronorm              |                      | ISO                |             |
|-----------------------|----------------------|--------------------|-------------|
| EN 12420 : 1999       | EN 12165             | ISO 428 : 1983     | ISO 1637    |
| EN 1652               |                      | ISO 1634-2         |             |
| Material number (DIN) |                      | DIN                |             |
| 2.0932                |                      | DIN 17665 : 1983]] |             |
|                       |                      | DIN 17670-1        | DIN 17675-1 |
|                       |                      | DIN 17671-1        | DIN 17672-1 |
| Japan                 |                      | Russia             |             |
| C 6140                | JIS H 3100           |                    |             |
| USA                   |                      |                    |             |
| ASTM                  |                      | UNS standard       |             |
| ASTM B 111 / B 111M   | ASTM B 608           | C61400             |             |
| ASTM B 432            | ASTM B 100           |                    |             |
| ASTM B 169 / B 169 M  | ASTM B 150 / B 150 M |                    |             |
| ASTM B 171 / B 171 M  | ASTM B 315           |                    |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

Flow curves

| State of material                                                                                                                                                              | Hot deformation |                | Cold deformation     |                                                                                                            |                 |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|----------------|----------------------|------------------------------------------------------------------------------------------------------------|-----------------|
|                                                                                                                                                                                | cast state      | deformed state | recrystallized (rec) | soft annealed (sa)                                                                                         | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                                                                                                                                                            | 154.5           | 150.7          |                      | 463.9                                                                                                      |                 |
| A                                                                                                                                                                              | 4878.436        | 4269.790       |                      | 1177.949                                                                                                   |                 |
| Effect of temperature $K_8$ :                                                                                                                                                  |                 |                |                      |                                                                                                            |                 |
| $m_1$                                                                                                                                                                          | −0.00508        | −0.00501       |                      | −0.00083                                                                                                   |                 |
| Effect of strain $K_\varphi$                                                                                                                                                   |                 |                |                      |                                                                                                            |                 |
| $m_2$                                                                                                                                                                          | 0.13616         | 0.11112        |                      | 0.43805                                                                                                    |                 |
| $m_4$                                                                                                                                                                          | 0.00028         | −0.00046       |                      | 0.00674                                                                                                    |                 |
| $m_5$                                                                                                                                                                          | 0.00025         | 0.000079       |                      |                                                                                                            |                 |
| $m_7$                                                                                                                                                                          | −0.42388        | −0.20453       |                      |                                                                                                            |                 |
| Effect of strain rate $K\dot{\varphi}$                                                                                                                                         |                 |                |                      |                                                                                                            |                 |
| $m_3$                                                                                                                                                                          |                 |                |                      | 0.01063                                                                                                    |                 |
| $m_8$                                                                                                                                                                          | 0.000273        | 0.000272       |                      |                                                                                                            |                 |
| Range of validity                                                                                                                                                              |                 |                |                      |                                                                                                            |                 |
| $\vartheta$ [°C]                                                                                                                                                               | 550 ... 900     | 550 ... 900    |                      | 20 ... 400                                                                                                 |                 |
| $\varphi$                                                                                                                                                                      | 0.03 ... 1.50   | 0.03 ... 1.50  |                      | 0.03 ... 1.00                                                                                              |                 |
| $\dot{\varphi}$ [1/s]                                                                                                                                                          | <100            | <100           |                      | <10                                                                                                        |                 |
| Hot deformation:                                                                                                                                                               |                 |                |                      | Cold deformation                                                                                           |                 |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |                 |                |                      | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |                 |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |                 |                |                      | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |                 |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     |                 |                |                      | [DOI: 978-3-642-14174-4_2]                                                                                 |                 |



**Fig. 5.85** Flow stress curves of CuAl<sub>8</sub>Fe<sub>3</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |          |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|----------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$      | $n_2$   |
| hot rolled        | 340 380                         | 42.40049 | 0.62692 | 570. . . 630                        | 12.28821 | 0.86639 |

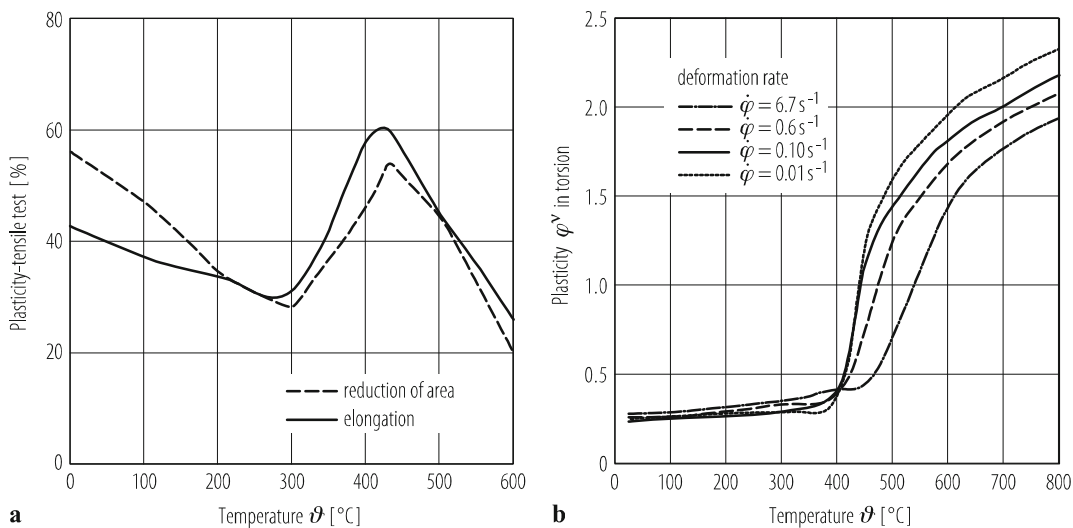
  

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$   | $n_4$    |                            |
| hot rolled        | 25. . . 30                              | 9.09032 | 0.07415 | -4.28517 | <50                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile and torsion test



**Fig. 5.86** Plasticity of CuAl<sub>8</sub>Fe<sub>3</sub> as a function of the temperature. State of material: extruding pressed; cold drawn; annealed by 650°C; quenched. (a) Compare cast and deformed state (b) Comparison of the plasticity at different strain rate

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 60.1                 | 378.1              | 15.41                                   | 7745.7                      | 109.0           |
| 100              | 66.0                 | 382.4              | 15.83                                   | 7727.9                      | 103.0           |
| 200              | 73.5                 | 387.7              | 16.36                                   | 7704.4                      | 94.0            |
| 300              | 80.9                 | 393.1              | 16.89                                   | 7679.3                      | 83.0            |
| 400              | 88.4                 | 398.4              | 17.42                                   | 7652.8                      | 67.0            |

(continued)



| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [10 <sup>-6</sup> /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 500                             | 95.8                                      | 403.8                                   | 17.95                                                                          | 7624.8                                 |                              |
| 600                             | 103.2                                     | 409.1                                   | 18.48                                                                          | 7595.3                                 |                              |
| 700                             | 110.7                                     | 414.5                                   | 19.01                                                                          | 7564.4                                 |                              |
| 800                             | 118.1                                     | 419.9                                   | 19.54                                                                          | 7531.9                                 |                              |
| 900                             | 125.6                                     | 425.2                                   | 20.07                                                                          | 7498.0                                 |                              |
| 950                             |                                           |                                         |                                                                                |                                        |                              |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese industrial standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuAl<sub>10</sub>Ni<sub>5</sub>Fe<sub>4</sub>

## 5.2 Copper- and Copper alloys

### 5.2.5 Copper – Aluminium - alloys

#### Designation

|             |               |               |                     |            |               |
|-------------|---------------|---------------|---------------------|------------|---------------|
| UNS number: | <b>C63000</b> | Chem. symbol: | <b>CuAl10Ni5Fe4</b> | EN number: | <b>CW307G</b> |
|-------------|---------------|---------------|---------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu   | Al          | Mn    | Fe          | Ni          | Si    | Pb    | Sb    | P     | Zn    | As    | Others |
|------|-------------|-------|-------------|-------------|-------|-------|-------|-------|-------|-------|--------|
| Bal. | 9.50...11.0 | <0.50 | 3.50...5.50 | 3.50...5.50 | <0.20 | <0.05 | <0.05 | <0.05 | <0.50 | <0.05 |        |

#### International comparison of standards

|                       |            |                      |             |
|-----------------------|------------|----------------------|-------------|
| Euronorm              |            | ISO                  |             |
| EN 12420 : 1999       | EN 12165   | ISO 428 : 1983       | ISO 1637    |
| EN 1653               |            | ISO 1634-2           | ISO 1640    |
| EN 12163              |            | ISO 1639             |             |
| EN 12167              |            |                      |             |
| Material number (DIN) |            | DIN                  |             |
| 2.0966                |            | [[DIN 17665 : 1983]] | DIN 17672-1 |
|                       |            | DIN 17670-1          | DIN 17675-1 |
|                       |            | DIN 17671-1          | DIN 17678-1 |
|                       |            | DIN 17673-1          |             |
| Japan                 |            | Russia               |             |
| C 6301                | JIS H 3100 | BrAZN10-4-4          | GOST 18175  |
|                       |            | GOST 1628            | GOST 1206   |
| USA                   |            |                      |             |
| ASTM, ASME and SAE    |            | UNS standard         |             |
| ASTM B 283            | ASTM B 171 | C63000               |             |
| ASTM B 150            | ASTM B 283 |                      |             |
| ASTM F468             | ASTM F467  |                      |             |
| ASME SB171            | ASME SB150 |                      |             |
| SAE J463              | SAE J461   |                      |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

Flow curves

| State of material                         | Hot deformation |                | Cold deformation     |                    |                 |
|-------------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                           | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                       |                 | 173.6          |                      |                    |                 |
| A                                         |                 | 13465.00       |                      |                    |                 |
| Effect of temperature $K_{\vartheta}$     |                 |                |                      |                    |                 |
| $m_1$                                     |                 | −0.00607       |                      |                    |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                      |                    |                 |
| $m_2$                                     |                 | 0.17628        |                      |                    |                 |
| $m_4$                                     |                 | 0.000041       |                      |                    |                 |
| $m_5$                                     |                 | −0.00137       |                      |                    |                 |
| $m_7$                                     |                 | 0.12266        |                      |                    |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                      |                    |                 |
| $m_3$                                     |                 |                |                      |                    |                 |
| $m_8$                                     |                 | 0.000237       |                      |                    |                 |
| Range of validity                         |                 |                |                      |                    |                 |
| $\vartheta$ [°C]                          |                 | 600 ... 950    |                      |                    |                 |
| $\varphi$                                 |                 | 0.03 ... 1.50  |                      |                    |                 |
| $\dot{\varphi}$ [1/s]                     |                 | <100           |                      |                    |                 |

|                                                                                                                                                                                |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    |

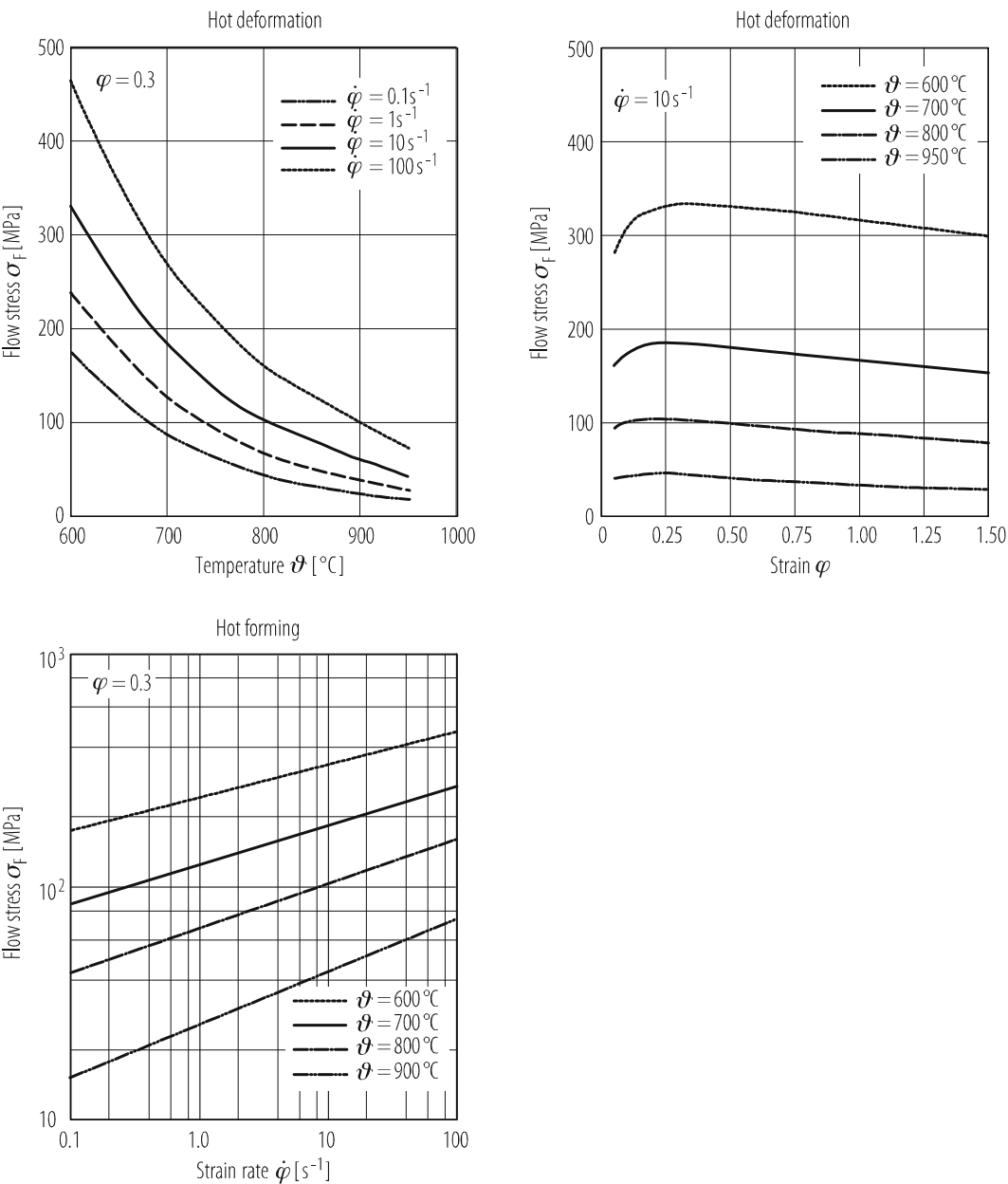


Fig. 5.87 Flow stress curves of CuAl10Ni5Fe4 by hot forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |     |       | Tensile strength $\Delta R_m$ [MPa] |          |         |
|-------------------|---------------------------------|-----|-------|-------------------------------------|----------|---------|
|                   | $A_0$                           | $A$ | $n_1$ | $B_0$                               | $B$      | $n_2$   |
| soft annealed     |                                 |     |       | 650. . . 700                        | 36.36875 | 0.64733 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |          |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|----------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$    | $n_4$    |                            |
| soft annealed     | 23. . . 28                              | 31.26346 | −0.04973 | −10.2645 | <40                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 70.4                 | 437.1              | 16.83                                   | 7525.4                      | 125.0           |
| 100              | 79.4                 | 441.4              | 17.65                                   | 7506.1                      | 122.0           |
| 200              | 90.5                 | 446.7              | 18.68                                   | 7479.4                      | 112.0           |
| 300              | 101.7                | 452.1              | 19.70                                   | 7449.9                      | 108.0           |
| 400              | 112.8                | 457.4              | 20.73                                   | 7417.6                      | 75.0            |
| 500              | 124.0                | 462.8              | 21.75                                   | 7382.6                      | 54.0            |
| 600              | 135.1                | 468.1              | 22.77                                   | 7344.8                      | 46.0            |
| 700              | 146.3                | 473.5              | 23.80                                   | 7304.2                      |                 |
| 800              | 157.4                | 478.9              | 24.82                                   | 7260.9                      |                 |
| 900              | 168.6                | 484.2              | 25.85                                   | 7214.7                      |                 |
| 950              | 174.2                | 486.9              | 26.36                                   | 7190.6                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| JIS                 | Japanese industrial standards                                         |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| SAE                 | society of automotive engineers                                       |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of CuAl<sub>9</sub>Ni<sub>5</sub>Fe<sub>4</sub>

## 5.2 Copper- and Copper alloys

### 5.2.5 Copper – Aluminium - alloys

#### Designation

|             |               |               |                    |              |               |
|-------------|---------------|---------------|--------------------|--------------|---------------|
| UNS number: | <b>C63000</b> | Chem. symbol: | <b>CuAl9Ni5Fe4</b> | (EN number): | <b>CW304G</b> |
|-------------|---------------|---------------|--------------------|--------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Al         | Mn    | Fe          | Ni          | Zn    | Pb    | Si    | Sn    | Others |
|-------------|------------|-------|-------------|-------------|-------|-------|-------|-------|--------|
| 78.0...82.0 | 8.5...11.0 | <1.00 | 4.00...6.00 | 4.00...6.00 | <0.40 | <0.05 | <0.20 | <0.10 |        |

#### International comparison of standards

|                       |                    |                      |             |
|-----------------------|--------------------|----------------------|-------------|
| Euronorm              |                    | ISO                  |             |
| EN 12420 : 1999       | EN 12165           | ISO 428 : 1983       | ISO 1637    |
| EN 1653               | EN 12167           | ISO 1634-2           | ISO 1640    |
| EN 12163              |                    | ISO 1639             |             |
| Material number (DIN) |                    | DIN                  |             |
| 2.0966                |                    | [[DIN 17665 : 1983]] | DIN 17670-1 |
|                       |                    | DIN 17678-1          | DIN 17672-1 |
|                       |                    | DIN 17671-1          | DIN 17673-1 |
| Japan                 |                    | Russia               |             |
| C 6301                | JIS H 3100         | BrAZN10-4-4          | GOST 18175  |
|                       |                    | GOST 1628            | GOST 1206   |
| USA                   |                    | UNS standard         |             |
| ASTM, ASME and SAE    |                    | C63000               |             |
| ASTM B 283            | ASTM B 124 / B 150 |                      |             |
| ASTM B 171            | ASTM B 283         |                      |             |
| ASTM F468             | ASTM F467          |                      |             |
| ASME SB171            | ASME SB150         |                      |             |
| SAE J463              | SAE J461           |                      |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

Flow curves

| State of material                                                                                                                                                              | Hot deformation |                | Cold deformation     |                                                                                                            |                 |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|----------------|----------------------|------------------------------------------------------------------------------------------------------------|-----------------|
|                                                                                                                                                                                | cast state      | deformed state | recrystallized (rec) | soft annealed (sa)                                                                                         | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                                                                                                                                                            |                 | 136.10         |                      | 427.9                                                                                                      |                 |
| A                                                                                                                                                                              |                 | 31891.240      |                      | 1099.673                                                                                                   |                 |
| Effect of temperature $K_8$                                                                                                                                                    |                 |                |                      |                                                                                                            |                 |
| $m_1$                                                                                                                                                                          |                 | −0.00764       |                      | −0.00083                                                                                                   |                 |
| Effect of strain $K_\varphi$                                                                                                                                                   |                 |                |                      |                                                                                                            |                 |
| $m_2$                                                                                                                                                                          |                 | 0.18083        |                      | 0.39883                                                                                                    |                 |
| $m_4$                                                                                                                                                                          |                 | 0.00066        |                      | −0.00465                                                                                                   |                 |
| $m_5$                                                                                                                                                                          |                 | −0.00004       |                      |                                                                                                            |                 |
| $m_7$                                                                                                                                                                          |                 | −0.40076       |                      |                                                                                                            |                 |
| Effect of strain rate $K\dot{\varphi}$                                                                                                                                         |                 |                |                      |                                                                                                            |                 |
| $m_3$                                                                                                                                                                          |                 |                |                      | 0.0155                                                                                                     |                 |
| $m_8$                                                                                                                                                                          |                 | 0.000213       |                      |                                                                                                            |                 |
| Range of validity                                                                                                                                                              |                 |                |                      |                                                                                                            |                 |
| $\vartheta$ [°C]                                                                                                                                                               |                 | 600 ... 950    |                      | 20 ... 300                                                                                                 |                 |
| $\varphi$                                                                                                                                                                      |                 | 0.03 ... 1.50  |                      | 0.03 ... 1.00                                                                                              |                 |
| $\dot{\varphi}$ [1/s]                                                                                                                                                          |                 | <100           |                      | <100                                                                                                       |                 |
| Hot deformation:                                                                                                                                                               |                 |                |                      | Cold deformation                                                                                           |                 |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |                 |                |                      | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |                 |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |                 |                |                      | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |                 |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     |                 |                |                      | [DOI: 978-3-642-14174-4_2]                                                                                 |                 |

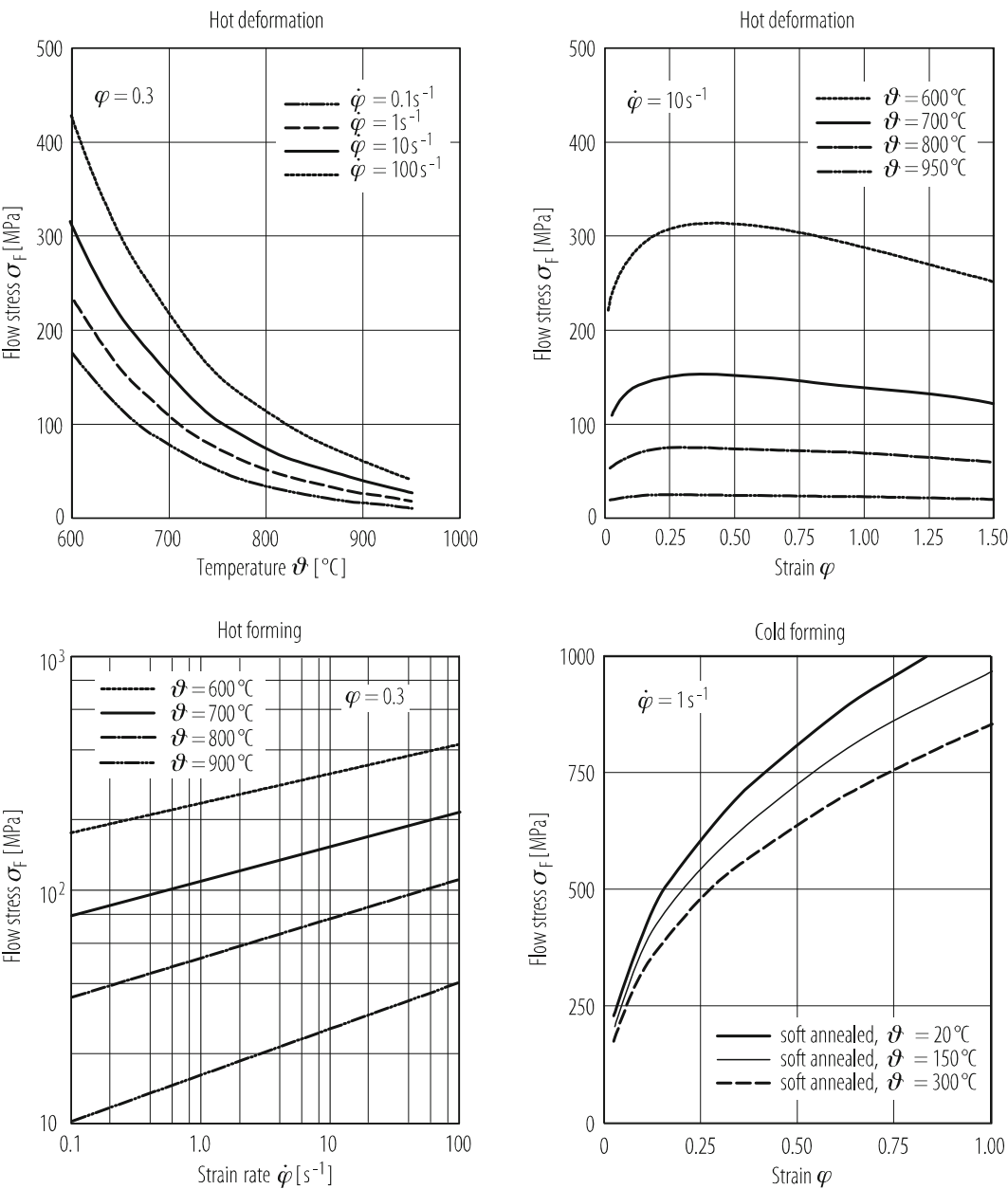
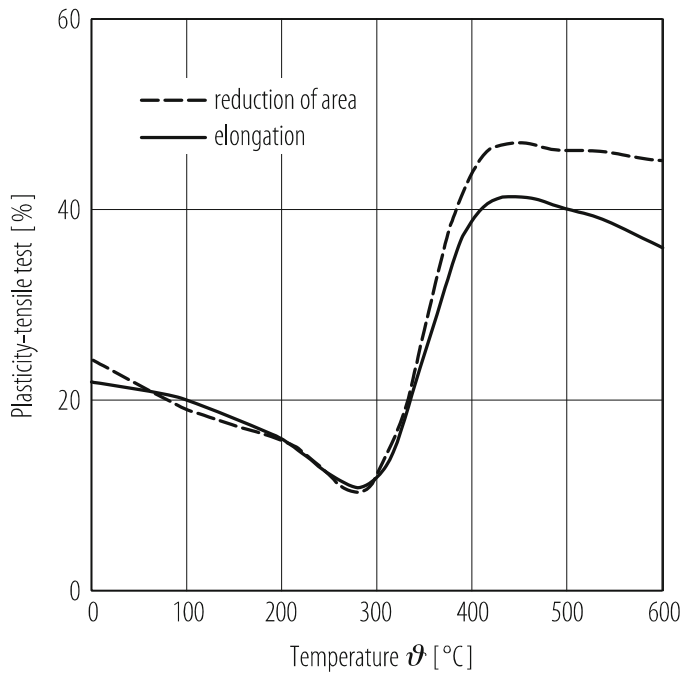


Fig. 5.88 Flow stress curves of CuAl9Ni4Fe by hot and cold forming.



Plasticity in tensile test



**Fig. 5.89** Cold plasticity of CuAl<sub>9</sub>Ni<sub>5</sub>Fe<sub>4</sub> as a function of the temperature. State of material: extruding pressed; cold drawn; annealed by 650°C; quenched.

Physical properties

| Temperature | Thermal conductivity | Mean specific heat       | Average coefficient of linear expansion | Density                | Young's-modulus |
|-------------|----------------------|--------------------------|-----------------------------------------|------------------------|-----------------|
| Θ [°C]      | λ [W/m·K]            | c <sub>pm</sub> [J/kg·K] | α <sub>m</sub> [10 <sup>-6</sup> /K]    | ρ [kg/m <sup>3</sup> ] | E [GPa]         |
| 20          | 67.4                 | 437.1                    | 14.61                                   | 7606.0                 | 121             |
| 100         | 76.4                 | 441.4                    | 15.03                                   | 7589.4                 |                 |
| 200         | 87.5                 | 446.7                    | 15.56                                   | 7567.4                 |                 |
| 300         | 98.7                 | 452.1                    | 16.09                                   | 7543.9                 |                 |
| 400         | 109.8                | 457.4                    | 16.62                                   | 7518.9                 |                 |
| 500         | 121.0                | 462.8                    | 17.15                                   | 7492.5                 |                 |
| 600         | 132.1                | 468.1                    | 17.68                                   | 7464.7                 |                 |
| 700         | 143.3                | 473.5                    | 18.21                                   | 7435.4                 |                 |
| 800         | 154.4                | 478.9                    | 18.74                                   | 7404.6                 |                 |

Symbols and abbreviations

| Short form                 | Full form                                                             |
|----------------------------|-----------------------------------------------------------------------|
| σ <sub>F</sub>             | flow stress                                                           |
| φ                          | strain                                                                |
| φ̇                         | strain rate                                                           |
| A <sub>5</sub>             | elongation to fracture                                                |
| A, B, C and n <sub>i</sub> | constants                                                             |
| ASME                       | American society of mechanical engineers                              |
| ASTM                       | American society for testing and materials                            |
| c <sub>pm</sub>            | mean specific heat                                                    |
| DIN                        | German institute for standardisation (Deutsches Institut Für Normung) |
| E                          | Young's modulus                                                       |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| EN             | Euronorm                                       |
| GOST           | gosudarstvennyy standart (state standard)      |
| ISO            | international organisation for standardization |
| JIS            | Japanese industrial standards                  |
| $R_m$          | tensile strength                               |
| $R_p$          | yield stress                                   |
| SAE            | society of automotive engineers                |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |

# Flow stress, mechanical and physical properties of CuAl<sub>10</sub>Fe<sub>3</sub>Mn<sub>2</sub>

## 5.2 Copper- and Copper alloys

### 5.2.5 Copper – Aluminium - alloys

#### Designation

|             |               |                     |            |               |
|-------------|---------------|---------------------|------------|---------------|
| UNS number: | Chem. Symbol: | <b>CuAl10Fe3Mn2</b> | EN number: | <b>CW306G</b> |
|-------------|---------------|---------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu    | Al         | Mn          | Fe          | Ni    | Zn    | Pb    | Si    | Sn    | Others |
|-------|------------|-------------|-------------|-------|-------|-------|-------|-------|--------|
| >79.7 | 8.5...11.0 | 1.50...3.50 | 2.00...4.00 | <1.00 | <0.50 | <0.05 | <0.20 | <0.10 | <0.30  |

#### International comparison of standards

| Euronorm              |          | ISO                  |                |
|-----------------------|----------|----------------------|----------------|
| EN 12420 : 1999       | EN 12163 | CuAl10Fe3            | ISO 428 : 1983 |
| EN 12164              |          | ISO 1637             | ISO 1639       |
| EN 12167              |          | ISO 1640             |                |
| Material number (DIN) |          | DIN                  |                |
| 2.0936                |          | [[DIN 17665 : 1983]] | DIN 17672-1    |
|                       |          | DIN 17671-1          | DIN 17678-1    |
| Japan                 |          | Russia               |                |
|                       |          | BrAZMc10-3-1,5       | GOST 18175-78  |
|                       |          | GOST 1628            | GOST 1208      |
| USA                   |          |                      |                |
| ASTM                  |          | UNS standard         |                |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

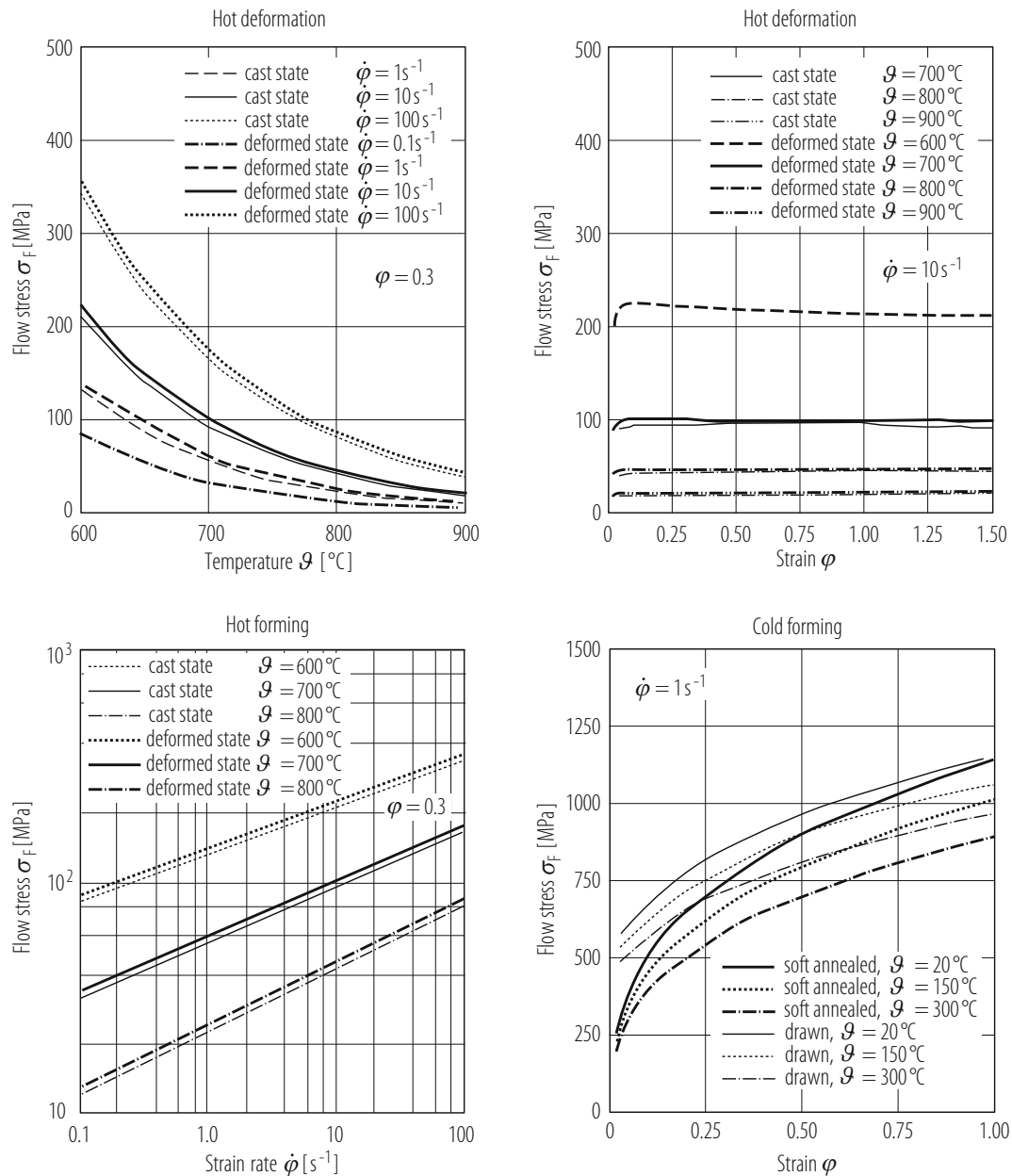
#### Flow curves

| State of material           | Hot deformation |                | Cold deformation   |            |
|-----------------------------|-----------------|----------------|--------------------|------------|
|                             | cast state      | deformed state | soft annealed (sa) | drawn (dr) |
| $\sigma_{F0}$ [MPa]         | 93.2            | 101.5          | 519.0              | 692.4      |
| A                           | 28952.640       | 24149.930      | 1166.075           | 1161.519   |
| Effect of temperature $K_9$ |                 |                |                    |            |
| $m_1$                       | -0.00918        | -0.00880       | -0.00089           | -0.00096   |

(continued)

| State of material                      | Hot deformation |                | Cold deformation   |               |
|----------------------------------------|-----------------|----------------|--------------------|---------------|
|                                        | cast state      | deformed state | soft annealed (sa) | drawn (dr)    |
| Effect of strain $K_\varphi$           |                 |                |                    |               |
| $m_2$                                  | −0.06151        | −0.08075       | 0.33902            | 0.26129       |
| $m_4$                                  | −0.00428        | −0.00655       | −0.00395           | 0.00716       |
| $m_5$                                  | 0.00123         | 0.00041        |                    |               |
| <b>Fig. 1.90</b> 2.0936. $m_7$         | −0.43705        | −0.08185       |                    |               |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                    |               |
| $m_3$                                  |                 |                | 0.01169            | 0.01355       |
| $m_8$                                  | 0.000341        | 0.00034        |                    |               |
| Range of validity                      |                 |                |                    |               |
| $\vartheta$ [°C]                       | 600 ... 900     | 600 ... 900    | 20 ... 300         | 20 ... 300    |
| $\varphi$                              | 0.03 ... 1.50   | 0.03 ... 1.50  | 0.03 ... 1.00      | 0.03 ... 1.00 |
| $\dot{\varphi}$ [1/s]                  | <100            | <100           | <100               | <100          |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |



**Fig. 5.90** Flow stress curves of  $\text{CuAl}_{10}\text{Fe}_3\text{Mn}_2$  by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |     |       | Tensile strength $\Delta R_m$ [MPa] |          |         |
|-------------------|---------------------------------|-----|-------|-------------------------------------|----------|---------|
|                   | $A_0$                           | $A$ | $n_1$ | $B_0$                               | $B$      | $n_2$   |
| soft annealed     |                                 |     |       | 575...625                           | 35.01337 | 0.62857 |

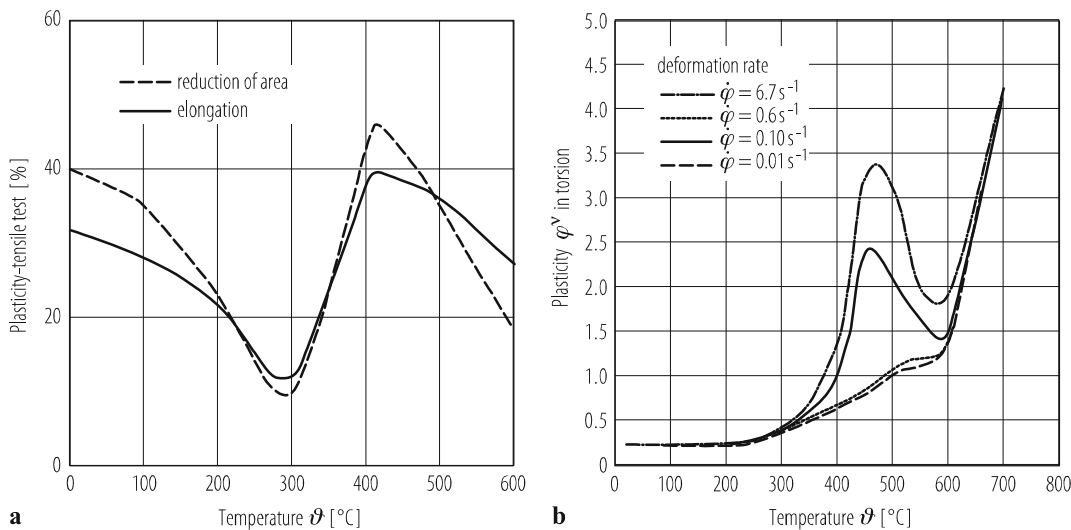
  

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| soft annealed     | 35...40                                 | 11.12662 | 0.32611 | -3.98566 | <50                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile and torsion test



**Fig. 5.91** Plasticity of CuAl<sub>10</sub>Fe<sub>3</sub>Mn<sub>2</sub> as a function of the temperature. State of material: extruding pressed; cold drawn; annealed by 650°C; quenched. (a) Compare cast and deformed state (b) Comparison of the plasticity at different strain rate

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 58.0                 | 399.1              | 15.61                                   | 7605.7                      | 120.0           |
| 100              | 62.2                 | 403.4              | 16.03                                   | 7588.0                      |                 |
| 200              | 67.3                 | 408.7              | 16.56                                   | 7564.6                      |                 |
| 300              | 72.5                 | 414.1              | 17.09                                   | 7539.8                      |                 |
| 400              | 77.6                 | 419.4              | 17.62                                   | 7513.5                      |                 |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 500              | 82.8                 | 424.8              | 18.15                                   | 7485.7                      |                 |
| 600              | 88.0                 | 430.1              | 18.68                                   | 7456.5                      |                 |
| 700              | 93.1                 | 435.5              | 19.21                                   | 7425.8                      |                 |
| 800              | 98.3                 | 440.9              | 19.74                                   | 7393.7                      |                 |
| 900              |                      |                    |                                         |                             |                 |
| 950              |                      |                    |                                         |                             |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress and plasticity of CuMn<sub>11</sub>Al<sub>8</sub>Ni<sub>3</sub>Fe<sub>3</sub>

## 5.2 Copper- and Copper alloys

### 5.2.5 Copper – Aluminium - alloys

#### Designation

|             |               |               |                        |            |               |
|-------------|---------------|---------------|------------------------|------------|---------------|
| UNS number: | <b>C63380</b> | Chem. symbol: | <b>CuMn11Al8Ni3Fe3</b> | EN number: | <b>CC212E</b> |
|-------------|---------------|---------------|------------------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu          | Al        | Mn         | Fe          | Ni          | Zn    | Si    | Sn    | Zn    |
|-------------|-----------|------------|-------------|-------------|-------|-------|-------|-------|
| 68.0...77.0 | 7.0...9.0 | 8.0...15.0 | 2.00...4.00 | 1.50...4.50 | <1.00 | <0.10 | <0.50 | <1.00 |

#### International comparison of standards

|                       |            |                  |                 |
|-----------------------|------------|------------------|-----------------|
| Euronorm              |            | ISO              |                 |
| EN 1982 : 1998        |            |                  |                 |
| Material number (DIN) |            | DIN              |                 |
| Japan                 |            | Russia           |                 |
| CAC704                | JIS H 5120 | BrA7Mc15Z3N2C2-P | GOST 493 : 1979 |
| USA                   |            |                  |                 |
| ASTM                  |            | UNS standard     |                 |
|                       |            | C63380           |                 |

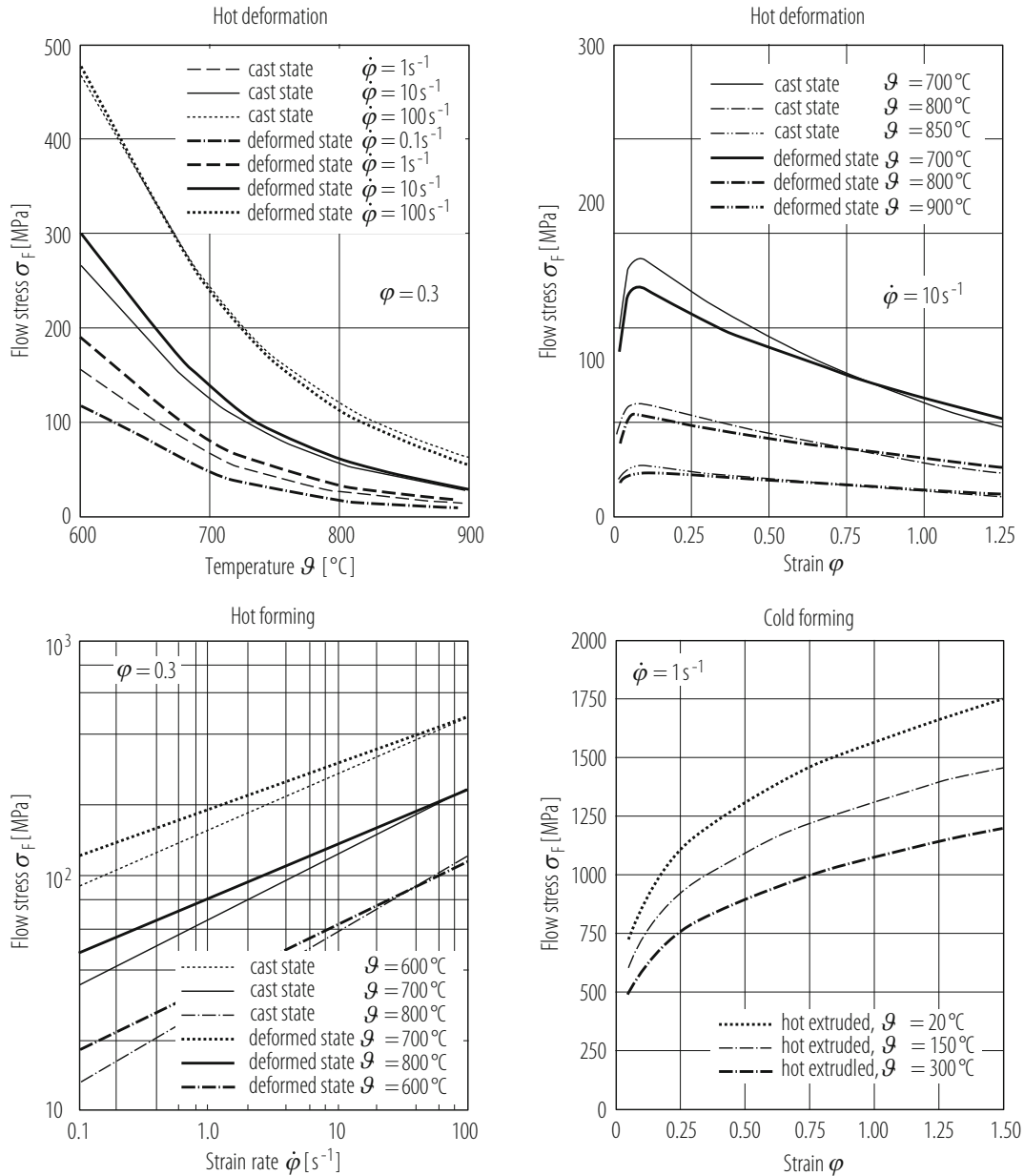
It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

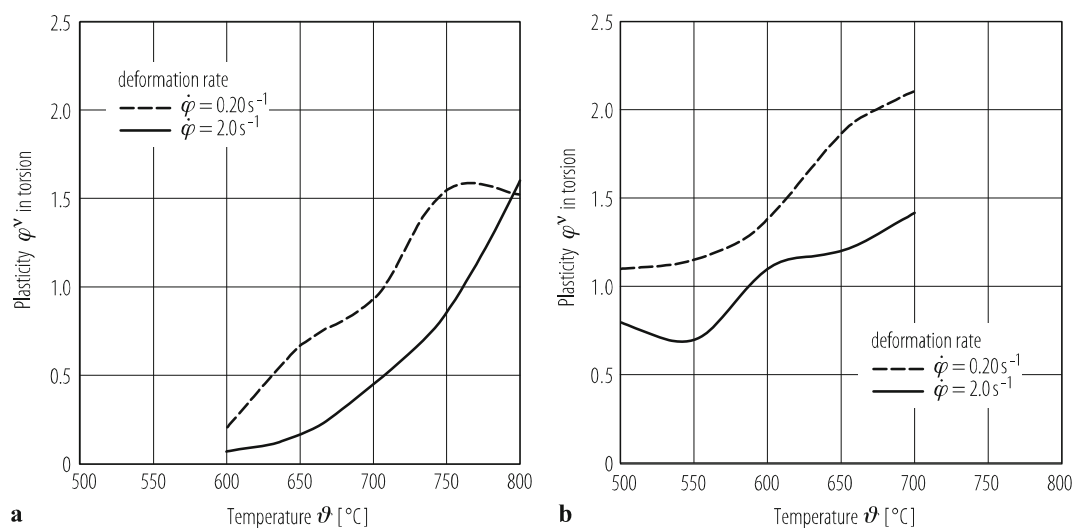
| State of material                   | Hot deformation |                | Cold deformation   |                   |
|-------------------------------------|-----------------|----------------|--------------------|-------------------|
|                                     | cast state      | deformed state | soft annealed (sa) | hot extruded (he) |
| $\sigma_{F0}$ [MPa]                 | 145.1           | 163.1          |                    | 888.8             |
| A                                   | 32090.668       | 42173.812      |                    | 1613.909          |
| Effect of temperature $K_\theta$    |                 |                |                    |                   |
| $m_1$                               | −0.00917        | −0.00908       |                    | −0.00137          |
| Effect of strain $K_\phi$           |                 |                |                    |                   |
| $m_2$                               | −0.23954        | −0.20145       |                    | 0.25599           |
| $m_4$                               | −0.01844        | −0.01761       |                    | −0.00098          |
| $m_5$                               | 0.00181         | 0.0014         |                    |                   |
| $m_7$                               | −1.14234        | −1.20211       |                    |                   |
| Effect of strain rate $K\dot{\phi}$ |                 |                |                    |                   |
| $m_3$                               |                 |                |                    | 0.01261           |
| $m_8$                               | 0.000401        | 0.000335       |                    |                   |
| Range of validity                   |                 |                |                    |                   |
| $\theta$ [°C]                       | 600 ... 900     | 600 ... 900    |                    | 20 ... 300        |
| $\phi$                              | 0.03 ... 1.25   | 0.03 ... 1.25  |                    | 0.03 ... 1.50     |
| $\dot{\phi}$ [1/s]                  | <100            | <100           |                    | <100              |



| Hot deformation:                                                                                                                                                            | Cold deformation                                                                                              |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \dot{\varphi}^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \dot{\varphi}^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                        | [Equation (2.25), Chapter 2.3.2.2.2]                                                                          |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                  | [DOI: 978-3-642-14174-4_2]                                                                                    |



**Fig. 5.92** Flow stress curves of  $\text{CuMn}_{11}\text{Al}_8\text{Ni}_3\text{Fe}_3$  by hot and cold forming.



**Fig. 5.93** Hot plasticity of CuMn<sub>11</sub>Al<sub>8</sub>Ni<sub>3</sub>Fe<sub>3</sub> as a function of the temperature. **(a)** Initial test: cast. **(b)** Initial test: deformed.

### Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| EN              | Euronorm                                                              |
| GOST            | gosudarstvennyy standart (state standard)                             |
| ISO             | international organisation for standardization                        |
| JIS             | Japanese industrial standards                                         |
| $T, \theta$     | temperature                                                           |
| UNS             | unified numbering system                                              |

# Flow stress, mechanical and physical properties of CuSi<sub>3</sub>Mn<sub>1</sub>

## 5.2 Copper- and Copper alloys

### 5.2.6 Copper – Silicon - alloys

#### Designation

|             |               |               |                 |            |               |
|-------------|---------------|---------------|-----------------|------------|---------------|
| UNS number: | <b>C65500</b> | Chem. symbol: | <b>CuSi3Mn1</b> | EN number: | <b>CW116C</b> |
|-------------|---------------|---------------|-----------------|------------|---------------|

#### Composition (EN) [Weight-%]

| Cu   | Si          | Mn          | Fe    | Zn    | Pb    | P     |
|------|-------------|-------------|-------|-------|-------|-------|
| Bal. | 2.70...3.20 | 0.70...1.30 | <0.20 | <0.40 | <0.05 | <0.05 |

#### International comparison of standards

|                       |                    |                  |            |
|-----------------------|--------------------|------------------|------------|
| Euronorm              |                    | ISO              |            |
| EN 12163 : 1988       | EN 12163 : 1998    | ISO 1187 : 1983  |            |
| EN 12166 : 1998       |                    | ISO 1634-2       | ISO 1637   |
| Material number (DIN) |                    | DIN              |            |
| 2.1522                |                    | DIN 17666 : 1970 |            |
| Japan                 |                    | Russia           |            |
|                       |                    | BrKMc3-1         | GOST 18175 |
| USA                   |                    |                  |            |
| ASTM                  |                    | UNS standard     |            |
| ASTM B 96 / B 96 M    | ASTM B 100         | C65500           |            |
| ASTM B 124 / B 124 M  | ASTM B 98 / B 98 M |                  |            |
| ASTM B 99 / B 99 M    | ASTM B 315         |                  |            |
| ASTM B 283            |                    |                  |            |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

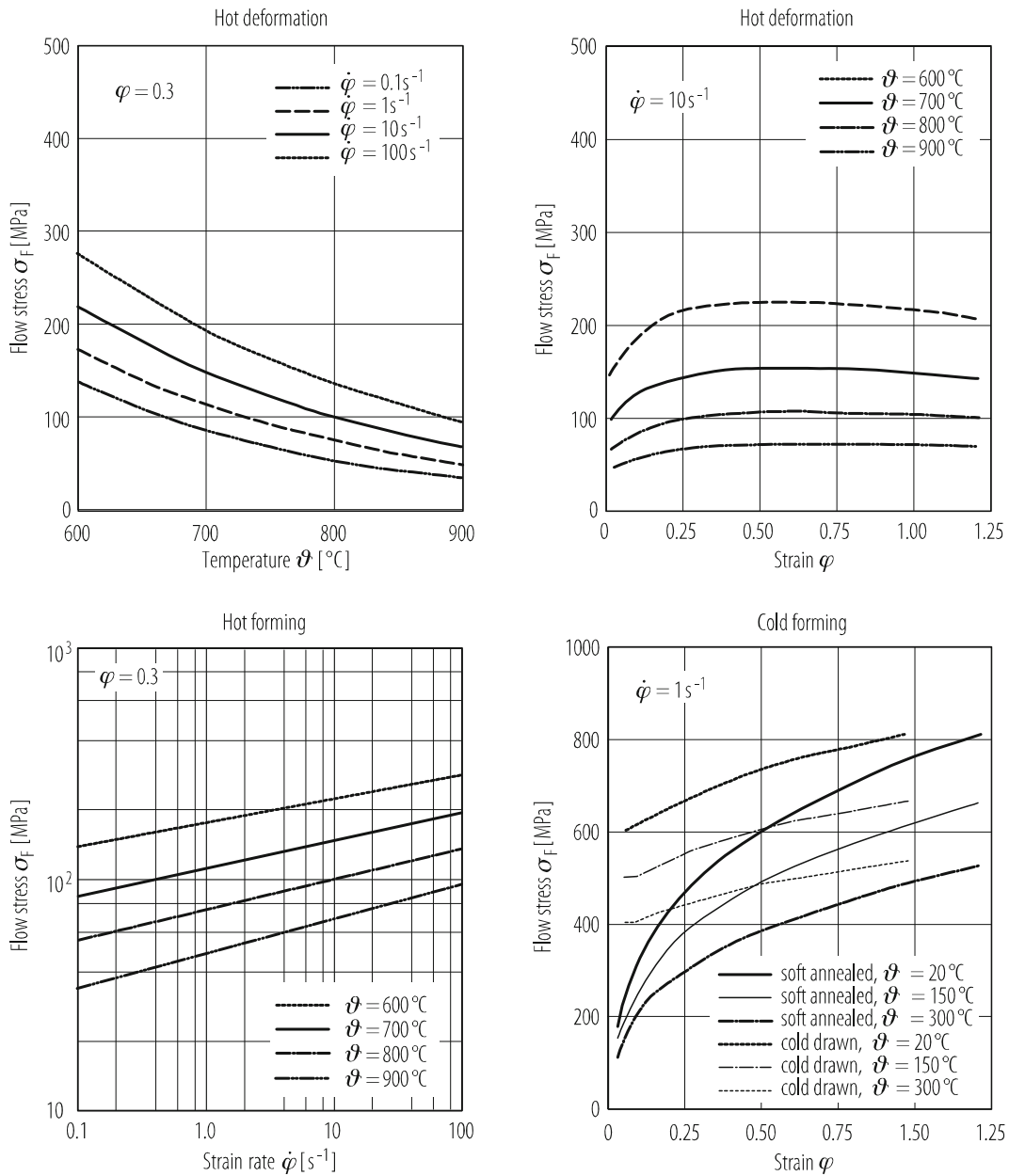
#### Flow curves

| State of material   | Hot deformation |                | Cold deformation   |                 |
|---------------------|-----------------|----------------|--------------------|-----------------|
|                     | cast state      | deformed state | soft annealed (sa) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa] |                 | 125.5          | 342.4              | 635.5           |
| A                   |                 | 3389.576       | 791.140            | 827.686         |

(continued)

| State of material                         | Hot deformation |                | Cold deformation   |                 |
|-------------------------------------------|-----------------|----------------|--------------------|-----------------|
|                                           | cast state      | deformed state | soft annealed (sa) | cold drawn (cd) |
| Effect of temperature $K_\vartheta$       |                 |                |                    |                 |
| $m_1$                                     |                 | -0.00441       | -0.00156           | -0.00148        |
| Effect of strain $K_\varphi$              |                 |                |                    |                 |
| $m_2$                                     |                 | 0.20376        | 0.32512            | 0.15886         |
| $m_4$                                     |                 | 0.00131        | -0.00921           | 0.00997         |
| $m_5$                                     |                 | 0.00046        |                    |                 |
| $m_7$                                     |                 | -0.53293       |                    |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                    |                 |
| $m_3$                                     |                 | 0.000167       | 0.01416            | 0.01357         |
| $m_8$                                     |                 |                |                    |                 |
| Range of validity                         |                 |                |                    |                 |
| $\vartheta$ [°C]                          |                 | 600 ... 900    | 20 ... 300         | 20 ... 300      |
| $\varphi$                                 |                 | 0.03 ... 1.25  | 0.03 ... 1.25      | 0.03 ... 1.00   |
| $\dot{\varphi}$ [1/s]                     |                 | <100           | <100               | <100            |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.94** Flow stress curves of  $\text{CuSi}_3\text{Mn}_1$  by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|----------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$      | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| soft annealed     | 120...150                       | 27.10180 | 0.75552 | 340...380                           | 7.94109 | 0.94651 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |          |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|----------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$      | $n_3$   | $n_4$    |                            |
| soft annealed     | 60...65                                 | 10.17323 | 0.42762 | -4.15896 | <70                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

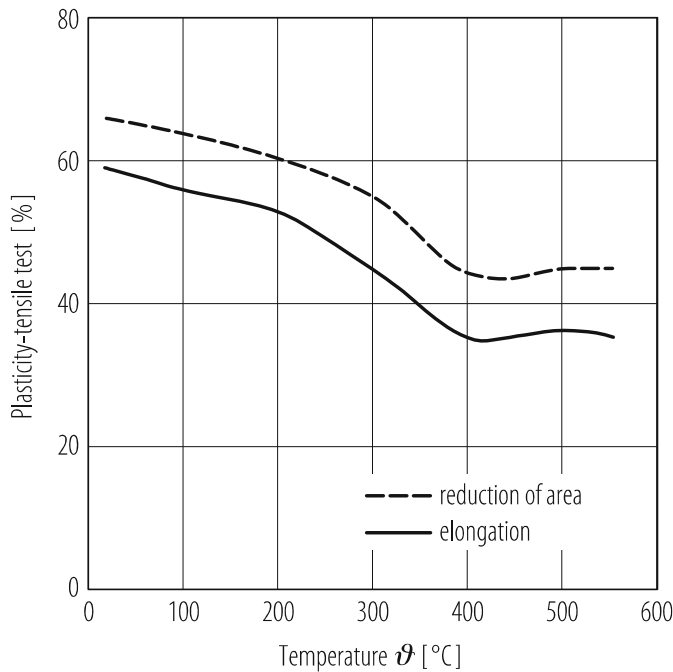


Fig. 5.95 Cold plasticity of CuSi<sub>3</sub>Mn<sub>1</sub> as a function of the temperature.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 42.5                 |                    |                                         |                             |                 |
| 100              | 49.4                 |                    |                                         |                             |                 |
| 200              | 52.6                 |                    | 17.8                                    |                             |                 |
| 300              | 54.6                 |                    |                                         |                             |                 |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}/K$ ]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 400              | 56.1                 |                    |                                         |                             |                 |
| 500              | 57.3                 |                    |                                         |                             |                 |
| 600              | 58.3                 |                    |                                         |                             |                 |
| 700              | 59.1                 |                    |                                         |                             |                 |
| 800              | 59.8                 |                    |                                         |                             |                 |
| 900              | 60.5                 |                    |                                         |                             |                 |
| 950              | 60.8                 |                    |                                         |                             |                 |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress and plasticity of CuSi<sub>3</sub>Mn

## 5.2 Copper- and Copper alloys

### 5.2.6 Copper – Silicon - alloys

#### Designation

|             |               |               |                |            |               |
|-------------|---------------|---------------|----------------|------------|---------------|
| UNS number: | <b>C65500</b> | Chem. symbol: | <b>CuSi3Mn</b> | EN number: | <b>CW116C</b> |
|-------------|---------------|---------------|----------------|------------|---------------|

#### Composition (EN) [Weight-%]

|      |      |      |      |        |
|------|------|------|------|--------|
| Cu   | Si   | Fe   | Mn   | Al     |
| 95.6 | 3.42 | 0.50 | ~1,0 | Traces |

#### International comparison of standards

|                       |                 |                  |                 |
|-----------------------|-----------------|------------------|-----------------|
| Euronorm              |                 | ISO              |                 |
| EN 12163 : 1988       | EN 12166 : 1998 | CuSi3Mn1         | ISO 1187 : 1983 |
|                       |                 | ISO 1634-2       | ISO 1637        |
| Material number (DIN) |                 | DIN              |                 |
| 2.1522                | CuSi2Mn         | DIN 17666 : 1970 |                 |
| Japan                 |                 | Russia           |                 |
|                       |                 | BrKMc3-1         | GOST 18175      |
| USA                   |                 |                  |                 |
| ASTM                  |                 | UNS standard     |                 |
| ASTM B 96 / B 96 M    |                 | C65500           |                 |

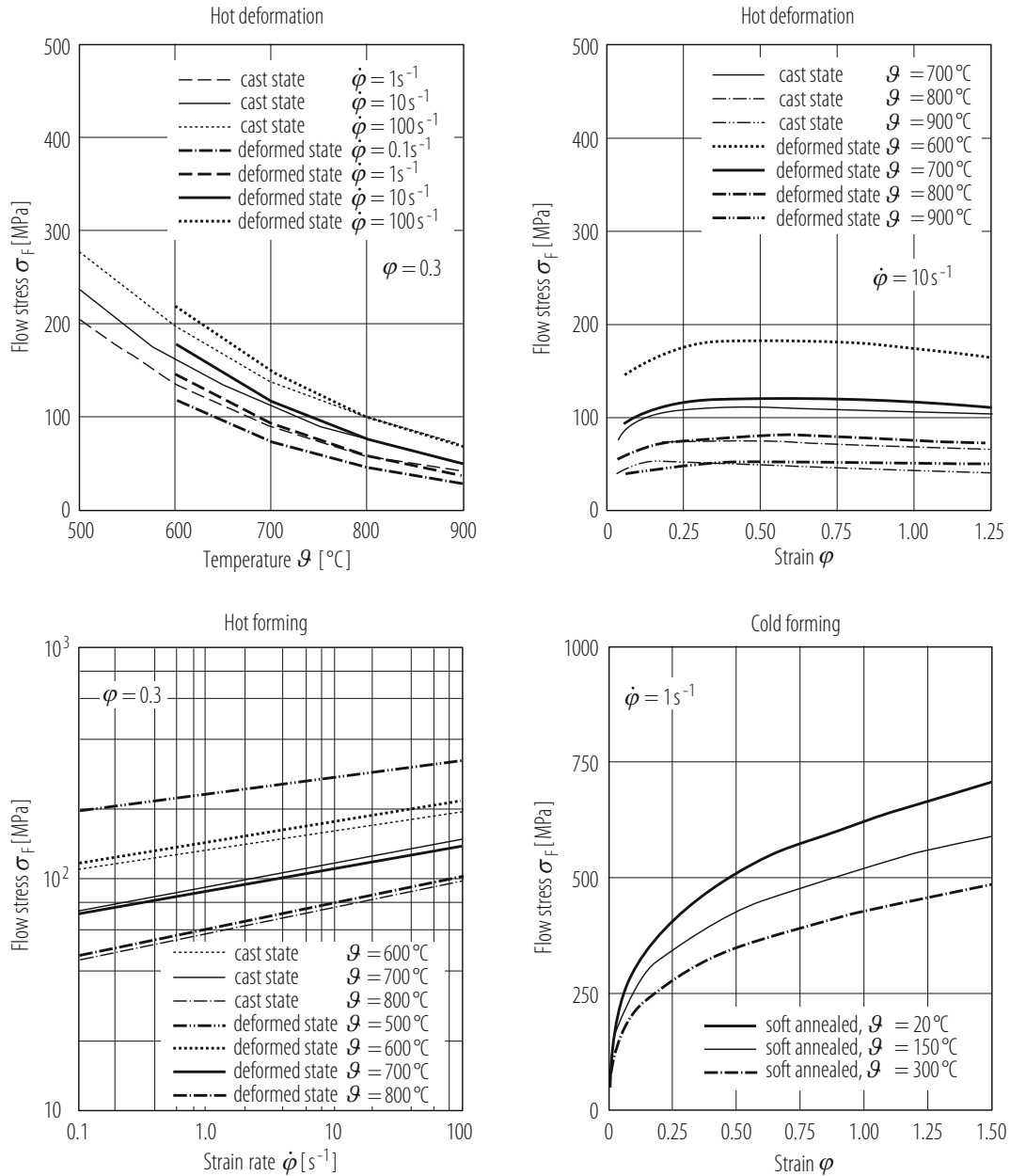
It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation     |                    |                 |
|----------------------------------------|-----------------|----------------|----------------------|--------------------|-----------------|
|                                        | cast state      | deformed state | recrystallized (rec) | soft annealed (sa) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                    | 97.4            | 101.3          |                      | 327.1              |                 |
| A                                      | 1867.993        | 3300.000       |                      | 642.580            |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                      |                    |                 |
| $m_1$                                  | −0.00368        | −0.00461       |                      | −0.00132           |                 |
| Effect of strain $K_{\phi}$            |                 |                |                      |                    |                 |
| $m_2$                                  | 0.18381         | 0.203131       |                      | 0.28861            |                 |
| $m_4$                                  | −0.00922        | 0.00082        |                      | −0.00489           |                 |
| $m_5$                                  | −0.00155        | 0.00024        |                      |                    |                 |
| $m_7$                                  | 0.25773         | −0.47227       |                      |                    |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                      |                    |                 |
| $m_3$                                  |                 |                |                      | 0.02749            |                 |
| $m_8$                                  | 0.000133        | 0.000145       |                      |                    |                 |
| Range of validity                      |                 |                |                      |                    |                 |
| $\theta$ [°C]                          | 500 ... 900     | 600 ... 900    |                      | 20 ... 300         |                 |
| $\phi$                                 | 0.03 ... 1.25   | 0.03 ... 1.25  |                      | 0.03 ... 1.50      |                 |
| $\dot{\phi}$ [1/s]                     | <100            | <100           |                      | <100               |                 |

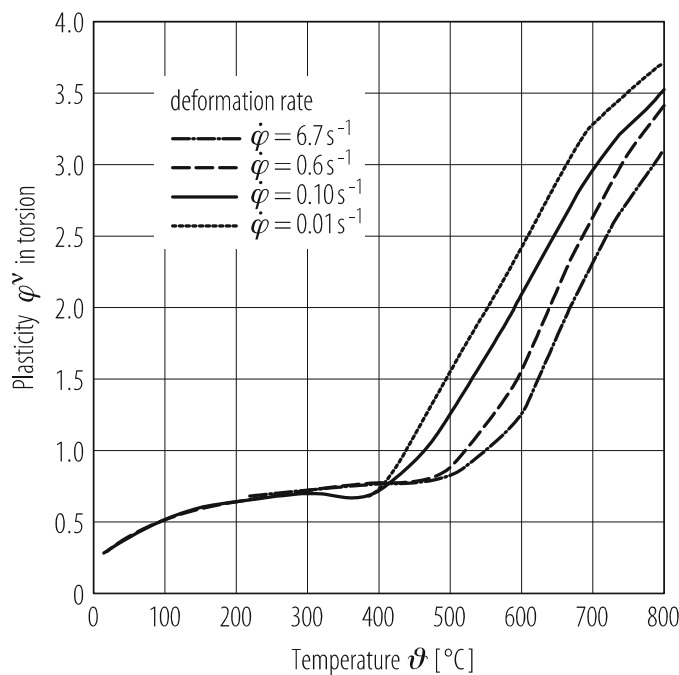


| Hot deformation:                                                                                                                                                      | Cold deformation                                                                                        |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                  | [Equation (2.25), Chapter 2.3.2.2.2]                                                                    |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                            | [DOI: 978-3-642-14174-4_2]                                                                              |



**Fig. 5.96** Flow stress curves of CuSi<sub>3</sub>Mn by hot and cold forming.

Plasticity in torsion test



**Fig. 5.97** Plasticity of CuSi<sub>3</sub>Mn as a function of the temperature.

Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| EN              | Euronorm                                                              |
| GOST            | gosudarstvennyy standart (state standard)                             |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |

# Flow stress and plasticity of CuSi<sub>5</sub>

## 5.2 Copper- and Copper alloys

### 5.2.6 Copper – Silicon - alloys

#### Designation

|             |               |              |            |
|-------------|---------------|--------------|------------|
| UNS number: | Chem. symbol: | <b>CuSi5</b> | EN number: |
|-------------|---------------|--------------|------------|

#### Composition [Weight-%]

|      |      |      |        |
|------|------|------|--------|
| Cu   | Si   | Fe   | Al     |
| 94.3 | 5.20 | 0.46 | Traces |

#### International comparison of standards

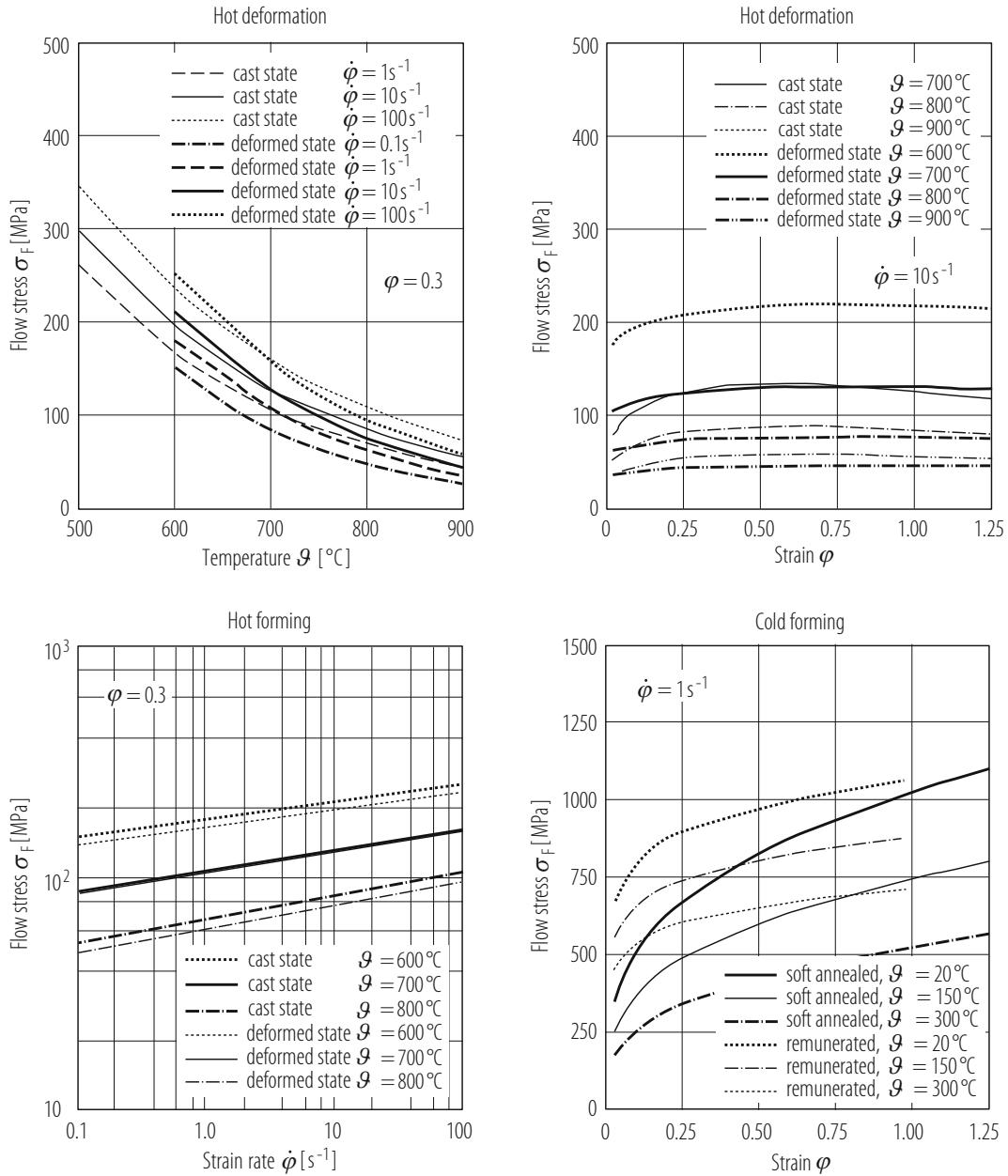
|                       |              |
|-----------------------|--------------|
| Euronorm              | ISO          |
|                       | ISO 1336     |
| Material number (DIN) | DIN          |
| Japan                 | Russia       |
| USA                   |              |
| ASTM                  | UNS standard |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                   | Hot deformation |                | Cold deformation   |                   |
|-------------------------------------|-----------------|----------------|--------------------|-------------------|
|                                     | cast state      | deformed state | soft annealed (sa) | remunerated (rem) |
| $\sigma_{F0}$ [MPa]                 | 109.1           | 117.10         | 523.8              | 837.8             |
| A                                   | 3795.988        | 5531.689       | 1064.701           | 1091.738          |
| Effect of temperature $K_\theta$    |                 |                |                    |                   |
| $m_1$                               | −0.00456        | −0.00545       | −0.00177           | −0.00143          |
| Effect of strain $K_\phi$           |                 |                |                    |                   |
| $m_2$                               | 0.23131         | 0.104482       | 0.30731            | 0.11966           |
| $m_4$                               | 0.00088         | 0.00121        | −0.000019          | −0.00139          |
| $m_5$                               | 0.00027         | 0.00006        |                    |                   |
| $m_7$                               | −0.54227        | −0.15918       |                    |                   |
| Effect of strain rate $K\dot{\phi}$ |                 |                |                    |                   |
| $m_3$                               |                 |                | 0.01416            | 0.02288           |
| $m_8$                               | 0.000125        | 0.000124       |                    |                   |
| Range of validity                   |                 |                |                    |                   |
| $\theta$ [°C]                       | 500 ... 900     | 600 ... 900    | 20 ... 400         | 20 ... 300        |
| $\phi$                              | 0.03 ... 1.25   | 0.03 ... 1.25  | 0.03 ... 1.25      | 0.03 ... 1.00     |
| $\dot{\phi}$ [1/s]                  | <100            | <100           | <100               | <100              |

| Hot deformation:                                                                                                                                                      | Cold deformation                                                                                        |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                  | [Equation (2.25), Chapter 2.3.2.2.2]                                                                    |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                            | [DOI: 978-3-642-14174-4_2]                                                                              |



**Fig. 5.98** Flow stress curves of CuSi<sub>5</sub> by hot and cold forming.

Plasticity in torsion test

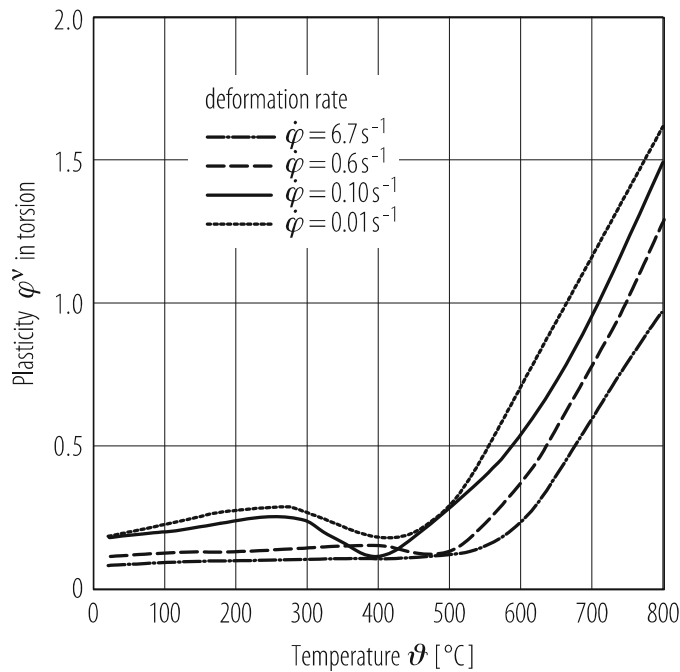


Fig. 5.99 Plasticity of CuSi5 as a function of the temperature.

Symbols and Abbreviations

| Short form     | Full form                                                             |
|----------------|-----------------------------------------------------------------------|
| $\sigma_F$     | flow stress                                                           |
| $\phi$         | strain                                                                |
| $\dot{\phi}$   | strain rate                                                           |
| ASTM           | American society for testing and materials                            |
| DIN            | German institute for standardisation (Deutsches Institut Für Normung) |
| EN             | Euronorm                                                              |
| ISO            | international organisation for standardization                        |
| $T, \vartheta$ | temperature                                                           |
| UNS            | unified numbering system                                              |

# Flow stress, plasticity and physical properties of Ni<sub>99.97</sub>

## 5.3 Nickel – and Nickel alloys

### 5.3.1 Pure Nickel and Nickel alloys with < 10% alloy content

#### Designation

|             |        |               |         |            |        |
|-------------|--------|---------------|---------|------------|--------|
| UNS number: | N02270 | Chem. symbol: | Ni99.97 | EN number: | CW009A |
|-------------|--------|---------------|---------|------------|--------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn | P | S | Cr | Mo | Ni   | V | Nb | Ti | Fe   |
|-------|-------|----|---|---|----|----|------|---|----|----|------|
| 0.001 | <0.01 |    |   |   |    |    | Bal. |   |    |    | 0.01 |

#### International comparison of standards

|                       |           |           |              |
|-----------------------|-----------|-----------|--------------|
| Euronorm              |           | ISO       |              |
| CW009A                |           |           |              |
| Material number (DIN) |           | DIN       |              |
| 2.4050                |           | DIN 17740 |              |
| United Kingdom        |           | Russia    |              |
|                       |           | NP1, NP2  | GOST 2179-75 |
| USA                   |           |           |              |
| ASME                  | ASTM      |           | UNS standard |
|                       | ASTM B39  | ASTM B160 | N02270       |
|                       | ASTM B161 | ASTM B162 |              |
|                       | ASTM B163 |           |              |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

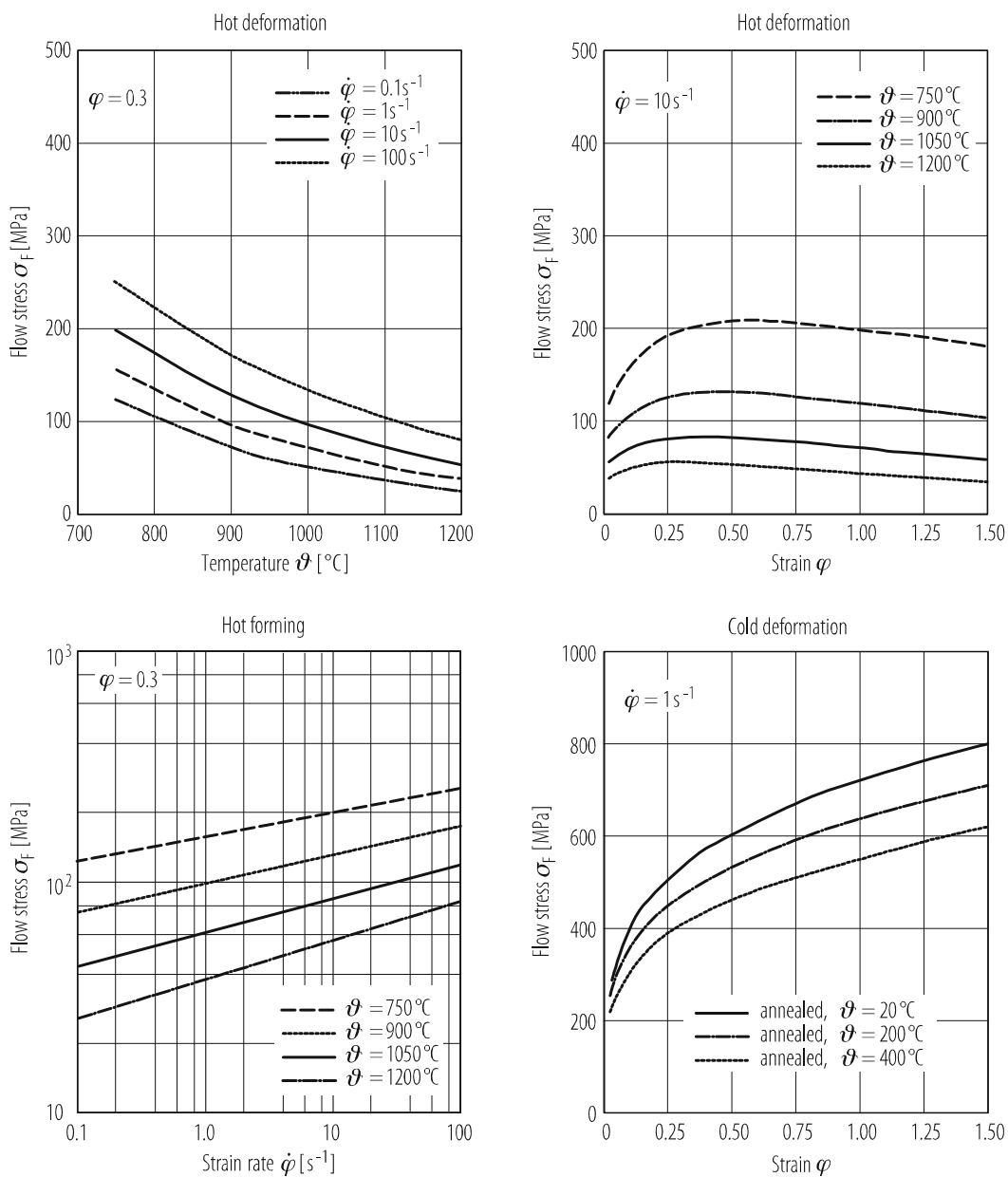
#### Flow curves

| State of material           | Hot deformation |                | Cold deformation |                 |                 |
|-----------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                             | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]         |                 | 81.3           | 547.5            |                 |                 |
| A                           |                 | 2785.631       | 734.790          |                 |                 |
| Effect of temperature $K_9$ |                 |                |                  |                 |                 |
| $m_1$                       |                 | −0.00283       | −0.00071         |                 |                 |
| Effect of strain $K_q$      |                 |                |                  |                 |                 |
| $m_2$                       |                 | 0.42416        | 0.24979          |                 |                 |
| $m_4$                       |                 | 0.00833        | −0.00135         |                 |                 |
| $m_5$                       |                 | −0.00130       |                  |                 |                 |
| $m_7$                       |                 | −0.09280       |                  |                 |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.00897          |                 |                 |
| $m_8$                                  |                 | 0.000139       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                       |                 | 750...1200     | 20...400         |                 |                 |
| $\varphi$                              |                 | 0.03 ... 1.50  | 0.03 ... 1.50    |                 |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.01 ... 500   | 0.01...100       |                 |                 |

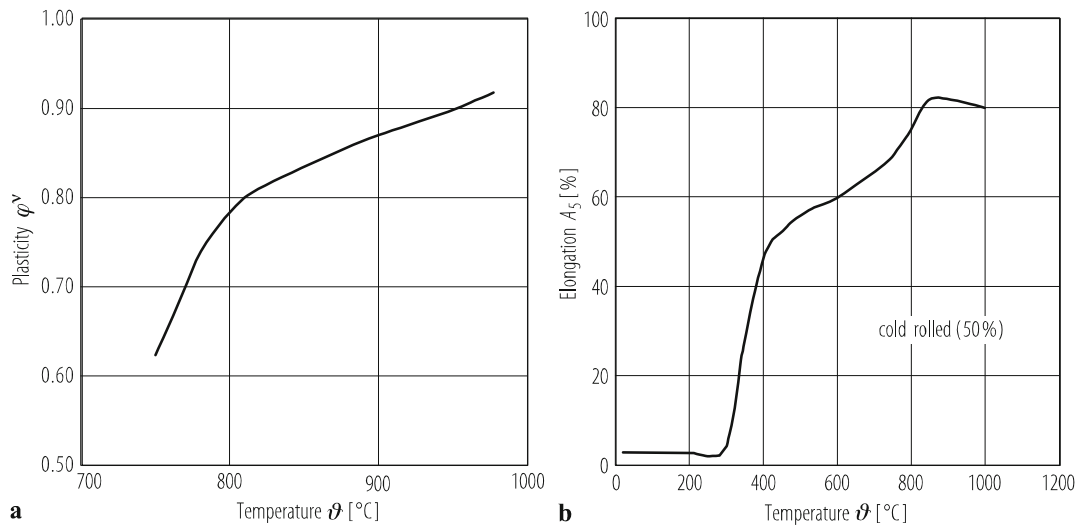
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |



**Fig. 5.100** Flow stress curves of Ni<sub>99.97</sub> by hot and cold forming.



### Plasticity in torsion and tensile test



**Fig. 5.101** Plasticity of Ni<sub>99.97</sub> as a function of the temperature. (a) Torsion test (b) Tensile test

### Physical properties

| Temperature<br>$\theta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                           | 90.7                                      | 425.5                                   | 13.19                                                                    | 8919.3                                 | 225                          |
| 100                          | 83.3                                      | 450.4                                   | 13.49                                                                    | 8882.2                                 | 218                          |
| 200                          | 73.9                                      | 481.7                                   | 13.86                                                                    | 8835.8                                 | 210                          |
| 300                          | 64.6                                      | 502.9                                   | 14.23                                                                    | 8789.4                                 | 202                          |
| 400                          | 60.4                                      | 533.3                                   | 14.60                                                                    | 8743.0                                 | 194                          |
| 500                          | 63.6                                      | 535.8                                   | 14.97                                                                    | 8696.7                                 | 186                          |
| 600                          | 66.3                                      | 538.3                                   | 15.33                                                                    | 8650.3                                 | 178                          |
| 700                          | 68.7                                      | 540.8                                   | 15.70                                                                    | 8603.9                                 | 172                          |
| 800                          | 70.9                                      | 543.3                                   | 16.07                                                                    | 8557.5                                 | 165                          |
| 900                          | 72.9                                      | 545.8                                   | 16.44                                                                    | 8511.1                                 |                              |
| 1000                         | 74.7                                      | 548.3                                   | 16.81                                                                    | 8464.7                                 |                              |
| 1100                         | 76.3                                      | 550.8                                   | 17.18                                                                    | 8418.3                                 |                              |
| 1200                         | 77.9                                      | 553.3                                   | 17.55                                                                    | 8371.9                                 |                              |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| $E$                 | Young's modulus                                                       |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| EN             | Euronorm                                       |
| GOST           | gosudarstvennyy standart (state standard)      |
| ISO            | international organisation for standardization |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |

# Flow stress, mechanical and physical properties of Ni<sub>99.6</sub>

## 5.3 Nickel – and Nickel alloys

### 5.3.1 Pure Nickel and Nickel alloys with < 10% alloy content

#### Designation

|             |               |               |               |            |
|-------------|---------------|---------------|---------------|------------|
| UNS number: | <b>N02200</b> | Chem. symbol: | <b>Ni99.6</b> | EN number: |
|-------------|---------------|---------------|---------------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn    | P | S      | Cu    | Mo | Ni   | Mg    | Nb | Ti    | Fe    |
|-------|-------|-------|---|--------|-------|----|------|-------|----|-------|-------|
| <0.08 | <0.15 | <0.35 |   | <0.005 | <0.15 |    | Bal. | <0.15 |    | <0.10 | <0.25 |

#### International comparison of standards

| Euronorm              |                | ISO       |                   |
|-----------------------|----------------|-----------|-------------------|
| EN ISO 6207           |                | ISO 6207  | ISO 6208          |
| Material number (DIN) |                | DIN       |                   |
| 2.4060                |                | DIN 17740 | DIN 17750 – 17754 |
| United Kingdom        |                | Russia    |                   |
| NA12                  | BS 3072 - 3074 | NP 2 E    | GOST 19241-80     |
| USA                   |                |           |                   |

| ASME           |              | ASTM       |            | UNS standard |
|----------------|--------------|------------|------------|--------------|
| ASME SB- 160   | ASME SB- 163 | ASTM B 160 | ASTM B 163 | N 02200      |
| ASME SB- 775   | ASME SB- 725 | ASTM B 775 | ASTM B 725 |              |
| ASME SB- 829 0 | ASME SB- 366 | ASTM B 829 | ASTM B 366 |              |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                  | Hot deformation |                | Cold deformation |                 |                 |
|------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                    | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                |                 | 98.8           | 422.9            | 428.9           |                 |
| A                                  |                 | 2556.78        | 748.760          | 752.071         |                 |
| Effect of temperature $K_{\theta}$ |                 |                |                  |                 |                 |
| $m_1$                              |                 | −0.00244       | −0.00074         | −0.00065        |                 |
| Effect of strain $K_{\varphi}$     |                 |                |                  |                 |                 |
| $m_2$                              |                 | 0.43181        | 0.23914          | 0.22981         |                 |

(continued)

| State of material                       | Hot deformation |                | Cold deformation |                 |                 |
|-----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                         | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| m <sub>4</sub>                          |                 | 0.00311        | −0.00281         | −0.00124        |                 |
| m <sub>5</sub>                          |                 | −0.00113       |                  |                 |                 |
| m <sub>7</sub>                          |                 | 0.01856        |                  |                 |                 |
| Effect of strain rate K $\dot{\varphi}$ |                 |                |                  |                 |                 |
| m <sub>3</sub>                          |                 |                | 0.00962          | −0.00311        |                 |
| m <sub>8</sub>                          |                 | 0.000111       |                  |                 |                 |
| Range of validity                       |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                        |                 | 700...1100     | 20...300         | 20...300        |                 |
| $\varphi$                               |                 | 0.03 ... 1.50  | 0.03 ... 1.50    | 0.03 ... 1.50   |                 |
| $\dot{\varphi}$ [1/s]                   |                 | 0.001...100    | 0.01...100       | 0.01...100      |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

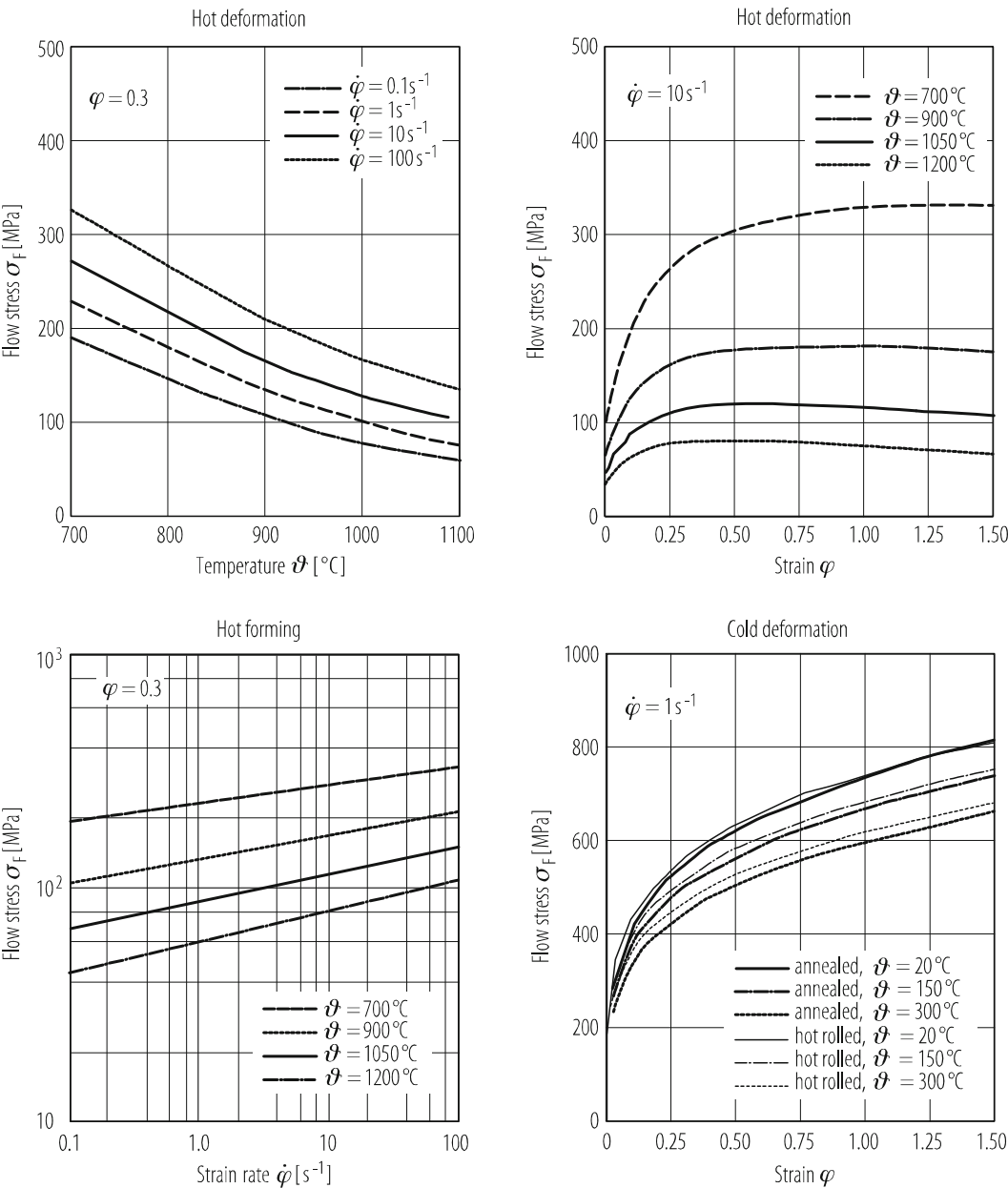


Fig. 5.102 Flow stress curves of Ni99.6 by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |         |        | Vickers hardness $\Delta H_v$ |        |        |
|-------------------|---------------------------------|---------|--------|-------------------------------|--------|--------|
|                   | $A_0$                           | $A$     | $n_1$  | $B_0$                         | $B$    | $n_2$  |
| hot rolled        | 270. . .300                     | 37.8208 | 0.6196 |                               |        |        |
| soft annealed     | 175. . .190                     | 49.4242 | 0.5943 |                               |        |        |
| soft annealed     |                                 |         |        | 80. . .100                    | 3.7418 | 0.9190 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |        |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|--------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$  | $n_4$   |                            |
| hot rolled        |                                         |         |        |         | <50                        |
| soft annealed     |                                         |         |        |         | <85                        |
| soft annealed     | 35...45                                 | 16.0579 | 0.1887 | -5.8743 | <75                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in torsion and tensile test

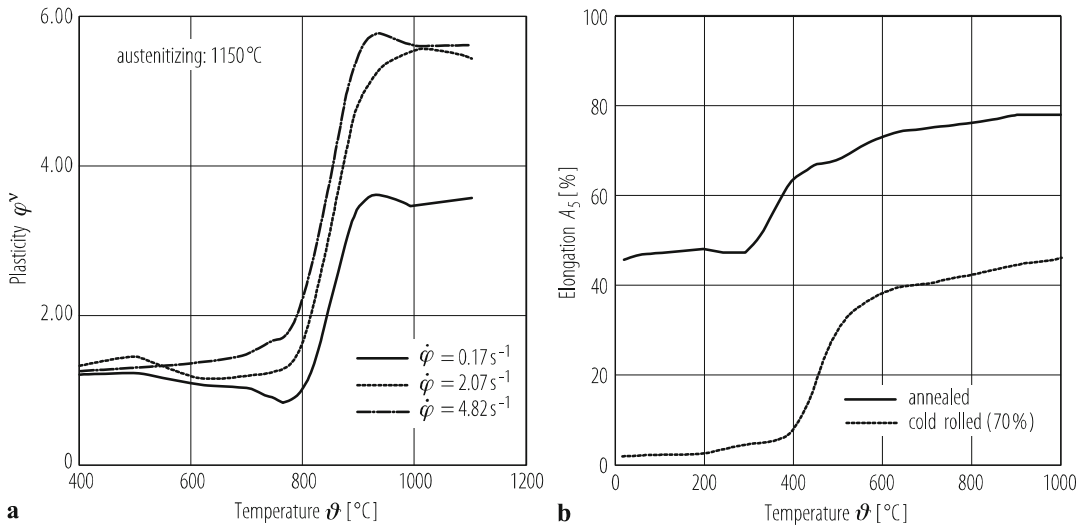


Fig. 5.103 Plasticity of Ni99.6 as a function of the temperature and deformation rate. (a) Torsion test (b) Tensile test

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 65.9                 | 427.8              | 13.21                                   | 8890.8                      | 200.1           |
| 100              | 62.1                 | 448.9              | 13.50                                   | 8873.4                      | 184.2           |
| 200              | 57.4                 | 470.0              | 13.87                                   | 8850.6                      | 163.8           |
| 300              | 52.6                 | 491.1              | 14.24                                   | 8826.6                      | 172.5           |
| 400              | 47.7                 | 512.2              | 14.61                                   | 8801.5                      | 163.8           |
| 500              | 50.8                 | 514.7              | 14.97                                   | 8775.1                      |                 |
| 600              | 53.9                 | 517.5              | 15.34                                   | 8747.6                      |                 |

(continued)

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}/K$ ] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 700                             | 56.9                                      | 520.3                                   | 15.71                                                                    | 8719.0                                 |                              |
| 800                             | 60.0                                      | 523.0                                   | 16.08                                                                    | 8689.1                                 |                              |
| 900                             | 63.1                                      | 525.8                                   | 16.44                                                                    | 8658.1                                 |                              |
| 1000                            | 66.2                                      | 528.5                                   | 16.81                                                                    | 8625.8                                 |                              |
| 1100                            | 69.3                                      | 531.3                                   | 17.18                                                                    | 8592.5                                 |                              |
| 1200                            | 72.3                                      | 534.0                                   | 17.55                                                                    | 8557.9                                 |                              |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| BS                  | British standards                                                     |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\Delta H_V$        | vickers hardness                                                      |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of Ni<sub>99.2</sub>

## 5.3 Nickel – and Nickel alloys

### 5.3.1 Pure Nickel and Nickel alloys with < 10% alloy content

#### Designation

|             |               |               |               |            |
|-------------|---------------|---------------|---------------|------------|
| UNS number: | <b>N02201</b> | Chem. symbol: | <b>Ni99.2</b> | EN number: |
|-------------|---------------|---------------|---------------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn    | P | S      | Cu    | Mo | Ni    | Mg    | Nb | Ti    | Fe    |
|-------|-------|-------|---|--------|-------|----|-------|-------|----|-------|-------|
| <0.10 | <0.25 | <0.35 |   | <0.005 | <0.25 |    | >99.2 | <0.15 |    | <0.10 | <0.40 |

#### International comparison of standards

| Euronorm              |                | ISO          |                  |
|-----------------------|----------------|--------------|------------------|
| EN ISO 6207           |                | ISO 6207     | ISO 9723 – 9725  |
| Material number (DIN) |                | DIN          |                  |
| 2.4066                |                | DIN 17740    | DIN 17750. 17754 |
| United Kingdom        |                | Russia       |                  |
| NA12                  | BS 3074 (1989) |              |                  |
| USA                   |                |              |                  |
| ASME                  | ASTM           | UNS standard |                  |
| ASME SB 160           | ASTM A 494-05  | N02201       |                  |
| ASME SB 161           | ASTM A 781-05  |              |                  |
| ASME SB 162           | ASTM B 564-06  |              |                  |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

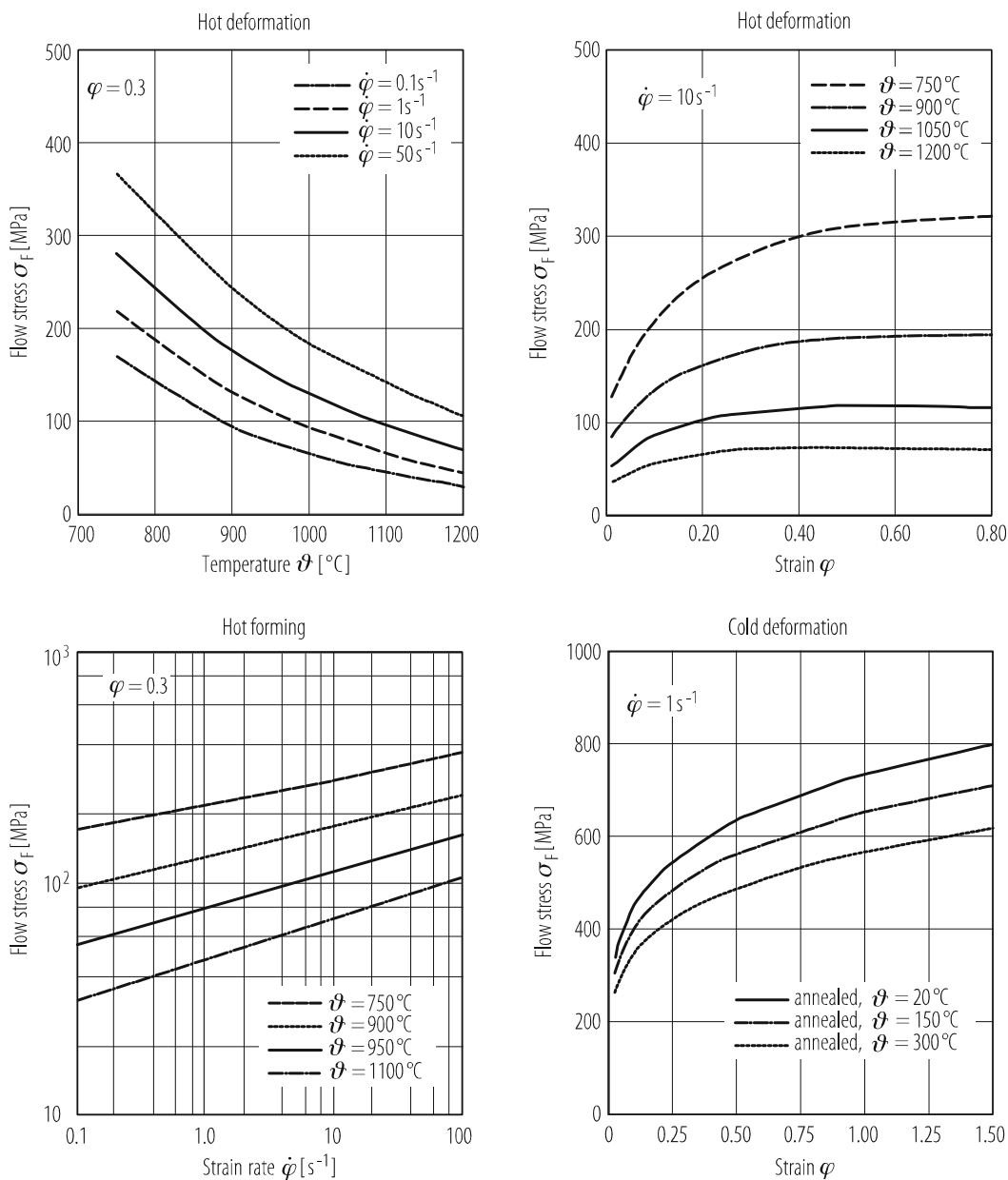
| State of material           | Hot deformation |                | Cold deformation |                 |                 |
|-----------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                             | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]         |                 | 100.3          | 458.1            |                 |                 |
| A                           |                 | 4882.259       | 745.607          |                 |                 |
| Effect of temperature $K_9$ |                 |                |                  |                 |                 |
| $m_1$                       |                 | –0.00318       | –0.00093         |                 |                 |

(continued)



| State of material                       | Hot deformation |                 | Cold deformation |                 |                 |
|-----------------------------------------|-----------------|-----------------|------------------|-----------------|-----------------|
|                                         | cast state      | deformed state  | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Effect of strain K                      |                 |                 |                  |                 |                 |
| m <sub>2</sub>                          |                 | 0.43214         | 0.20983          |                 |                 |
| m <sub>4</sub>                          |                 | 0.00475         | −0.00113         |                 |                 |
| m <sub>5</sub>                          |                 | −0.00094        |                  |                 |                 |
| m <sub>7</sub>                          |                 | −0.11016        |                  |                 |                 |
| Effect of strain rate K $\dot{\varphi}$ |                 |                 |                  |                 |                 |
| m <sub>3</sub>                          |                 |                 | 0.01124          |                 |                 |
| m <sub>8</sub>                          |                 | 0.000149        |                  |                 |                 |
| Range of validity                       |                 |                 |                  |                 |                 |
| $\vartheta$ [°C]                        |                 | 750. . . 1200   | 20. . . 300      |                 |                 |
| $\varphi$                               |                 | 0.03 . . . 0.80 | 0.03 . . . 1.50  |                 |                 |
| $\dot{\varphi}$ [1/s]                   |                 | 0.001 . . . 100 | 0.01 . . . 100   |                 |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |



**Fig. 5.104** Flow stress curves of Ni<sub>99.2</sub> by hot and cold forming.

### Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |     |       | Vickers hardness $\Delta H_V$ |         |        |
|-------------------|---------------------------------|-----|-------|-------------------------------|---------|--------|
|                   | $A_0$                           | $A$ | $n_I$ | $B_0$                         | $B$     | $n_2$  |
| soft annealed     |                                 |     |       | 80...100                      | 12.7612 | 0.6359 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |        |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|--------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$  | $n_4$   |                            |
| soft annealed     | 40. . . 45                              | 36.5942 | 0.0457 | −9.3518 | <75                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

## Physical properties

| Temperatur<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [10 <sup>−6</sup> /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|--------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                             | 65.9                                      | 427.8                                   | 13.21                                                                          | 8890.8                                 | 200.1                        |
| 100                            | 62.1                                      | 448.9                                   | 13.50                                                                          | 8873.4                                 | 184.2                        |
| 200                            | 57.4                                      | 470.0                                   | 13.87                                                                          | 8850.6                                 | 163.8                        |
| 300                            | 52.6                                      | 491.1                                   | 14.24                                                                          | 8826.6                                 | 172.5                        |
| 400                            | 47.7                                      | 512.2                                   | 14.61                                                                          | 8801.5                                 | 163.8                        |
| 500                            | 50.8                                      | 514.7                                   | 14.97                                                                          | 8775.1                                 |                              |
| 600                            | 53.9                                      | 517.5                                   | 15.34                                                                          | 8747.6                                 |                              |
| 700                            | 56.9                                      | 520.3                                   | 15.71                                                                          | 8719.0                                 |                              |
| 800                            | 60.0                                      | 523.0                                   | 16.08                                                                          | 8689.1                                 |                              |
| 900                            | 63.1                                      | 525.8                                   | 16.44                                                                          | 8658.1                                 |                              |
| 1000                           | 66.2                                      | 528.5                                   | 16.81                                                                          | 8625.8                                 |                              |
| 1100                           | 69.3                                      | 531.3                                   | 17.18                                                                          | 8592.5                                 |                              |
| 1200                           | 72.3                                      | 534.0                                   | 17.55                                                                          | 8557.9                                 |                              |

Physical properties of 2.4060 Ni99.6 was used

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| BS                  | British standards                                                     |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| ISO            | international organisation for standardization |
| $R_p$          | yield stress                                   |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\Delta H_V$   | vickers hardness                               |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |

# Flow stress, mechanical and physical properties of LC-Ni<sub>99</sub>

## 5.3 Nickel – and Nickel alloys

### 5.3.1 Pure Nickel and Nickel alloys with < 10% alloy content

#### Designation

|             |        |               |         |            |
|-------------|--------|---------------|---------|------------|
| UNS number: | N02201 | Chem. symbol: | LC-Ni99 | EN number: |
|-------------|--------|---------------|---------|------------|

#### Composition (DIN) [Weight-%]

| C     | Si    | Mn    | P | S      | Cu    | Mo | Ni    | Mg    | Nb | Ti    | Fe    |
|-------|-------|-------|---|--------|-------|----|-------|-------|----|-------|-------|
| <0.02 | <0.25 | <0.35 |   | <0.005 | <0.25 |    | >99.0 | <0.15 |    | <0.10 | <0.40 |

#### International comparison of standards

| Euronorm              |                | ISO          |           |
|-----------------------|----------------|--------------|-----------|
|                       |                | ISO 1456     |           |
| Material number (DIN) |                | DIN          |           |
| 2.4068                |                | DIN 17740    | DIN 17741 |
| United Kingdom        |                | Russia       |           |
| NA12                  | BS 3076 (1989) |              |           |
| USA                   |                | UNS standard |           |
| ASME                  | ASTM           |              |           |
| ASME 5553 F           | ASTM B 160-05  | N02201       |           |
|                       | ASTM B 163-04  |              |           |
|                       | ASTM B 924-06  |              |           |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                  | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]              |                 | 103.9          | 440.0            | 534.1           |                 |
| A                                |                 | 1429.814       | 813.011          | 813.126         |                 |
| Effect of temperature $K_\theta$ |                 |                |                  |                 |                 |
| $m_1$                            |                 | -0.00180       | -0.00107         | -0.00119        |                 |
| Effect of strain $K_\varphi$     |                 |                |                  |                 |                 |
| $m_2$                            |                 | 0.40416        | 0.26840          | 0.20640         |                 |
| $m_4$                            |                 | 0.00326        | 0.00280          | 0.00808         |                 |
| $m_5$                            |                 | -0.00083       |                  |                 |                 |
| $m_7$                            |                 | -0.08280       |                  |                 |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | -0.00111         | -0.00089        |                 |
| $m_8$                                  |                 | 0.000071       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                       |                 | 400...1100     | 20...300         | 20...300        |                 |
| $\varphi$                              |                 | 0.03...1.50    | 0.03...1.50      | 0.03...1.50     |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.1...100      | 0.01...100       | 0.01...100      |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

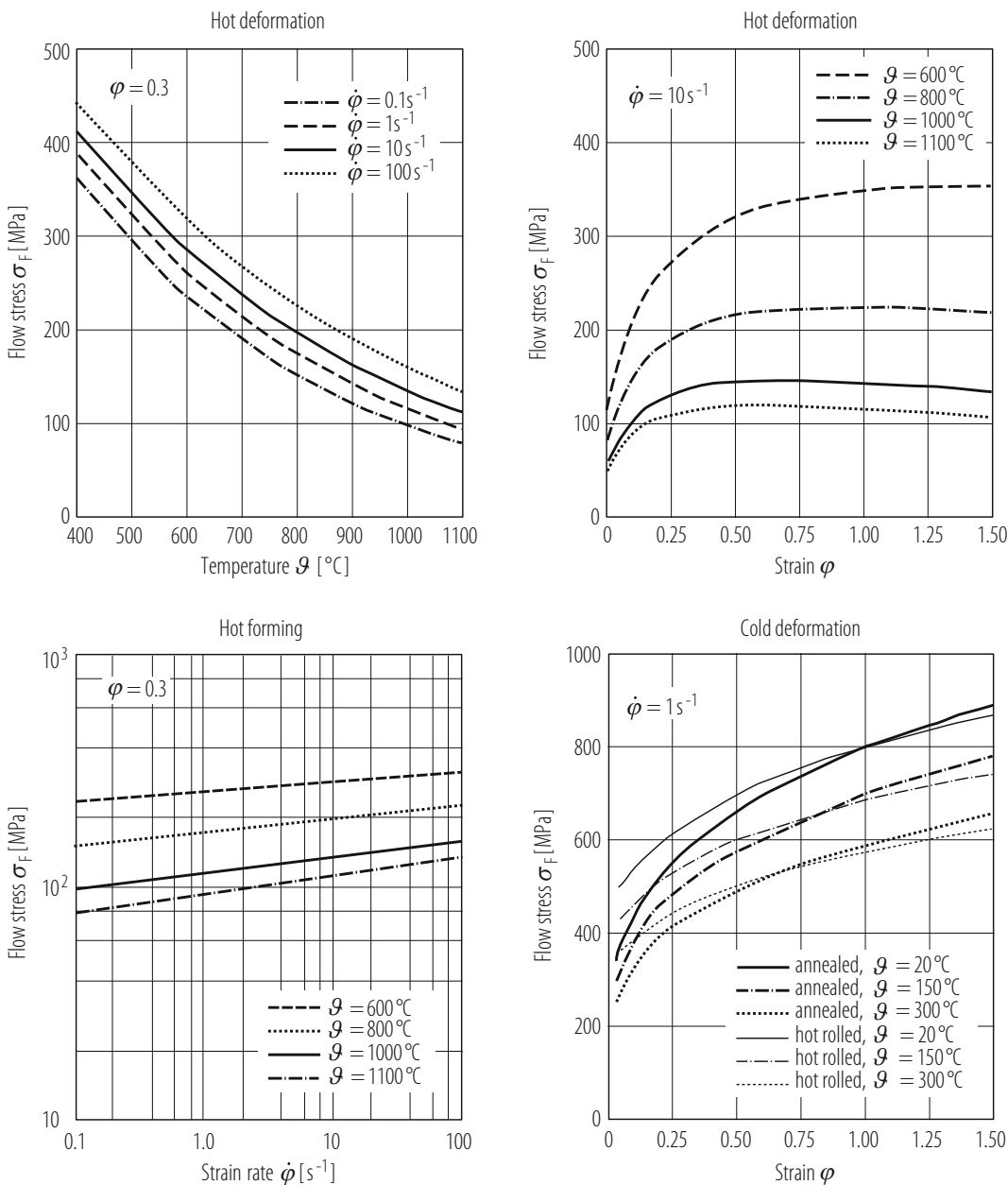


Fig. 5.105 Flow stress curves of LC-Ni99 by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |         |        | Tensile strength $\Delta R_m$ [MPa] |         |        |
|-------------------|---------------------------------|---------|--------|-------------------------------------|---------|--------|
|                   | $A_0$                           | $A$     | $n_1$  | $B_0$                               | $B$     | $n_2$  |
| soft annealed     | 75...100                        | 60.7283 | 0.5666 | 340...400                           | 32.5967 | 0.5662 |
| hot rolled        | 80...110                        | 95.2019 | 0.4770 | 380...420                           | 2.0977  | 1.2875 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |         |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|---------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$   | $n_4$   |                            |
| soft annealed     | 40. . .45                               | 74.8054 | -0.1334 | -6.9024 | <80                        |
| hot rolled        | 40. . .45                               | 40.8081 | 0.0564  | -9.4571 | <80                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in torsion and tensile test

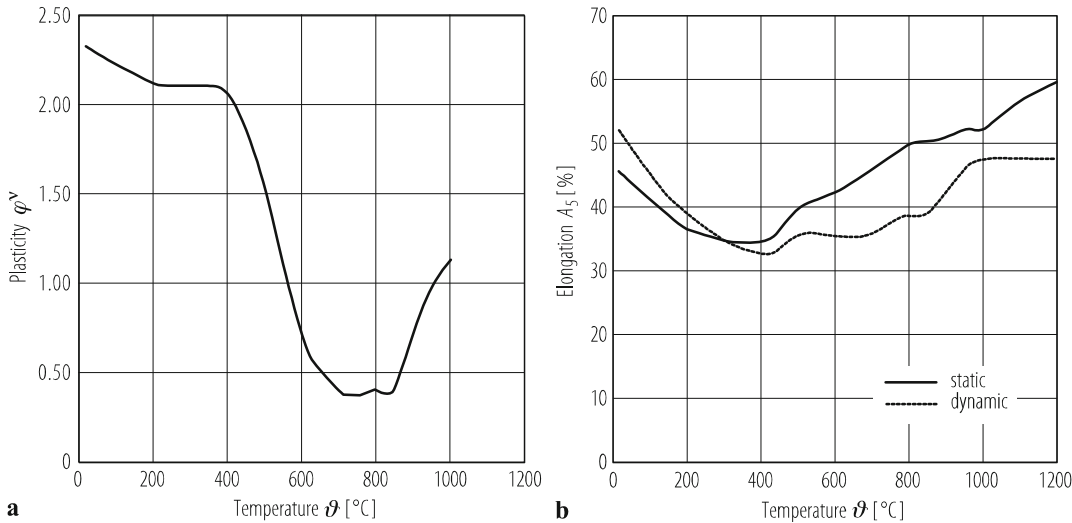


Fig. 5.106 Plasticity of LC-Ni99 as a function of the temperature. (a) Torsion test (b) Tensile test

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 63.9                 | 427.8              | 13.40                                   | 8905.7                      | 213             |
| 100              | 61.5                 | 448.9              | 13.60                                   | 8888.2                      | 207             |
| 200              | 58.4                 | 470.0              | 14.00                                   | 8865.1                      | 200             |
| 300              | 55.3                 | 491.1              | 14.60                                   | 8839.8                      | 193             |
| 400              | 51.7                 | 512.2              | 14.98                                   | 8813.9                      | 185             |
| 500              | 54.3                 | 514.7              | 15.20                                   | 8788.1                      | 178             |
| 600              | 56.6                 | 517.5              | 15.56                                   | 8760.3                      | 171             |
| 700              | 58.9                 | 520.3              | 15.80                                   | 8732.6                      | 163             |

(continued)



| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 800              | 61.3                 | 523.0              | 16.13                                   | 8703.0                      | 156             |
| 900              | 63.6                 | 525.8              | 16.58                                   | 8670.7                      | 149             |
| 1000             | 65.9                 | 528.5              | 16.94                                   | 8638.3                      | 141             |
| 1100             | 68.3                 | 531.3              | 17.30                                   | 8604.8                      | 134             |
| 1200             | 70.6                 | 534.0              | 17.66                                   | 8570.2                      | 127             |

Temperature dependence of mean specific heat of 2.4060 Ni<sub>99.6</sub> was used

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of NiMn<sub>4</sub>Si

## 5.3 Nickel – and Nickel alloys

### 5.3.1 Pure Nickel and Nickel alloys with < 10% alloy content

#### Designation

|             |         |               |                      |            |
|-------------|---------|---------------|----------------------|------------|
| UNS number: | N 02211 | Chem. symbol: | NiMn <sub>4</sub> Si | EN number: |
|-------------|---------|---------------|----------------------|------------|

#### Composition (DIN) [Weight-%]

| C     | Si    | Mn          | P | S | Cu    | Mo | Ni    | V | Nb | Ti | Fe    |
|-------|-------|-------------|---|---|-------|----|-------|---|----|----|-------|
| <0.10 | <2.00 | 3.00...5.00 |   |   | <0.50 |    | >94.0 |   |    |    | <1.00 |

#### International comparison of standards

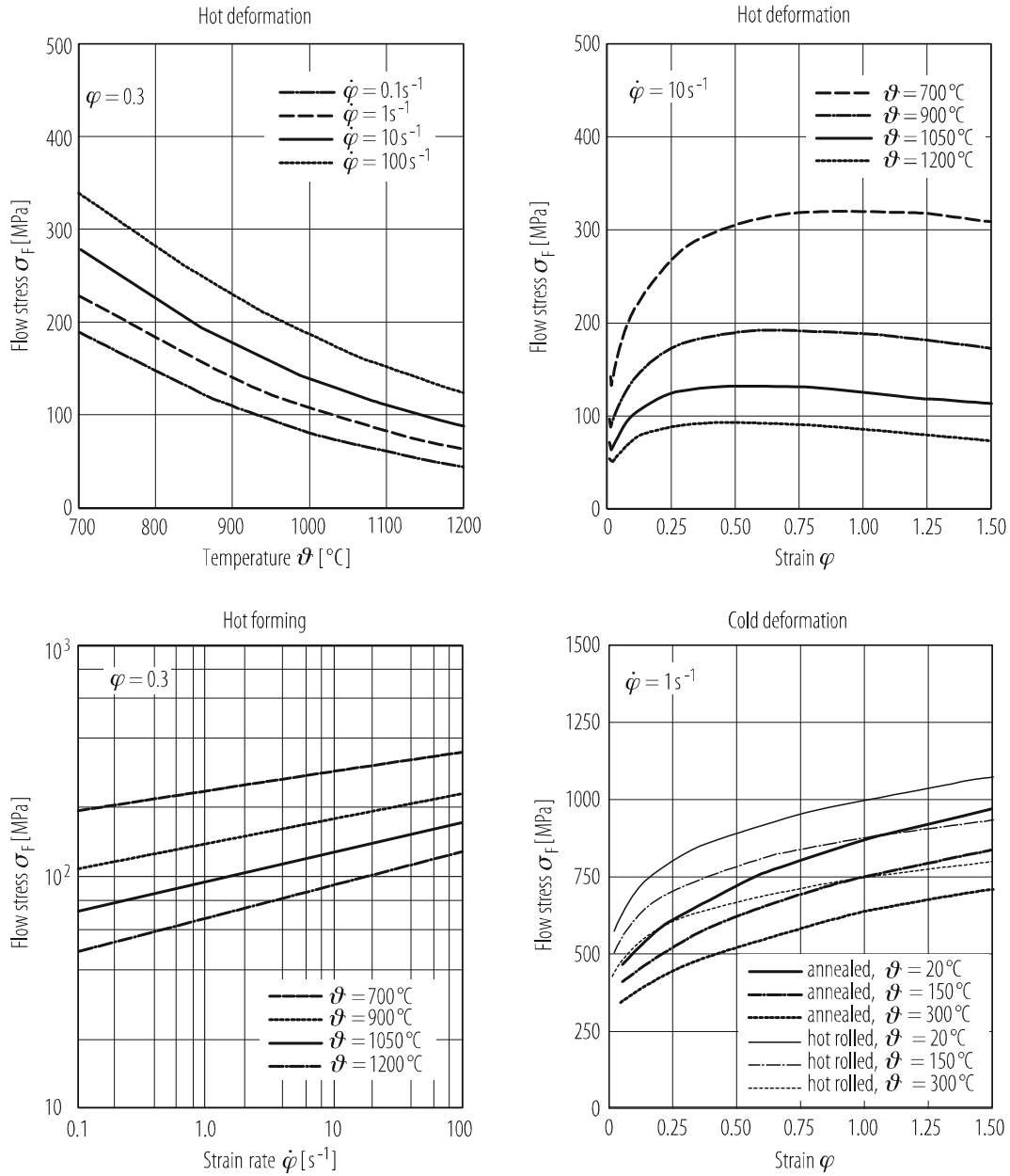
|                       |                |              |
|-----------------------|----------------|--------------|
| Euronorm              | ISO            |              |
| Material number (DIN) | DIN            |              |
| 2.4116                | DIN 17740      |              |
| Japan                 | Russia         |              |
| USA                   |                |              |
| ASME                  | ASTM           | UNS standard |
|                       | ASTM F290 - 94 | N 02211      |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                   | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                     | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                 |                 | 110.5          | 519.2            | 717.6           |                 |
| A                                   |                 | 2291.93        | 877.185          | 1020.304        |                 |
| Effect of temperature $K_\theta$    |                 |                |                  |                 |                 |
| $m_1$                               |                 | -0.00229       | -0.00112         | -0.00104        |                 |
| Effect of strain $K_\phi$           |                 |                |                  |                 |                 |
| $m_2$                               |                 | 0.41843        | 0.28100          | 0.16212         |                 |
| $m_4$                               |                 | 0.00475        | 0.01164          | 0.00142         |                 |
| $m_5$                               |                 | -0.00094       |                  |                 |                 |
| $m_7$                               |                 | -0.11016       |                  |                 |                 |
| Effect of strain rate $K\dot{\phi}$ |                 |                |                  |                 |                 |
| $m_3$                               |                 |                | 0.01242          | 0.01211         |                 |
| $m_8$                               |                 | 0.000119       |                  |                 |                 |
| Range of validity                   |                 |                |                  |                 |                 |
| $\theta$ [°C]                       |                 | 700...1200     | 20...300         | 20...300        |                 |
| $\phi$                              |                 | 0.03...1.50    | 0.03...1.50      | 0.03...1.50     |                 |
| $\dot{\phi}$ [1/s]                  |                 | 0.1...100      | 0.01...100       | 0.01...100      |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.107** Flow stress curves of NiMn<sub>4</sub>Si by hot and cold forming.

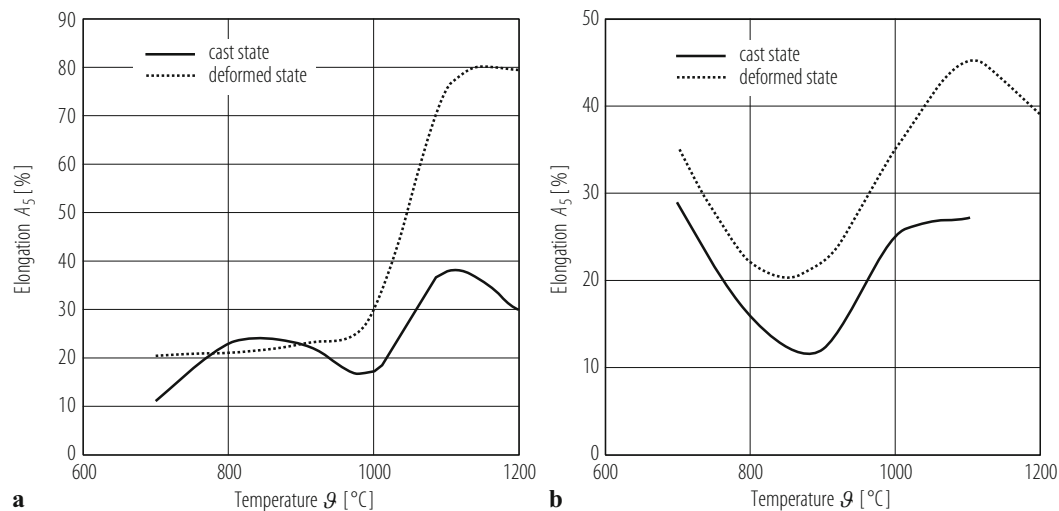
### Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |     |       | Vickers hardness $\Delta H_V$ [MPa] |         |        |
|-------------------|---------------------------------|-----|-------|-------------------------------------|---------|--------|
|                   | $A_0$                           | $A$ | $n_1$ | $B_0$                               | $B$     | $n_2$  |
| soft annealed     |                                 |     |       | 110...130                           | 17.5310 | 0.5341 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |         |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|---------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$   | $n_4$   |                            |
| soft annealed     | 27...33                                 | 46.8340 | −0.1178 | −4.2422 | <80                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

### Plasticity in tensile test



**Fig. 5.108** Hot plasticity of NiMn4Si as a function of the temperature. (a) Initial test: static, (b) Initial test: dynamic.

### Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               |                      |                    |                                         | 8750                        |                 |
| 100              |                      | 544                | 12.9                                    |                             |                 |
| 200              |                      |                    |                                         |                             |                 |
| 300              | 37.6                 |                    |                                         |                             |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\Delta H_v$        | vickers hardness                                                      |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress and mechanical properties of NiCr<sub>5</sub>MnSi

## 5.3 Nickel – and Nickel alloys

### 5.3.1 Pure Nickel and Nickel alloys with < 10% alloy content

#### Designation

|             |  |               |                        |            |
|-------------|--|---------------|------------------------|------------|
| UNS number: |  | Chem. symbol: | NiCr <sub>5</sub> MnSi | EN number: |
|-------------|--|---------------|------------------------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn          | P | S | Cr    | Cu    | Ni    | V | Nb | Ti | Fe    |
|-------|-------|-------------|---|---|-------|-------|-------|---|----|----|-------|
| <0.10 | <2.00 | 2.00...4.00 |   |   | <5.00 | <0.50 | >90.0 |   |    |    | <1.00 |

#### International comparison of standards

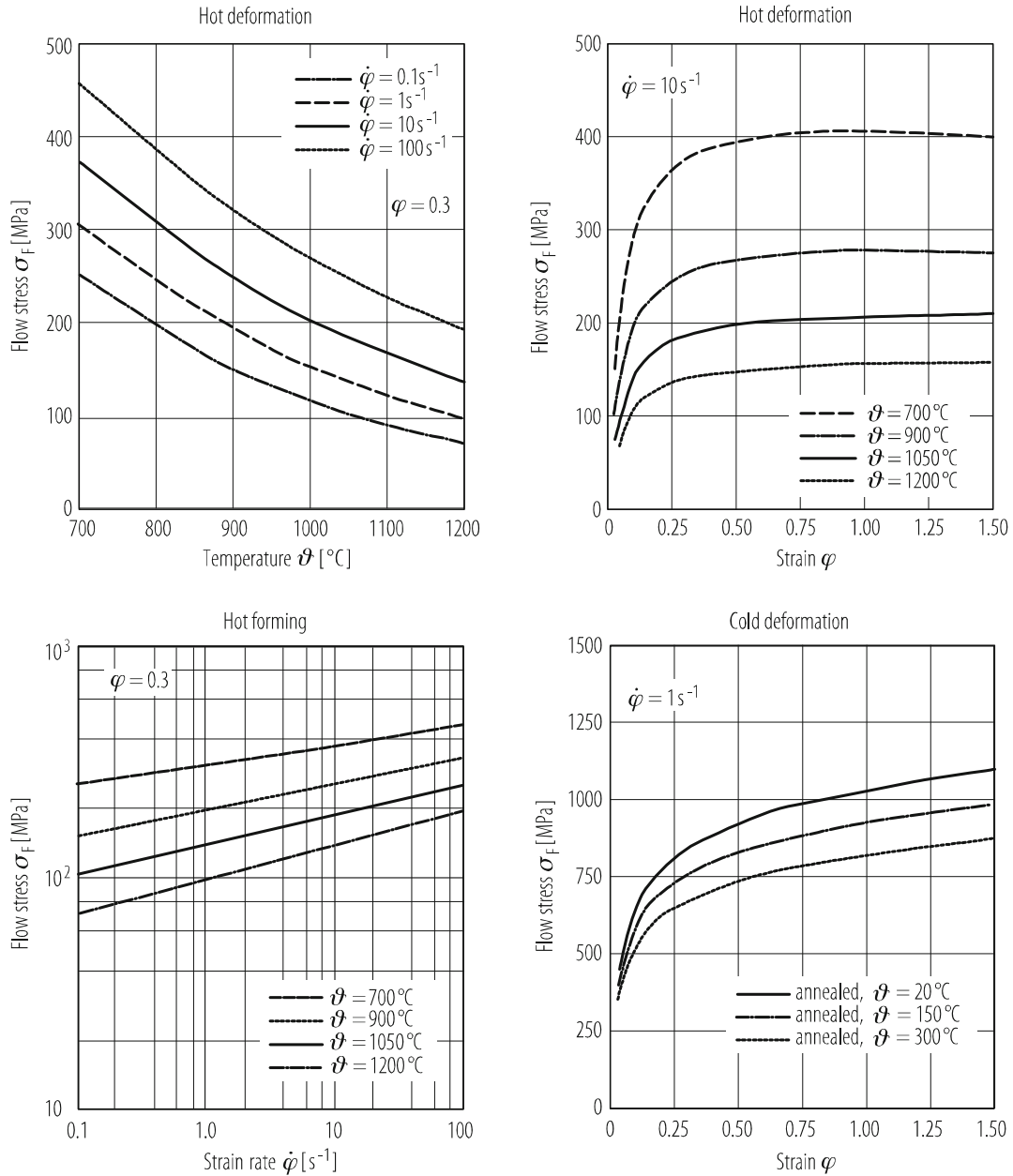
|                       |             |           |              |
|-----------------------|-------------|-----------|--------------|
| Euronorm              |             | ISO       |              |
| EN ISO 1456           | EN ISO 1456 | ISO 1456  | ISO 1456     |
| Material number (DIN) |             | DIN       |              |
| 2.4151                |             | DIN 17742 |              |
| Japan                 |             | Russia    |              |
| USA                   |             |           |              |
| ASME                  | ASTM        |           | UNS standard |
|                       | ASTM B76    | ASTM B512 |              |
|                       | ASTM B344   |           |              |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                    | Hot deformation |                | Cold deformation |                 |                 |
|--------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                      | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                  |                 | 150.1          | 547.5            |                 |                 |
| A                                    |                 | 1812.842       | 1066.136         |                 |                 |
| Effect of temperature $K_\theta$     |                 |                |                  |                 |                 |
| $m_1$                                |                 | −0.00232       | −0.00083         |                 |                 |
| Effect of strain $K_\phi$            |                 |                |                  |                 |                 |
| $m_2$                                |                 | 0.01028        | 0.13534          |                 |                 |
| $m_4$                                |                 | −0.04125       | −0.01662         |                 |                 |
| $m_5$                                |                 | 0.00017        |                  |                 |                 |
| $m_7$                                |                 | −0.11706       |                  |                 |                 |
| Effect of strain rate $K_\dot{\phi}$ |                 |                |                  |                 |                 |
| $m_3$                                |                 |                | 0.00986          |                 |                 |
| $m_8$                                |                 | 0.000123       |                  |                 |                 |
| Range of validity                    |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                     |                 | 700...1200     | 20...300         |                 |                 |
| $\phi$                               |                 | 0.03 ... 1.50  | 0.03 ... 1.50    |                 |                 |
| $\dot{\phi}$ [1/s]                   |                 | 0.1...100      | 0.01...100       |                 |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.109** Flow stress curves of NiCr<sub>5</sub>MnSi by hot and cold forming.

**Mechanical properties after cold deformation**

| State of material | Yield stress $\Delta R_p$ [MPa] |         |        | Validity $\varepsilon$ [%] |
|-------------------|---------------------------------|---------|--------|----------------------------|
|                   | $A_0$                           | $A$     | $n_I$  |                            |
| hot rolled        | 300...350                       | 81.4549 | 0.5388 | 85                         |

Yield stress:

$$R_p = A_0 + A \cdot \varepsilon^{n_I}$$

[Equation (2.10), Chapter 2.3.2.1.1]

[Equation (4.1), Chapter 5.1.4] [DOI: [978-3-642-14174-4\\_5](https://doi.org/10.1007/978-3-642-14174-4_5)]**Symbols and abbreviations**

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| BS                  | British standards                                                     |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |



# Flow stress, mechanical and physical properties of NiCu<sub>30</sub>Fe

## 5.3 Nickel – and Nickel alloys

### 5.3.2 Nickel – Copper – alloys

#### Designation

|             |               |               |                 |            |
|-------------|---------------|---------------|-----------------|------------|
| UNS number: | <b>N04400</b> | Chem. symbol: | <b>NiCu30Fe</b> | EN number: |
|-------------|---------------|---------------|-----------------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn    | P | S      | Cu          | Mo | Ni    | V | Al    | Ti    | Fe          |
|-------|-------|-------|---|--------|-------------|----|-------|---|-------|-------|-------------|
| <0.15 | <0.50 | <2.00 |   | <0.020 | 28.0...34.0 |    | >63.0 |   | <0.50 | >0.30 | 1.00...2.50 |

#### International comparison of standards

|                       |             |              |            |                |                   |
|-----------------------|-------------|--------------|------------|----------------|-------------------|
| Euronorm              |             |              |            | ISO            |                   |
| EN ISO 1456           |             |              |            | ISO 1456       |                   |
| Material number (DIN) |             |              |            | DIN            |                   |
| 2.4360                |             |              |            | DIN 17743      | DIN 17750 – 17754 |
| Japan                 |             |              |            | United Kingdom |                   |
| H 4553                |             |              |            | NA 13          | BS 3074 (1989)    |
| USA                   |             |              |            |                |                   |
| ASME                  |             | ASTM         |            |                | UNS standard      |
| ASME SB-127           | AMSE SB-163 | ASTM B 127   | ASTM B 163 | N04400         |                   |
| ASME SB-165           | ASME SB-366 | ASTM B164-03 | ASTM B 165 |                |                   |
| ASME SB-564           | ASME SB-725 | ASTM B 564   | ASTM B 366 |                |                   |
| ASME SB-730           | ASME SB-751 | ASTM B 725   | ASTM B 730 |                |                   |
| ASME SB-775           | ASME SB-829 | ASTM B 751   | ASTM B 775 |                |                   |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

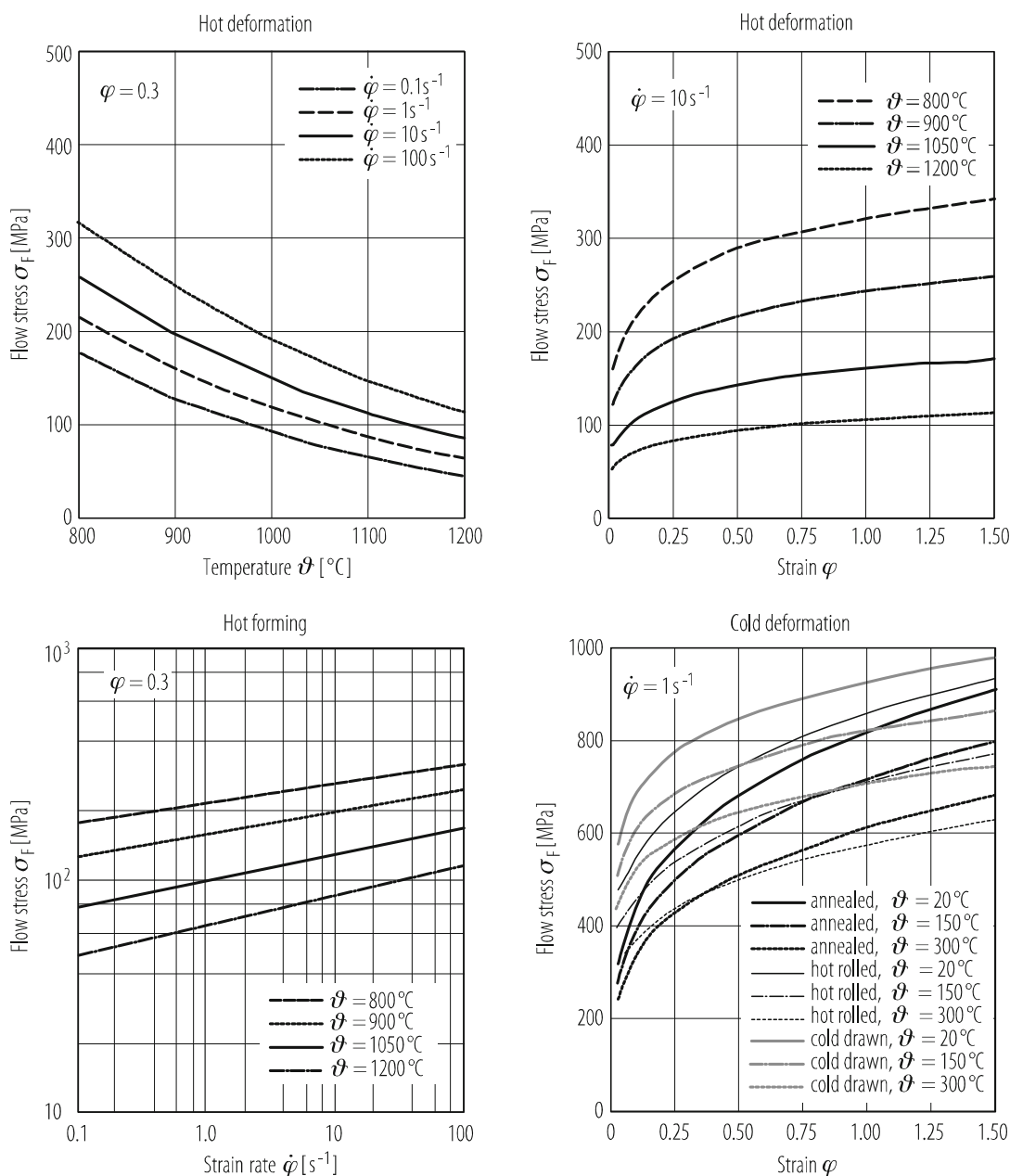
#### Flow curves

| State of material           | Hot deformation |                | Cold deformation |                 |                 |
|-----------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                             | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]         |                 | 120.5          | 455.5            | 560.6           | 698.1           |
| A                           |                 | 3226.844       | 835.882          | 870.184         | 944.67          |
| Effect of temperature $K_9$ |                 |                |                  |                 |                 |
| $m_1$                       |                 | −0.00307       | −0.00104         | −0.00106        | −0.00098        |
| Effect of strain $K_\phi$   |                 |                |                  |                 |                 |
| $m_2$                       |                 | 0.20785        | 0.25978          | 0.21292         | 0.12989         |
| $m_4$                       |                 | 0.0019         | −0.00140         | 0.00499         | −0.00070        |
| $m_5$                       |                 | 0.00006        |                  |                 |                 |
| $m_7$                       |                 | −0.08259       |                  |                 |                 |

(continued)

|                                        |                 |                |                  |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.01121          | 0.00947         | 0.01006         |
| $m_8$                                  |                 | 0.000106       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                       |                 | 800...1200     | 20...300         | 20...300        | 20...300        |
| $\varphi$                              |                 | 0.03...1.50    | 0.03...1.50      | 0.03...1.50     | 0.03...1.50     |
| $\dot{\varphi}$ [1/s]                  |                 | 0.1...100      | 0.1...100        | 0.1...100       | 0.1...100       |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |



**Fig. 5.110** Flow stress curves of NiCu<sub>30</sub>Fe by hot and cold forming.

### Mechanical properties after cold deformation

| State of material            | Yield stress $\Delta R_p$ [MPa] |          |        | Tensile strength $\Delta R_m$ [MPa] |         |        |
|------------------------------|---------------------------------|----------|--------|-------------------------------------|---------|--------|
|                              | $A_0$                           | $A$      | $n_1$  | $B_0$                               | $B$     | $n_2$  |
| hot rolled                   | 300..350                        | 25.4389  | 0.7536 | 475. . . 525                        | 11.7493 | 0.8536 |
| soft annealed                | 175..200                        | 111.8345 | 0.4075 | 450. . . 500                        | 23.544  | 0.6372 |
| Vickers hardness $\Delta Hv$ |                                 |          |        |                                     |         |        |
|                              |                                 |          |        | $B_0$                               | $B$     | $n_2$  |
| soft annealed                |                                 |          |        | 110. . . 130                        | 8.9171  | 0.7212 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |        |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|--------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$  | $n_4$   |                            |
| hot rolled        | 28. . . 34                              | 17.9595 | 0.1121 | -2.4189 | <70                        |
| soft annealed     | 30. . . 35                              | 22.4027 | 0.1111 | -6.6422 | <80                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in torsion test

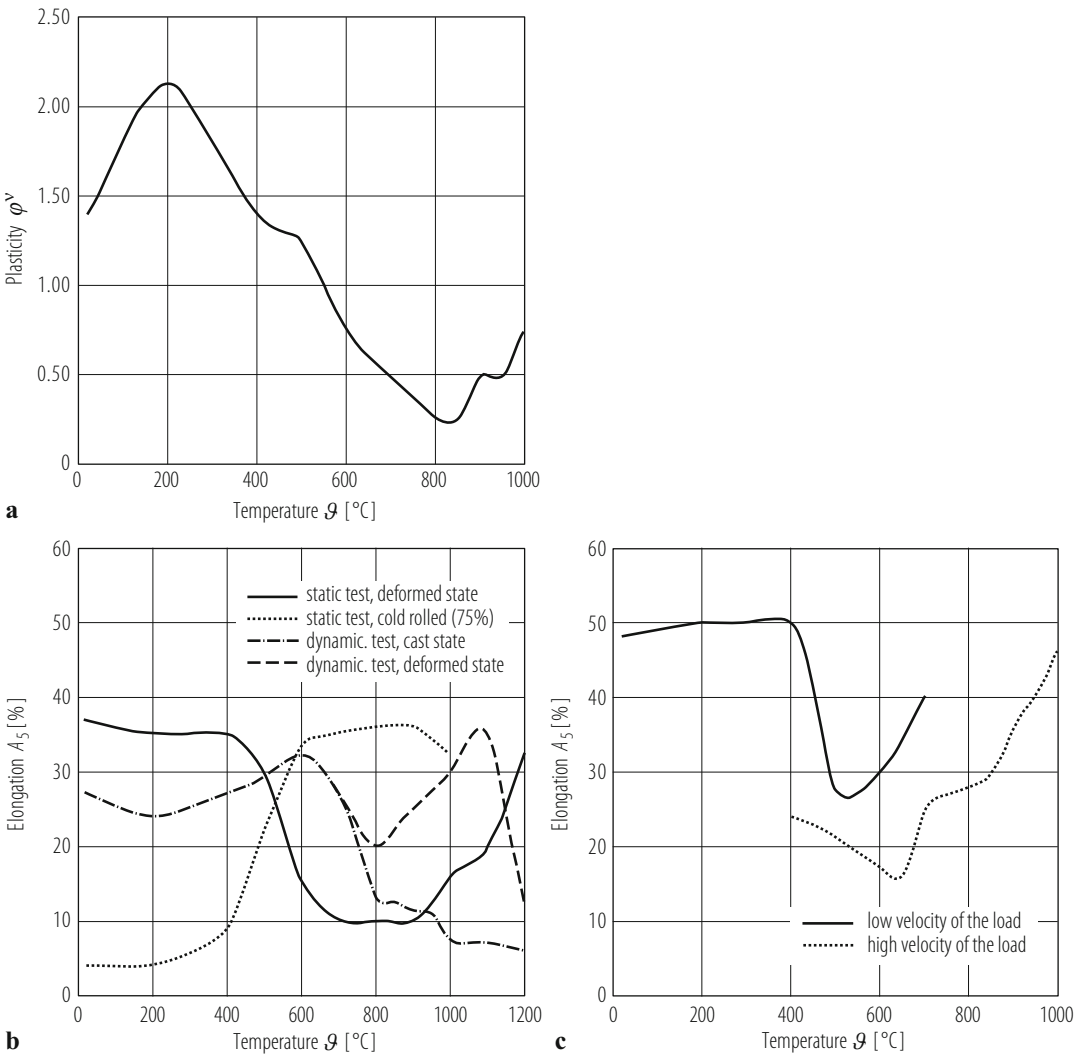


Fig. 5.111 Plasticity of NiCu30Fe as a function of the temperature. (a) Torsion test (b) and (c) Tensile test

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 25.8                 | 427.4              | 14,76                                   | 8850.8                      | 184             |
| 100              | 27.2                 | 463.9              | 15,07                                   | 8832.4                      | 174             |
| 200              | 29.0                 | 479.0              | 15,46                                   | 8806.5                      | 162             |
| 300              | 30.8                 | 487.8              | 15,85                                   | 8777.1                      | 150             |
| 400              | 32.6                 | 493.3              | 16,24                                   | 8744.4                      | 137             |
| 500              | 34.4                 | 497.8              | 16,63                                   | 8708.4                      | 121             |
| 600              | 36.2                 | 500.9              | 17,02                                   | 8668.9                      | 104             |
| 700              | 38.0                 | 503.3              | 14,41                                   | 8626.1                      | 87              |
| 800              | 39.7                 | 505.2              | 17,80                                   | 8579.9                      | 70              |
| 900              | 41.5                 | 506.8              |                                         | 8530.3                      | 53              |
| 1000             | 43.3                 | 508.2              |                                         | 8477.4                      | 36              |
| 1100             | 45.1                 | 509.4              |                                         | 8421.1                      |                 |
| 1200             | 46.9                 | 510.5              |                                         | 8361.4                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| BS                  | British standards                                                     |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\Delta Hv$         | vickers hardness                                                      |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, Plasticity and physical properties of NiCu<sub>30</sub>Al

## 5.3 Nickel – and Nickel alloys

### 5.3.2 Nickel – Copper – alloys

#### Designation

|             |               |               |                 |            |
|-------------|---------------|---------------|-----------------|------------|
| UNS number: | <b>N05500</b> | Chem. symbol: | <b>NiCu30Al</b> | EN number: |
|-------------|---------------|---------------|-----------------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn    | P | S      | Cu          | Mo | Ni    | V | Al          | Ti          | Fe          |
|-------|-------|-------|---|--------|-------------|----|-------|---|-------------|-------------|-------------|
| <0.20 | <0.50 | <1.50 |   | <0.015 | 27.0...34.0 |    | >63.0 |   | 2.20...3.50 | 0.30...1.00 | 0.50...2.50 |

#### International comparison of standards

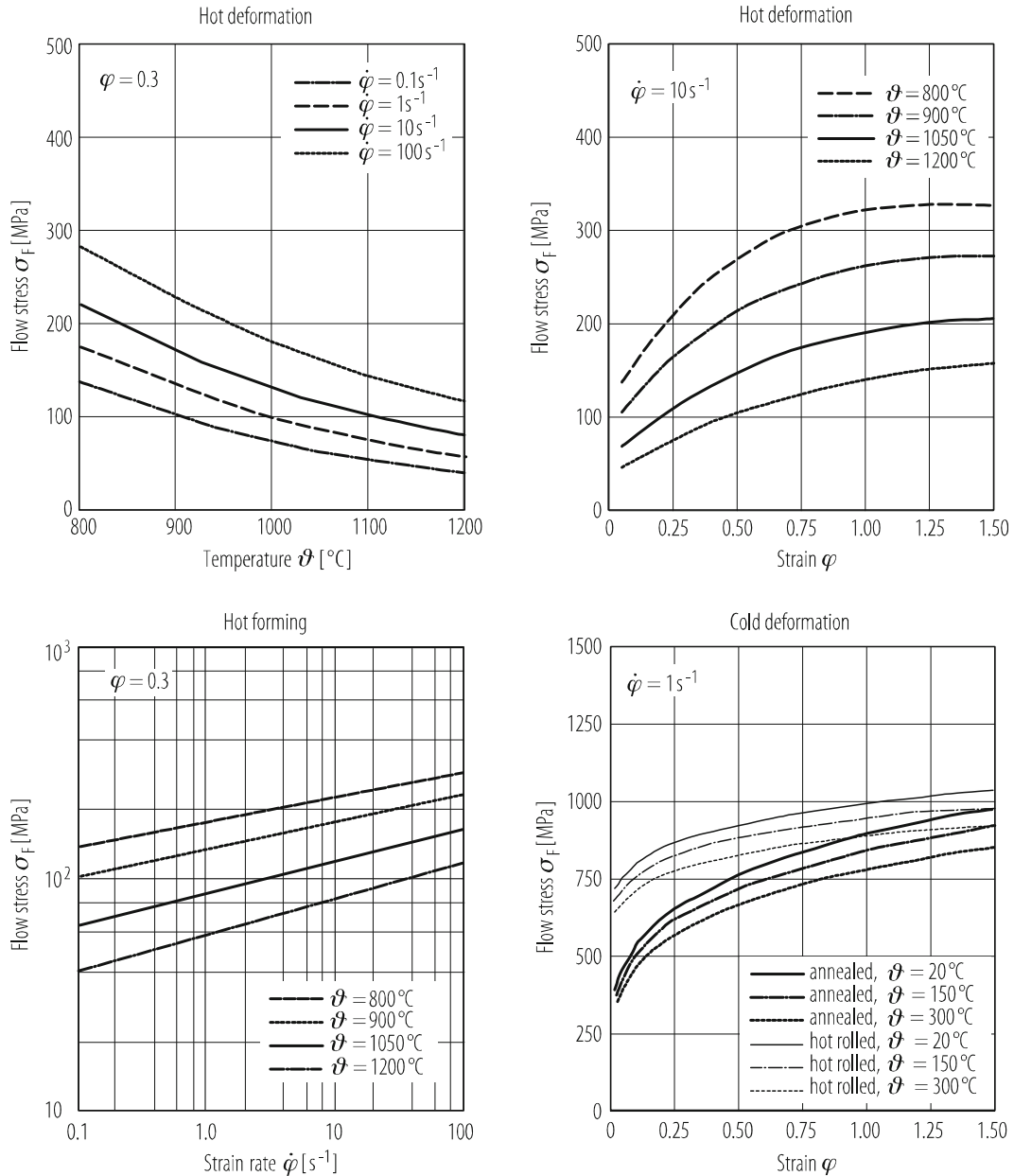
|                       |  |                       |           |              |                   |
|-----------------------|--|-----------------------|-----------|--------------|-------------------|
| Euronorm              |  |                       | ISO       |              |                   |
| EN ISO 1456           |  |                       | ISO 6208  |              | ISO 9723 - 9725   |
| Material number (DIN) |  |                       | DIN       |              |                   |
| 2.4375                |  |                       | DIN 17743 |              | DIN 17752 - 17754 |
| United Kingdom        |  |                       | Russia    |              |                   |
| NA 18                 |  | BS 3072 - 3076 (1989) |           |              |                   |
| ASME                  |  | ASTM                  |           | UNS standard |                   |
|                       |  | ASTM B 865            |           | N05500       |                   |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

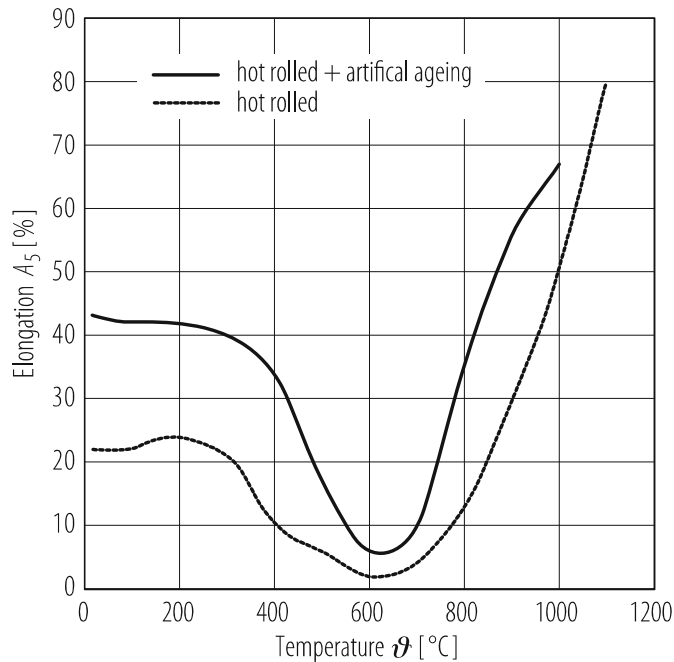
| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 | 90.1           | 547.5            | 819.3           |                 |
| A                                      |                 | 3369.863       | 899.441          | 999.591         |                 |
| Effect of temperature $K_\theta$       |                 |                |                  |                 |                 |
| $m_1$                                  |                 | −0.00310       | −0.00049         | −0.00041        |                 |
| Effect of strain $K_\varphi$           |                 |                |                  |                 |                 |
| $m_2$                                  |                 | 0.45561        | 0.22920          | 0.10120         |                 |
| $m_4$                                  |                 | 0.01960        | 0.00149          | 0.00147         |                 |
| $m_5$                                  |                 | 0.00104        |                  |                 |                 |
| $m_7$                                  |                 | −0.70709       |                  |                 |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.01139          | 0.01201         |                 |
| $m_8$                                  |                 | 0.000131       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                       |                 | 800...1200     | 20...300         | 20...300        |                 |
| $\varphi$                              |                 | 0.03...1.50    | 0.03...1.50      | 0.03...1.50     |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.1...100      | 0.1...100        | 0.1...100       |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                                                 |



**Fig. 5.112** Flow stress curves of NiCu<sub>30</sub>Al by hot and cold forming.

### Plasticity in tensile test



**Fig. 5.113** Plasticity of NiCu<sub>30</sub>Al as a function of the temperature.

### Physical properties

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [10 <sup>-6</sup> /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                              | 17.9                                      | 426.8                                   | 13.44                                                                          | 8460.9                                 | 182                          |
| 100                             | 20.0                                      | 470.1                                   | 14.04                                                                          | 8443.6                                 | 180                          |
| 200                             | 22.8                                      | 485.5                                   | 14.80                                                                          | 8419.9                                 | 179                          |
| 300                             | 25.5                                      | 493.6                                   | 15.55                                                                          | 8393.9                                 | 174                          |
| 400                             | 28.2                                      | 498.6                                   | 16.30                                                                          | 8365.7                                 | 170                          |
| 500                             | 30.9                                      | 502.8                                   | 17.05                                                                          | 8335.1                                 | 165                          |
| 600                             | 33.6                                      | 498.4                                   | 17.80                                                                          | 8302.2                                 | 161                          |
| 700                             | 36.3                                      | 495.5                                   | 18.56                                                                          | 8267.1                                 | 156                          |
| 800                             | 39.0                                      | 493.4                                   | 19.31                                                                          | 8229.6                                 | 151                          |
| 900                             | 41.8                                      | 491.9                                   | 20.06                                                                          | 8189.9                                 | 147                          |
| 1000                            | 44.5                                      | 490.8                                   | 20.81                                                                          | 8147.9                                 | 142                          |
| 1100                            | 47.2                                      |                                         | 21.56                                                                          | 8103.6                                 | 137                          |
| 1200                            | 49.9                                      |                                         | 22.32                                                                          | 8057.0                                 | 133                          |

### Symbols and abbreviations

| Short form      | Full form                                  |
|-----------------|--------------------------------------------|
| $\sigma_F$      | flow stress                                |
| $\varphi$       | strain                                     |
| $\dot{\varphi}$ | strain rate                                |
| ASME            | American society of mechanical engineers   |
| ASTM            | American society for testing and materials |
| BS              | British standards                          |

(continued)



| Short form     | Full form                                                             |
|----------------|-----------------------------------------------------------------------|
| $c_{pm}$       | mean specific heat                                                    |
| DIN            | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$            | Young's modulus                                                       |
| EN             | Euronorm                                                              |
| ISO            | international organisation for standardization                        |
| $T, \vartheta$ | temperature                                                           |
| UNS            | unified numbering system                                              |
| $\alpha_m$     | average coefficient of linear expansion                               |
| $\lambda$      | thermal conductivity                                                  |
| $\rho$         | density                                                               |

# Flow stress, Plasticity and physical properties of Ni<sub>36</sub>

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |               |               |             |            |
|-------------|---------------|---------------|-------------|------------|
| UNS number: | <b>K93600</b> | Chem. symbol: | <b>Ni36</b> | EN number: |
|-------------|---------------|---------------|-------------|------------|

#### Composition (DIN) [Weight-%]

| C     | Si    | Mn    | P | S | Cr | Mo | Ni          | V | Nb | Ti | Fe   |
|-------|-------|-------|---|---|----|----|-------------|---|----|----|------|
| <0.10 | <0.50 | <0.50 |   |   |    |    | 35.0...37.0 |   |    |    | Bal. |

#### International comparison of standards

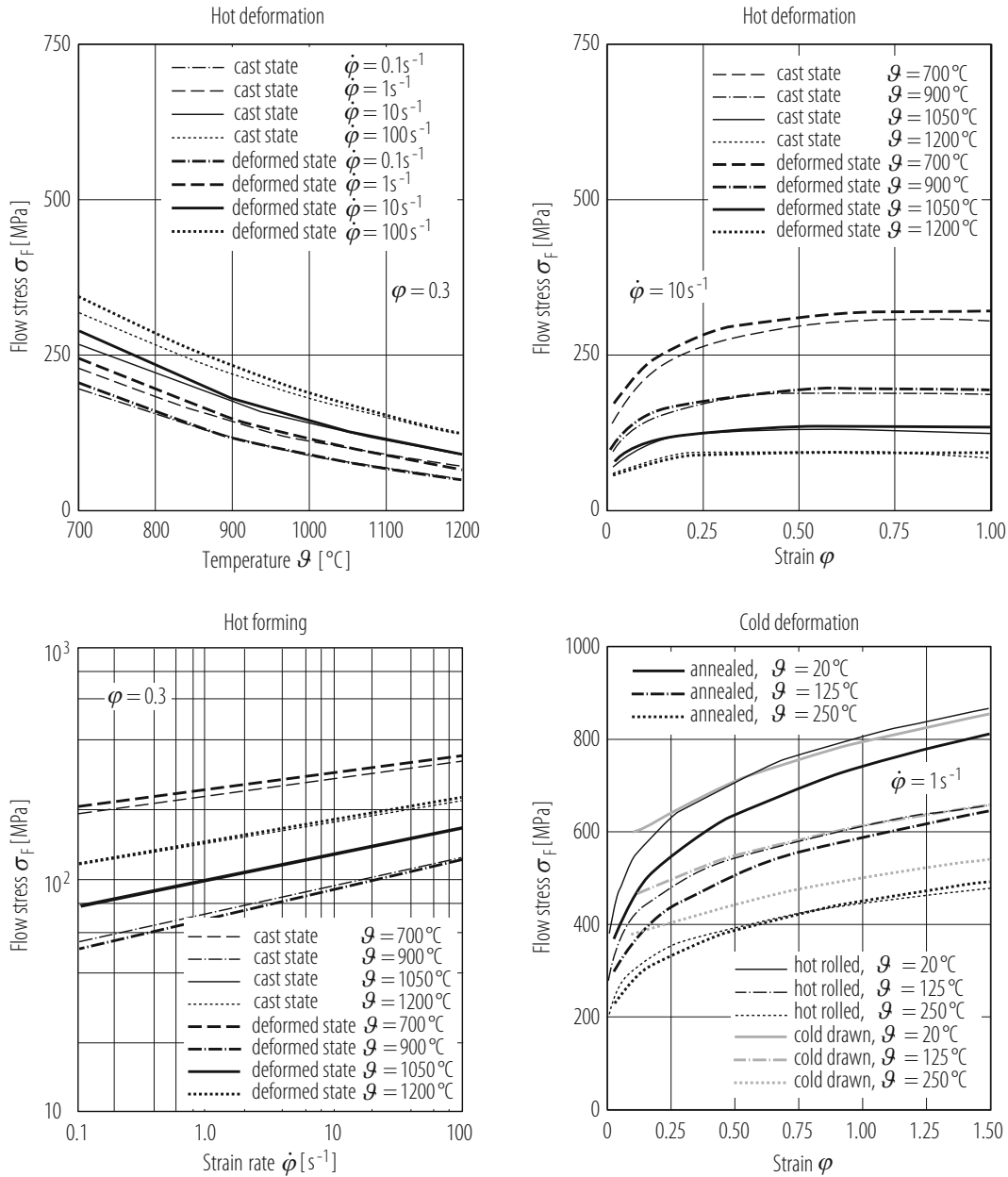
|                       |                 |                   |
|-----------------------|-----------------|-------------------|
| Euronorm              | ISO             |                   |
| Material number (DIN) | DIN             |                   |
| 1.3912                | DIN 385         | DIN 1715          |
| France                | United Kingdom  |                   |
| Fe-Ni 36              | A 54-301 (1973) | NILOMAG 36        |
| Japan                 | Russia          |                   |
|                       | 36N             | GOST 10994 (1974) |
| USA                   |                 |                   |
| ASME                  | ASTM            | UNS standard      |
|                       | ASTM F30-96     | K93600            |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    | 116.1           | 118.4          | 479.0            | 560.3           | 620.40          |
| A                                      | 1836.000        | 2221.260       | 772.449          | 836.992         | 812.174         |
| Effect of temperature $K_\theta$       |                 |                |                  |                 |                 |
| $m_1$                                  | -0.00212        | -0.00243       | -0.00217         | -0.00210        | -0.00199        |
| Effect of strain $K_\varphi$           |                 |                |                  |                 |                 |
| $m_2$                                  | 0.35556         | 0.31162        | 0.22262          | 0.17440         | 0.19372         |
| $m_4$                                  | 0.00355         | 0.00332        | 0.00357          | 0.00067         | 0.01824         |
| $m_5$                                  | -0.00095        | -0.00052       |                  |                 |                 |
| $m_7$                                  | -0.01622        | -0.16485       |                  |                 |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.01843          | 0.01543         | 0.01479         |
| $m_8$                                  | 0.000102        | 0.000108       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\theta$ [°C]                          | 700...1200      | 700...1200     | 20...300         | 20...300        | 20...300        |
| $\varphi$                              | 0.03...1.00     | 0.03...1.00    | 0.03...1.50      | 0.03...1.50     | 0.03...1.50     |
| $\dot{\varphi}$ [1/s]                  | 0.1...100       | 0.1...100      | 0.01...100       | 0.01...100      | 0.01...100      |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.114** Flow stress curves of Ni<sub>36</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |         |        | Tensile strength $\Delta R_m$ [MPa] |         |        |
|-------------------|---------------------------------|---------|--------|-------------------------------------|---------|--------|
|                   | $A_0$                           | $A$     | $n_1$  | $B_0$                               | $B$     | $n_2$  |
| soft annealed     | 280...330                       | 18.1460 | 0.7611 | 450...500                           | 10.7114 | 0.8047 |
|                   |                                 |         |        | Vickers hardness $\Delta Hv$        |         |        |
|                   |                                 |         |        | $B_0$                               | $B$     | $n_2$  |
| soft annealed     |                                 |         |        | 110...130                           | 8.9171  | 0.7212 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |         |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|---------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$   | $n_4$   |                            |
| soft annealed     | 32...38                                 | 43.1887 | −0.0476 | −8.1506 | <80                        |
| hot rolled        | 30...35                                 | 22.2618 | 0.0792  | −4.8304 | <60                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in torsion

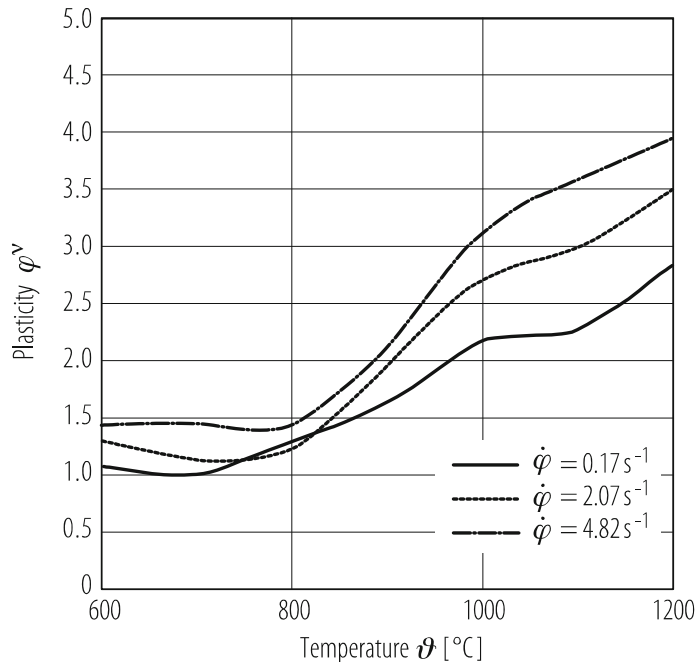


Fig. 5.115 Hot plasticity of Ni36 as a function of the temperature and deformation rate.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 13.0                 | 515                |                                         | 8200                        | 137             |
| 100              | 14.6                 |                    | 1.5                                     | 8197.8                      |                 |
| 200              | 16.4                 |                    | 2.6                                     | 8192.3                      |                 |
| 300              | 17.9                 |                    | 5.3                                     | 8176.5                      |                 |
| 400              | 19.1                 |                    | 8.1                                     | 8152.2                      |                 |
| 500              | 20.1                 |                    | 9.9                                     | 8126.9                      |                 |
| 600              | 20.9                 |                    | 11.1                                    | 8101.7                      |                 |
| 700              | 21.4                 |                    |                                         |                             |                 |
| 800              | 21.6                 |                    |                                         |                             |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\Delta Hv$         | vickers hardness                                                      |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of Ni<sub>42</sub>

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |               |               |             |            |
|-------------|---------------|---------------|-------------|------------|
| UNS number: | <b>K94100</b> | Chem. symbol: | <b>Ni42</b> | EN number: |
|-------------|---------------|---------------|-------------|------------|

#### Composition (DIN) [Weight-%]

| C     | Si    | Mn    | P | S | Cr | Mo | Ni          | V | Nb | Ti | Fe   |
|-------|-------|-------|---|---|----|----|-------------|---|----|----|------|
| <0.05 | <0.30 | <1.00 |   |   |    |    | 41.0...43.0 |   |    |    | Bal. |

#### International comparison of standards

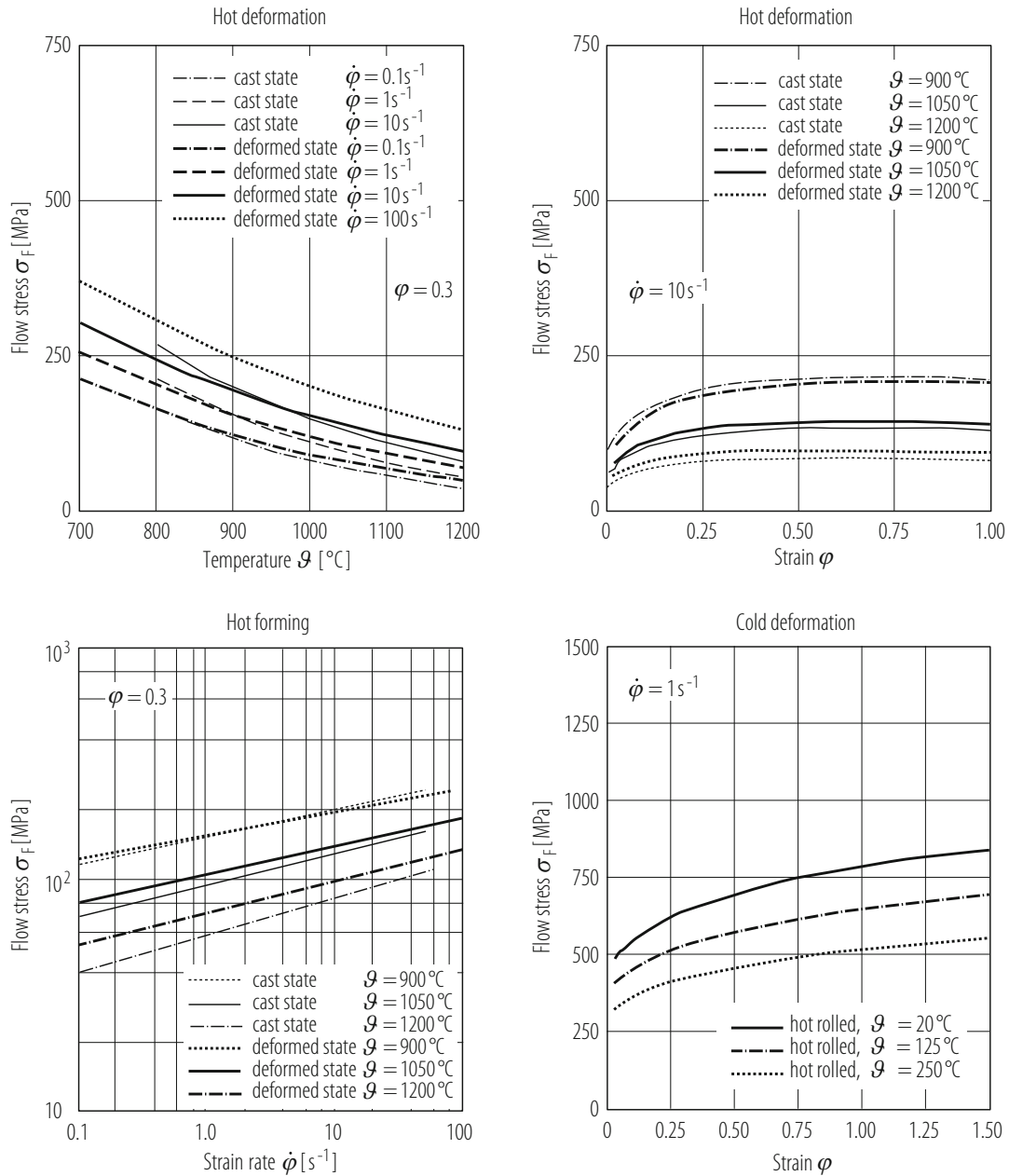
| Material number (DIN): |                 | ISO        |                   |
|------------------------|-----------------|------------|-------------------|
| 1.3917                 |                 |            |                   |
| France                 |                 | DIN        |                   |
| Fe-Ni 42               | A 54-301 (1973) | DIN 1715-1 | DIN 17746         |
|                        |                 | DIN 17745  |                   |
| Japan                  |                 | Russia     |                   |
|                        |                 | 42N        | GOST 10994 (1974) |
| USA                    |                 |            |                   |
| ASME                   | ASTM            |            | UNS standard      |
| ASME B753              | ASTM F29        | ASTM F30   | K94100            |
|                        | ASTM A658,      | ASTM B753  |                   |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    | 126.8           | 122.6          |                  | 565.6           |                 |
| A                                      | 4498.360        | 2462.877       |                  | 812.871         |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                  |                 |                 |
| $m_1$                                  | -0.00322        | -0.00235       |                  | -0.00184        |                 |
| Effect of strain $K_{\phi}$            |                 |                |                  |                 |                 |
| $m_2$                                  | 0.28813         | 0.37291        |                  | 0.17198         |                 |
| $m_4$                                  | 0.00160         | 0.00365        |                  | 0.00422         |                 |
| $m_5$                                  | -0.00024        | -0.00086       |                  |                 |                 |
| $m_7$                                  | -0.29216        | -0.06052       |                  |                 |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                |                  | 0.01212         |                 |
| $m_8$                                  | 0.000131        | 0.000113       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\theta$ [°C]                          | 800...1200      | 700...1200     |                  | 20...250        |                 |
| $\phi$                                 | 0.03...1.00     | 0.03...1.00    |                  | 0.03...1.50     |                 |
| $\dot{\phi}$ [1/s]                     | 0.2...50        | 0.1...100      |                  | 0.01...100      |                 |

| Hot deformation:                                                                                                                                                            | Cold deformation                                                                                              |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \dot{\varphi}^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \dot{\varphi}^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                        | [Equation (2.25), Chapter 2.3.2.2.2]                                                                          |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                  | [DOI: 978-3-642-14174-4_2]                                                                                    |



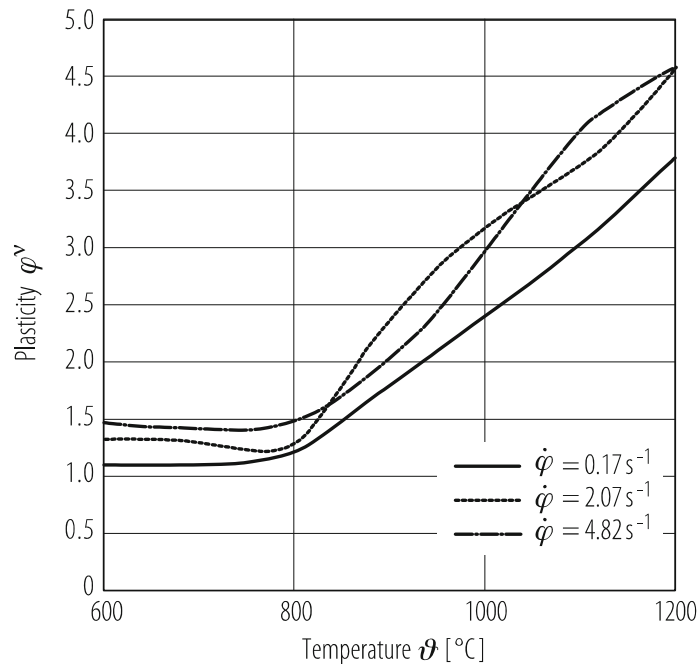
**Fig. 5.116** Flow stress curves of Ni<sub>42</sub> by hot and cold forming.

**Mechanical properties after cold deformation**

| State of material | Yield stress $\Delta R_p$ [MPa] |          |        | Vickers hardness $\Delta H_v$ |        |        |
|-------------------|---------------------------------|----------|--------|-------------------------------|--------|--------|
|                   | $A_0$                           | $A$      | $n_1$  | $B_0$                         | $B$    | $n_2$  |
| soft annealed     | 280...330                       | 129.2153 | 0.3183 | 120...140                     | 5.1154 | 0.7701 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |        |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|--------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$  | $n_4$   |                            |
| soft annealed     | 30...35                                 | 21.3775 | 0.0999 | -6.0690 | <65                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

**Plasticity in torsion****Fig. 5.117** Hot plasticity of Ni<sub>42</sub> as a function of the temperature and deformation rate.**Physical properties**

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 15.0                 |                    |                                         | 8200                        | 142             |
| 100              | 15.5                 |                    | 7.9                                     | 8180.6                      |                 |
| 200              | 16.1                 |                    | 7.7                                     | 8162.1                      |                 |
| 300              | 16.5                 |                    | 7.4                                     | 8145.4                      |                 |

(continued)



| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 400              | 16.9                 |                    | 7.3                                     | 8128.2                      |                 |
| 500              | 17.3                 |                    | 8.6                                     | 8094.2                      |                 |
| 600              | 17.6                 |                    | 9.7                                     | 8056.9                      |                 |
| 700              | 17.8                 |                    |                                         |                             |                 |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\Delta H_v$        | vickers hardness                                                      |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress and physical properties of Ni<sub>43</sub>

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |                |               |             |            |
|-------------|----------------|---------------|-------------|------------|
| UNS number: | <b>K 94101</b> | Chem. symbol: | <b>Ni43</b> | EN number: |
|-------------|----------------|---------------|-------------|------------|

#### Composition (DIN) [Weight-%]

| C     | Si    | Mn    | P | S | Cr    | Mo | Ni          | V | Nb | Ti | Fe   |
|-------|-------|-------|---|---|-------|----|-------------|---|----|----|------|
| <0.10 | <0.50 | <1.00 |   |   | <1.00 |    | 42.0...44.0 |   |    |    | Bal. |

#### International comparison of standards

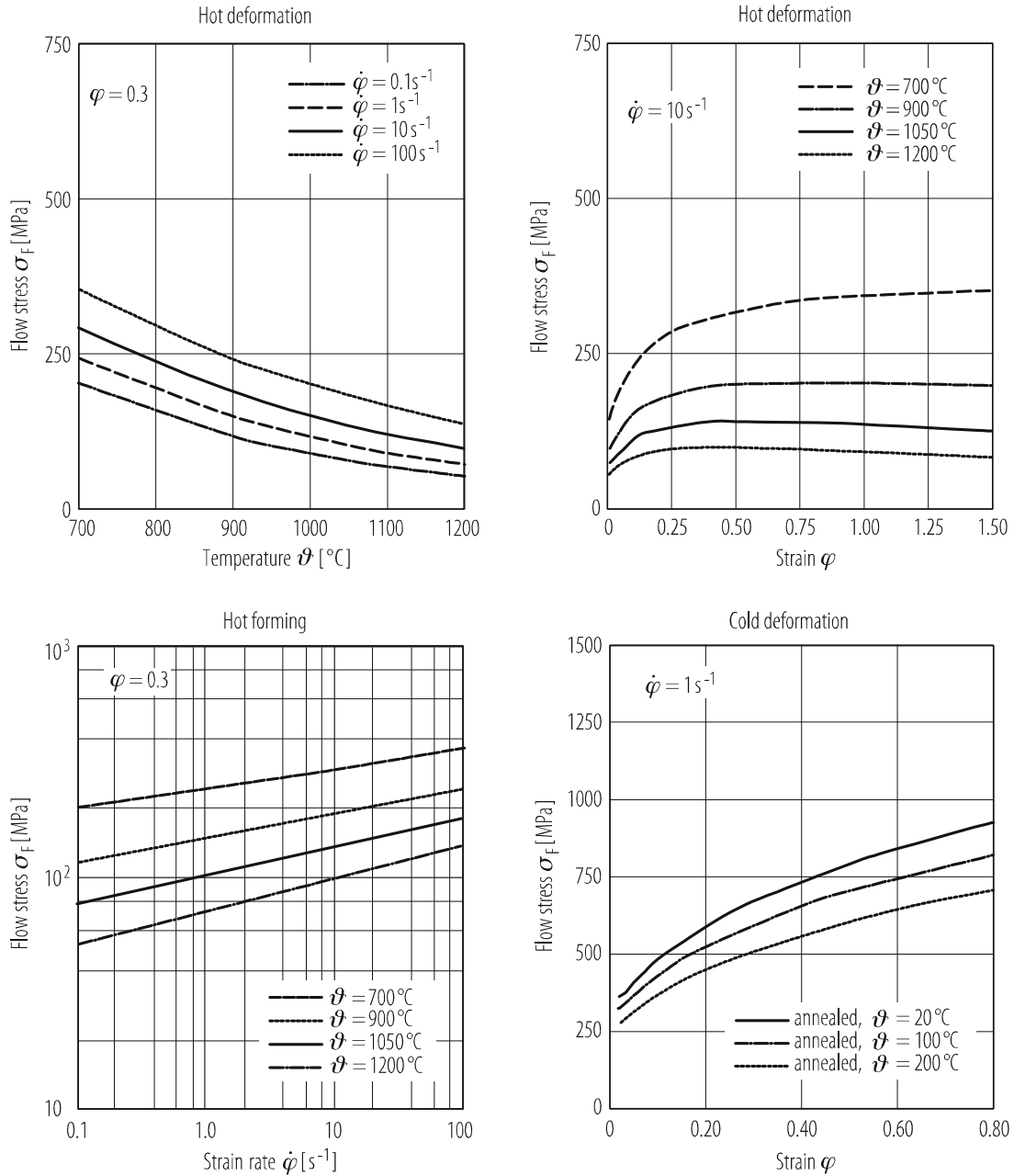
|                       |                |        |              |
|-----------------------|----------------|--------|--------------|
| SEW                   |                | ISO    |              |
| SEW 385               |                |        |              |
| Material number (DIN) |                | DIN    |              |
| 1.3918                |                |        |              |
| Japan                 |                | Russia |              |
| USA                   |                |        |              |
| ASME                  | ASTM           |        | UNS standard |
|                       | ASTM A753 - 08 |        | K 94101      |
|                       | ASTM A 334 04  |        |              |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 | 123.7          | 497.4            |                 |                 |
| A                                      |                 | 1987.418       | 1019.726         |                 |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                  |                 |                 |
| $m_1$                                  |                 | -0.00217       | -0.00150         |                 |                 |
| Effect of strain $K_{\phi}$            |                 |                |                  |                 |                 |
| $m_2$                                  |                 | 0.35486        | 0.33789          |                 |                 |
| $m_4$                                  |                 | 0.00311        | 0.00648          |                 |                 |
| $m_5$                                  |                 | -0.00107       |                  |                 |                 |
| $m_7$                                  |                 | 0.08521        |                  |                 |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.01104          |                 |                 |
| $m_8$                                  |                 | 0.000118       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\theta$ [°C]                          |                 | 700...1200     | 20...200         |                 |                 |
| $\phi$                                 |                 | 0.03...1.50    | 0.03...0.80      |                 |                 |
| $\dot{\phi}$ [1/s]                     |                 | 0.1...100      | 0.01...100       |                 |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.118** Flow stress curves of Ni<sub>43</sub> by hot and cold forming.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 15                   |                    |                                         | 8200                        | 147             |
| 100              |                      |                    | 6.3                                     | 8184.5                      |                 |
| 200              |                      |                    | 6.1                                     | 8170.7                      |                 |
| 300              |                      |                    | 6                                       | 8155.7                      |                 |
| 400              |                      |                    | 6.5                                     | 8136.0                      |                 |
| 500              |                      |                    | 8.1                                     | 8100.4                      |                 |
| 600              |                      |                    | 9.5                                     | 8069.8                      |                 |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, mechanical and physical properties of Ni<sub>46</sub>

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |               |               |             |            |
|-------------|---------------|---------------|-------------|------------|
| UNS number: | <b>K93603</b> | Chem. symbol: | <b>Ni46</b> | EN number: |
|-------------|---------------|---------------|-------------|------------|

#### Composition (DIN) [Weight-%]

| C     | Si    | Mn    | P | S | Cr | Mo | Ni          | V | Nb | Ti | Fe   |
|-------|-------|-------|---|---|----|----|-------------|---|----|----|------|
| <0.10 | <0.50 | <1.00 |   |   |    |    | 45.0...47.0 |   |    |    | Bal. |

#### International comparison of standards

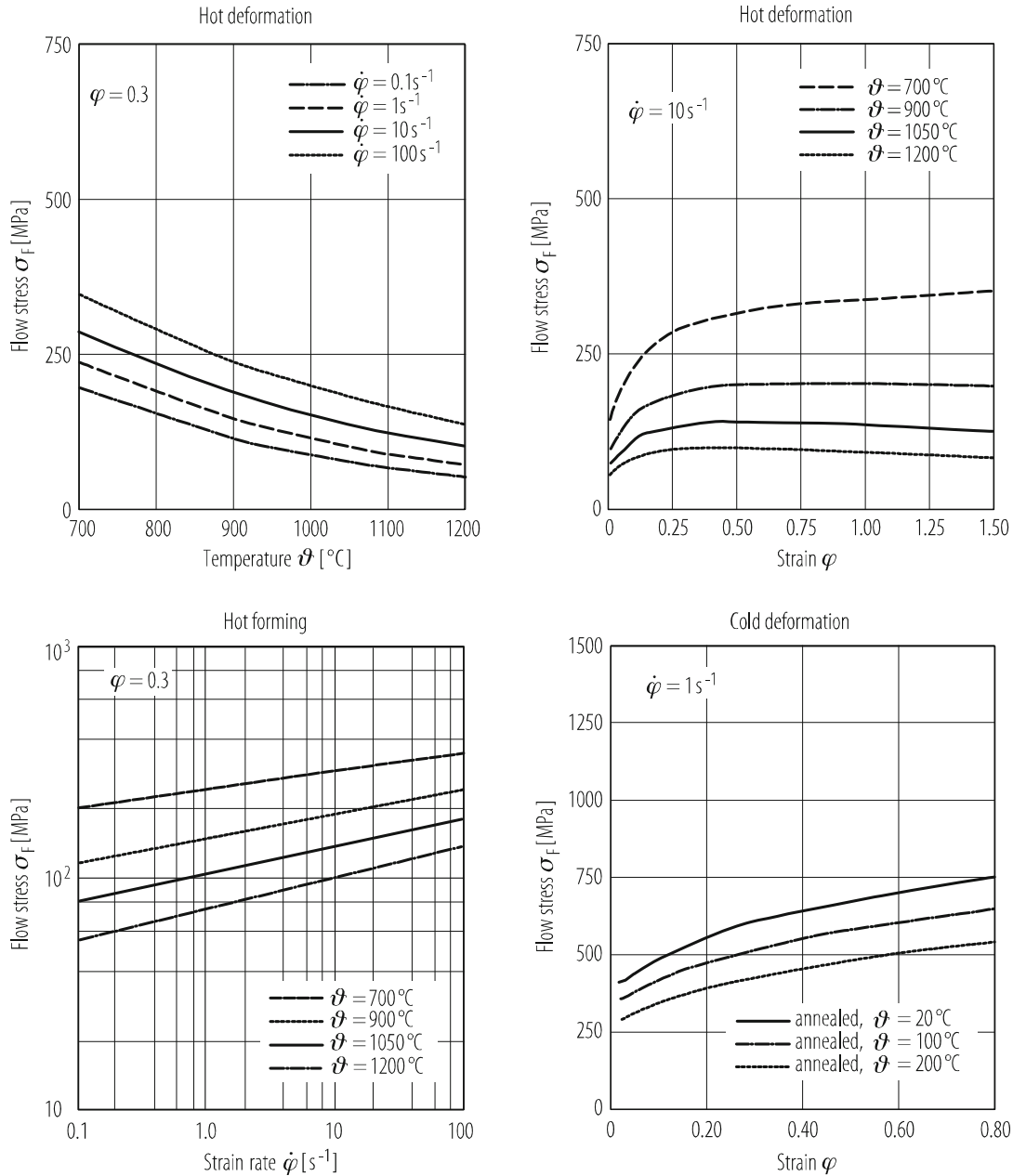
|                       |          |              |           |
|-----------------------|----------|--------------|-----------|
| SEW                   |          | ISO          |           |
| SEW 385               |          |              |           |
| Material number (DIN) |          | DIN          |           |
| 1.3920                |          | DIN 1715-1,  | DIN 17745 |
| Japan                 |          | Russia       |           |
| USA                   |          |              |           |
| ASME                  | ASTM     | UNS standard |           |
| ASME: F30             | ASTM F30 | K93603       |           |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 | 127.1          | 502.4            |                 |                 |
| A                                      |                 | 1745.420       | 814.220          |                 |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                  |                 |                 |
| $m_1$                                  |                 | −0.00203       | −0.00194         |                 |                 |
| Effect of strain $K_{\phi}$            |                 |                |                  |                 |                 |
| $m_2$                                  |                 | 0.33846        | 0.22294          |                 |                 |
| $m_4$                                  |                 | 0.00253        | 0.00422          |                 |                 |
| $m_5$                                  |                 | −0.00121       |                  |                 |                 |
| $m_7$                                  |                 | 0.17408        |                  |                 |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.01173          |                 |                 |
| $m_8$                                  |                 | 0.000114       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\theta$ [°C]                          |                 | 700...1200     | 20...200         |                 |                 |
| $\phi$                                 |                 | 0.03...1.50    | 0.03...0.80      |                 |                 |
| $\dot{\phi}$ [1/s]                     |                 | 0.1...100      | 0.01...100       |                 |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.119** Flow stress curves of Ni<sub>46</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |          |        | Vickers hardness $\Delta Hv$ |         |        |
|-------------------|---------------------------------|----------|--------|------------------------------|---------|--------|
|                   | $A_0$                           | $A$      | $n_I$  | $B_0$                        | $B$     | $n_2$  |
| soft annealed     | 300...350                       | 102.5489 | 0.3889 | 120...140                    | 13.6050 | 0.5146 |

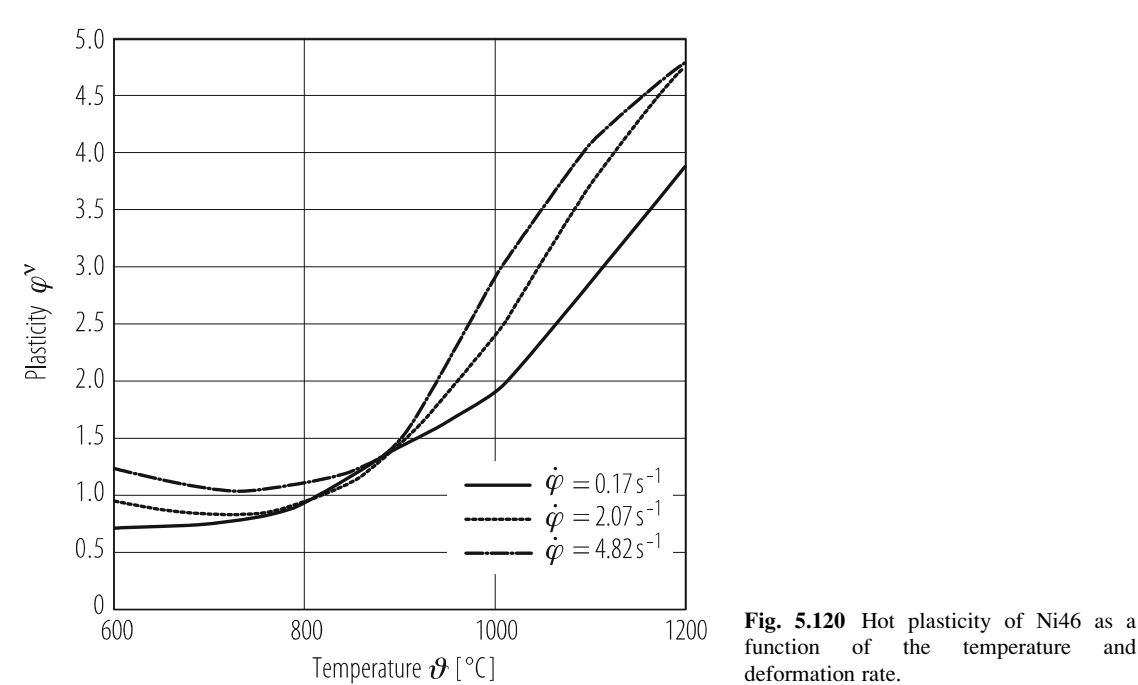
  

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |        |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|--------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$  | $n_4$   |                            |
| soft annealed     | 28...34                                 | 29.4558 | 0.0059 | −9.2102 | <80                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in torsion



## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}/K$ ]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 18.8                 |                    |                                         | 8200                        | 152             |
| 100              | 19.3                 |                    | 7.9                                     | 8180.6                      |                 |
| 200              | 19.8                 |                    | 7.7                                     | 8162.1                      |                 |
| 300              | 20.2                 |                    | 7.4                                     | 8145.4                      |                 |
| 400              | 20.5                 |                    | 7.3                                     | 8128.2                      |                 |
| 500              | 20.7                 |                    | 8.6                                     | 8094.2                      |                 |
| 600              | 20.9                 |                    | 9.7                                     | 8056.8                      |                 |
| 700              | 20.9                 |                    |                                         |                             |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\Delta Hv$         | vickers hardness                                                      |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |



# Flow stress, mechanical and physical properties of Ni<sub>51</sub>

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |                |               |             |            |
|-------------|----------------|---------------|-------------|------------|
| UNS number: | <b>K 94101</b> | Chem. symbol: | <b>Ni51</b> | EN number: |
|-------------|----------------|---------------|-------------|------------|

#### Composition (DIN) [Weight-%]

| C     | Si    | Mn    | P      | S      | Cr          | Mo | Ni          | V | Nb | Ti | Fe          |
|-------|-------|-------|--------|--------|-------------|----|-------------|---|----|----|-------------|
| <0.05 | <0.30 | <1.00 | <0.030 | <0.030 | 0.40...1.00 |    | 50.5...52.5 |   |    |    | 47.0...49.0 |

#### International comparison of standards

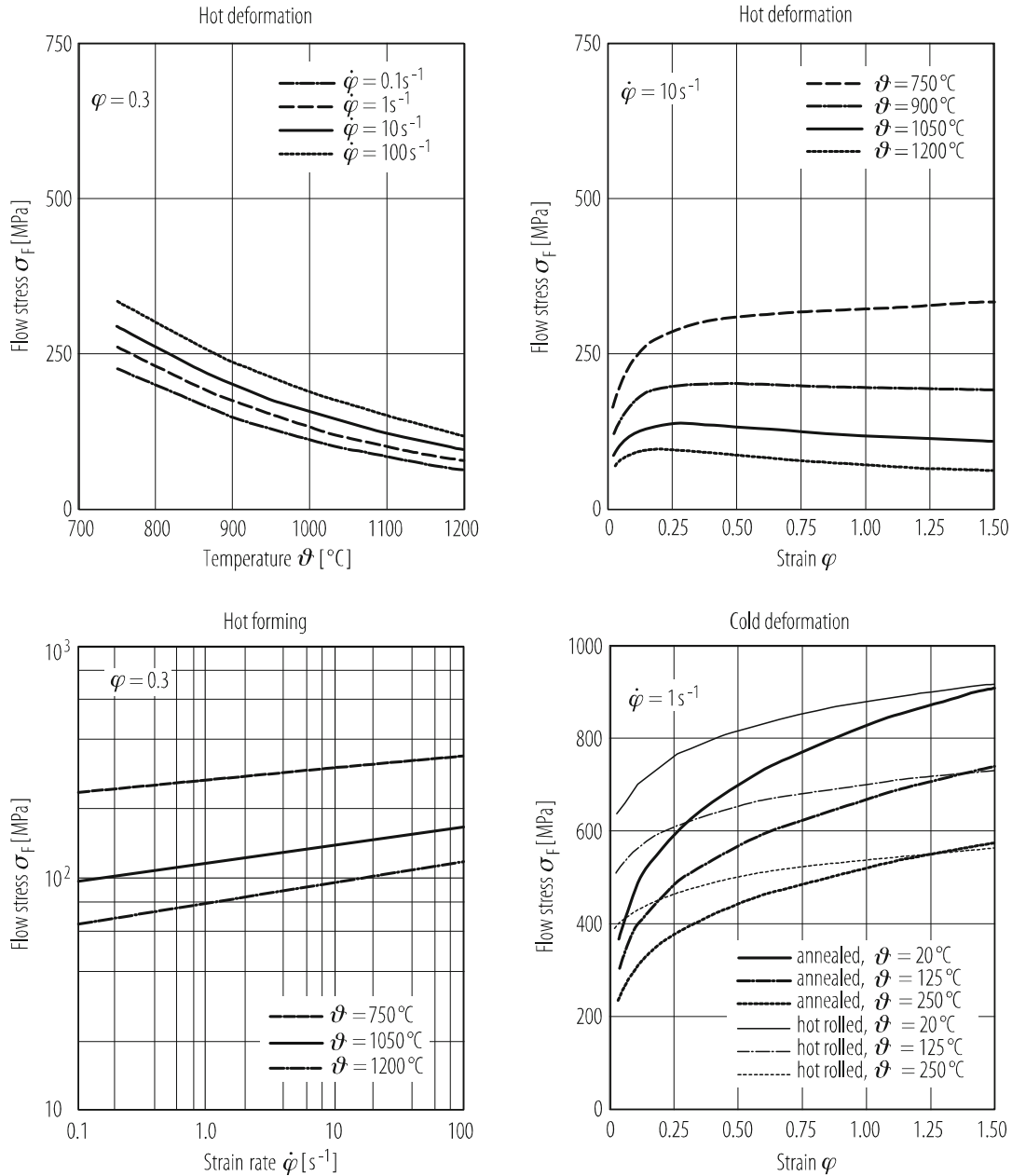
|                       |                 |               |                   |
|-----------------------|-----------------|---------------|-------------------|
| Euronorm              |                 | ISO           |                   |
| Material number (DIN) |                 | DIN           |                   |
| 1.3923                |                 |               |                   |
| France                |                 | Russia        |                   |
| Fe-Ni 50 Cr 1         | A 54-301 (1973) | 52N           | GOST 10994 (1974) |
| USA                   |                 |               |                   |
| ASME                  | ASTM            | UNS standard  |                   |
|                       | ASTM A753 - 08  | ASTM F1684-06 | K 94101           |
|                       | ASTM A 334_04   |               |                   |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 | 138.8          | 490.9            | 713.7           |                 |
| A                                      |                 | 1423.694       | 859.788          | 914.010         |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                  |                 |                 |
| $m_1$                                  |                 | -0.00222       | -0.00201         | -0.00214        |                 |
| Effect of strain $K_{\phi}$            |                 |                |                  |                 |                 |
| $m_2$                                  |                 | 0.03286        | 0.23825          | 0.10715         |                 |
| $m_4$                                  |                 | -0.02125       | 0.00091          | 0.00201         |                 |
| $m_5$                                  |                 | 0.00013        |                  |                 |                 |
| $m_7$                                  |                 | -0.11661       |                  |                 |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.00833          | 0.00958         |                 |
| $m_8$                                  |                 | 0.00006        |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\theta$ [°C]                          |                 | 900...1200     | 20...250         | 20...250        |                 |
| $\phi$                                 |                 | 0.03...1.50    | 0.03...1.50      | 0.03...1.50     |                 |
| $\dot{\phi}$ [1/s]                     |                 | 0.1...100      | 0.01...100       | 0.01...100      |                 |

| Hot deformation:                                                                                                                                                                     | Cold deformation                                                                                                 |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \dot{\varphi}^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \dot{\varphi}^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                                 | [Equation (2.25), Chapter 2.3.2.2.2]                                                                             |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                                | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                            |



**Fig. 5.121** Flow stress curves of Ni<sub>51</sub> by hot and cold forming.

**Mechanical properties after cold deformation**

| State of material | Yield stress $\Delta R_p$ [MPa] |          |        | Vickers hardness $\Delta Hv$ |     |       |
|-------------------|---------------------------------|----------|--------|------------------------------|-----|-------|
|                   | $A_0$                           | $A$      | $n_1$  | $B_0$                        | $B$ | $n_2$ |
| soft annealed     | 250...300                       | 101.5255 | 0.4181 |                              |     |       |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |        |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|--------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$  | $n_4$   |                            |
| soft annealed     | 32...36                                 | 25.0562 | 0.0778 | -2.1979 | <85                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

**Physical properties**

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               |                      |                    |                                         | 8200                        |                 |
| 100              |                      |                    |                                         |                             |                 |
| 200              |                      |                    | 10.6                                    | 8147.8                      |                 |
| 300              |                      |                    | 9.9                                     | 8126.9                      |                 |
| 400              |                      |                    | 9.7                                     | 8104.6                      |                 |
| 500              |                      |                    | 9.7                                     | 8080.7                      |                 |
| 600              |                      |                    | 10.4                                    | 8046.5                      |                 |
| 700              |                      |                    | 11.3                                    | 8006.4                      |                 |
| 800              |                      |                    | 12                                      | 7963.8                      |                 |

**Symbols and abbreviations**

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |

(continued)

| Short form     | Full form                               |
|----------------|-----------------------------------------|
| $T, \vartheta$ | temperature                             |
| UNS            | unified numbering system                |
| $\Delta H_V$   | vickers hardness                        |
| $\alpha_m$     | average coefficient of linear expansion |
| $\lambda$      | thermal conductivity                    |
| $\rho$         | density                                 |

# Flow stress, mechanical and physical properties of NiMn<sub>20-6</sub>

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |  |             |          |            |
|-------------|--|-------------|----------|------------|
| UNS number: |  | Chem. symb: | NiMn20–6 | EN number: |
|-------------|--|-------------|----------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn          | P | S | Cr | Mo | Ni          | V | Nb | Ti | Fe   |
|-------|-------|-------------|---|---|----|----|-------------|---|----|----|------|
| <0.20 | <1.00 | 6.00...7.00 |   |   |    |    | 19.0...21.0 |   |    |    | Bal. |

#### International comparison of standards

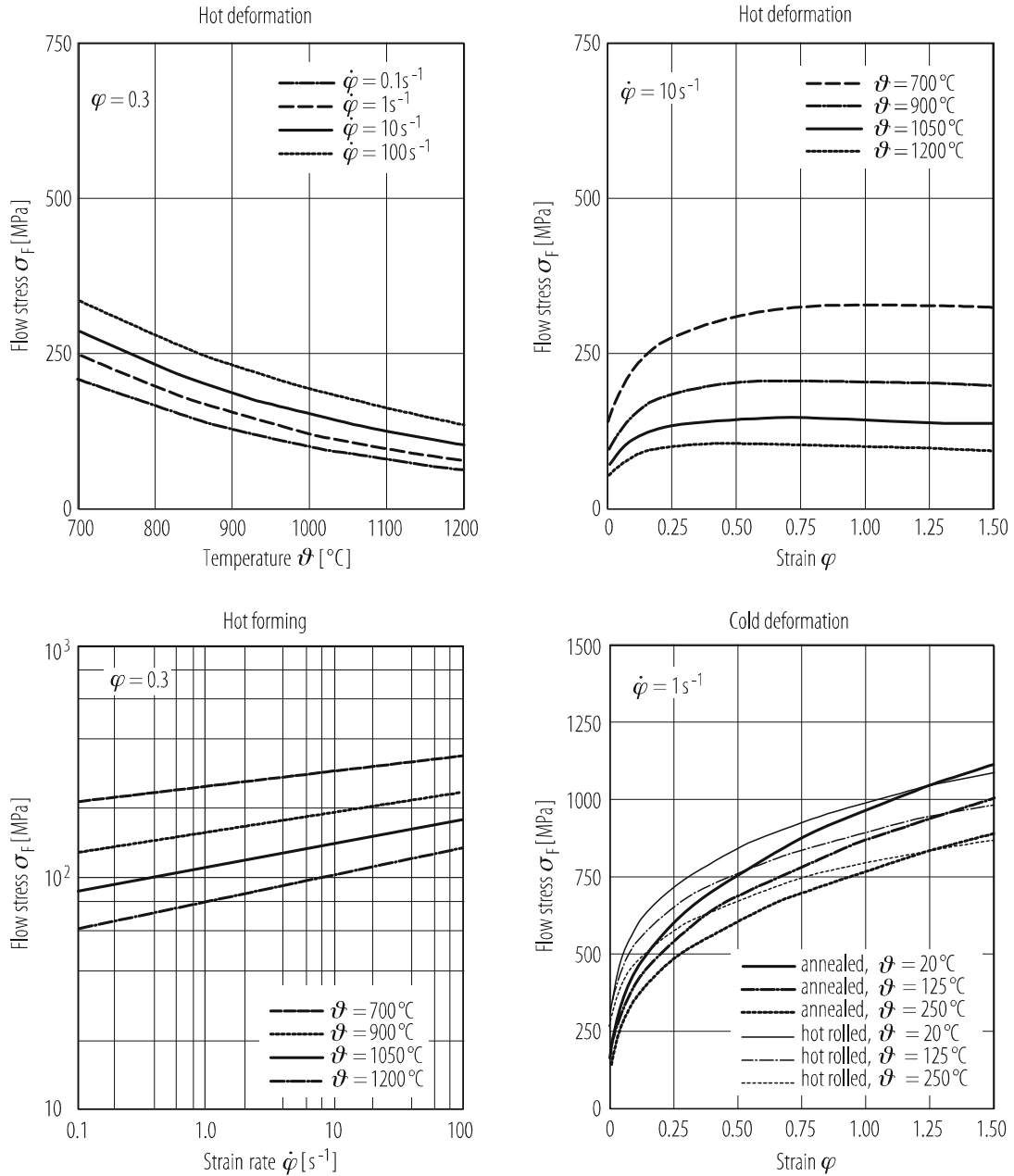
|                       |          |                   |
|-----------------------|----------|-------------------|
| SEW                   | ISO      |                   |
| SEW 385               |          |                   |
| Material number (DIN) | DIN      |                   |
| 1.3932                | DIN 1715 | DIN 17457         |
| Japan                 | Russia   |                   |
|                       | 20NG     | GOST 10994 (1974) |
| USA                   |          |                   |
| ASME                  | ASTM     | UNS standard      |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                           | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 123.7          | 453.4            | 597.2           |                 |
| A                                         |                 | 1827.500       | 989.005          | 1011.984        |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                  |                 |                 |
| $m_1$                                     |                 | –0.00210       | –0.00100         | –0.00097        |                 |
| Effect of strain $K_{\varphi a3}$         |                 |                |                  |                 |                 |
| $m_2$                                     |                 | 0.33512        | 0.34695          | 0.23526         |                 |
| $m_4$                                     |                 | 0.00281        | 0.00093          | 0.00069         |                 |
| $m_5$                                     |                 | –0.00067       |                  |                 |                 |
| $m_7$                                     |                 | –0.08655       |                  |                 |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |                 |                 |
| $m_3$                                     |                 |                | 0.01289          | 0.01164         |                 |
| $m_8$                                     |                 | 0.000097       |                  |                 |                 |
| Range of validity                         |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                          |                 | 700...1200     | 20...200         | 20...200        |                 |
| $\varphi$                                 |                 | 0.03...1.50    | 0.03...0.80      | 0.03...0.80     |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.1...100      | 0.01...100       | 0.01...100      |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.122** Flow stress curves of NiMn<sub>20-6</sub> by hot and cold forming.

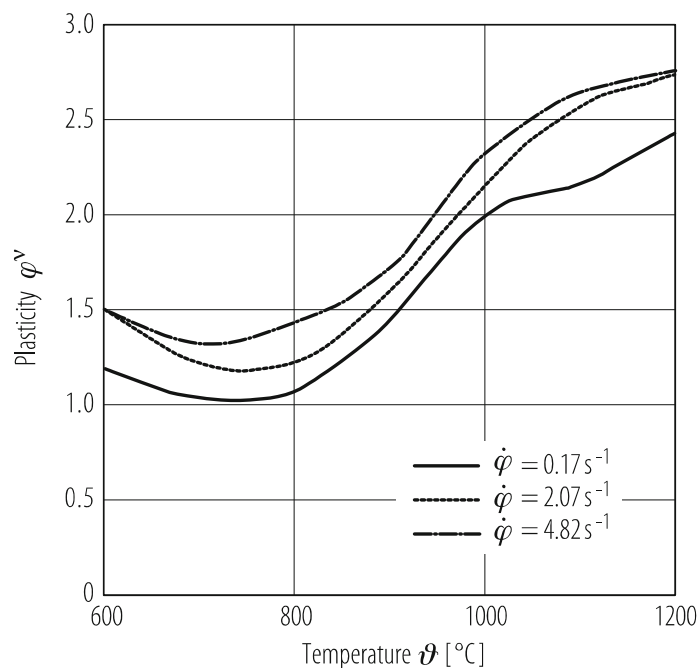
## Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |     |       | Vickers hardness $\Delta H_V$ |         |        |
|-------------------|---------------------------------|-----|-------|-------------------------------|---------|--------|
|                   | $A_0$                           | $A$ | $n_1$ | $B_0$                         | $B$     | $n_2$  |
| soft annealed     |                                 |     |       | 80...100                      | 17.4136 | 0.5649 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |         |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|---------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$   | $n_4$   |                            |
| soft annealed     | 35...40                                 | 48.8684 | -0.0597 | -9.8924 | <75                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

## Plasticity in torsion



**Fig. 5.123** Hot plasticity of NiMn20-6 as a function of the temperature and deformation rate.

## Physical properties

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                              | 13.0                                      |                                         |                                                                          | 8000                                   | 196                          |
| 100                             |                                           |                                         | 19.8                                                                     | 7952.6                                 |                              |
| 200                             |                                           |                                         | 19.9                                                                     | 7904.5                                 |                              |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 300              |                      |                    | 20                                      | 7856.0                      |                 |
| 400              |                      |                    | 20.1                                    | 7807.0                      |                 |
| 500              |                      |                    | 20.2                                    | 7757.6                      |                 |
| 600              |                      |                    | 20.3                                    | 7707.7                      |                 |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\Delta H_v$        | vickers hardness                                                      |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |



# Flow stress of X8NiCr<sub>17-10</sub>

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |               |                    |            |
|-------------|---------------|--------------------|------------|
| UNS number: | Chem. symbol: | <b>X8NiCr17-10</b> | EN number: |
|-------------|---------------|--------------------|------------|

#### Composition (DIN) [Weight-%]

| C     | Si    | Mn    | P      | S      | Cr          | Mo | Ni          | V | Nb | Ti | Fe   |
|-------|-------|-------|--------|--------|-------------|----|-------------|---|----|----|------|
| <0.10 | <0.50 | <1.00 | <0.025 | <0.025 | 9.50...11.5 |    | 16.0...18.0 |   |    |    | Bal. |

#### International comparison of standards

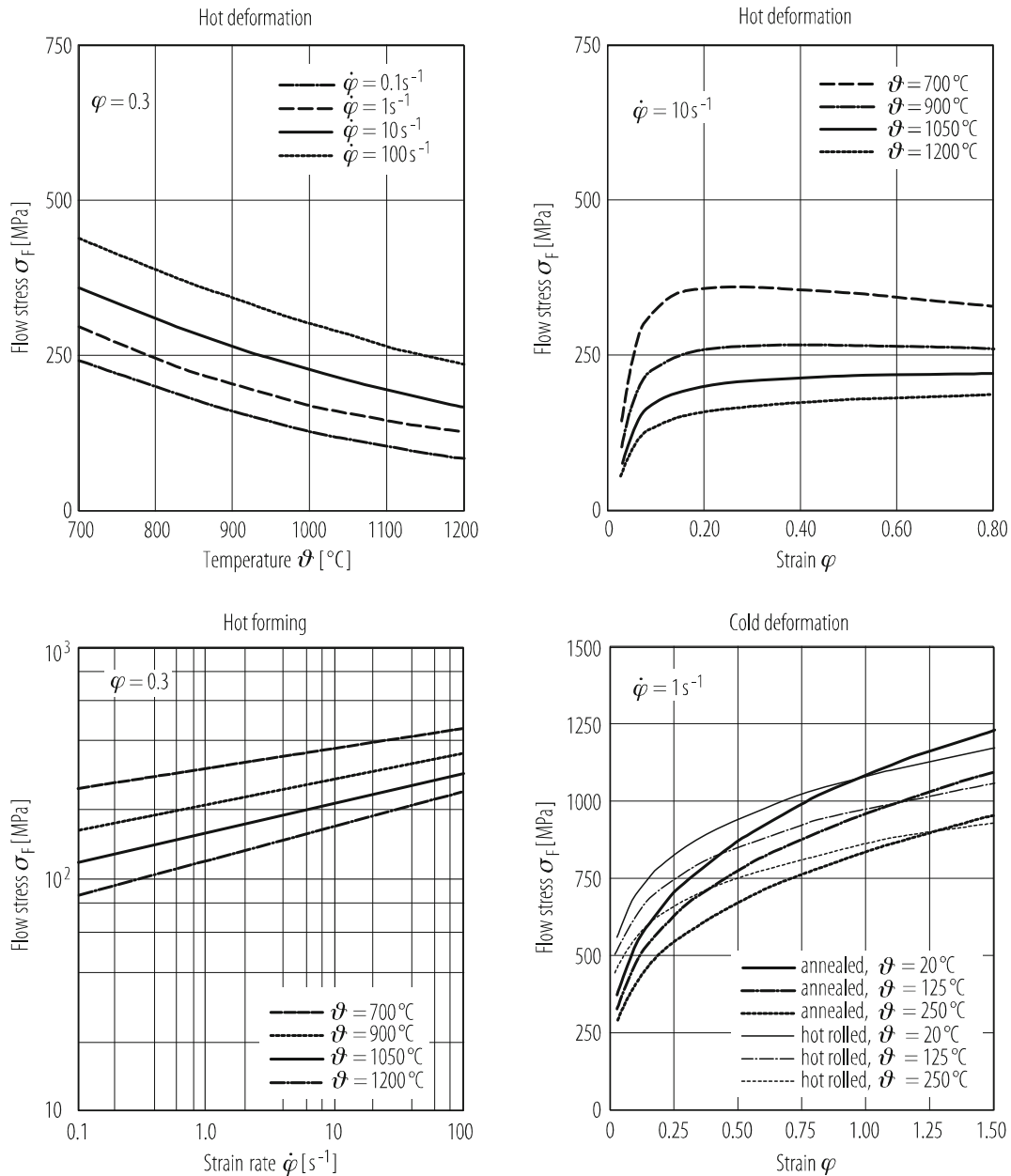
|                       |      |           |              |
|-----------------------|------|-----------|--------------|
| Euronorm              |      | ISO       |              |
| Material number (DIN) |      | DIN       |              |
| 1.3938                |      | DIN 17744 |              |
| Japan                 |      | Russia    |              |
| USA                   |      |           |              |
| ASME                  | ASTM |           | UNS standard |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                   | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                     | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                 |                 | 191.8          | 531.4            | 697.1           |                 |
| A                                   |                 | 1099.455       | 1105.217         | 1100.740        |                 |
| Effect of temperature $K_9$         |                 |                |                  |                 |                 |
| $m_1$                               |                 | −0.00216       | −0.00114         | −0.00100        |                 |
| Effect of strain $K_\phi$           |                 |                |                  |                 |                 |
| $m_2$                               |                 | −0.22441       | 0.31358          | 0.19374         |                 |
| $m_4$                               |                 | −0.04561       | 0.00095          | 0.00064         |                 |
| $m_5$                               |                 | 0.00130        |                  |                 |                 |
| $m_7$                               |                 | −0.53824       |                  |                 |                 |
| Effect of strain rate $K\dot{\phi}$ |                 |                |                  |                 |                 |
| $m_3$                               |                 |                | 0.00130          | 0.00123         |                 |
| $m_8$                               |                 | 0.000123       |                  |                 |                 |
| Range of validity                   |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                    |                 | 700...1200     | 20...250         | 20...250        |                 |
| $\phi$                              |                 | 0.03 ... 0.80  | 0.03 ... 1.50    | 0.03 ... 1.50   |                 |
| $\dot{\phi}$ [1/s]                  |                 | 0.1...100      | 0.01...100       | 0.01...100      |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.124** Flow stress curves of X8NiCr<sub>17-10</sub> by hot and cold forming.

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |

# Flow stress of X<sub>8</sub>NiCr<sub>22-3</sub>

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |               |                   |            |
|-------------|---------------|-------------------|------------|
| UNS number: | Chem. symbol: | <b>X8NiCr22-3</b> | EN number: |
|-------------|---------------|-------------------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn    | P | S | Cr          | Mo | Ni          | V | Nb | Ti | Fe   |
|-------|-------|-------|---|---|-------------|----|-------------|---|----|----|------|
| <0.20 | <0.50 | <1.00 |   |   | 2.50...3.50 |    | 21.0...23.0 |   |    |    | Bal. |

#### International comparison of standards

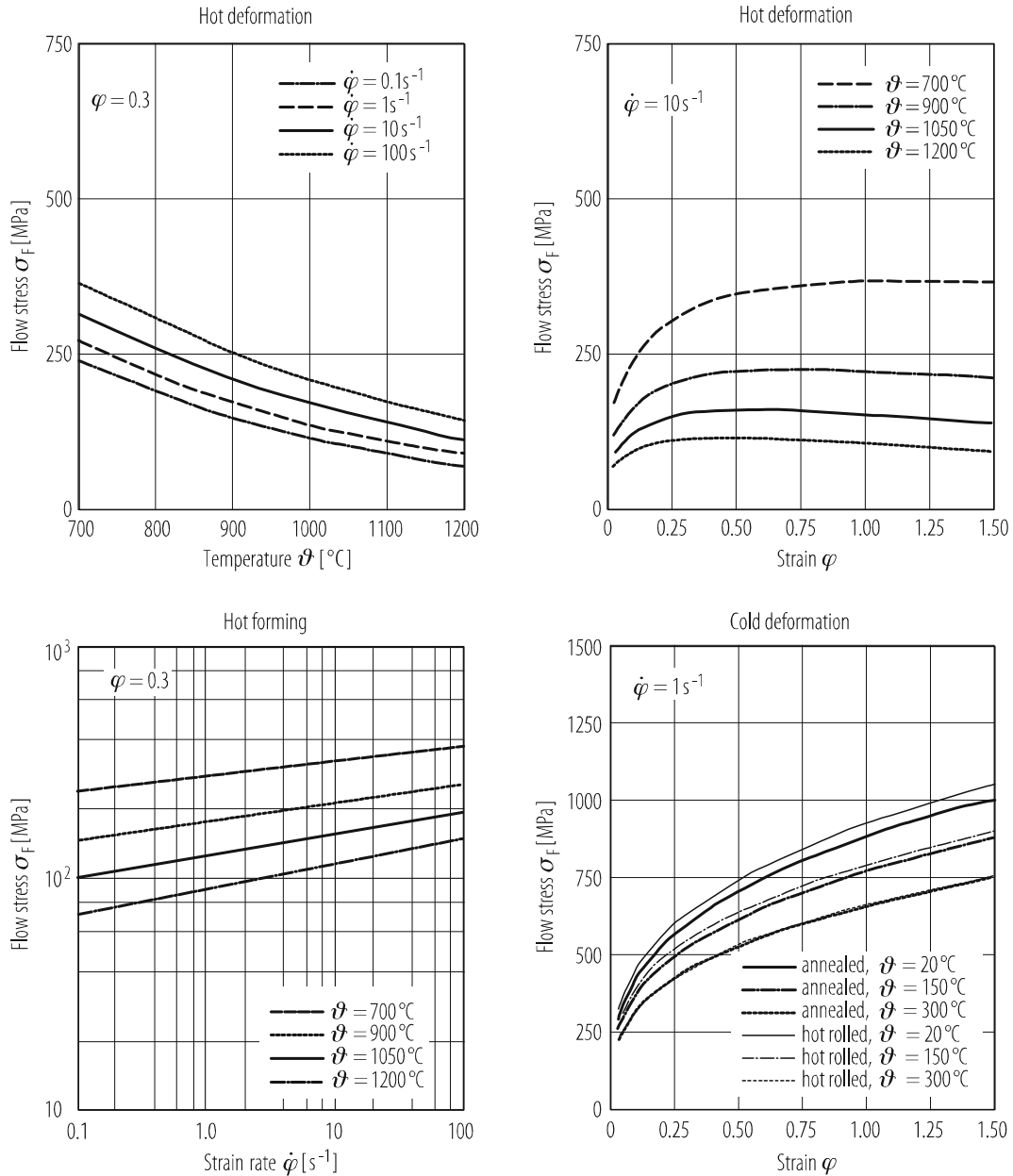
|                       |  |              |  |
|-----------------------|--|--------------|--|
| SEW                   |  | ISO          |  |
| SEW 385               |  |              |  |
| Material number (DIN) |  | DIN          |  |
| 1.3942                |  | DIN 17744    |  |
| Japan                 |  | Russia       |  |
| USA                   |  |              |  |
| ASME                  |  | ASTM         |  |
|                       |  | UNS standard |  |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                           | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 135.7          | 438.9            | 470.1           |                 |
| A                                         |                 | 2095.753       | 899.657          | 945.291         |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                  |                 |                 |
| $m_1$                                     |                 | −0.00198       | −0.00104         | −0.00121        |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                  |                 |                 |
| $m_2$                                     |                 | 0.39429        | 0.31851          | 0.30775         |                 |
| $m_4$                                     |                 | 0.00466        | 0.00091          | 0.00091         |                 |
| $m_5$                                     |                 | −0.00102       |                  |                 |                 |
| $m_7$                                     |                 | −0.01091       |                  |                 |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |                 |                 |
| $m_3$                                     |                 |                | 0.01192          | 0.01093         |                 |
| $m_8$                                     |                 | 0.000088       |                  |                 |                 |
| Range of validity                         |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                          |                 | 700...1200     | 20...300         | 20...300        |                 |
| $\varphi$                                 |                 | 0.03...1.50    | 0.03...1.50      | 0.03...1.50     |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.1...100      | 0.01...100       | 0.01...100      |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.125** Flow stress curves of X<sub>8</sub>NiCr<sub>22-3</sub> by hot and cold forming.

# Flow stress, plasticity and physical properties of Ni<sub>42</sub>Cr<sub>6</sub>

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |  |               |                |            |
|-------------|--|---------------|----------------|------------|
| UNS number: |  | Chem. symbol: | <b>Ni42Cr6</b> | EN number: |
|-------------|--|---------------|----------------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn    | P | S | Cr          | Mo | Ni          | V | Nb | Ti | Fe   |
|-------|-------|-------|---|---|-------------|----|-------------|---|----|----|------|
| <0.10 | <0.50 | <1.00 |   |   | 6.00...7.00 |    | 41.0...43.0 |   |    |    | Bal. |

#### International comparison of standards

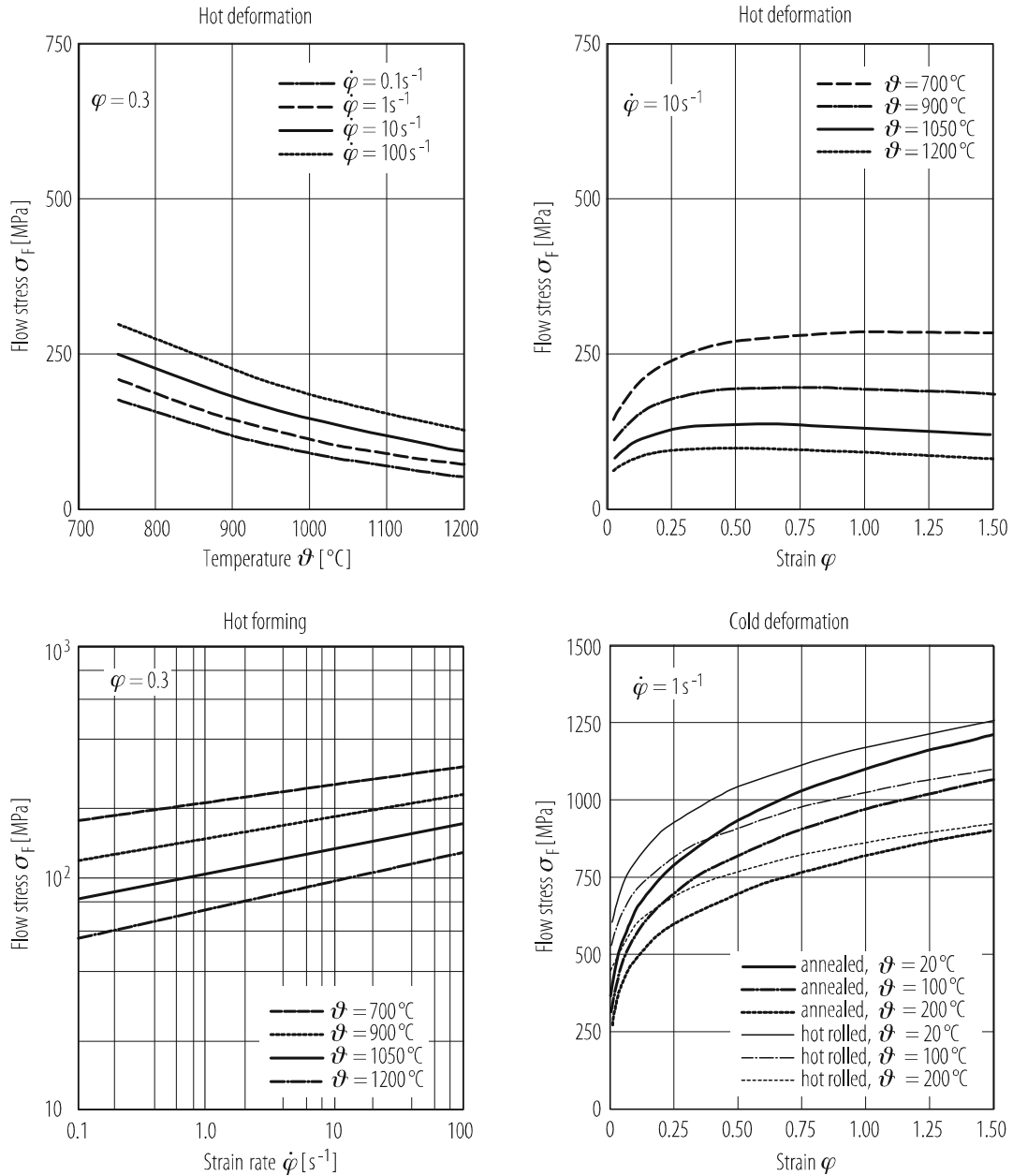
|                       |                 |
|-----------------------|-----------------|
| Euronorm              | ISO             |
| EN 10088-1...3        |                 |
| Material number (DIN) | DIN             |
| 1.3946                | DIN 17744       |
| France                | Japan           |
| Fe-Ni 42 Cr 6         | A 54-301 (1973) |
| USA                   | NRS-1           |
| ASME                  | ASTM            |
|                       | UNS standard    |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

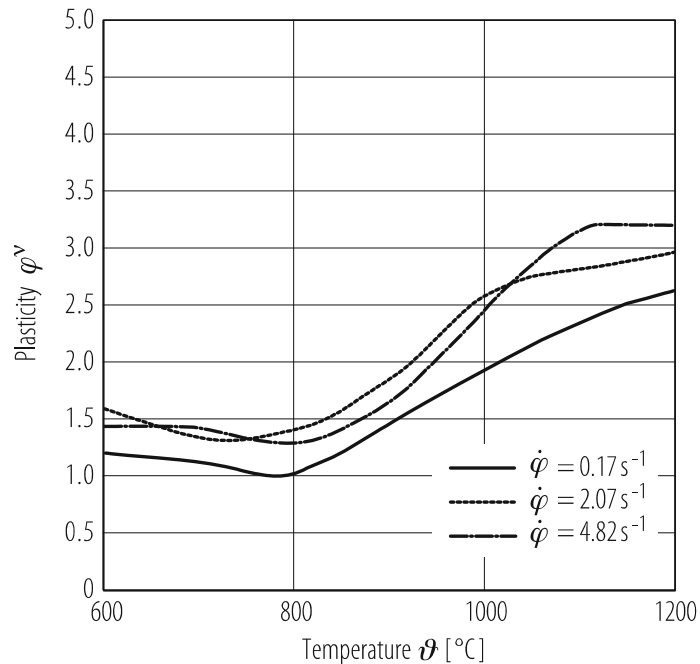
| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 | 120.6          | 653.2            | 819.1           |                 |
| A                                      |                 | 1801.081       | 1135.128         | 1208.957        |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                  |                 |                 |
| $m_1$                                  |                 | -0.00210       | -0.00163         | -0.00170        |                 |
| Effect of strain $K_{\phi}$            |                 |                |                  |                 |                 |
| $m_2$                                  |                 | 0.33579        | 0.23843          | 0.16984         |                 |
| $m_4$                                  |                 | 0.00228        | 0.00061          | 0.00126         |                 |
| $m_5$                                  |                 | -0.00101       |                  |                 |                 |
| $m_7$                                  |                 | 0.06246        |                  |                 |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.00994          | 0.01006         |                 |
| $m_8$                                  |                 | 0.000103       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\theta$ [°C]                          |                 | 750...1200     | 20...200         | 20...200        |                 |
| $\phi$                                 |                 | 0.03...1.50    | 0.03...1.50      | 0.03...1.50     |                 |
| $\dot{\phi}$ [1/s]                     |                 | 0.1...100      | 0.01...100       | 0.01...100      |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.126** Flow stress curves of Ni<sub>42</sub>Cr<sub>6</sub> by hot and cold forming.

## Plasticity in torsion



**Fig. 5.127** Hot plasticity of Ni<sub>42</sub>Cr<sub>6</sub> as a function of the temperature and deformation rate.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 12.6                 |                    |                                         | 8150                        | 147             |
| 100              |                      |                    | 6.9                                     | 8133.1                      |                 |
| 200              |                      |                    | 7.2                                     | 8114.8                      |                 |
| 300              |                      |                    | 8.3                                     | 8089.1                      |                 |
| 400              |                      |                    | 10.1                                    | 8051.2                      |                 |
| 500              |                      |                    | 11.4                                    | 8010.6                      |                 |
| 600              |                      |                    | 12.4                                    | 7968.1                      |                 |
| 700              |                      |                    |                                         |                             |                 |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |

(continued)



| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| EN             | Euronorm                                       |
| ISO            | international organisation for standardization |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |

# Flow stress and physical properties of NiCo<sub>29-18</sub>

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |               |               |                  |            |
|-------------|---------------|---------------|------------------|------------|
| UNS number: | <b>K94610</b> | Chem. symbol: | <b>NiCo29-18</b> | EN number: |
|-------------|---------------|---------------|------------------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn    | P      | S      | Cr | Mo | Ni          | V | Nb | Co          | Fe   |
|-------|-------|-------|--------|--------|----|----|-------------|---|----|-------------|------|
| <0.05 | <0.30 | <0.50 | <0.030 | <0.030 |    |    | 28.0...30.0 |   |    | 17.0...18.0 | Bal. |

#### International comparison of standards

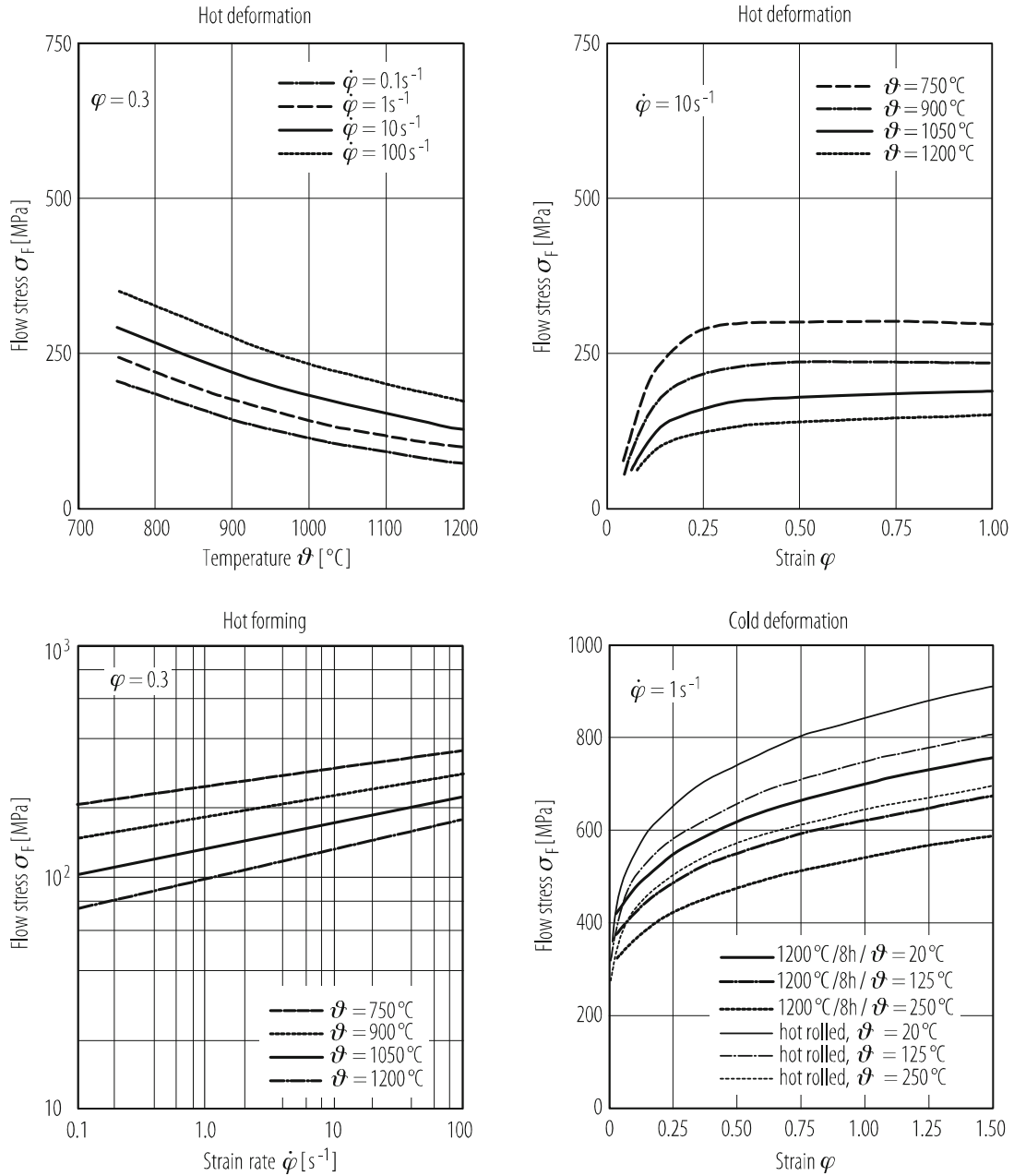
| SEW                   |  |  | ISO               |  |  |
|-----------------------|--|--|-------------------|--|--|
| SEW 385               |  |  |                   |  |  |
| Material number (DIN) |  |  | DIN               |  |  |
| 1.3981                |  |  | DIN 17745         |  |  |
| France                |  |  | Russia            |  |  |
| Fe-Ni 29 Co 17        |  |  | 29NK-W1           |  |  |
| A 54-301 (1973)       |  |  | GOST 10994 (1974) |  |  |
| USA                   |  |  |                   |  |  |
| AMS                   |  |  | UNS standard      |  |  |
| AMS 7726              |  |  | K94610            |  |  |
| AMS 7727              |  |  |                   |  |  |
| AMS 7728              |  |  |                   |  |  |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |                         |                 |
|----------------------------------------|-----------------|----------------|------------------|-------------------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | annealed 1200°C/8h (an) | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                    |                 | 116.0          | 530.0            | 487.0                   | 567.0           |
| A                                      |                 | 1093.280       | 853.961          | 715.485                 | 864.053         |
| Effect of temperature $K_\theta$       |                 |                |                  |                         |                 |
| $m_1$                                  |                 | -0.00224       | -0.00125         | -0.00112                | -0.00118        |
| Effect of strain $K_\phi$              |                 |                |                  |                         |                 |
| $m_2$                                  |                 | -0.37431       | 0.22165          | 0.18513                 | 0.18341         |
| $m_4$                                  |                 | -0.11675       | 0.00413          | 0.00413                 | 0.00056         |
| $m_5$                                  |                 | 0.00068        |                  |                         |                 |
| $m_7$                                  |                 | -0.04399       |                  |                         |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |                         |                 |
| $m_3$                                  |                 |                | 0.00741          | 0.00985                 | 0.00828         |
| $m_8$                                  |                 | 0.000105       |                  |                         |                 |
| Range of validity                      |                 |                |                  |                         |                 |
| $\theta$ [°C]                          |                 | 750...1200     | 20...250         | 20...250                | 20...250        |
| $\phi$                                 |                 | 0.03...1.00    | 0.03...1.50      | 0.03...1.50             | 0.03...1.50     |
| $\dot{\phi}$ [1/s]                     |                 | 0.1...100      | 0.01...100       | 0.01...100              | 0.01...100      |

| Hot deformation:                                                                                                                                                                     | Cold deformation                                                                                                 |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \dot{\varphi}^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \dot{\varphi}^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                                 | [Equation (2.25), Chapter 2.3.2.2.2]                                                                             |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                                | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                            |



**Fig. 5.128** Flow stress curves of NiCo<sub>29-18</sub> by hot and cold forming.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 14.2                 |                    |                                         | 8300                        | 157             |
| 100              |                      |                    | 5.8                                     | 8285.5                      |                 |
| 200              | 15.0                 |                    | 5.3                                     | 8273.6                      |                 |
| 300              |                      |                    | 5                                       | 82627                       |                 |
| 400              | 16.6                 |                    | 4.9                                     | 8251.2                      |                 |
| 500              |                      |                    | 6                                       | 8225.3                      |                 |
| 600              | 18.4                 |                    | 7.6                                     | 8186.5                      |                 |
| 700              |                      |                    | 9.1                                     | 8141.4                      |                 |
| 800              | 20.2                 |                    | 10.2                                    | 8096.8                      |                 |
| 900              |                      |                    |                                         |                             |                 |
| 1000             | 21.9                 |                    |                                         |                             |                 |
| 1100             |                      |                    |                                         |                             |                 |
| 1200             |                      |                    |                                         |                             |                 |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| AMS             | aerospace material standards                                          |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| GOST            | gosudarstvennyy standart (state standard)                             |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress and physical properties of NiCo<sub>28-23</sub>

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |               |           |            |
|-------------|---------------|-----------|------------|
| UNS number: | Chem. symbol: | NiCo28-23 | EN number: |
|-------------|---------------|-----------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn    | P      | S      | Cr | Mo | Ni          | V | Nb | Co          | Fe   |
|-------|-------|-------|--------|--------|----|----|-------------|---|----|-------------|------|
| <0.05 | <0.30 | <0.50 | <0.030 | <0.030 |    |    | 27.0...29.0 |   |    | 22.0...24.0 | Bal. |

#### International comparison of standards

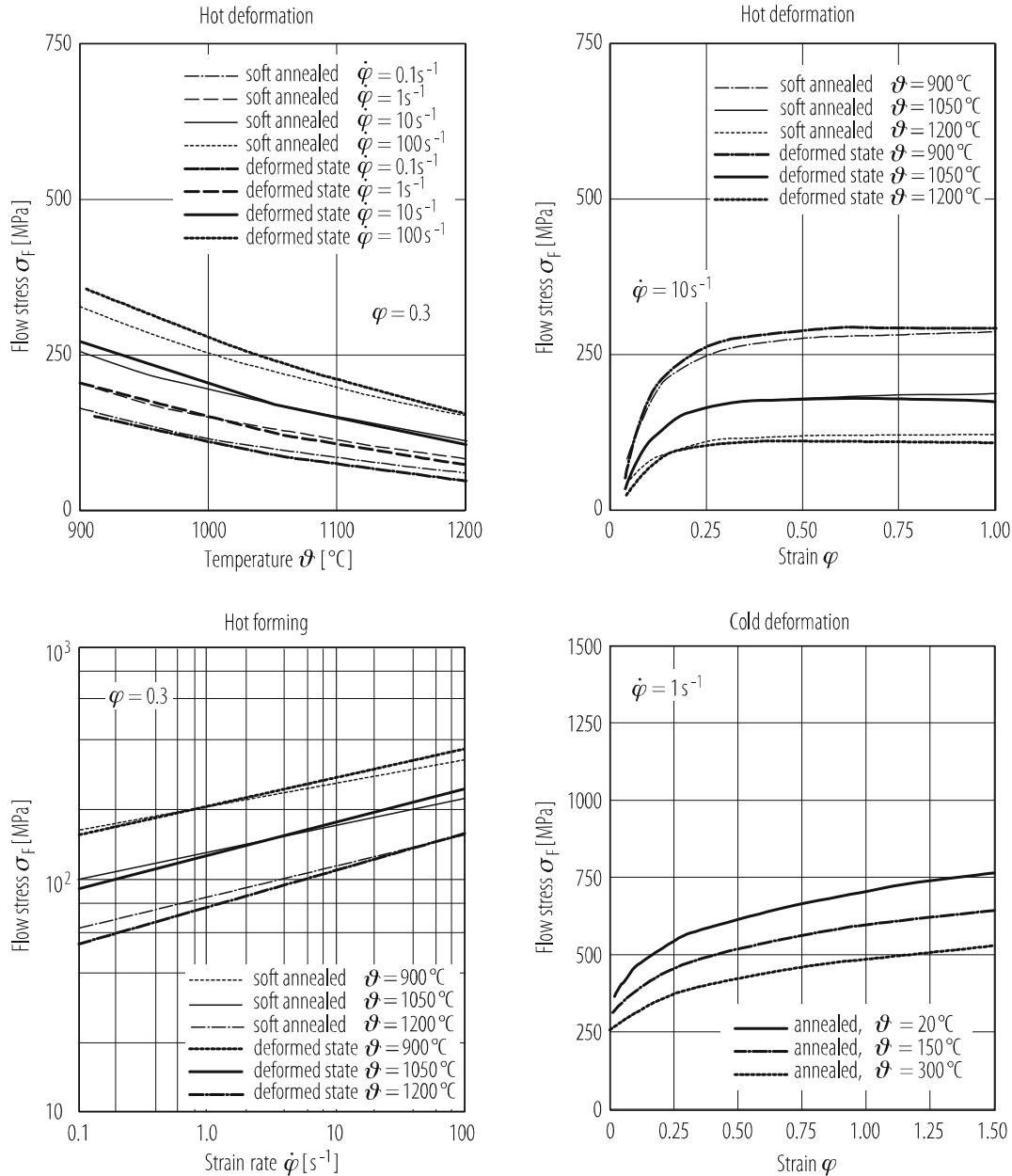
|                                       |           |              |
|---------------------------------------|-----------|--------------|
| SEW                                   |           | ISO          |
| SEW 385                               |           |              |
| Material number (DIN)                 |           | DIN          |
| 1.3982                                |           | DIN 17745    |
| Japan                                 |           | Russia       |
| USA                                   |           |              |
| ASME                                  | ASTM      | UNS standard |
| ASME 7726F F 15 F 15-98 N12160 N10242 | ASTM F 15 |              |
| ASME 7727D F 29 F 29-97 N10665        | ASTM F 29 |              |
| ASME 7728G B626 - 10e1                |           |              |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                         | Hot deformation |                |                       | Cold deformation |                 |
|-------------------------------------------|-----------------|----------------|-----------------------|------------------|-----------------|
|                                           | soft annealed   | deformed state | coarse grain annealed | annealed (an)    | hot rolled (hr) |
| $\sigma_{F0}$ [MPa]                       | 130.10          | 127.1          | 100.4                 | 471.5            |                 |
| A                                         | 3267.069        | 5183.470       | 1343.873              | 727.209          |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                       |                  |                 |
| $m_1$                                     | -0.00291        | -0.00322       | -0.00210              | -0.00135         |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                       |                  |                 |
| $m_2$                                     | -0.09501        | -0.02327       | 0.21711               | 0.19774          |                 |
| $m_4$                                     | -0.07829        | -0.08124       | -0.02259              | 0.00259          |                 |
| $m_5$                                     | -0.00042        | -0.00059       | -0.00059              |                  |                 |
| $m_7$                                     | 0.30206         | 0.18163        | 0.18163               |                  |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                       |                  |                 |
| $m_3$                                     |                 |                |                       | 0.01004          |                 |
| $m_8$                                     | 0.000112        | 0.000134       | 0.000127              |                  |                 |
| Range of validity                         |                 |                |                       |                  |                 |
| $\theta$ [°C]                             | 900...1200      | 900...1200     | 900...1200            | 20...300         |                 |
| $\varphi$                                 | 0.03...1.00     | 0.03...1.00    | 0.03...1.00           | 0.03...1.50      |                 |
| $\dot{\varphi}$ [1/s]                     | 0.1...100       | 0.1...100      | 0.01...50             | 0.01...100       |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.129** Flow stress curves of NiCo<sub>28-23</sub> by hot and cold forming.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 16.7                 | 481                |                                         | 8300                        | 157             |
| 100              |                      |                    | 7.1                                     | 8282.3                      |                 |
| 200              |                      |                    | 8.2                                     | 8259.2                      |                 |
| 300              |                      |                    | 7.8                                     | 8241.7                      |                 |
| 400              |                      |                    | 7.4                                     | 8226.3                      |                 |
| 500              |                      |                    | 7.1                                     | 8211.6                      |                 |
| 600              |                      |                    | 7.9                                     | 8182.0                      |                 |
| 700              |                      |                    | 9.2                                     | 8139.6                      |                 |
| 800              |                      |                    | 10.1                                    | 8098.8                      |                 |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, mechanical and physical properties of NiFe<sub>45</sub>

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |               |               |               |            |
|-------------|---------------|---------------|---------------|------------|
| UNS number: | <b>K94490</b> | Chem. symbol: | <b>NiFe45</b> | EN number: |
|-------------|---------------|---------------|---------------|------------|

#### Composition (DIN) [Weight-%]

| C     | Si    | Mn    | P | S | Cr | Mo | Ni    | V | Nb | Ti | Fe          |
|-------|-------|-------|---|---|----|----|-------|---|----|----|-------------|
| <0.05 | <0.30 | <0.60 |   |   |    |    | >53.0 |   |    |    | 45.0...47.0 |

#### International comparison of standards

|                       |                |              |
|-----------------------|----------------|--------------|
| Euronorm              | ISO            |              |
| Material number (DIN) | DIN            |              |
| 2.4472                | DIN 17745      |              |
| Japan                 | Russia         |              |
| USA                   |                |              |
| ASME                  | ASTM           | UNS standard |
|                       | ASTM A753 - 08 | K94490       |

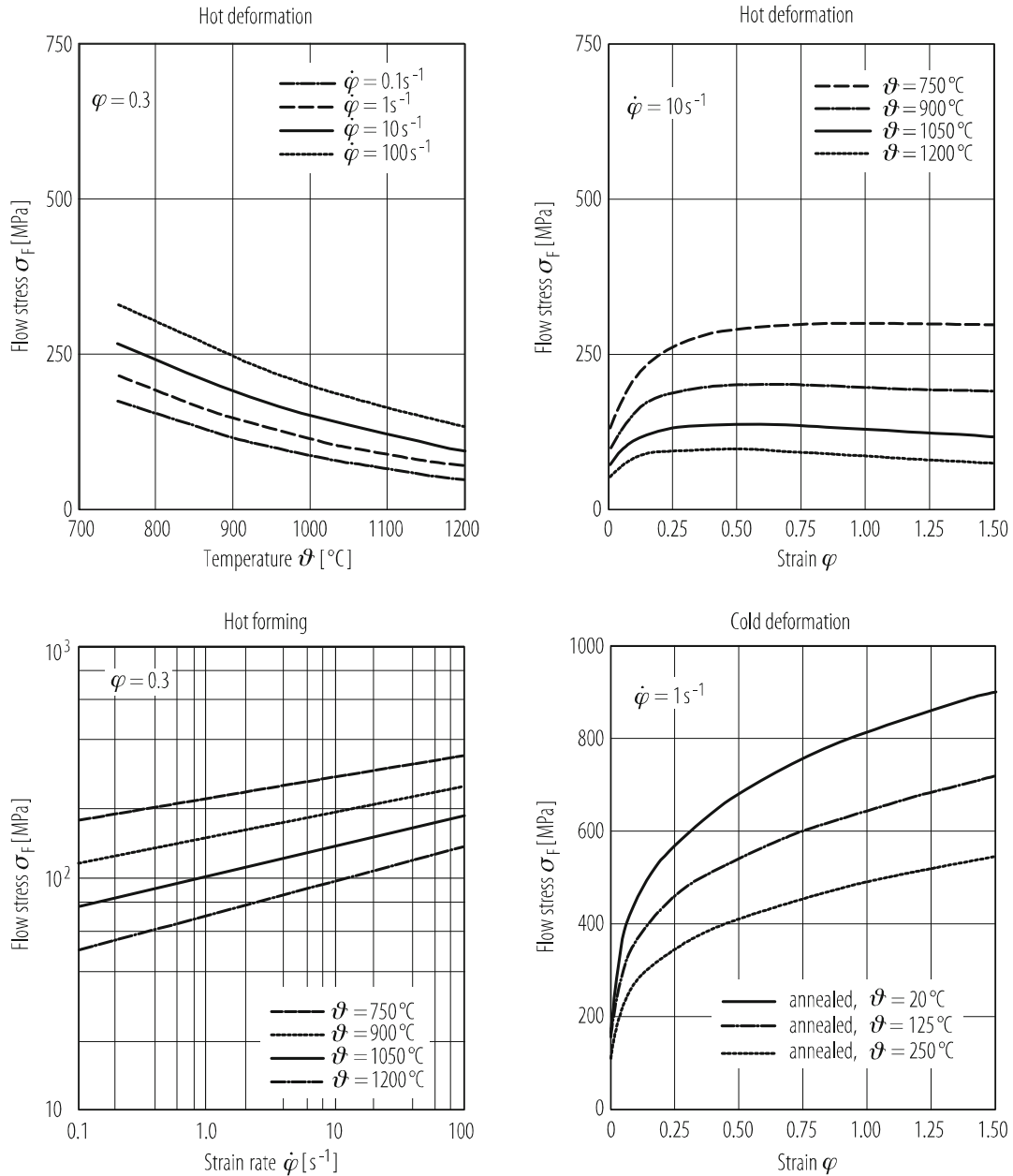
It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                   | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                     | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                 |                 | 138.82         | 464.1            |                 |                 |
| A                                   |                 | 2518.894       | 850.965          |                 |                 |
| Effect of temperature $K_8$         |                 |                |                  |                 |                 |
| $m_1$                               |                 | −0.00221       | −0.00221         |                 |                 |
| Effect of strain $K_\phi$           |                 |                |                  |                 |                 |
| $m_2$                               |                 | 0.32348        | 0.24979          |                 |                 |
| $m_4$                               |                 | 0.00155        | 0.00135          |                 |                 |
| $m_5$                               |                 | −0.00183       |                  |                 |                 |
| $m_7$                               |                 | 0.41893        |                  |                 |                 |
| Effect of strain rate $K\dot{\phi}$ |                 |                |                  |                 |                 |
| $m_3$                               |                 |                | 0.01153          |                 |                 |
| $m_8$                               |                 | 0.000075       |                  |                 |                 |
| Range of validity                   |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                    |                 | 750...1200     | 20...250         |                 |                 |
| $\phi$                              |                 | 0.03...1.50    | 0.03...1.50      |                 |                 |
| $\dot{\phi}$ [1/s]                  |                 | 0.1...100      | 0.01...100       |                 |                 |



| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.130** Flow stress curves of NiFe<sub>45</sub> by hot and cold forming.

**Mechanical properties after cold deformation**

| State of material | Yield stress $\Delta R_p$ [MPa] |          |        | Validity $\varepsilon$ [%] |
|-------------------|---------------------------------|----------|--------|----------------------------|
|                   | $A_0$                           | $A$      | $n_I$  |                            |
| soft annealed     | 175...200                       | 101.4829 | 0.4521 | <70                        |

Yield stress:

$$R_p = A_0 + A \cdot \varepsilon^{n_I}$$

[Equation (4.1), Chapter 5.1.4]

[DOI: [978-3-642-14174-4\\_5](https://doi.org/10.1007/978-3-642-14174-4_5)]**Physical properties**

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 18.8                 |                    |                                         | 8200                        |                 |
| 100              |                      |                    | 10.3                                    | 8174.6                      |                 |
| 200              |                      |                    | 10.3                                    | 8149.3                      |                 |
| 300              |                      |                    | 10.2                                    | 8124.7                      |                 |
| 400              |                      |                    | 10.1                                    | 8100.6                      |                 |
| 500              |                      |                    | 10.2                                    | 8074.5                      |                 |
| 600              |                      |                    | 10.8                                    | 8040.6                      |                 |

**Symbols and abbreviations**

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| UNS                 | unified numbering system                                              |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| ASTM                | American society for testing and materials                            |
| ASME                | American society of mechanical engineers                              |
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $T, \vartheta$      | temperature                                                           |
| $R_p$               | yield stress                                                          |
| $A, B, C$ and $n_i$ | constants                                                             |
| $\lambda$           | thermal conductivity                                                  |
| $c_{pm}$            | mean specific heat                                                    |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\rho$              | density                                                               |
| $E$                 | Young's modulus                                                       |

# Flow stress and physical properties of NiFe<sub>47</sub>Cr

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |               |               |                 |            |
|-------------|---------------|---------------|-----------------|------------|
| UNS number: | <b>N14080</b> | Chem. symbol: | <b>NiFe47Cr</b> | EN number: |
|-------------|---------------|---------------|-----------------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn    | P | S | Cr          | Mo | Ni    | V | Nb | Ti | Fe         |
|-------|-------|-------|---|---|-------------|----|-------|---|----|----|------------|
| <0.05 | <0.30 | <1.00 |   |   | 0.70...1.00 |    | <50.0 |   |    |    | 47.0..49.0 |

#### International comparison of standards

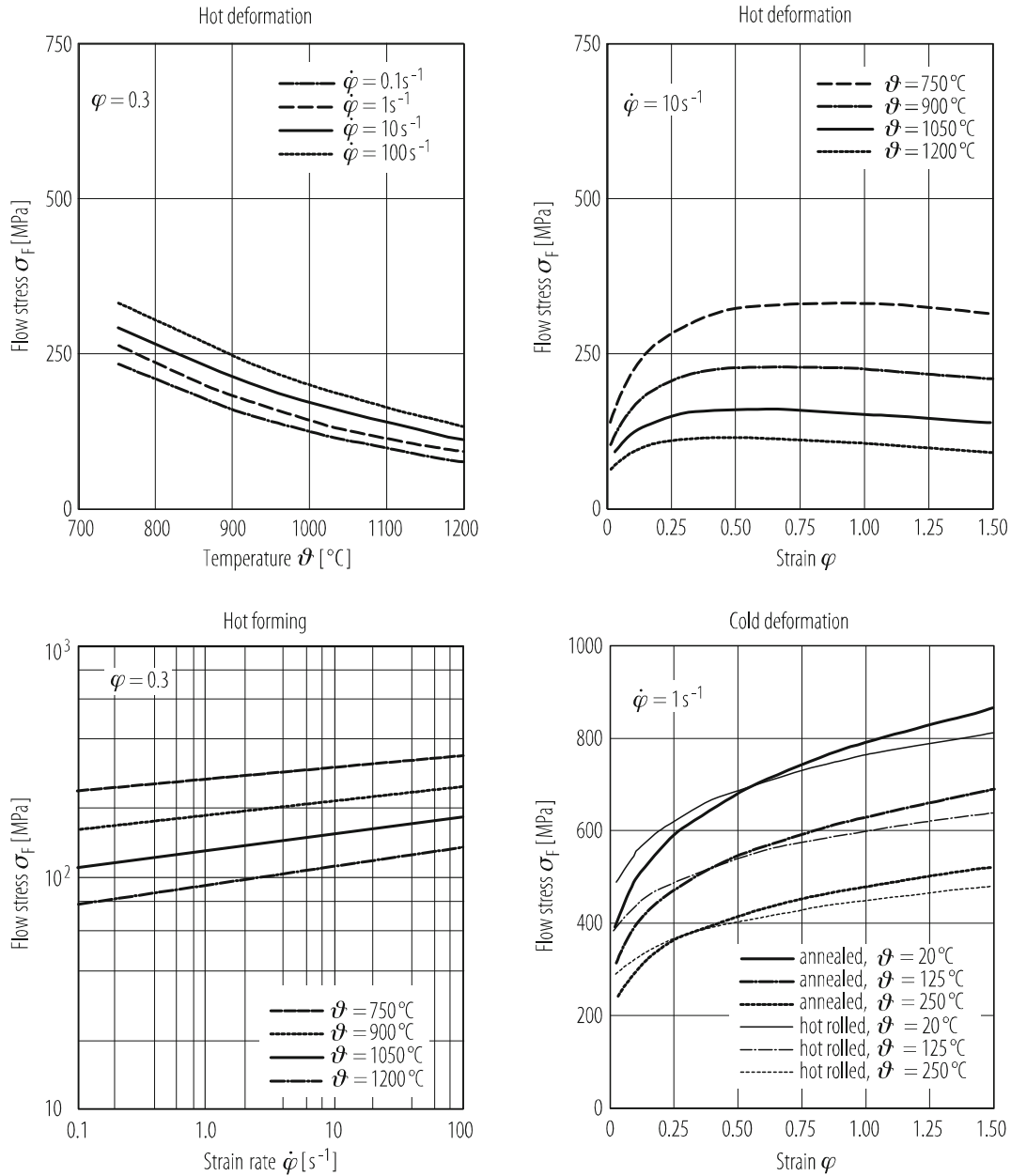
|                       |                |              |
|-----------------------|----------------|--------------|
| SEW                   |                | ISO          |
| SEW 385               |                |              |
| Material number (DIN) |                | DIN          |
| 2.4486                |                | DIN 17745    |
| Japan                 |                | Russia       |
| USA                   |                |              |
| ASME                  | ASTM           | UNS standard |
| ASME: F30             | ASTM A753 - 08 | N14080       |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                   | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                     | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                 |                 | 128.3          | 505.4            | 575.7           |                 |
| A                                   |                 | 2519.628       | 823.189          | 811.140         |                 |
| Effect of temperature $K_\theta$    |                 |                |                  |                 |                 |
| $m_1$                               |                 | -0.00207       | -0.00217         | -0.00231        |                 |
| Effect of strain $K_\phi$           |                 |                |                  |                 |                 |
| $m_2$                               |                 | 0.41843        | 0.21581          | 0.15390         |                 |
| $m_4$                               |                 | 0.00475        | 0.00296          | 0.00325         |                 |
| $m_5$                               |                 | -0.00094       |                  |                 |                 |
| $m_7$                               |                 | -0.11016       |                  |                 |                 |
| Effect of strain rate $K\dot{\phi}$ |                 |                |                  |                 |                 |
| $m_3$                               |                 |                | 0.00998          | 0.01095         |                 |
| $m_8$                               |                 | 0.000067       |                  |                 |                 |
| Range of validity                   |                 |                |                  |                 |                 |
| $\theta$ [°C]                       |                 | 750...1200     | 20...250         | 20...250        |                 |
| $\phi$                              |                 | 0.03...1.50    | 0.03...1.50      | 0.03...1.50     |                 |
| $\dot{\phi}$ [1/s]                  |                 | 0.1...100      | 0.01...100       | 0.01...100      |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.131** Flow stress curves of NiFe<sub>47</sub>Cr by hot and cold forming.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 17.0                 |                    |                                         | 8300                        | 160             |
| 100              |                      |                    | 10.3                                    | 8274.4                      |                 |
| 200              |                      |                    | 10.2                                    | 8249.2                      |                 |
| 300              |                      |                    | 10.1                                    | 8224.6                      |                 |
| 400              |                      |                    | 9.9                                     | 8201.4                      |                 |
| 500              |                      |                    | 10                                      | 8175.5                      |                 |
| 600              |                      |                    | 10.9                                    | 8137.2                      |                 |
| 700              |                      |                    | 11.8                                    | 8094.3                      |                 |
| 800              |                      |                    |                                         |                             |                 |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, plasticity and physical properties of NiFe<sub>16</sub>CuCr

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |               |               |                   |            |
|-------------|---------------|---------------|-------------------|------------|
| UNS number: | <b>K94490</b> | Chem. symbol: | <b>NiFe16CuCr</b> | EN number: |
|-------------|---------------|---------------|-------------------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn    | P | S | Cr          | Mo | Ni    | V | Nb | Cu          | Fe          |
|-------|-------|-------|---|---|-------------|----|-------|---|----|-------------|-------------|
| <0.05 | <0.30 | <1.00 |   |   | 1.50...2.50 |    | >75.5 |   |    | 4.00...6.00 | 15.0...18.0 |

#### International comparison of standards

|                       |                |              |        |
|-----------------------|----------------|--------------|--------|
| Euronorm              | ISO            |              |        |
| EN1092 3              |                |              |        |
| Material number (DIN) | DIN            |              |        |
| 2.4500                | DIN 17745      |              |        |
| United Kingdom        | Russia         |              |        |
| BS 4504               |                |              |        |
| USA                   |                |              |        |
| ASME                  | ASTM           | UNS standard |        |
|                       | ASTM A753 - 08 | K94490       | N14080 |
|                       |                | N14076       |        |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

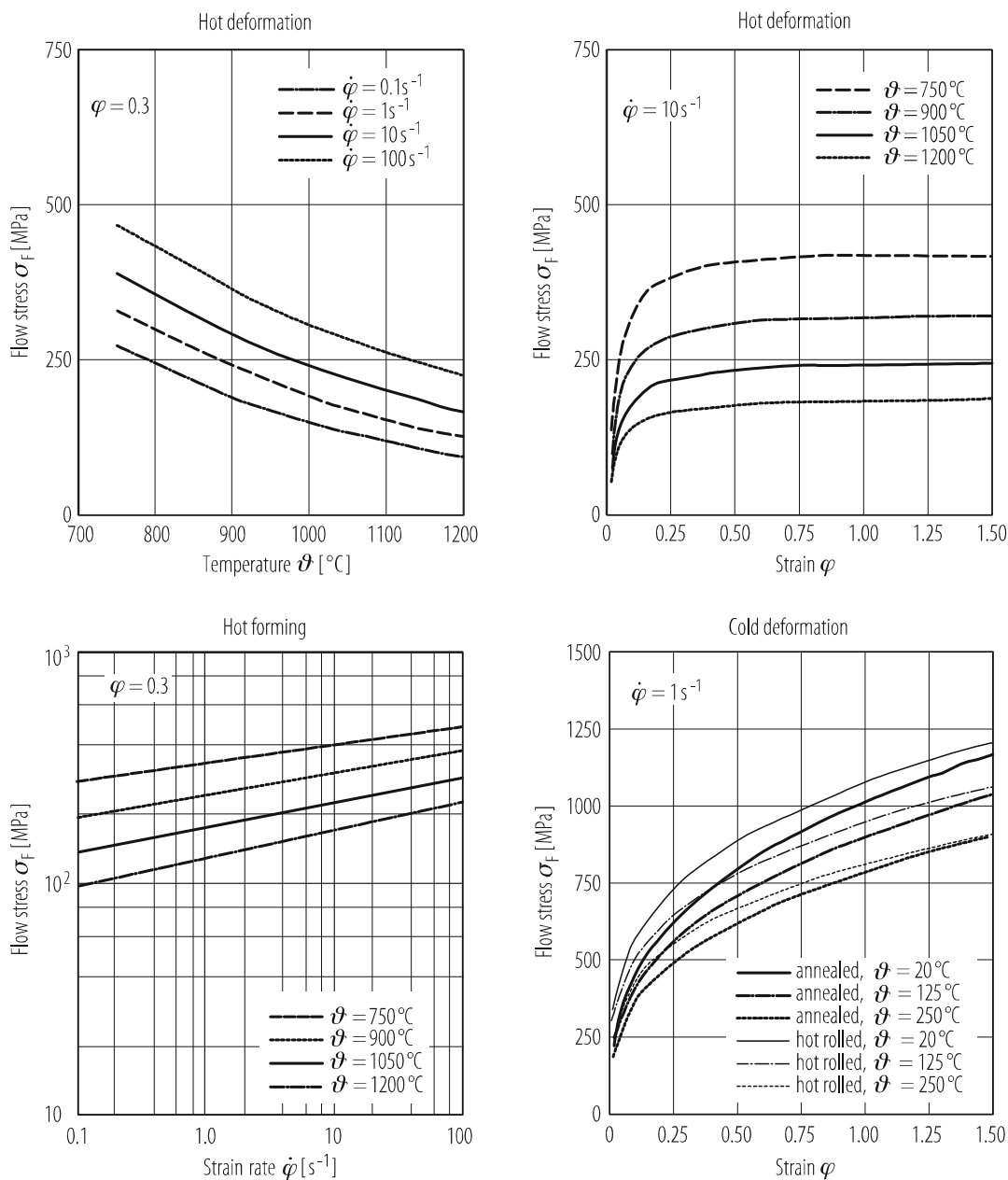
#### Flow curves

| State of material                  | Hot deformation |                | Cold deformation |                 |                 |
|------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                    | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                |                 | 202.3          | 470.5            | 583.2           |                 |
| A                                  |                 | 1855.963       | 1036.501         | 1105.501        |                 |
| Effect of temperature $K_{\theta}$ |                 |                |                  |                 |                 |
| $m_1$                              |                 | -0.00216       | -0.00111         | -0.00124        |                 |
| Effect of strain $K_{\varphi}$     |                 |                |                  |                 |                 |
| $m_2$                              |                 | 0.03426        | 0.34400          | 0.27780         |                 |
| $m_4$                              |                 | -0.02215       | 0.00087          | 0.00062         |                 |
| $m_5$                              |                 | 0.00017        |                  |                 |                 |
| $m_7$                              |                 | -0.11761       |                  |                 |                 |

(continued)

| State of material                      | Hot deformation |                 | Cold deformation |                 |                 |
|----------------------------------------|-----------------|-----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state  | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                 |                  |                 |                 |
| $m_3$                                  |                 |                 | 0.00682          | 0.00815         |                 |
| $m_8$                                  |                 | 0.000104        |                  |                 |                 |
| Range of validity                      |                 |                 |                  |                 |                 |
| $\vartheta$ [°C]                       |                 | 750. . . 1200   | 20. . . 250      | 20. . . 250     |                 |
| $\varphi$                              |                 | 0.03 . . . 1.50 | 0.03 . . . 1.50  | 0.03 . . . 1.50 |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.1 . . . 100   | 0.01 . . . 100   | 0.01 . . . 100  |                 |

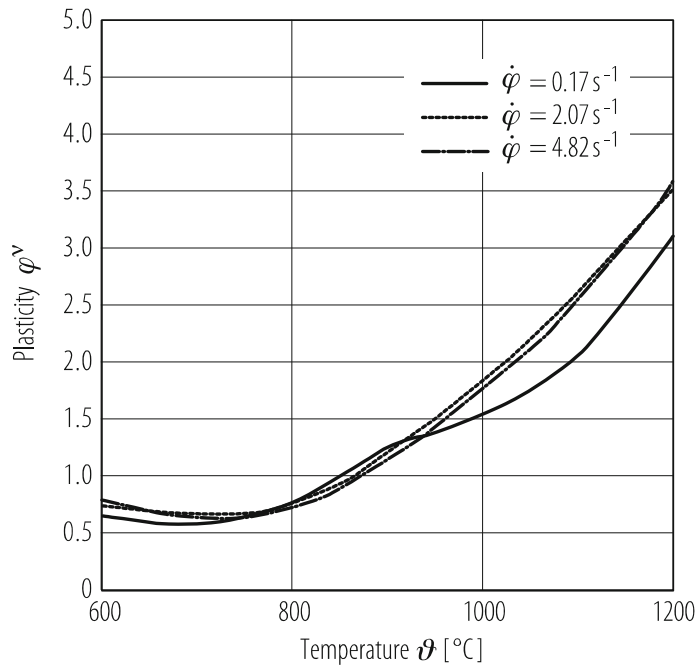
|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |



**Fig. 5.132** Flow stress curves of NiFe<sub>16</sub>CuCr by hot and cold forming.



Plasticity in torsion



**Fig. 5.133** Hot plasticity of NiFe16CuCr as a function of the temperature and deformation rate.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 30.4                 | 502                |                                         | 8600                        | 200             |
| 100              | 31.7                 |                    |                                         |                             |                 |
| 200              | 33.2                 |                    |                                         |                             |                 |
| 300              | 34.4                 |                    | 13.5                                    | 8495.5                      |                 |
| 400              | 35.4                 |                    |                                         |                             |                 |
| 500              | 36.2                 |                    | 13.0                                    | 8419.4                      |                 |
| 600              | 36.6                 |                    |                                         |                             |                 |
| 700              | 36.9                 |                    |                                         |                             |                 |
| 800              | 36.8                 |                    |                                         |                             |                 |
| 900              | 36.5                 |                    |                                         |                             |                 |
| 1000             | 36.0                 |                    |                                         |                             |                 |
| 1100             | 35.2                 |                    |                                         |                             |                 |
| 1200             | 34.2                 |                    |                                         |                             |                 |

Temperature dependence of thermal conductivity of FeNi80 was used

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| BS              | British standards                                                     |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches institut für normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress of NiFe<sub>16</sub>CuMo

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |               |               |                   |            |
|-------------|---------------|---------------|-------------------|------------|
| UNS number: | <b>K94840</b> | Chem. symbol: | <b>NiFe16CuMo</b> | EN number: |
|-------------|---------------|---------------|-------------------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn    | P | S | Cr | Mo          | Ni    | V | Nb | Cu          | Fe          |
|-------|-------|-------|---|---|----|-------------|-------|---|----|-------------|-------------|
| <0.05 | <0.30 | <1.00 |   |   |    | 3.00...5.00 | >75.5 |   |    | 4.00...6.00 | 13.0...17.0 |

#### International comparison of standards

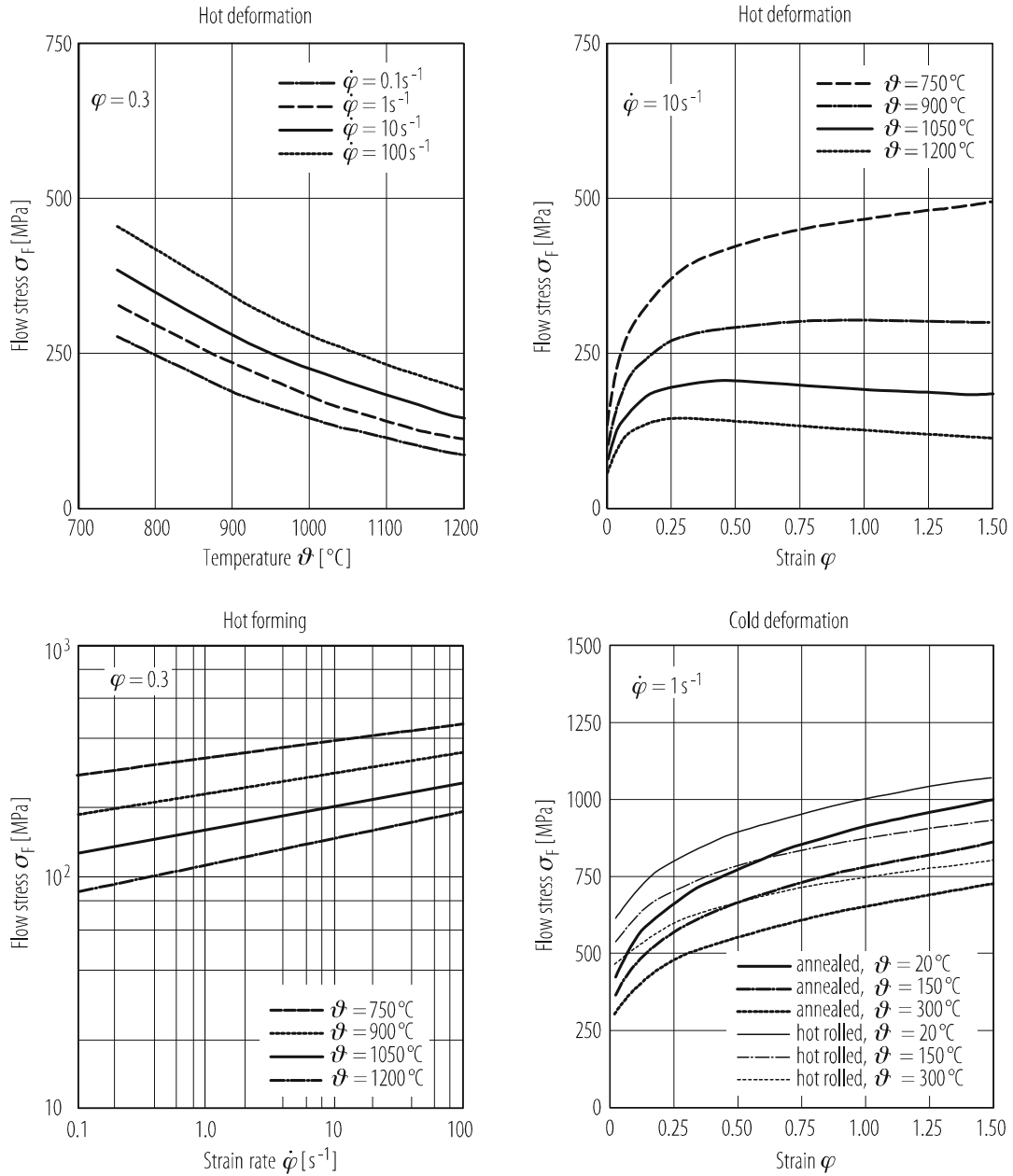
|                       |                |              |        |
|-----------------------|----------------|--------------|--------|
| Euronorm              | ISO            |              |        |
| EN 10155              |                |              |        |
| Material number (DIN) | DIN            |              |        |
| 2.4520                | DIN 17745      |              |        |
| Japan                 | Russia         |              |        |
| USA                   |                |              |        |
| ASME                  | ASTM           | UNS standard |        |
|                       | ASTM A753 - 08 | K94840       | N14080 |
|                       |                | N14080       |        |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                           | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 179.1          | 561.1            | 720.0           |                 |
| A                                         |                 | 2832.316       | 925.998          | 1018.759        |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                  |                 |                 |
| $m_1$                                     |                 | −0.00192       | −0.00117         | −0.00106        |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                  |                 |                 |
| $m_2$                                     |                 | 0.41236        | 0.23065          | 0.16546         |                 |
| $m_4$                                     |                 | 0.00181        | 0.00307          | 0.00329         |                 |
| $m_5$                                     |                 | −0.00178       |                  |                 |                 |
| $m_7$                                     |                 | 0.39231        |                  |                 |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |                 |                 |
| $m_3$                                     |                 |                | 0.00991          | 0.00964         |                 |
| $m_8$                                     |                 | 0.000096       |                  |                 |                 |
| Range of validity                         |                 |                |                  |                 |                 |
| $\theta$ [°C]                             |                 | 750...1200     | 20...300         | 20...300        |                 |
| $\varphi$                                 |                 | 0.03...1.50    | 0.03...1.50      | 0.03...1.50     |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.1...100      | 0.01...100       | 0.01...100      |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.134** Flow stress curves of NiFe<sub>16</sub>CuMo by hot and cold forming.

**Symbols and abbreviations**

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |

# Flow stress of NiFe<sub>15</sub>Mo

## 5.3 Nickel – and Nickel alloys

### Nickel – Ferrous – alloys

#### Designation

|             |               |               |                 |            |
|-------------|---------------|---------------|-----------------|------------|
| UNS number: | <b>K94840</b> | Chem. symbol: | <b>NiFe15Mo</b> | EN number: |
|-------------|---------------|---------------|-----------------|------------|

#### Composition (EN) [Weight-%]

| C     | Si    | Mn    | P | S | Cr | Mo          | Ni    | V | Nb | Ti | Fe          |
|-------|-------|-------|---|---|----|-------------|-------|---|----|----|-------------|
| <0.05 | <0.30 | <1.00 |   |   |    | 3.00...5.00 | >78.5 |   |    |    | 14.0...17.0 |

#### International comparison of standards

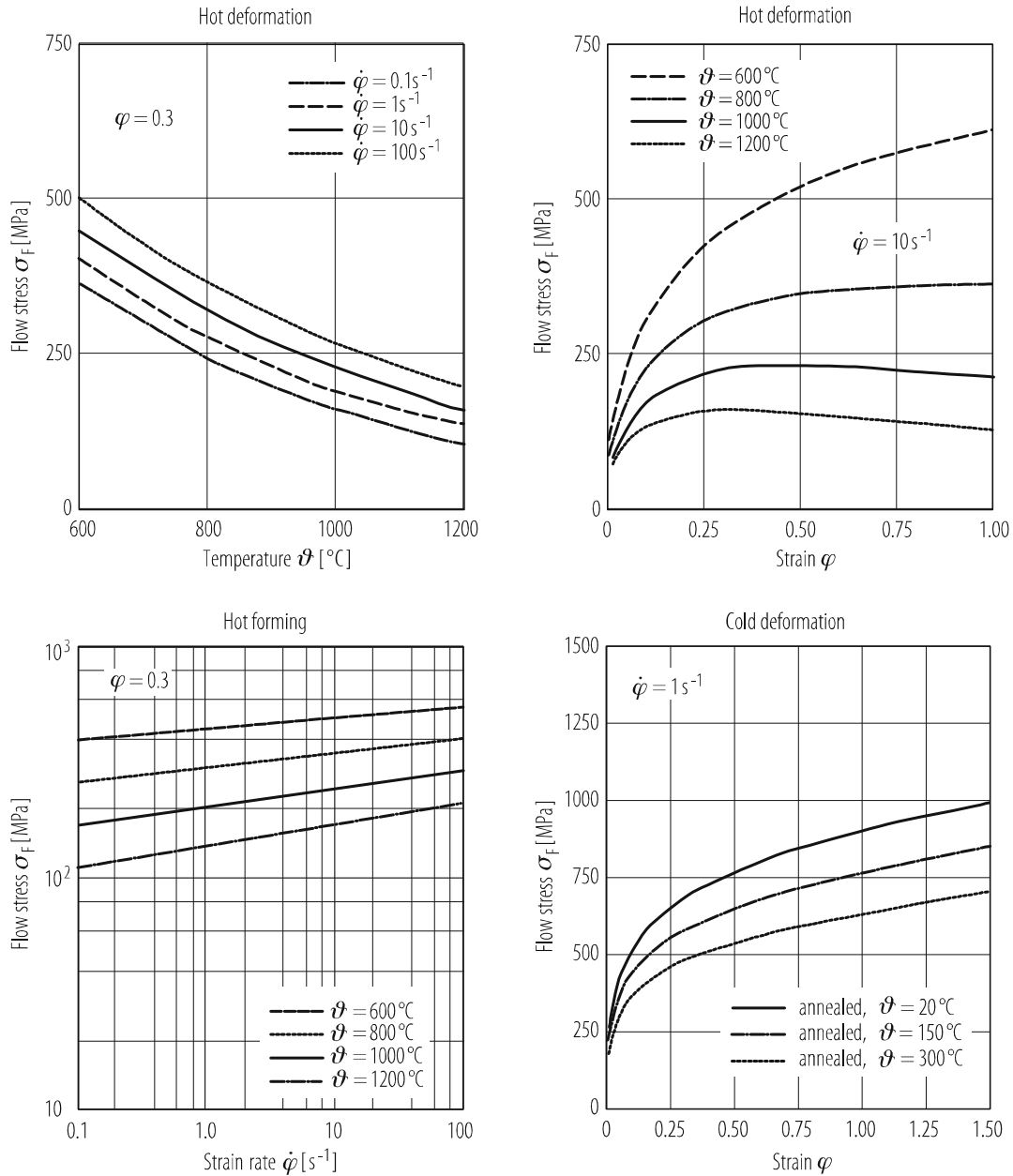
|                       |                |                   |
|-----------------------|----------------|-------------------|
| Euronorm              | ISO            |                   |
| EN 1044               | ISO 17672      |                   |
| Material number (DIN) | DIN            |                   |
| 2.4540                | DIN 17745      |                   |
| Japan                 | Russia         |                   |
|                       | 81NMA          | GOST 10994 (1974) |
| USA                   |                |                   |
| ASME                  | ASTM           | UNS standard      |
|                       | ASTM A753 - 08 | K94840            |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                           | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 173.2          | 530.0            |                 |                 |
| A                                         |                 | 2093.74        | 930.966          |                 |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                  |                 |                 |
| $m_1$                                     |                 | −0.00135       | −0.00128         |                 |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                  |                 |                 |
| $m_2$                                     |                 | 0.50937        | 0.22963          |                 |                 |
| $m_4$                                     |                 | 0.00214        | −0.00347         |                 |                 |
| $m_5$                                     |                 | −0.00208       |                  |                 |                 |
| $m_7$                                     |                 | 0.33677        |                  |                 |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |                 |                 |
| $m_3$                                     |                 |                | 0.01116          |                 |                 |
| $m_8$                                     |                 | 0.000075       |                  |                 |                 |
| Range of validity                         |                 |                |                  |                 |                 |
| $\theta$ [°C]                             |                 | 600...1200     | 20...300         |                 |                 |
| $\varphi$                                 |                 | 0.03 ... 1.00  | 0.03 ... 1.50    |                 |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.1 ... 100    | 0.01...100       |                 |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.135** Flow stress curves of NiFe<sub>15</sub>Mo by hot and cold forming.

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| EN              | Euronorm                                                              |
| GOST            | gosudarstvennyy standart (state standard)                             |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |



# Flow stress, plasticity and physical properties of NiMo<sub>16</sub>Cr<sub>16</sub>Ti

## 5.4 Chemical resistant and elevated-temperature alloys

### Designation

|             |               |               |                     |            |
|-------------|---------------|---------------|---------------------|------------|
| UNS number: | <b>N06450</b> | Chem. symbol: | <b>NiMo16Cr16Ti</b> | EN number: |
|-------------|---------------|---------------|---------------------|------------|

### Composition (DIN) [Weight-%]

| C      | Si    | Mn    | P      | S      | Cr          | Mo          | Ni   | Co    | Cu    | Ti    | Fe    |
|--------|-------|-------|--------|--------|-------------|-------------|------|-------|-------|-------|-------|
| <0.015 | <0.08 | <1.00 | <0.025 | <0.015 | 14.0...18.0 | 14.0...17.0 | Bal. | <2.00 | <0.50 | <0.70 | <3.00 |

### International comparison of standards

| Euronorm              |                | ISO            |              |
|-----------------------|----------------|----------------|--------------|
|                       |                | NiMo16Cr16Ti   | 9722         |
| Material number (DIN) |                | DIN            |              |
| 2.4610                |                | DIN 17744      |              |
| China                 |                | United Kingdom |              |
| H03350                | T 15007 (1994) | NA 45          | BS 3076      |
| USA                   |                |                |              |
| ASME                  | ASTM           |                | UNS standard |
| ASME B16.11           | ASTM B366 - 10 | ASTM B446 - 03 | N06450       |
|                       | ASTM B 899-09  | ASTM B 755-00  |              |
|                       | ASTM B 455-00  |                |              |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material           | Hot deformation |                | Cold deformation |                 |                 |
|-----------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                             | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]         |                 | 341.8          | 805.6            |                 |                 |
| A                           |                 | 9125.494       | 1443.366         |                 |                 |
| Effect of temperature $K_9$ |                 |                |                  |                 |                 |
| $m_1$                       |                 | -0.00293       | -0.00079         |                 |                 |

(continued)

| State of material                      | Hot deformation |                 | Cold deformation |                 |                 |
|----------------------------------------|-----------------|-----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state  | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Effect of strain $K_\varphi$           |                 |                 |                  |                 |                 |
| $m_2$                                  |                 | 0.23974         | 0.26880          |                 |                 |
| $m_4$                                  |                 | 0.00136         | 0.00223          |                 |                 |
| $m_5$                                  |                 | −0.00012        |                  |                 |                 |
| $m_7$                                  |                 | −0.42485        |                  |                 |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                 |                  |                 |                 |
| $m_3$                                  |                 |                 | 0.01272          |                 |                 |
| $m_8$                                  |                 | 0.000103        |                  |                 |                 |
| Range of validity                      |                 |                 |                  |                 |                 |
| $\vartheta$ [°C]                       |                 | 900. . . 1200   | 20. . . 300      |                 |                 |
| $\varphi$                              |                 | 0.03 . . . 0.50 | 0.03 . . . 0.80  |                 |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.10. . . 50    | 0.01. . . 50     |                 |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

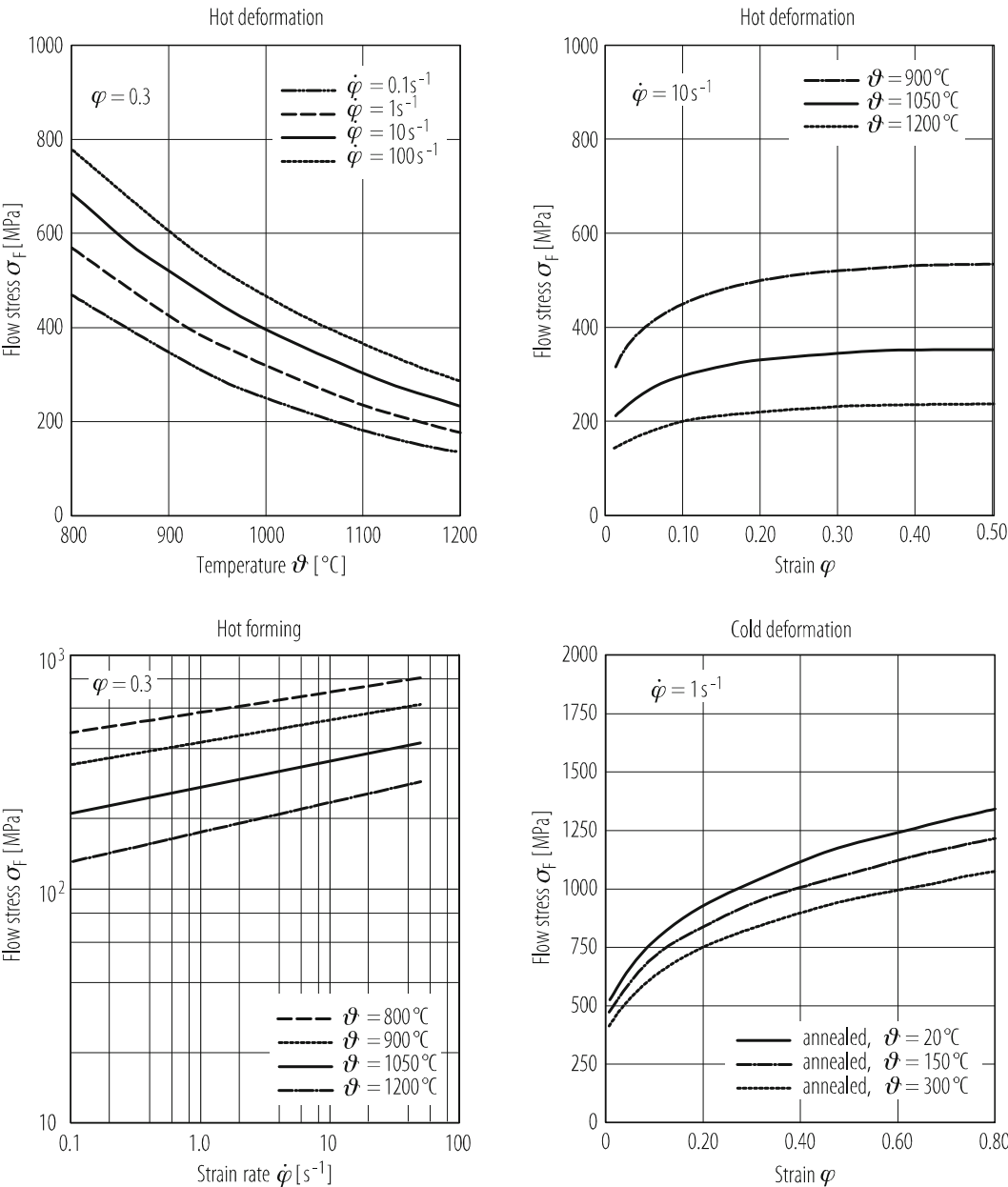
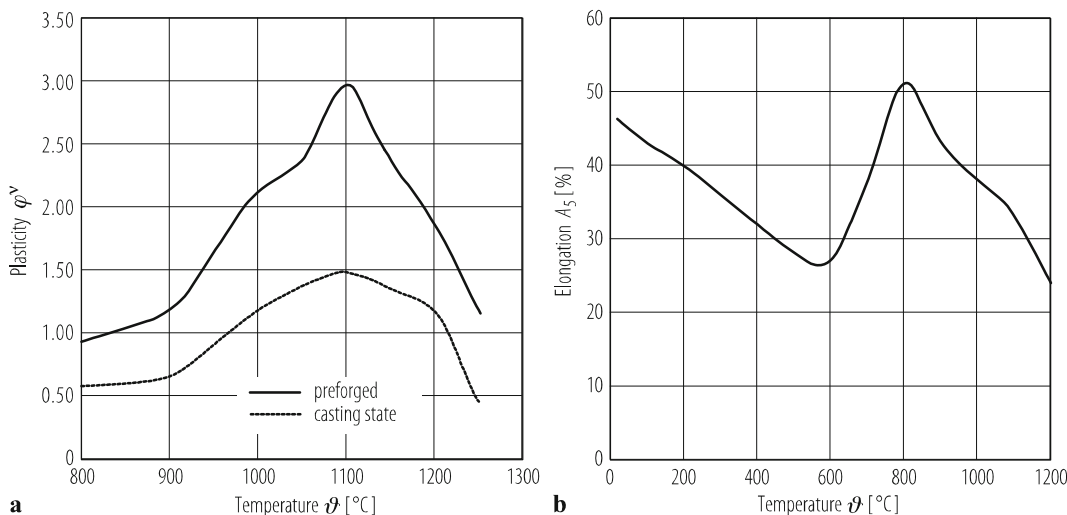


Fig. 5.136 Flow stress curves of NiMo16Cr16Ti by hot and cold forming.

Plasticity in torsion and tensile test



**Fig. 5.137** Hot and cold plasticity of NiMo<sub>16</sub>Cr<sub>16</sub>Ti as a function of the temperature. Hot deformation (a) Torsion test (b) Tensile test.

Physical properties

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [10 <sup>-6</sup> /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                              | 10.1                                      | 408.0                                   |                                                                                | 8600                                   | 211                          |
| 100                             | 11.4                                      | 426.0                                   | 10.9                                                                           | 8571.9                                 | 207                          |
| 200                             | 13.2                                      | 448.0                                   | 11.9                                                                           | 8538.6                                 | 202                          |
| 300                             | 15.0                                      | 465.0                                   | 12.5                                                                           | 8503.3                                 | 195                          |
| 400                             | 16.7                                      | 477.0                                   | 12.9                                                                           | 8466.9                                 | 188                          |
| 500                             | 18.4                                      | 490.0                                   | 13.2                                                                           | 8429.7                                 | 181                          |
| 600                             | 20.5                                      | 502.0                                   | 13.6                                                                           | 8389.5                                 | 175                          |
| 700                             | 22.6                                      | 518.0                                   | 14                                                                             | 8347.2                                 | 168                          |
| 800                             | 24.8                                      | 533.3                                   | 14.5                                                                           | 8300.7                                 | 158                          |
| 900                             | 26.3                                      | 548.4                                   | 15.1                                                                           | 8249.4                                 | 149                          |
| 1000                            | 28.1                                      | 563.4                                   | 15.9                                                                           | 8189.8                                 | 138                          |
| 1100                            | 30.0                                      | 578.5                                   | 16.6                                                                           | 8128.9                                 | 123                          |
| 1200                            | 31.9                                      | 593.5                                   | 17.3                                                                           | 8064.4                                 | 106                          |

Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| BS              | British standards                                                     |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| $E$            | Young's modulus                                |
| EN             | Euronorm                                       |
| ISO            | international organisation for standardization |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |

# Flow stress, plasticity and physical properties of NiMo<sub>28</sub>

## 5.4 Chemical resistant and elevated-temperature alloys

### Designation

|             |               |               |               |            |
|-------------|---------------|---------------|---------------|------------|
| UNS number: | <b>N10665</b> | Chem. symbol: | <b>NiMo28</b> | EN number: |
|-------------|---------------|---------------|---------------|------------|

### Composition (DIN) [Weight-%]

| C     | Si    | Mn    | P      | S      | Cr    | Mo          | Ni   | V | Co    | Cu    | Fe    |
|-------|-------|-------|--------|--------|-------|-------------|------|---|-------|-------|-------|
| <0.01 | <0.08 | <1.00 | <0.025 | <0.015 | <1.00 | 26.0...30.0 | Bal. |   | <1.00 | <0.50 | <2.00 |

### International comparison of standards

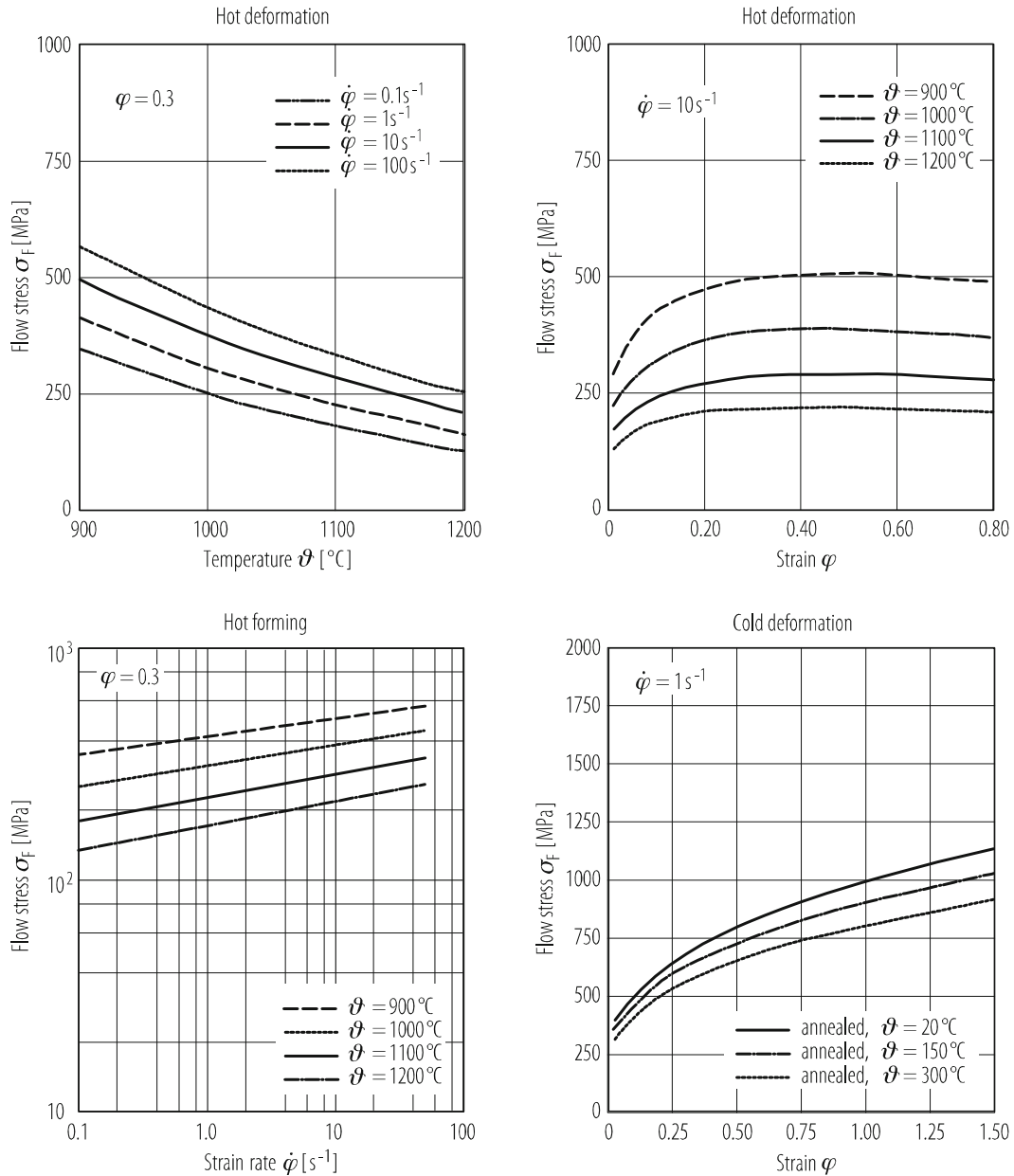
|                       |                |               |         |
|-----------------------|----------------|---------------|---------|
| Euronorm              |                | ISO           |         |
|                       |                | NiMo28        | 9722    |
| Material number (DIN) |                | DIN           |         |
| 2.4617                |                | 17744         |         |
| China                 |                | Russia        |         |
| H03220                | T 15007 (1994) |               |         |
| USA                   |                |               |         |
| ASME                  | ASTM           | UNS standard  |         |
| ASME SB 333           | ASTM B 462-10  | ASTMB333-03   | N 10665 |
| ASME SB 366           | ASTM B335-03   | ASTM B 622-10 | R30007  |
| ASME SB 626           | ASTM B 626-10  |               |         |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

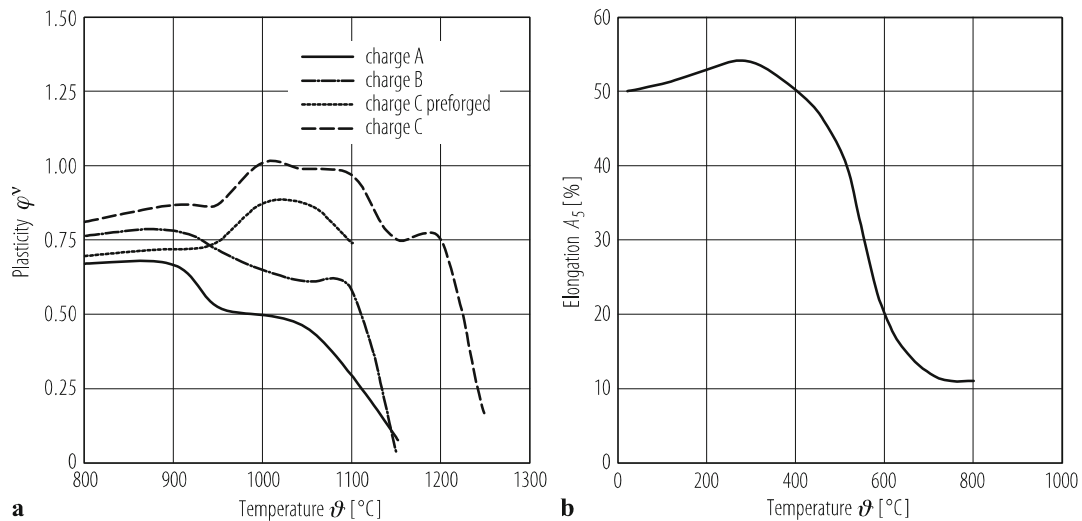
| State of material                         | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                           | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 322.72         | 515.8            |                 |                 |
| A                                         |                 | 9125.494       | 1006.690         |                 |                 |
| Effect of temperature $K_\theta$          |                 |                |                  |                 |                 |
| $m_1$                                     |                 | -0.00293       | -0.00078         |                 |                 |
| Effect of strain $K_\varphi$              |                 |                |                  |                 |                 |
| $m_2$                                     |                 | 0.24897        | 0.31762          |                 |                 |
| $m_4$                                     |                 | 0.00129        | 0.00563          |                 |                 |
| $m_5$                                     |                 | -0.00015       |                  |                 |                 |
| $m_7$                                     |                 | -0.43028       |                  |                 |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |                 |                 |
| $m_3$                                     |                 |                | 0.00953          |                 |                 |
| $m_8$                                     |                 | 0.000089       |                  |                 |                 |
| Range of validity                         |                 |                |                  |                 |                 |
| $\theta$ [°C]                             |                 | 900...1200     | 20...300         |                 |                 |
| $\varphi$                                 |                 | 0.03...0.8     | 0.03...1.50      |                 |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.10...50      | 0.01...100       |                 |                 |

| Hot deformation:                                                                                                                                                                     | Cold deformation                                                                                                 |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \dot{\varphi}^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \dot{\varphi}^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                                 | [Equation (2.25), Chapter 2.3.2.2.2]                                                                             |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                                | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                            |



**Fig. 5.138** Flow stress curves of NiMo<sub>28</sub> by hot and cold forming.

## Plasticity in torsion and tensile test



**Fig. 5.139** Hot and cold plasticity of NiMo<sub>28</sub> as a function of the temperature. (a) Torsion test (b) Tensile test.

## Physical properties

| Temperature<br>$\theta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                           | 11.4                                      | 377.0                                   |                                                                          | 9200.0                                 | 217                          |
| 100                          | 12.2                                      | 389.0                                   | 10.30                                                                    | 9171.6                                 | 213                          |
| 200                          | 13.4                                      | 406.0                                   | 10.80                                                                    | 9140.4                                 | 208                          |
| 300                          | 14.6                                      | 423.0                                   | 11.10                                                                    | 9108.1                                 | 203                          |
| 400                          | 16.0                                      | 431.0                                   | 11.40                                                                    | 9074.1                                 | 197                          |
| 500                          | 17.3                                      | 444.0                                   | 11.60                                                                    | 9039.9                                 | 191                          |
| 600                          | 18.7                                      | 456.0                                   | 11.80                                                                    | 9004.6                                 | 184                          |
| 700                          | 19.9                                      | 417.6                                   | 12.00                                                                    | 8968.2                                 | 176                          |
| 800                          | 21.2                                      | 431.2                                   | 12.10                                                                    | 8932.8                                 | 172                          |
| 900                          | 22.5                                      | 444.7                                   | 12.20                                                                    | 8897.0                                 | 165                          |
| 1000                         | 23.7                                      | 458.3                                   | 12.39                                                                    | 8858.0                                 | 160                          |
| 1100                         | 25.0                                      | 471.8                                   | 12.54                                                                    | 8819.3                                 | 154                          |
| 1200                         | 26.3                                      | 485.4                                   | 12.69                                                                    | 8779.7                                 | 148                          |

## Symbols and abbreviations

| Short form   | Full form                                                             |
|--------------|-----------------------------------------------------------------------|
| $\sigma_F$   | flow stress                                                           |
| $\phi$       | strain                                                                |
| $\dot{\phi}$ | strain rate                                                           |
| ASME         | American society of mechanical engineers                              |
| ASTM         | American society for testing and materials                            |
| $c_{pm}$     | mean specific heat                                                    |
| DIN          | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$          | Young's modulus                                                       |
| EN           | Euronorm                                                              |

(continued)



| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| ISO            | international organisation for standardization |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |

# Flow stress and plasticity of NiCr<sub>20</sub>Co<sub>18</sub>Ti

## 5.4 Chemical resistant and elevated-temperature alloys

### Designation

|             |               |               |                     |            |
|-------------|---------------|---------------|---------------------|------------|
| UNS number: | <b>N07090</b> | Chem. symbol: | <b>NiCr20Co18Ti</b> | EN number: |
|-------------|---------------|---------------|---------------------|------------|

### Composition (EN) [Weight-%]

| C     | Si    | Mn    | P      | S     | Cr          | Co          | Ni   | Cu    | B      | Ti          | Fe    | Al          | Zr    |
|-------|-------|-------|--------|-------|-------------|-------------|------|-------|--------|-------------|-------|-------------|-------|
| <0.13 | <1.00 | <1.00 | <0.020 | 0.015 | 18.0...21.0 | 15.0...21.0 | Bal. | <0.20 | <0.020 | 2.00...3.00 | <1.50 | 1.00...2.00 | <0.15 |

### International comparison of standards

| Euronorm              |  | ISO             |                |
|-----------------------|--|-----------------|----------------|
| NiCr20Co18Ti          |  | 10302 (05/2002) |                |
| Material number (DIN) |  | DIN             |                |
| 2.4632                |  | DIN 17742       |                |
| France                |  | United Kingdom  |                |
| NiCr20Co18Ti          |  | NA 20           | BS 3076 (1989) |
| USA                   |  |                 |                |
| AMS                   |  | ASTM            | UNS standard   |
| AMS 5829              |  | ASTM B 899-09   | N07090         |
|                       |  | ASTM E292-09    |                |
|                       |  | ASTM B 637-12   |                |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                           | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 492.1          |                  |                 |                 |
| A                                         |                 | 228396.740     |                  |                 |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                  |                 |                 |
| $m_1$                                     |                 | -0.00656       |                  |                 |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                  |                 |                 |
| $m_2$                                     |                 | -0.04269       |                  |                 |                 |
| $m_4$                                     |                 | -0.00603       |                  |                 |                 |
| $m_5$                                     |                 | 0.00120        |                  |                 |                 |
| $m_7$                                     |                 | -0.80342       |                  |                 |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |                 |                 |
| $m_3$                                     |                 |                |                  |                 |                 |
| $m_8$                                     |                 | 0.000151       |                  |                 |                 |
| Range of validity                         |                 |                |                  |                 |                 |
| $\theta$ [°C]                             |                 | 850...1200     |                  |                 |                 |
| $\varphi$                                 |                 | 0.03...0.5     |                  |                 |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.01...100     |                  |                 |                 |

|                                                                                                                                                                                |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          |

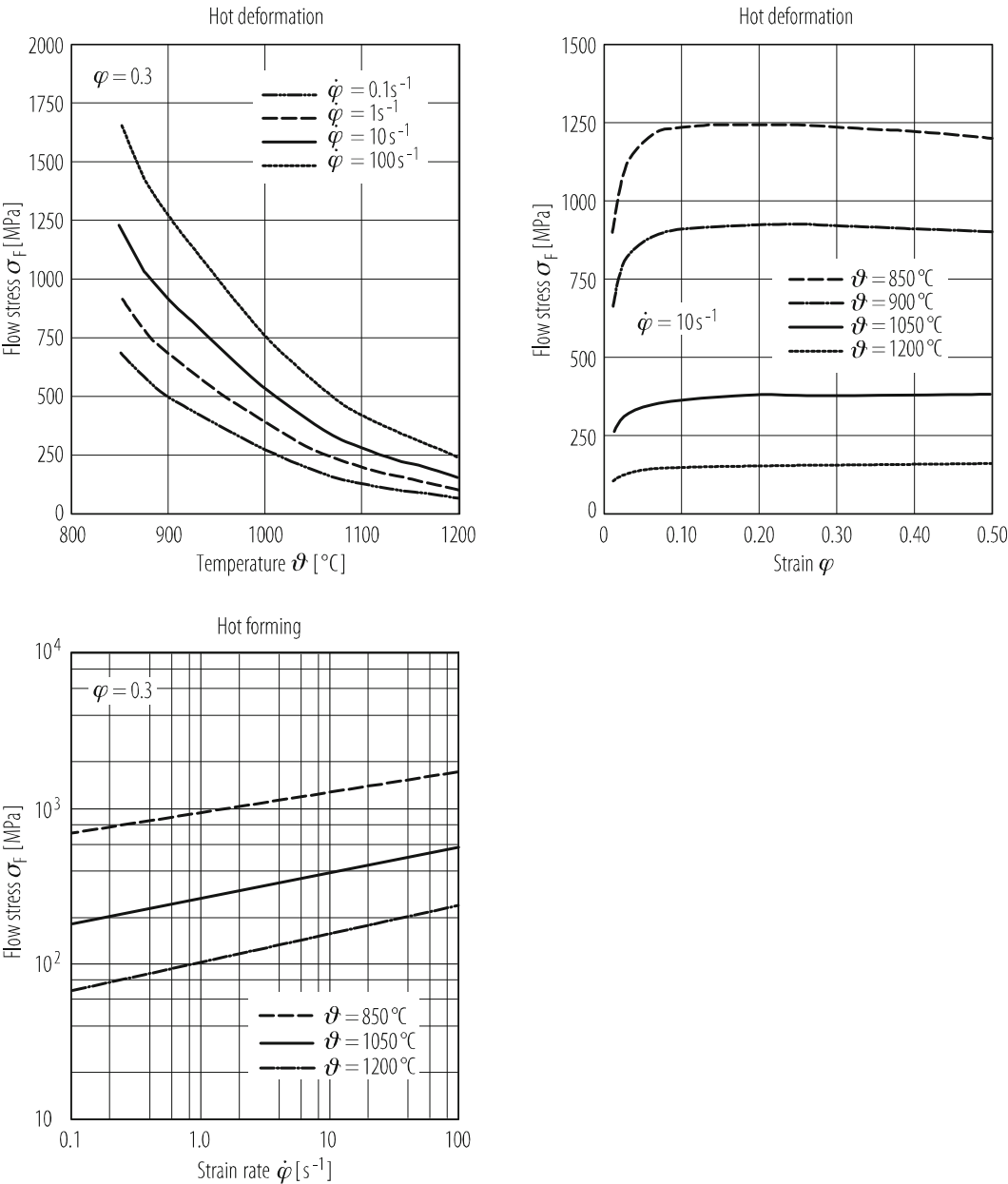
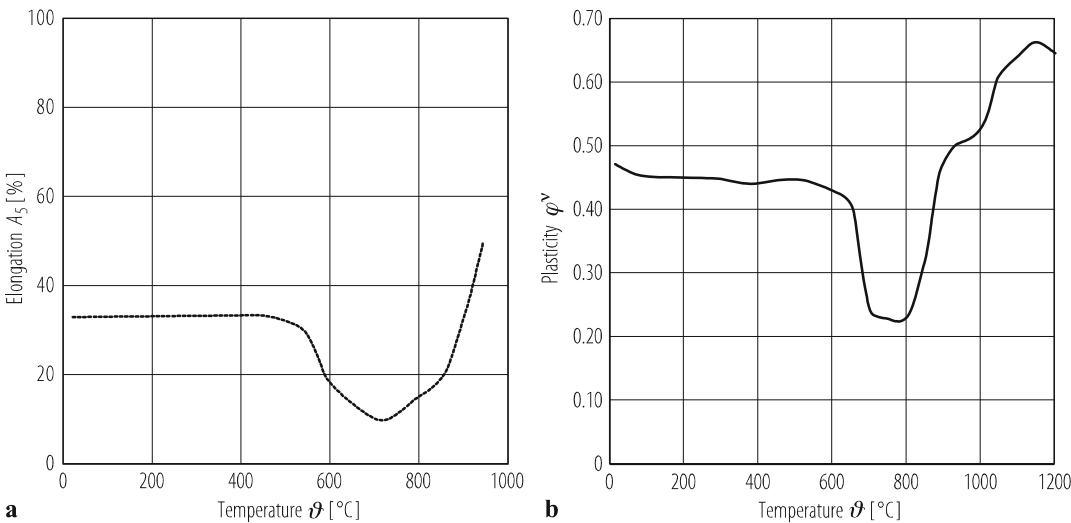


Fig. 5.140 Flow stress curves of NiCr20Co18Ti by hot forming.

Plasticity in torsion



**Fig. 5.141** Hot and cold plasticity of NiCr<sub>20</sub>Co<sub>18</sub>Ti as a function of the temperature. (a) Tensile test (b) Torsion test.

Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| AMS             | aerospace material standards                                          |
| ASTM            | American society for testing and materials                            |
| BS              | British standards                                                     |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |

# Flow stress, plasticity and physical properties of NiCo<sub>20</sub>Cr<sub>15</sub>MoAlTi

## 5.4 Chemical resistant and elevated-temperature alloys

### Designation

|             |               |               |                         |            |
|-------------|---------------|---------------|-------------------------|------------|
| UNS number: | <b>N13021</b> | Chem. symbol: | <b>NiCo20Cr15MoAlTi</b> | EN number: |
|-------------|---------------|---------------|-------------------------|------------|

### Composition (EN) [Weight-%]

| C           | Si    | Mn    | P      | S      | Cr          | Mo          | Ni   | Co          | Cu    | Ti          | Fe    | Al          | B            | Zr    |
|-------------|-------|-------|--------|--------|-------------|-------------|------|-------------|-------|-------------|-------|-------------|--------------|-------|
| 0.12...0.17 | <1.00 | <1.00 | <0.045 | <0.015 | 14.0...15.7 | 4.50...5.50 | Bal. | 18.0...22.0 | <0.20 | 0.90...1.50 | <1.00 | 4.50...4.90 | 0.003...0.01 | <0.15 |

### International comparison of standards

| Euronorm              |                | ISO               |              |
|-----------------------|----------------|-------------------|--------------|
| AECMA                 |                | ISO NW 3021       | ISO 9725     |
|                       |                | ISO 9723          |              |
| Material number (DIN) |                | DIN               |              |
| 2.4634                |                |                   |              |
| France                |                | United Kingdom    |              |
| AFNOR NK 20 CDA       | AIR 9165       | NIMONIC alloy 105 | BS HR3       |
| USA                   |                |                   |              |
| ASME                  | ASTM           |                   | UNS standard |
| ASME B16.11           | ASTM B626 - 10 | ASTM B619 - 10    | N13021       |
| ASME B16.9            | ASTM B622 - 10 | ASTM B666 - 10    |              |
|                       | ASTM B333 - 03 | ASTM B899 - 09    |              |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

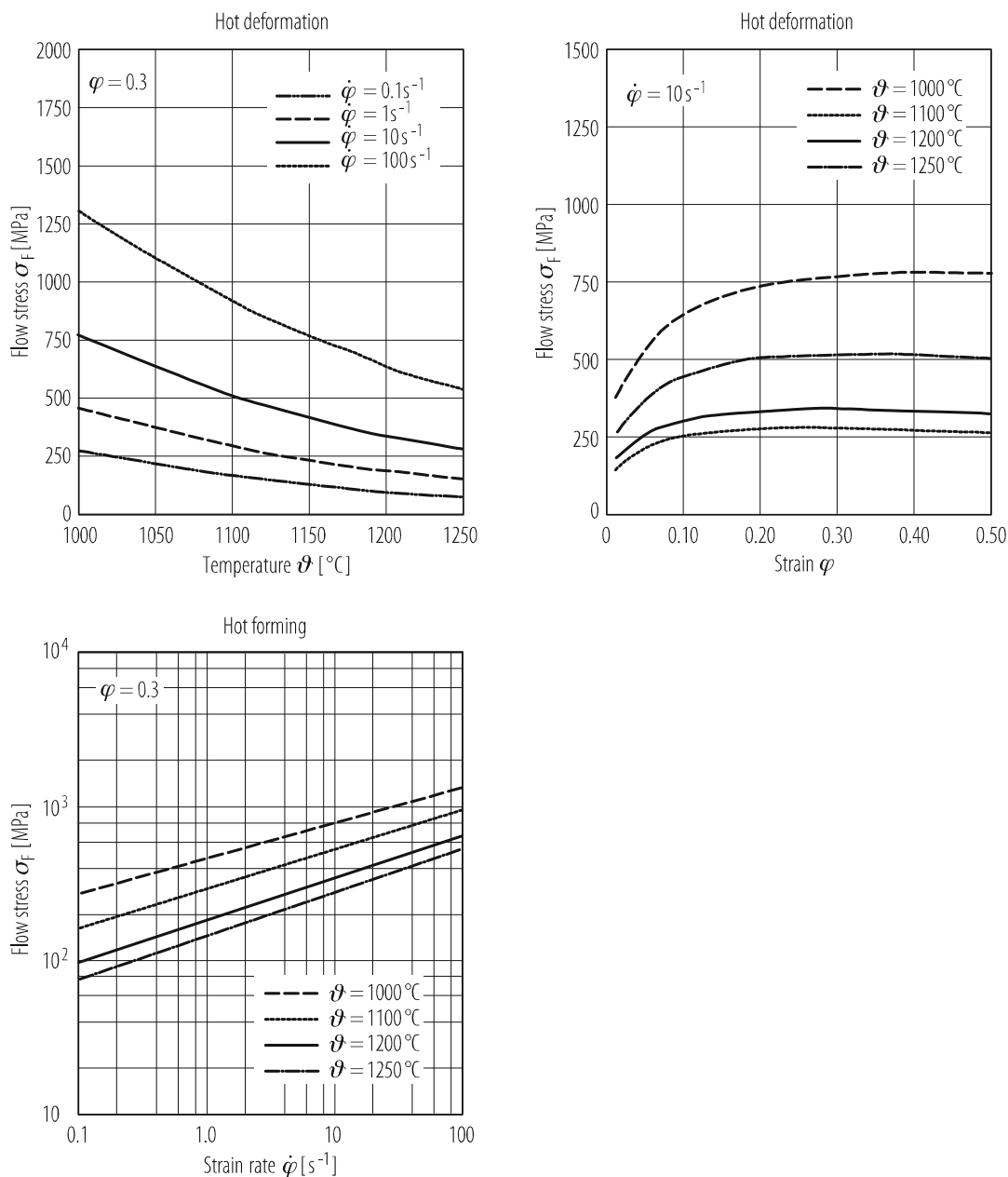
### Flow curves

| State of material            | Hot deformation |                | Cold deformation |                 |                 |
|------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                              | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]          |                 | 643.76         |                  |                 |                 |
| A                            |                 | 65898.700      |                  |                 |                 |
| Effect of temperature $K_9$  |                 |                |                  |                 |                 |
| $m_1$                        |                 | -0.00412       |                  |                 |                 |
| Effect of strain $K_\varphi$ |                 |                |                  |                 |                 |
| $m_2$                        |                 | 0.39533        |                  |                 |                 |
| $m_4$                        |                 | 0.00191        |                  |                 |                 |
| $m_5$                        |                 | -0.00187       |                  |                 |                 |
| $m_7$                        |                 | 0.34893        |                  |                 |                 |

(continued)

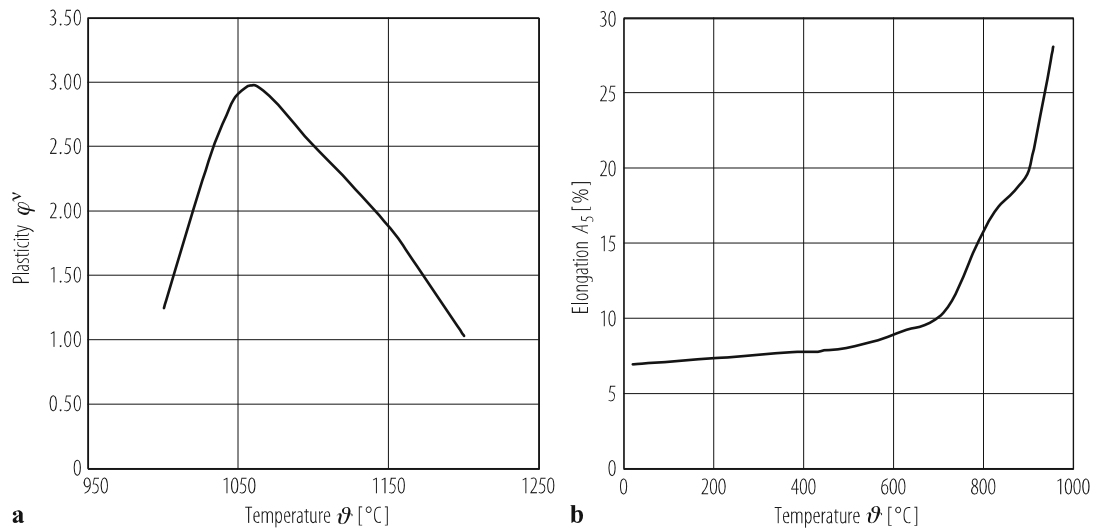
| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                |                  |                 |                 |
| $m_8$                                  |                 | 0.000228       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                       |                 | 1000. . . 1250 |                  |                 |                 |
| $\varphi$                              |                 | 0.03 . . . 0.5 |                  |                 |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.1 . . . 100  |                  |                 |                 |

|                                                                                                                                                                                  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                                 |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4 / \varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                             |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                            |



**Fig. 5.142** Flow stress curves of NiCo<sub>20</sub>Cr<sub>15</sub>MoAlTi by hot and cold forming.

### Plasticity in torsion and tensile test



**Fig. 5.143** Hot and cold plasticity of NiCo<sub>20</sub>Cr<sub>15</sub>MoAlTi as a function of the temperature. **(a)** Hot deformation. **(b)** Cold deformation.

### Physical properties

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                              | 10.8                                      | 461.6                                   |                                                                          | 8180                                   |                              |
| 100                             | 11.6                                      | 467.9                                   | 9.70                                                                     | 8156.2                                 | 223                          |
| 200                             | 13.1                                      | 476.0                                   | 11.60                                                                    | 8123.1                                 | 219                          |
| 300                             | 14.7                                      | 484.2                                   | 12.30                                                                    | 8089.4                                 | 213                          |
| 400                             | 15.9                                      | 492.6                                   | 12.80                                                                    | 8054.4                                 | 206                          |
| 500                             | 17.4                                      | 501.1                                   | 13.30                                                                    | 8016.8                                 | 200                          |
| 600                             | 19.3                                      | 509.7                                   | 13.70                                                                    | 7978.3                                 | 193                          |
| 700                             | 21.1                                      | 518.5                                   | 14.50                                                                    | 7930.9                                 | 186                          |
| 800                             | 23.0                                      | 527.4                                   | 15.40                                                                    | 7877.7                                 | 178                          |
| 900                             | 25.1                                      | 536.5                                   | 16.80                                                                    | 7809.0                                 | 169                          |
| 1000                            | 26.6                                      | 545.8                                   | 17.67                                                                    | 7746.5                                 | 155                          |
| 1100                            | 28.2                                      | 555.2                                   | 18.51                                                                    | 7680.4                                 | 138                          |
| 1200                            | 29.9                                      | 564.8                                   | 19.35                                                                    | 7610.2                                 | 126                          |



**Symbols and abbreviations**

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| AFNOR           | Association Française de Normalisation                                |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| BS              | British standards                                                     |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress of NiCo<sub>15</sub>Cr<sub>15</sub>MoAlTi

## 5.4 Chemical resistant and elevated-temperature alloys

### Designation

|             |  |               |                  |            |
|-------------|--|---------------|------------------|------------|
| UNS number: |  | Chem. symbol: | NiCo15Cr15MoAlTi | EN number: |
|-------------|--|---------------|------------------|------------|

### Composition (EN) [Weight-%]

| C    | Si   | Mn   | P     | S     | Cr   | Mo   | Ni   | V | Nb | Ti   | Fe   | Co   | Cu   | Al   | B     | Zr   |
|------|------|------|-------|-------|------|------|------|---|----|------|------|------|------|------|-------|------|
| 0.12 | 0.03 | 0.03 | 0.03  | 0.03  | 14.0 | 3.00 | Bal. |   |    | 3.50 | 0.03 | 13.0 | 0.03 | 4.50 | 0.01  | 0.03 |
| ...  | ...  | ...  | ...   | ...   | ...  | ...  |      |   |    | ...  | ...  | ...  | ...  | ...  | ...   | ...  |
| 0.20 | 1.00 | 1.00 | 0.045 | 0.030 | 16.0 | 5.00 |      |   |    | 4.50 | 1.00 | 17.0 | 0.20 | 5.50 | 0.025 | 0.25 |

### International comparison of standards

|                       |         |                 |
|-----------------------|---------|-----------------|
| Euronorm              |         | ISO             |
| EN 2582               | EN 2929 |                 |
| Material number (DIN) |         | DIN             |
| 2.4636                |         |                 |
| United Kingdom        |         | France          |
| NIMONIC alloy 115     | BS HR 4 | AFNOR NCK 15ATD |
| USA                   |         |                 |
| ASME                  | ASTM    | UNS standard.   |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                           | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 865.5          |                  |                 |                 |
| A                                         |                 | 13053106.000   |                  |                 |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                  |                 |                 |
| $m_1$                                     |                 | -0.00883       |                  |                 |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                  |                 |                 |
| $m_2$                                     |                 | 0.44284        |                  |                 |                 |
| $m_4$                                     |                 | 0.00463        |                  |                 |                 |
| $m_5$                                     |                 | -0.00230       |                  |                 |                 |
| $m_7$                                     |                 | 0.50382        |                  |                 |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |                 |                 |
| $m_3$                                     |                 |                |                  |                 |                 |
| $m_8$                                     |                 | 0.000152       |                  |                 |                 |
| Range of validity                         |                 |                |                  |                 |                 |
| $\theta$ [°C]                             |                 | 1000...1250    |                  |                 |                 |
| $\varphi$                                 |                 | 0.03...1.0     |                  |                 |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.1...50       |                  |                 |                 |

|                                                                                                                                                                                |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          |

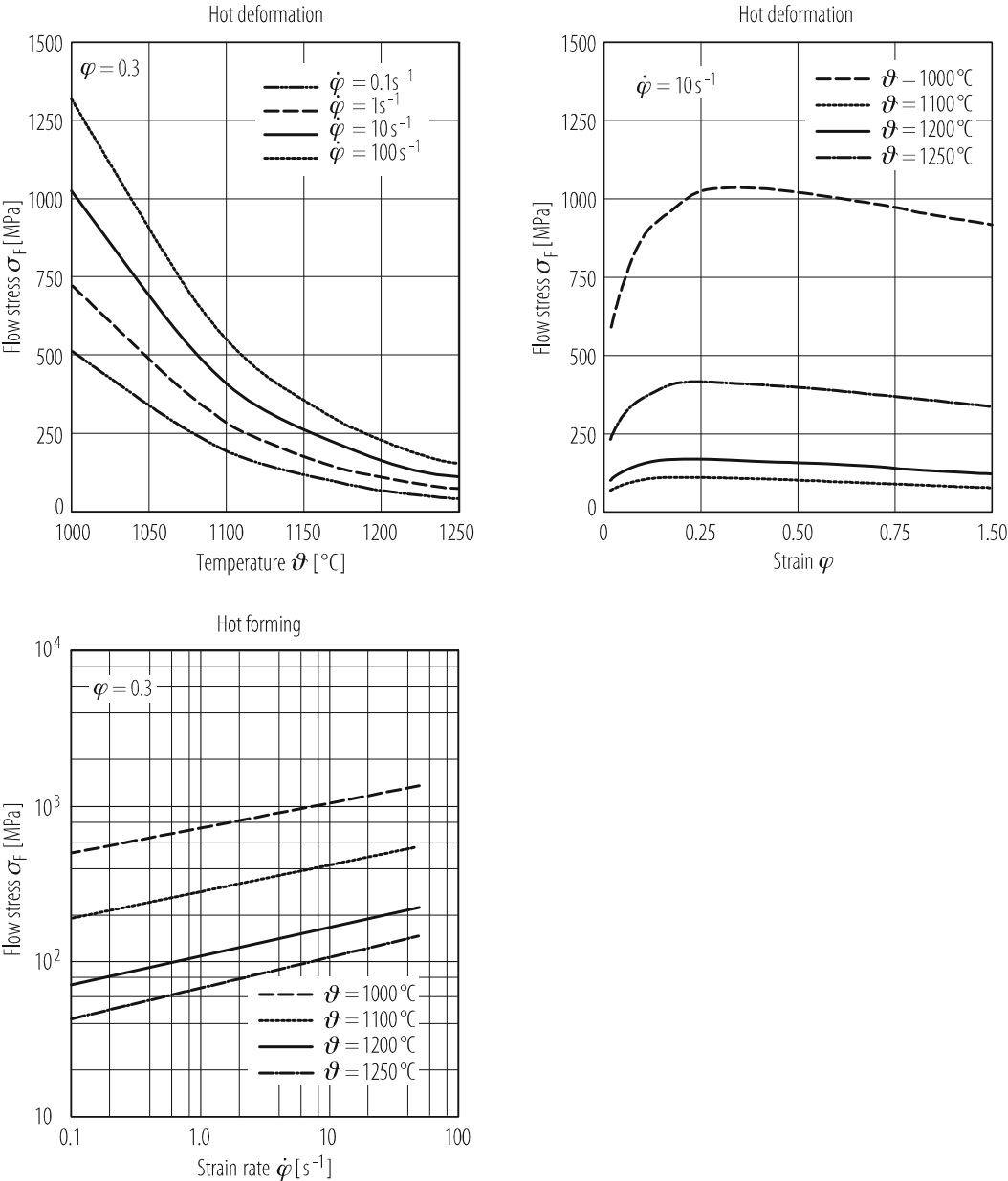


Fig. 5.144 Flow stress curves of NiCo15Cr15MoAlTi by hot and cold forming.

**Symbols and abbreviations**

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| AFNOR           | Association Française de Normalisation                                |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| BS              | British standards                                                     |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |

# Flow stress of SG-NiCr<sub>29</sub>Mo

## 5.4 Chemical resistant and elevated-temperature alloys

### Designation

|             |               |               |                    |            |
|-------------|---------------|---------------|--------------------|------------|
| UNS number: | <b>N06625</b> | Chem. symbol: | <b>SG-NiCr29Mo</b> | EN number: |
|-------------|---------------|---------------|--------------------|------------|

### Composition (EN) [Weight-%]

| C     | Si    | Mn   | P | S      | Cr   | Mo   | Ni   | V | Nb | Ti    | Fe    | Co    | Cu          | Al    | B | Zr |
|-------|-------|------|---|--------|------|------|------|---|----|-------|-------|-------|-------------|-------|---|----|
| <0.02 | <0.50 | 1.00 |   | <0.015 | 27.0 | 2.50 | 35.0 |   |    | <1.00 | <30.0 | <0.50 | 1.50...3.00 | <0.20 |   |    |
|       |       | ...  |   |        | ...  | ...  | ...  |   |    |       |       |       |             |       |   |    |
|       |       | 3.00 |   |        | 31.0 | 4.50 | 40.0 |   |    |       |       |       |             |       |   |    |

### International comparison of standards

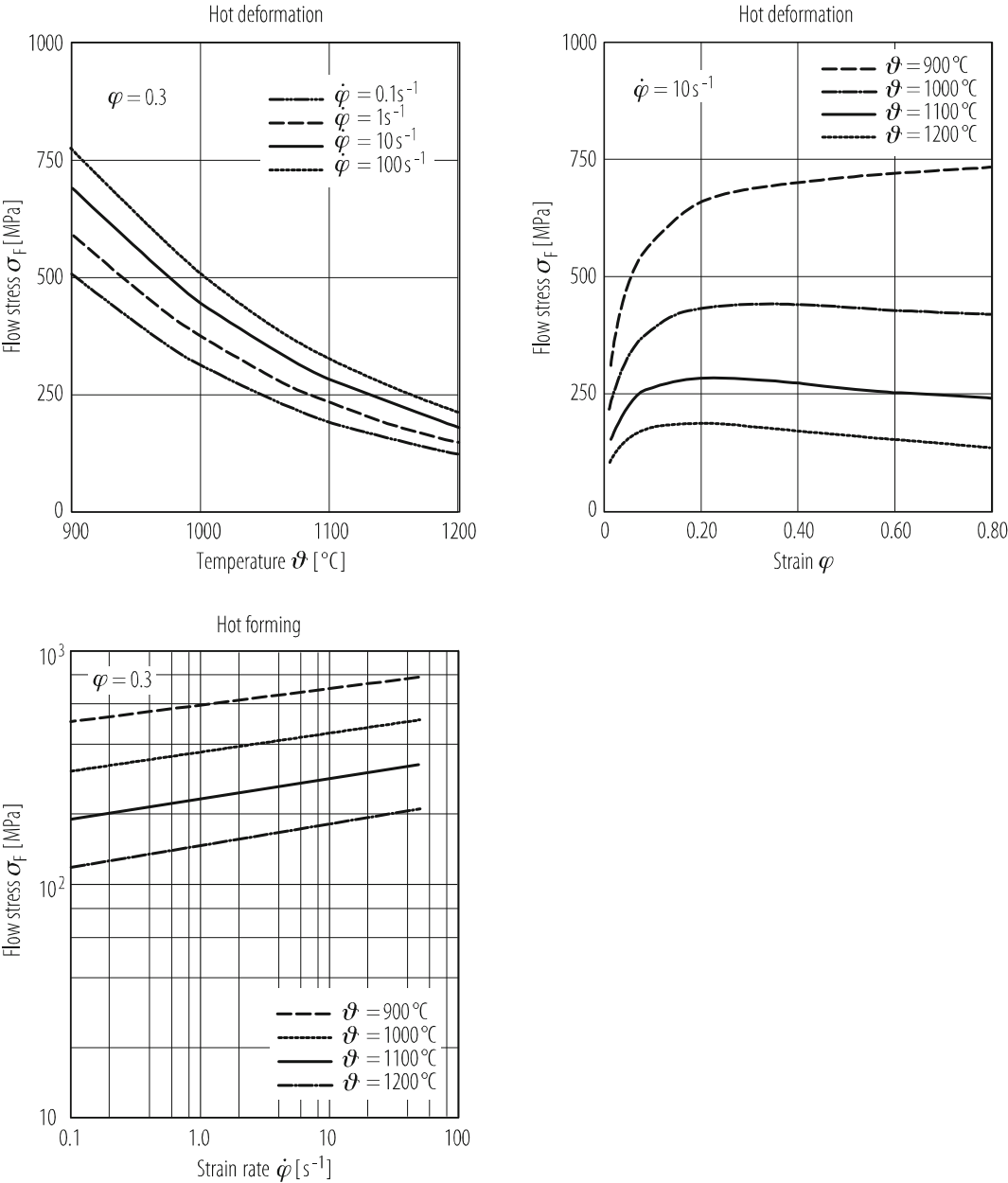
|                       |           |                  |
|-----------------------|-----------|------------------|
| Euronorm              |           | ISO              |
| EN 14172              |           | ISO 14172 : 2008 |
| Material number (DIN) |           | DIN              |
| 2.4656                | 2.4657    | DIN 1736         |
| France                |           | United Kingdom   |
| NC 22 D Nb            |           | NA21             |
| USA                   |           |                  |
| ASTM                  | AWS       | UNS standard     |
| ASTM B443             | AWS A 5.9 | N06625           |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                   | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                     | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                 |                 | 390.7          |                  |                 |                 |
| A                                   |                 | 39445.700      |                  |                 |                 |
| Effect of temperature $K_\theta$    |                 |                |                  |                 |                 |
| $m_1$                               |                 | -0.00373       |                  |                 |                 |
| Effect of strain $K_\phi$           |                 |                |                  |                 |                 |
| $m_2$                               |                 | 0.38163        |                  |                 |                 |
| $m_4$                               |                 | 0.00028        |                  |                 |                 |
| $m_5$                               |                 | -0.00344       |                  |                 |                 |
| $m_7$                               |                 | 1.39344        |                  |                 |                 |
| Effect of strain rate $K\dot{\phi}$ |                 |                |                  |                 |                 |
| $m_3$                               |                 |                |                  |                 |                 |
| $m_8$                               |                 | 0.000078       |                  |                 |                 |
| Range of validity                   |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                    |                 | 900...1200     |                  |                 |                 |
| $\phi$                              |                 | 0.03...0.8     |                  |                 |                 |
| $\dot{\phi}$ [1/s]                  |                 | 0.01...50      |                  |                 |                 |

|                                                                                                                                                                                |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          |



**Fig. 5.145** Flow stress curves of SG–NiCr<sub>29</sub>Mo by hot and cold forming.

**Symbols and abbreviations**

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| AWS             | American welding society                                              |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |

# Flow stress and physical properties of NiCr<sub>23</sub>Co<sub>12</sub>Mo

## 5.4 Chemical resistant and elevated-temperature alloys

### Designation

|             |               |               |                     |            |
|-------------|---------------|---------------|---------------------|------------|
| UNS number: | <b>N06617</b> | Chem. symbol: | <b>NiCr23Co12Mo</b> | EN number: |
|-------------|---------------|---------------|---------------------|------------|

### Composition (EN) [Weight-%]

| C    | Si    | Mn    | P      | S      | Cr   | Mo   | Ni   | V | Nb | Ti   | Fe    | Co   | Cu    | Al   | B      | Zr |
|------|-------|-------|--------|--------|------|------|------|---|----|------|-------|------|-------|------|--------|----|
| 0.05 | <0.20 | <0.20 | <0.010 | <0.010 | 20.0 | 8.50 | Bal. |   |    | 0.20 | <2.00 | 11.0 | <0.50 | 0.70 | <0.006 |    |
| ...  |       |       |        |        | ...  | ...  |      |   |    | ...  |       | ...  |       | ...  |        |    |
| 0.10 |       |       |        |        | 23.0 | 10.0 |      |   |    | 0.60 |       | 14.0 |       | 1.40 |        |    |

### International comparison of standards

|                       |               |                |          |
|-----------------------|---------------|----------------|----------|
| Euronorm              |               | ISO            |          |
| EN 10302 (05/2002)    |               | ISO 6207       | ISO 6208 |
|                       |               | ISO 9724       |          |
| France                |               | United Kingdom |          |
| NiCr23Co12Mo          |               |                |          |
| Material number (DIN) |               | DIN            |          |
| 2.4663                |               | DIN 17744      |          |
| USA                   |               |                |          |
| ASME                  | ASTM          | UNS standard   |          |
| ASME SB 166           | ASTM B 166-04 | N06617         |          |
| ASME SB 168           | ASTM B 168-04 |                |          |
| ASME SB 546           | ASTM B 564-06 |                |          |
| ASME SB 564           | ASTM B 546-06 |                |          |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

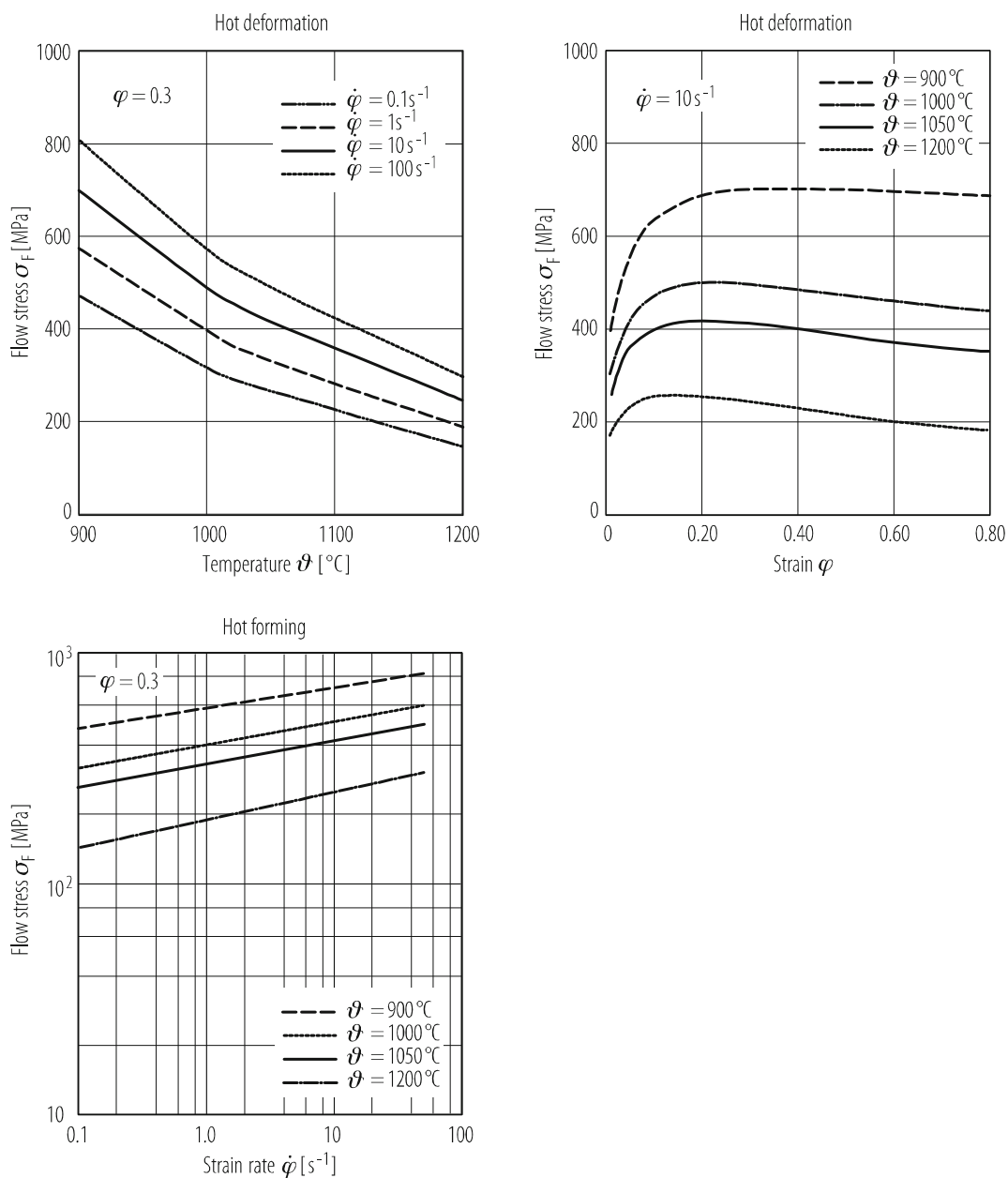
| State of material           | Hot deformation |                | Cold deformation |                 |                 |
|-----------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                             | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]         |                 | 465.9          |                  |                 |                 |
| A                           |                 | 17029.700      |                  |                 |                 |
| Effect of temperature $K_8$ |                 |                |                  |                 |                 |
| $m_1$                       |                 | -0.00296       |                  |                 |                 |
| Effect of strain $K_\phi$   |                 |                |                  |                 |                 |
| $m_2$                       |                 | 0.30065        |                  |                 |                 |
| $m_4$                       |                 | 0.00020        |                  |                 |                 |
| $m_5$                       |                 | -0.00291       |                  |                 |                 |
| $m_7$                       |                 | 1.07175        |                  |                 |                 |

(continued)



| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                |                  |                 |                 |
| $m_8$                                  |                 | 0.000096       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                       |                 | 900. . . 1200  |                  |                 |                 |
| $\varphi$                              |                 | 0.03 . . . 0.8 |                  |                 |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.01 . . . 50  |                  |                 |                 |

|                                                                                                                                                                                  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                                 |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4 / \varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                             |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                            |



**Fig. 5.146** Flow stress curves of NiCr<sub>23</sub>Co<sub>12</sub>Mo by hot and cold forming.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 13.4                 | 461.6              | 11.54                                   | 8400                        | 212             |
| 100              | 14.7                 | 467.9              | 11.93                                   | 8369.9                      | 206             |
| 200              | 16.2                 | 476.0              | 12.41                                   | 8337.4                      | 200             |
| 300              | 17.8                 | 484.2              | 12.90                                   | 8302.5                      | 194             |
| 400              | 19.3                 | 492.6              | 13.39                                   | 8265.0                      | 188             |
| 500              | 20.9                 | 501.1              | 13.88                                   | 8225.2                      | 181             |
| 600              | 22.4                 | 509.7              | 14.36                                   | 8182.8                      | 173             |
| 700              | 24.0                 | 518.5              | 14.85                                   | 8138.1                      | 166             |
| 800              | 25.5                 | 527.4              | 15.34                                   | 8090.8                      | 157             |
| 900              | 27.1                 | 536.5              | 15.82                                   | 8041.1                      | 149             |
| 1000             | 28.6                 | 545.8              | 16.31                                   | 7989.0                      | 139             |
| 1100             | 30.2                 | 555.2              | 16.80                                   | 7934.4                      |                 |
| 1200             | 31.7                 | 564.8              | 17.28                                   | 7877.3                      |                 |

Temperature dependence of the mean specific heat capacities of 2.4634 NiCo20Cr15MoTiAl was used

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, plasticity and physical properties of NiCr<sub>19</sub>Fe<sub>19</sub>Nb<sub>5</sub>Mo<sub>3</sub>

## 5.4 Chemical resistant and elevated-temperature alloys

### Designation

|             |               |               |                         |            |
|-------------|---------------|---------------|-------------------------|------------|
| UNS number: | <b>N07718</b> | Chem. symbol: | <b>NiCr19Fe19Nb5Mo3</b> | EN number: |
|-------------|---------------|---------------|-------------------------|------------|

### Composition (EN) [Weight-%]

| C    | Si    | Mn    | P      | S      | Cr   | Mo   | Ni   | V | Nb   | Ti   | Fe   | Co    | Cu    | Al   | B     | Zr |
|------|-------|-------|--------|--------|------|------|------|---|------|------|------|-------|-------|------|-------|----|
| 0.02 | <0.35 | <0.35 | <0.015 | <0.015 | 17.0 | 2.80 | 50.0 |   | 4.80 | 0.70 | Bal. | <1.00 | <0.20 | 0.30 | 0.002 |    |
| ...  |       |       |        |        | ...  | ...  | ...  |   | ...  | ...  |      |       |       | ...  | ...   |    |
| 0.08 |       |       |        |        | 21.0 | 3.30 | 55.0 |   | 5.50 | 1.15 |      |       |       | 0.70 | 0.006 |    |

### International comparison of standards

|                       |               |                |                |
|-----------------------|---------------|----------------|----------------|
| Euronorm              |               | China          |                |
| EN 10302 (05/2002)    |               | H41690         | T 14992 (200%) |
| Material number (DIN) |               | DIN            |                |
| 2.4668                |               | DIN E 17742    |                |
| France                |               | United Kingdom |                |
| NiCr19Fe19Nb5Mo3      |               |                |                |
| USA                   |               |                |                |
| AMS                   | ASTM          | UNS standard   |                |
| ASME SB-637           | ASTM B 637-03 | N 07718        |                |
| ASME SB-670           | ASTM B 670-03 |                |                |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

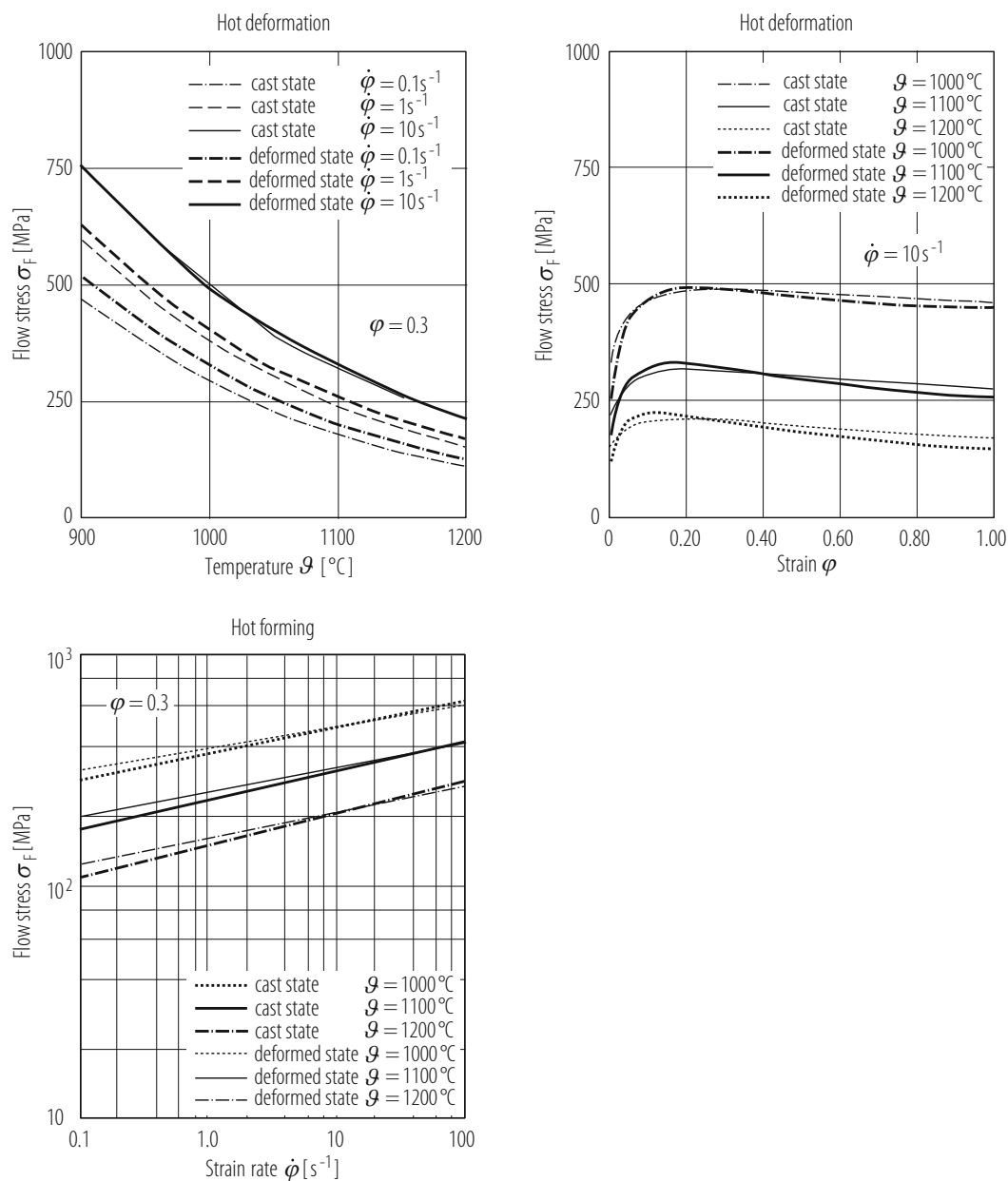
### Flow curves

| State of material                  | Hot deformation |                | Cold deformation |                 |                 |
|------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                    | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                | 462.9           | 467.8          |                  |                 |                 |
| A                                  | 39972.100       | 33721.800      |                  |                 |                 |
| Effect of temperature $K_{\theta}$ |                 |                |                  |                 |                 |
| $m_1$                              | -0.00419        | -0.00369       |                  |                 |                 |
| Effect of strain $K_{\varphi}$     |                 |                |                  |                 |                 |
| $m_2$                              | 0.19267         | 0.27783        |                  |                 |                 |
| $m_4$                              | 0.00063         | 0.00005        |                  |                 |                 |
| $m_5$                              | -0.00161        | -0.00305       |                  |                 |                 |
| $m_7$                              | 0.57659         | 1.27955        |                  |                 |                 |

(continued)

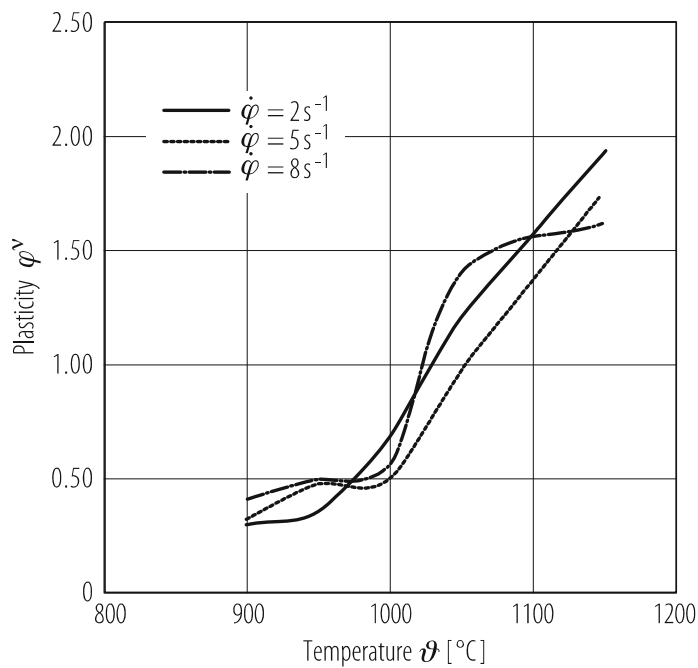
| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                |                  |                 |                 |
| $m_8$                                  | 0.000115        | 0.000093       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                       | 900...1200      | 900...1200     |                  |                 |                 |
| $\varphi$                              | 0.03 ... 1.00   | 0.03 ... 1.00  |                  |                 |                 |
| $\dot{\varphi}$ [1/s]                  | 0.1...100       | 0.01..100      |                  |                 |                 |

|                                                                                                                                                                                |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          |



**Fig. 5.147** Flow stress curves of NiCr<sub>19</sub>FeNb<sub>5</sub>Mo<sub>3</sub> by hot and cold forming.

Plasticity in torsion



**Fig. 5.148** Hot plasticity of  $\text{NiCr}_{19}\text{Fe}_{19}\text{Nb}_5\text{Mo}_3$  as a function of the temperature and deformation rate.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 11.1                 | 437.5              |                                         | 8200                        | 205             |
| 100              | 12.2                 | 443.5              | 12.6                                    | 8169.0                      | 199             |
| 200              | 13.6                 | 451.2              | 13.4                                    | 8134.1                      | 192             |
| 300              | 15.2                 | 459.0              | 13.8                                    | 8098.2                      | 187             |
| 400              | 17.0                 | 466.9              | 14.1                                    | 8061.3                      | 181             |
| 500              | 18.9                 | 474.9              | 14.4                                    | 8022.9                      | 175             |
| 600              | 20.8                 | 483.1              | 14.77                                   | 7982.0                      | 169             |
| 700              | 22.4                 | 491.4              | 15.44                                   | 7934.1                      | 161             |
| 800              | 24.4                 | 499.9              | 16.11                                   | 7883.0                      | 150             |
| 900              | 26.1                 | 508.5              | 16.78                                   | 7828.5                      | 136             |
| 1000             | 28.0                 | 517.3              | 17.45                                   | 7770.7                      | 120             |
| 1100             | 29.7                 | 526.2              | 18.12                                   | 7709.7                      | 100             |
| 1200             |                      | 535.3              | 18.79                                   | 7645.3                      | ~80             |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| AMS             | aerospace material standards                                          |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |



# Flow stress of G – NiCo<sub>15</sub>Cr<sub>10</sub>AlTiMo

## 5.4 Chemical resistant and elevated-temperature alloys

### Designation

|             |               |               |                             |            |
|-------------|---------------|---------------|-----------------------------|------------|
| UNS number: | <b>N13100</b> | Chem. symbol: | <b>G – NiCo15Cr10AlTiMo</b> | EN number: |
|-------------|---------------|---------------|-----------------------------|------------|

### Composition (EN) [Weight-%]

| C    | Si    | Mn    | P | S      | Cr   | Mo   | Ni  | V    | Nb | Ti   | Fe    | Co   | Cu    | Al   | B     | Zr   | Pb     |
|------|-------|-------|---|--------|------|------|-----|------|----|------|-------|------|-------|------|-------|------|--------|
| 0.15 | <0.20 | <0.20 |   | <0.020 | 8.00 | 2.00 | Bal | 0.70 |    | 4.50 | <0.70 | 13.0 | <0.20 | 5.00 | 0.010 | 0.03 | <0.002 |
| ...  |       |       |   |        | ...  | ...  |     | ...  |    | ...  |       | ..   |       | ...  | ...   | ...  |        |
| 0.20 |       |       |   |        | 11.0 | 4.00 |     | 1.20 |    | 5.00 |       | 17.0 |       | 6.00 | 0.020 | 0.09 |        |

### International comparison of standards

|                       |                |              |
|-----------------------|----------------|--------------|
| Euronorm              |                | ISO          |
| EN ISO 4674-2         |                | ISO 4674-2   |
| Material number (DIN) |                | DIN          |
| 2.4674                |                | WL 2.4674    |
| China                 |                | Russia       |
| K 417                 | T 14992 (2005) |              |
| C74170                |                |              |
| USA                   |                |              |
| ASME                  | ASTM           | UNS standard |
| AMS 5397              | ASTM B622 - 10 | N13100       |
|                       | ASTM B619 - 05 |              |
|                       | ASTM B626 - 10 |              |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

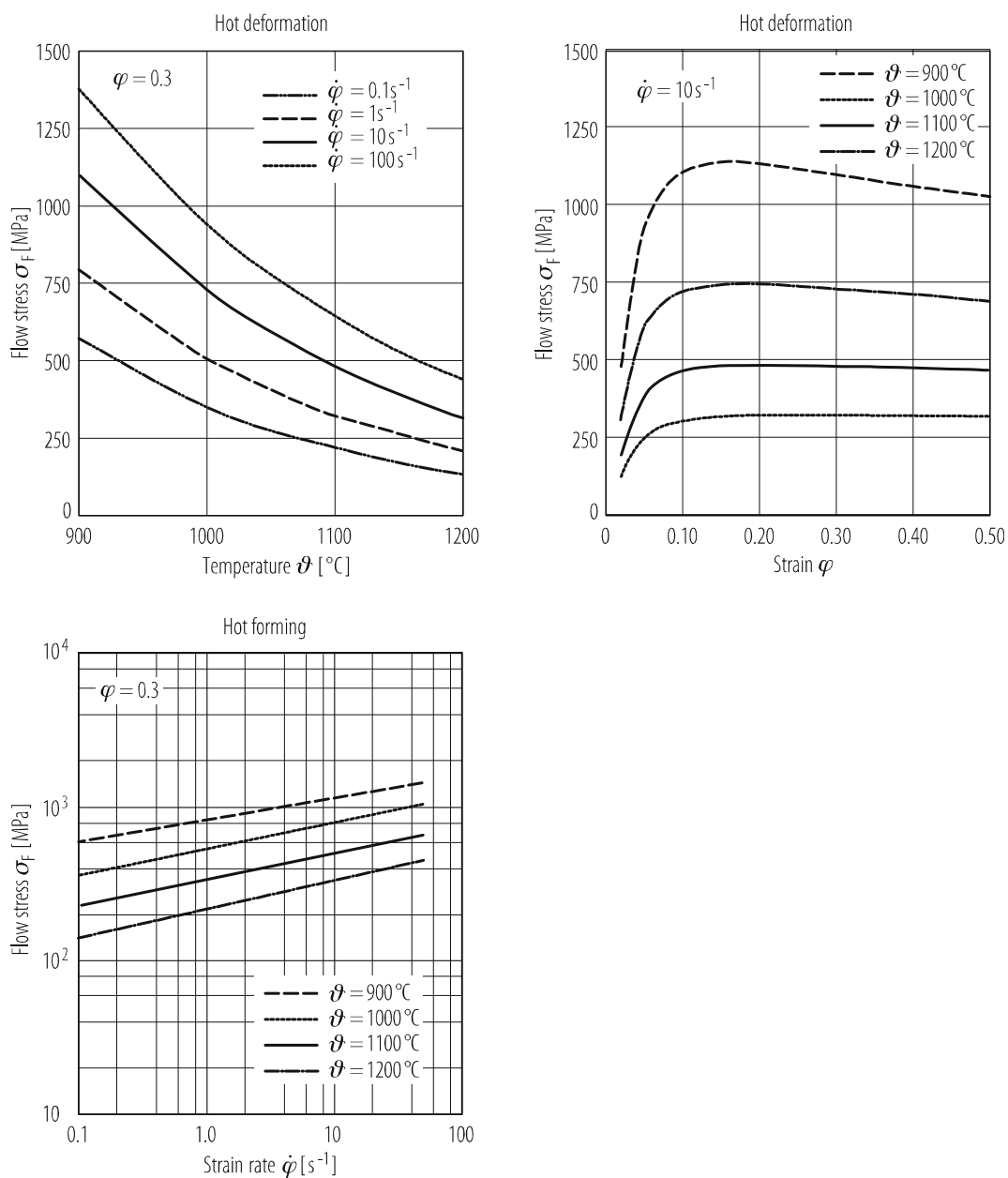
### Flow curves

| State of material           | Hot deformation |                | Cold deformation |                 |                 |
|-----------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                             | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]         |                 | 721.7          |                  |                 |                 |
| A                           |                 | 45387.980      |                  |                 |                 |
| Effect of temperature $K_8$ |                 |                |                  |                 |                 |
| $m_1$                       |                 | –0.00477       |                  |                 |                 |
| Effect of strain $K_\phi$   |                 |                |                  |                 |                 |
| $m_2$                       |                 | –0.24108       |                  |                 |                 |
| $m_4$                       |                 | –0.03291       |                  |                 |                 |
| $m_5$                       |                 | 0.00118        |                  |                 |                 |
| $m_7$                       |                 | –0.71437       |                  |                 |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                |                  |                 |                 |
| $m_8$                                  |                 | 0.000157       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                       |                 | 900. . . 1200  |                  |                 |                 |
| $\varphi$                              |                 | 0.03 . . . 0.5 |                  |                 |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.01 . . . 50  |                  |                 |                 |

|                                                                                                                                                                                |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          |



**Fig. 5.149** Flow stress curves of G–NiCo<sub>15</sub>Cr<sub>10</sub>AlTiMo by hot and cold forming

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| AMS             | aerospace material standards                                          |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |

# Flow stress, mechanical and physical properties of NiCr<sub>20</sub>Ti

## 5.4 Chemical resistant and elevated-temperature alloys

### Designation

|             |               |               |                 |            |
|-------------|---------------|---------------|-----------------|------------|
| UNS number: | <b>N06075</b> | Chem. symbol: | <b>NiCr20Ti</b> | EN number: |
|-------------|---------------|---------------|-----------------|------------|

### Composition (EN) [Weight-%]

| C           | Si    | Mn    | P       | S      | Cr          | Co    | Ni  | Cu    | Pb     | Ti          | Fe    |
|-------------|-------|-------|---------|--------|-------------|-------|-----|-------|--------|-------------|-------|
| 0.08...0.15 | <1.00 | <1.00 | <0.02q0 | <0.015 | 18.0...21.0 | <5.00 | Bal | <0.50 | <0.005 | 0.20...0.60 | <5.00 |

### International comparison of standards

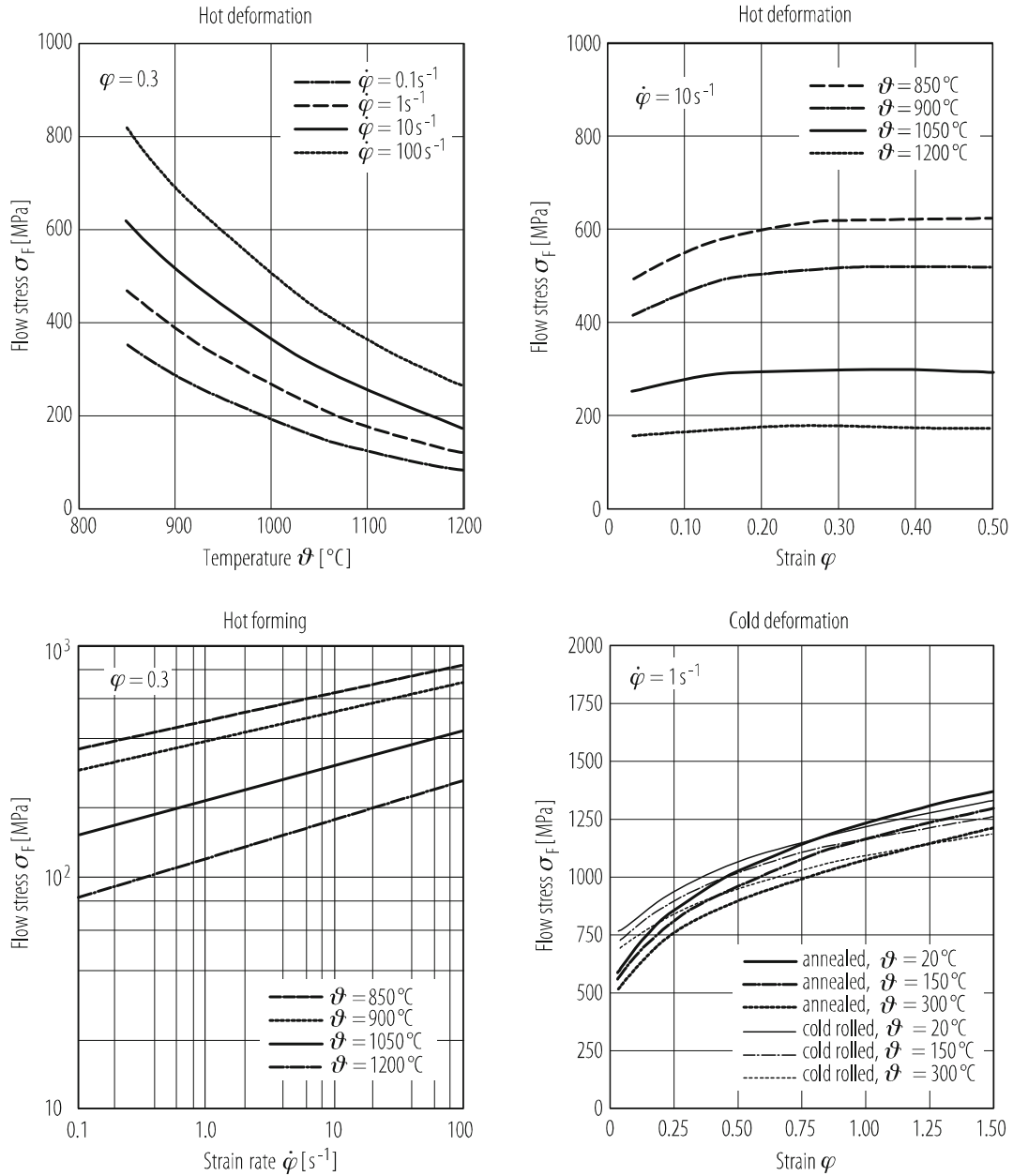
| Euronorm              |  |  |  | ISO            |                   |
|-----------------------|--|--|--|----------------|-------------------|
| EN 10095 (03/1999)    |  |  |  |                |                   |
| EN 3974               |  |  |  |                |                   |
| France                |  |  |  | United Kingdom |                   |
| NiCr20Ti              |  |  |  | BS HR5         | HR203             |
|                       |  |  |  | HR403          | HR504             |
| Material number (DIN) |  |  |  | DIN            |                   |
| 2.4631                |  |  |  | DIN 17742      | DIN 17750 - 17752 |
| USA                   |  |  |  |                |                   |
| ASME                  |  |  |  | UNS standard   |                   |
| ASME SFA 5.14         |  |  |  | ASTM B167-11   |                   |
|                       |  |  |  | N06075         |                   |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |                  |                 |
|-------------------------------------------|-----------------|----------------|------------------|------------------|-----------------|
|                                           | cast state      | deformed state | annealed (an)    | cold rolled (cr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 331.7          | 711.5            | 836.8            |                 |
| A                                         |                 | 17735.61422    | 1232.650         | 1221.702         |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                  |                  |                 |
| $m_1$                                     |                 | -0.00358       | -0.00046         | -0.00040         |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                  |                  |                 |
| $m_2$                                     |                 | 0.30021        | 0.27580          | 0.20770          |                 |
| $m_4$                                     |                 | 0.00783        | 0.00716          | 0.00854          |                 |
| $m_5$                                     |                 | -0.00131       |                  |                  |                 |
| $m_7$                                     |                 | 0.11858        |                  |                  |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |                  |                 |
| $m_3$                                     |                 |                | 0.01004          | 0.00974          |                 |
| $m_8$                                     |                 | 0.000142       |                  |                  |                 |
| Range of validity                         |                 |                |                  |                  |                 |
| $\theta$ [°C]                             |                 | 850...1200     | 20...300         | 20...300         |                 |
| $\varphi$                                 |                 | 0.03...0.50    | 0.03...1.50      | 0.03...1.50      |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.001...100    | 0.01...100       | 0.01...100       |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.150** Flow stress curves of NiCr<sub>20</sub>Ti by hot and cold forming

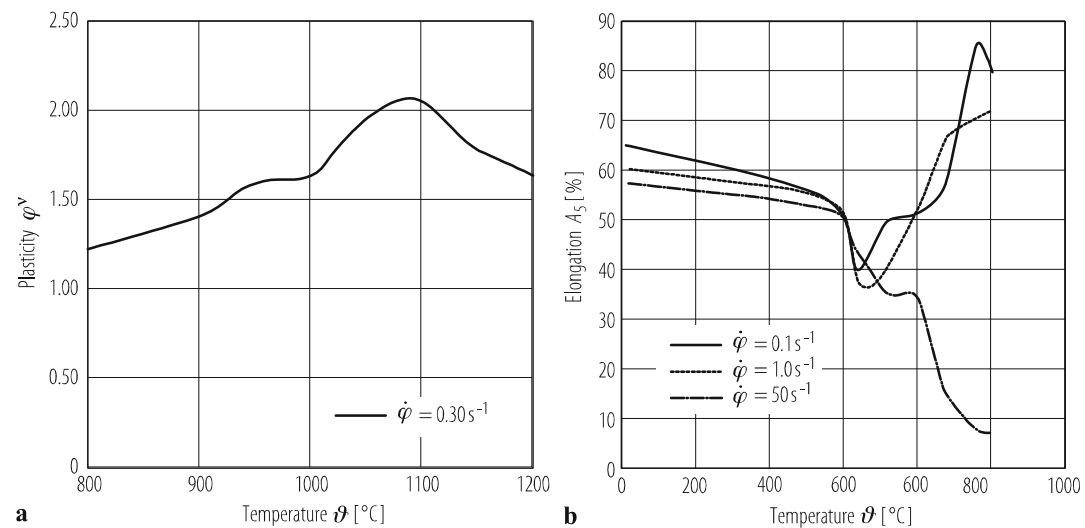
### Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |         |        | Tensile strength $\Delta R_m$ [MPa] |         |        |
|-------------------|---------------------------------|---------|--------|-------------------------------------|---------|--------|
|                   | $A_0$                           | $A$     | $n_1$  | $B_0$                               | $B$     | $n_2$  |
| soft annealed     | 350...450                       | 69.6512 | 0.5265 | 700...800                           | 12.7530 | 0.8648 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |        |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|--------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$  | $n_4$   |                            |
| soft annealed     | 35...40                                 | 15.1509 | 0.2070 | -3.0553 | <50                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

### Plasticity in torsion and tensile test



**Fig. 5.151** Hot and cold plasticity of NiCr<sub>20</sub>Ti as a function of the temperature. (a) Torsion test (b) Tensile test

### Physical properties

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [10 <sup>-6</sup> /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                              | 13.0                                      | 461.6                                   | 11.0                                                                           | 8370                                   | 221                          |
| 100                             | 13.8                                      | 467.9                                   | 12.2                                                                           | 8339.4                                 | 216                          |
| 200                             | 15.8                                      | 476.0                                   | 13.0                                                                           | 8304.7                                 | 210                          |
| 300                             | 17.5                                      | 484.2                                   | 13.4                                                                           | 8269.1                                 | 203                          |
| 400                             | 19.1                                      | 492.6                                   | 13.8                                                                           | 8231.4                                 | 196                          |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 500              | 20.9                 | 501.1              | 14.1                                    | 8193.0                      | 186             |
| 600              | 22.4                 | 509.7              | 14.7                                    | 8148.5                      | 181             |
| 700              | 24.1                 | 518.5              | 15.4                                    | 8099.3                      | 173             |
| 800              | 25.7                 | 527.4              | 15.5                                    | 8058.6                      | 165             |
| 900              | 29.0                 | 536.5              | 16.0                                    | 8008.4                      | 153             |
| 1000             | 30.7                 | 545.8              | 17.1                                    | 7940.6                      | 143             |
| 1100             | 32.5                 | 555.2              | 17.6                                    | 7884.3                      | 134             |
| 1200             | 34.2                 | 564.8              | 18.1                                    | 7824.2                      | 125             |

Temperature dependence of the mean specific heat capacities of 2.4634 NiCo20Cr15MoTiAl was used

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |



# Flow stress, plasticity and physical properties of NiCr<sub>20</sub>TiAl

## 5.4 Chemical resistant and elevated-temperature alloys

### Designation

|             |               |               |                   |            |
|-------------|---------------|---------------|-------------------|------------|
| UNS number: | <b>N07080</b> | Chem. symbol: | <b>NiCr20TiAl</b> | EN number: |
|-------------|---------------|---------------|-------------------|------------|

### Composition (EN) [Weight-%]

| C    | Si    | Mn    | P      | S      | Cr          | Mo | Ni   | V | Nb | Ti   | Fe    | Co    | Cu    | Al   | B      |
|------|-------|-------|--------|--------|-------------|----|------|---|----|------|-------|-------|-------|------|--------|
| 0.04 | <1.00 | <1.00 | <0.020 | <0.015 | 18.0...21.0 |    | Bal. |   |    | 1.80 | <3.00 | <2.00 | <0.20 | 1.00 | <0.008 |
| ...  |       |       |        |        |             |    |      |   |    | ...  |       |       |       | ...  |        |
| 0.10 |       |       |        |        |             |    |      |   |    | 2.70 |       |       |       | 1.80 |        |

### International comparison of standards

|                    |            |                       |       |
|--------------------|------------|-----------------------|-------|
| Euronorm           |            | ISO                   |       |
| EN 10269 (04/2006) |            | ISO 683-15 (1992)     |       |
| France             |            | United Kingdom        |       |
| NiCr20TiAl         |            | BS 3076 (NA20)        | HR1   |
|                    |            | HR401                 | HR601 |
| Japan              |            | Material number (DIN) |       |
| NCF80A             | G 4902     | 2.4952                |       |
| USA                |            |                       |       |
| ASME               | ASTM       | UNS standard          |       |
| ASME SB 637        | ASTM B 637 | N07080                |       |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material           | Hot deformation |                | Cold deformation |                 |                 |
|-----------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                             | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]         |                 | 365.3          | 670.35           |                 |                 |
| A                           |                 | 16650.83       | 1006.690         |                 |                 |
| Effect of temperature $K_9$ |                 |                |                  |                 |                 |
| $m_1$                       |                 | -0.00354       | -0.00054         |                 |                 |
| Effect of strain $K_q$      |                 |                |                  |                 |                 |
| $m_2$                       |                 | 0.25005        | 0.23512          |                 |                 |
| $m_4$                       |                 | 0.00123        | -0.00196         |                 |                 |
| $m_5$                       |                 | -0.00015       |                  |                 |                 |
| $m_7$                       |                 | -0.43128       |                  |                 |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | -0.00216         |                 |                 |
| $m_8$                                  |                 | 0.000148       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                       |                 | 900...1200     | 20...300         |                 |                 |
| $\varphi$                              |                 | 0.03...1.00    | 0.03...0.80      |                 |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.1...50       | 0.01...50        |                 |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

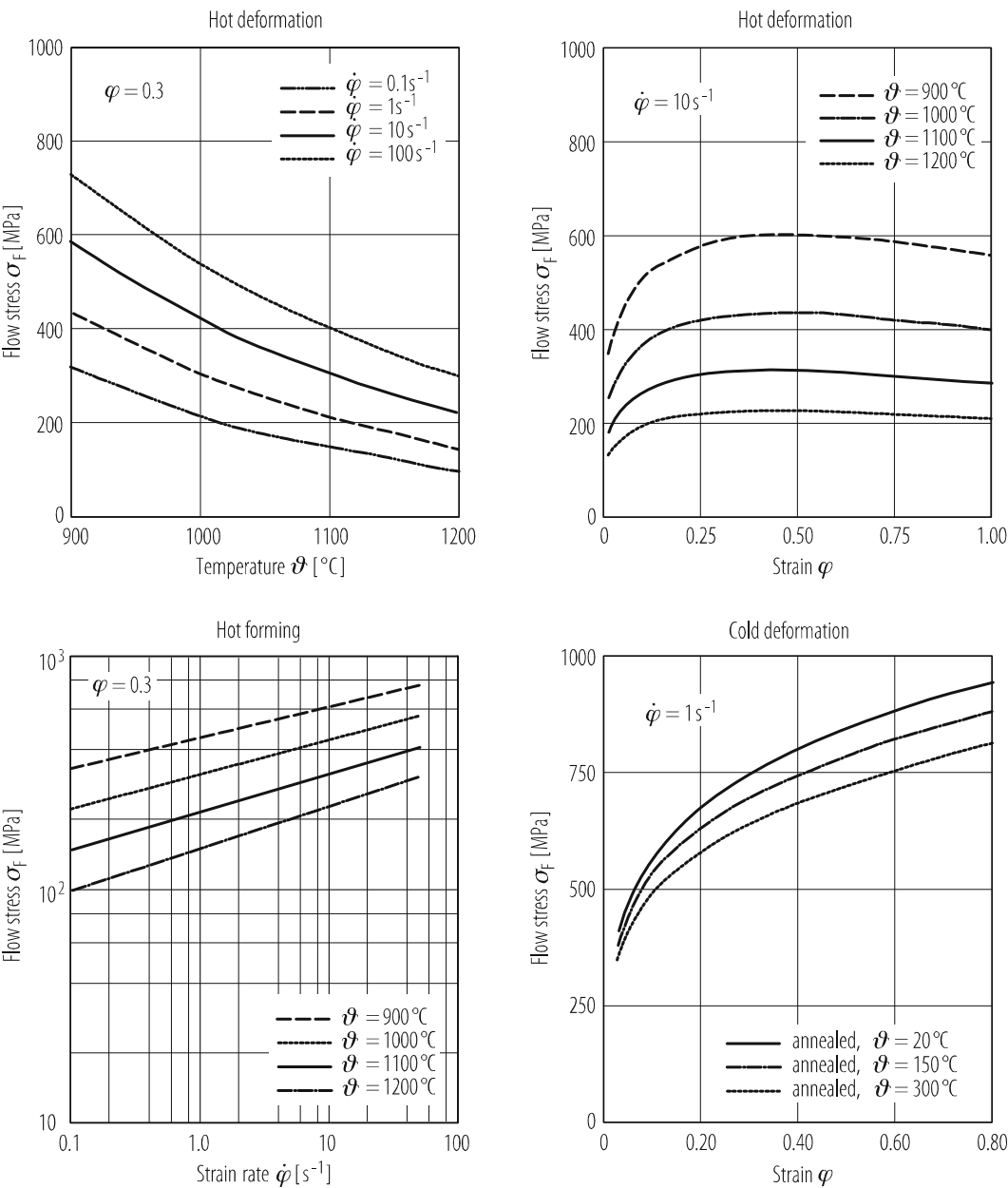
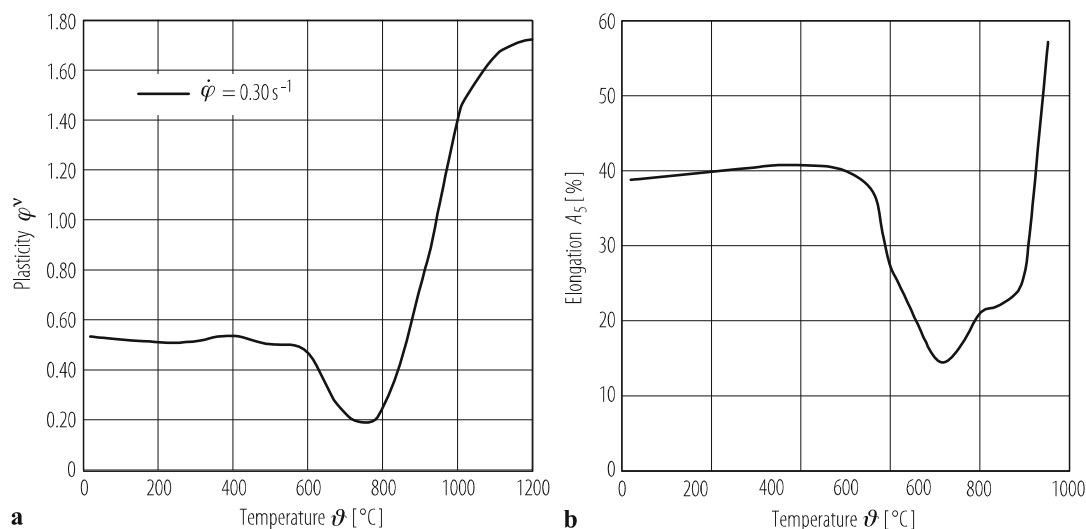


Fig. 5.152 Flow stress curves of NiCr<sub>20</sub>TiAl by hot and cold forming

### Plasticity in torsion and tensile test



**Fig. 5.153** Plasticity of NiCr<sub>20</sub>TiAl as a function of the temperature. (a) Torsion test (b) Tensile test

### Physical properties

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}/\text{K}$ ] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|---------------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                              | 10.9                                      | 430.5                                   |                                                                                 | 8170                                   | 222                          |
| 100                             | 12.0                                      | 436.4                                   | 11.1                                                                            | 8142.8                                 | 217                          |
| 200                             | 13.8                                      | 443.9                                   | 12.5                                                                            | 8108.7                                 | 210                          |
| 300                             | 15.5                                      | 451.6                                   | 13.2                                                                            | 8072.9                                 | 204                          |
| 400                             | 16.7                                      | 459.4                                   | 13.7                                                                            | 8035.7                                 | 197                          |
| 500                             | 18.4                                      | 467.3                                   | 14.1                                                                            | 7997.2                                 | 191                          |
| 600                             | 20.9                                      | 475.4                                   | 14.8                                                                            | 7952.4                                 | 183                          |
| 700                             | 23.4                                      | 483.6                                   | 15.5                                                                            | 7904.1                                 | 176                          |
| 800                             | 25.5                                      | 491.9                                   | 16.3                                                                            | 7850.4                                 | 166                          |
| 900                             | 27.4                                      | 500.4                                   | 17.4                                                                            | 7786.2                                 | 153                          |
| 1000                            | 28.8                                      | 509.0                                   | 18.8                                                                            | 7709.2                                 | 140                          |
| 1100                            | 30.7                                      | 517.8                                   | 19.8                                                                            | 7637.5                                 | 129                          |
| 1200                            | 32.6                                      | 526.7                                   | 20.9                                                                            | 7556.8                                 | 116                          |

Temperature dependence of the mean specific heat capacities of 2.4634 NiCo<sub>20</sub>Cr<sub>15</sub>MoTiAl was used.

**Symbols and abbreviations**

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| BS              | British standards                                                     |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, plasticity and physical properties of NiCr<sub>15</sub>Fe

## 5.5 Heat resistant Nickel – Chromium – alloys

### Designation

|             |               |               |                 |            |
|-------------|---------------|---------------|-----------------|------------|
| UNS number: | <b>N06600</b> | Chem. symbol: | <b>NiCr15Fe</b> | EN number: |
|-------------|---------------|---------------|-----------------|------------|

### Composition (EN) [Weight-%]

| C    | Si    | Mn    | P      | S      | Cr   | Mo | Ni    | V | Nb | Ti     | Fe   | Co    | Cu    | Al    | B      | Zr |
|------|-------|-------|--------|--------|------|----|-------|---|----|--------|------|-------|-------|-------|--------|----|
| 0.05 | <0.50 | <1.00 | <0.020 | <0.015 | 14.0 |    | >72.0 |   |    | <0.030 | 6.00 | <1.00 | <0.50 | <0.30 | <0.006 |    |
| ...  |       |       |        |        | ...  |    |       |   |    |        | ...  |       |       |       |        |    |
| 0.10 |       |       |        |        | 17.0 |    |       |   |    |        | 10.0 |       |       |       |        |    |

### International comparison of standards

|                       |             |            |                |                   |
|-----------------------|-------------|------------|----------------|-------------------|
| Euronorm              |             |            | China          |                   |
| EN 10095 (03/1999)    |             |            | H03120         | T 15007 (1994)    |
| France                |             |            | United Kingdom |                   |
| NiCr15Fe8             |             |            | NA 14          |                   |
|                       |             |            | BS 3072 – 3076 |                   |
| Material number (DIN) |             |            | DIN            |                   |
| 2.4816                |             |            | DIN 17742      | DIN 17750 – 17754 |
| USA                   |             |            |                |                   |
| ASME                  |             | ASTM       |                | UNS standard      |
| ASME SB-163           | ASME SB-166 | ASTM B 163 | ASTM B 166     | N06600            |
| ASME SB-168           | ASME SB-366 | ASTM B 168 | ASTM B 516     |                   |
| ASME SB-516           | ASME SB-751 | ASTM B 751 | ASTM B 829     |                   |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

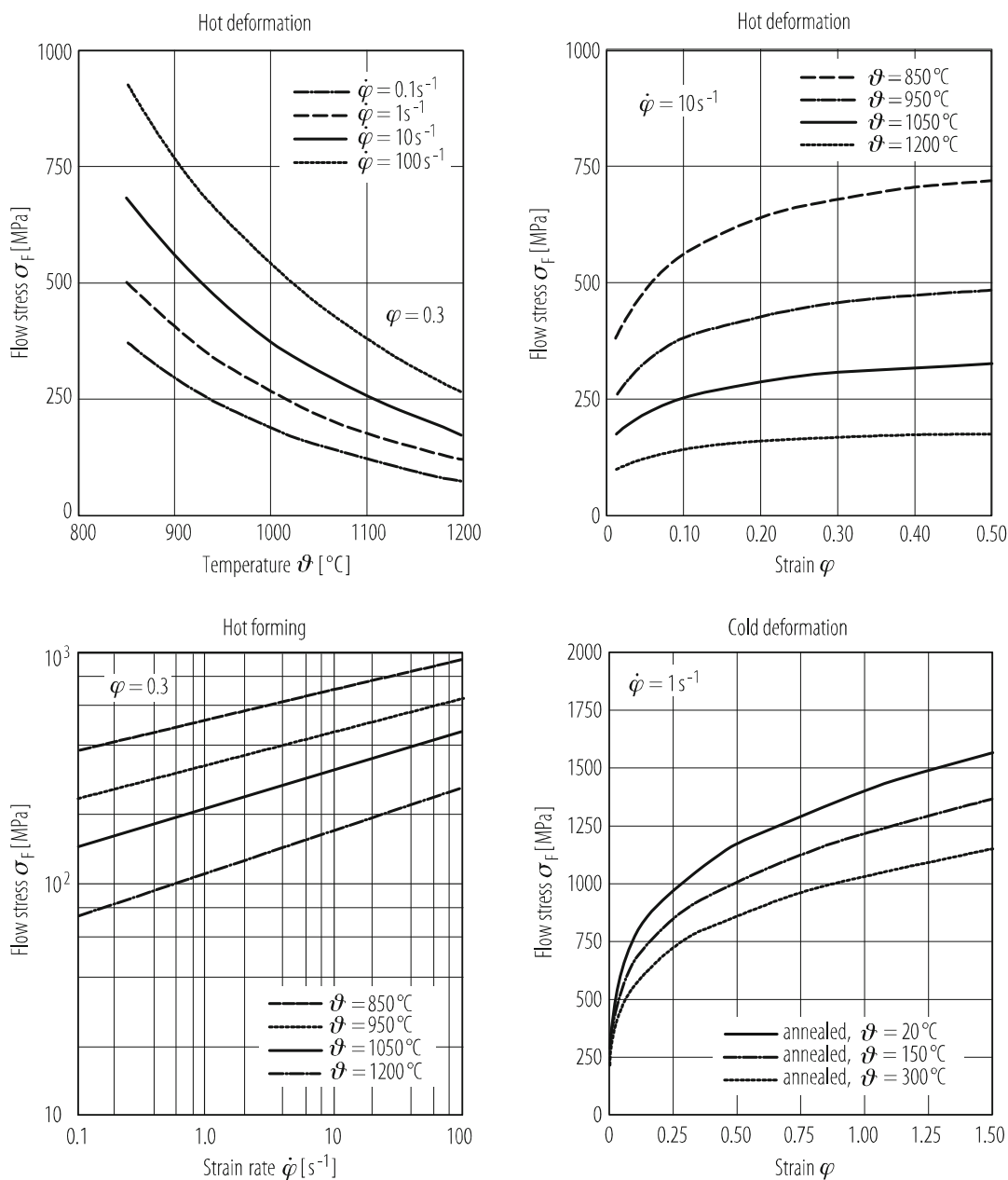
### Flow curves

| State of material           | Hot deformation |                | Cold deformation |                 |                 |
|-----------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                             | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]         |                 | 311.74         | 782.9            |                 |                 |
| A                           |                 | 28342.36       | 1437.764         |                 |                 |
| Effect of temperature $K_9$ |                 |                |                  |                 |                 |
| $m_1$                       |                 | –0.00426       | –0.00111         |                 |                 |
| Effect of strain $K_\phi$   |                 |                |                  |                 |                 |
| $m_2$                       |                 | 0.24975        | 0.25978          |                 |                 |
| $m_4$                       |                 | 0.00126        | –0.00140         |                 |                 |
| $m_5$                       |                 | –0.00021       |                  |                 |                 |

(continued)

| State of material                       | Hot deformation |                 | Cold deformation |                 |                 |
|-----------------------------------------|-----------------|-----------------|------------------|-----------------|-----------------|
|                                         | cast state      | deformed state  | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| m <sub>7</sub>                          |                 | −0.22838        |                  |                 |                 |
| Effect of strain rate K $\dot{\varphi}$ |                 |                 |                  |                 |                 |
| m <sub>3</sub>                          |                 |                 | 0.01152          |                 |                 |
| m <sub>8</sub>                          |                 | 0.000154        |                  |                 |                 |
| Range of validity                       |                 |                 |                  |                 |                 |
| $\vartheta$ [°C]                        |                 | 850. . . 1200   | 20. . . 300      |                 |                 |
| $\varphi$                               |                 | 0.03 . . . 0.50 | 0.03 . . . 1.50  |                 |                 |
| $\dot{\varphi}$ [1/s]                   |                 | 0.001 . . . 100 | 0.01 . . . 100   |                 |                 |

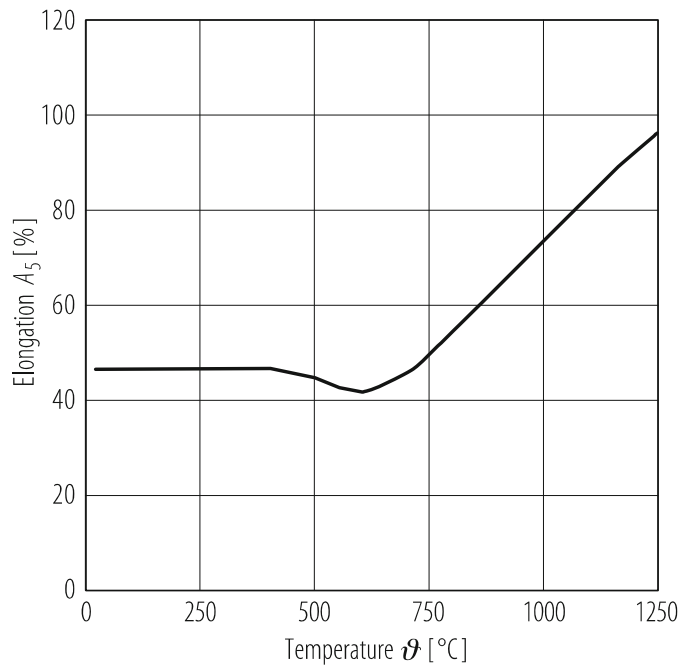
|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                                                 |



**Fig. 5.154** Flow stress curves of NiCr<sub>15</sub>Fe by hot and cold forming.



### Plasticity in tensile test



**Fig. 5.155** Plasticity of NiCr<sub>15</sub>Fe as a function of the temperature.

### Physical properties

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [10 <sup>-6</sup> /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                              | 14.8                                      | 455.6                                   |                                                                                | 8510                                   | 214                          |
| 100                             | 15.9                                      | 461.8                                   | 13.7                                                                           | 8475.0                                 | 209                          |
| 200                             | 17.3                                      | 469.8                                   | 14.1                                                                           | 8438.0                                 | 205                          |
| 300                             | 18.9                                      | 477.9                                   | 14.4                                                                           | 8399.7                                 | 200                          |
| 400                             | 20.4                                      | 486.1                                   | 14.8                                                                           | 8358.9                                 | 194                          |
| 500                             | 22.2                                      | 494.5                                   | 15.1                                                                           | 8317.2                                 | 187                          |
| 600                             | 23.9                                      | 503.1                                   | 15.4                                                                           | 8274.1                                 | 180                          |
| 700                             | 25.6                                      | 511.7                                   | 15.8                                                                           | 8227.6                                 | 172                          |
| 800                             | 27.3                                      | 520.6                                   | 16.1                                                                           | 8181.2                                 | 163                          |
| 900                             | 29.1                                      | 529.5                                   | 16.4                                                                           | 8133.2                                 | 153                          |
| 1000                            | 31.2                                      | 538.7                                   | 16.9                                                                           | 8078.5                                 | 143                          |
| 1100                            | 32.4                                      | 548.0                                   | 17.3                                                                           | 8024.2                                 | 133                          |
| 1200                            | 34.1                                      | 557.4                                   | 17.8                                                                           | 7964.7                                 | 122                          |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| BS              | British standards                                                     |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, plasticity and physical properties of NiCr<sub>22</sub>Mo<sub>9</sub>Nb

## 5.5 Heat resistant Nickel – Chromium – alloys

### Designation

|             |                |               |                    |            |
|-------------|----------------|---------------|--------------------|------------|
| UNS number: | <b>N 06625</b> | Chem. symbol: | <b>NiCr22Mo9Nb</b> | EN number: |
|-------------|----------------|---------------|--------------------|------------|

### Composition (EN) [Weight-%]

| C    | Si    | Mn    | P      | S      | Cr   | Mo   | Ni   | Cu    | Nb   | Ti    | Fe    | Co    | Al    |
|------|-------|-------|--------|--------|------|------|------|-------|------|-------|-------|-------|-------|
| 0.03 | <0.50 | <0.50 | <0.020 | <0.015 | 20.0 | 8.00 | Bal. | <0.50 | 3.15 | <0.40 | <5.00 | <1.00 | <0.40 |
| ...  |       |       |        |        | ...  | ...  |      |       | ...  |       |       |       |       |
| 0.10 |       |       |        |        | 23.0 | 10.0 |      |       | 4.15 |       |       |       |       |

### International comparison of standards

|                       |             |            |                |                   |
|-----------------------|-------------|------------|----------------|-------------------|
| Euronorm              |             |            | ISO            |                   |
| EN 10095 (03/1999)    |             |            | ISO 6207       | ISO 9723 - 9725   |
| Material number (DIN) |             |            | DIN            |                   |
| 2.4856                |             |            | DIN 17744      | DIN 17750 - 17752 |
| France                |             |            | United Kingdom |                   |
| NC 22DNb              |             |            | NA 21          | BS 3072 (1989)    |
|                       |             |            | BS 3074        | BS 3076 (1989)    |
| USA                   |             |            |                |                   |
| AMS                   |             | ASTM       |                | UNS standard      |
| ASME SB-366           | ASME SB-444 | ASTM B 366 | ASTM B444      | N 06625           |
| ASME SB-445           | ASME SB-564 | ASTM B445  | ASTM B564      |                   |
| ASME SB-704           | ASME SB-751 | ASTM B 704 | ASTM B 751     |                   |
| ASME SB-775           | ASME SB-829 | ASTM B 775 | ASTM B 829     |                   |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

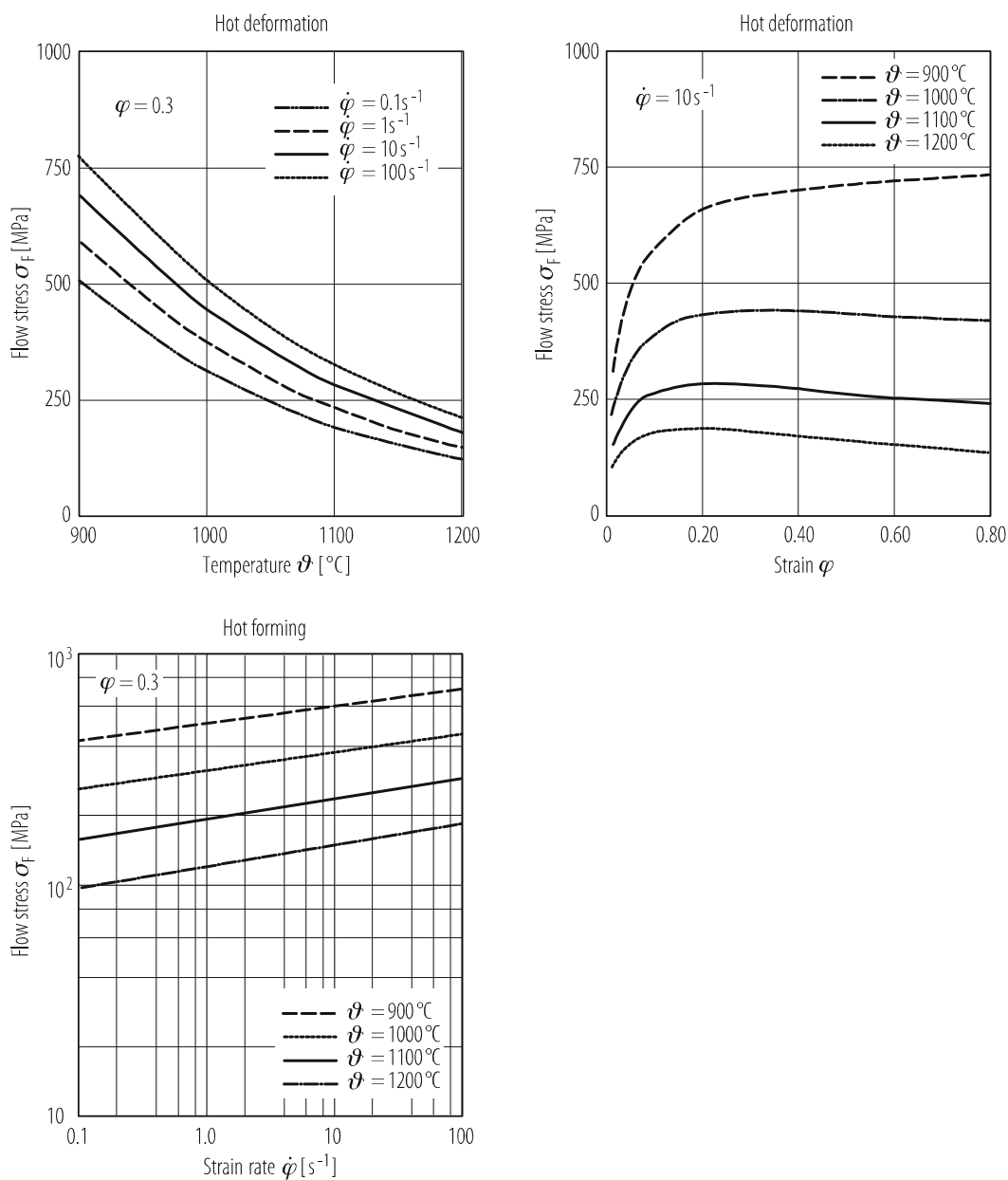
### Flow curves

| State of material           | Hot deformation |                | Cold deformation |                 |                 |
|-----------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                             | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]         |                 | 390.9          |                  |                 |                 |
| A                           |                 | 39445.700      |                  |                 |                 |
| Effect of temperature $K_9$ |                 |                |                  |                 |                 |
| $m_1$                       |                 | -0.00373       |                  |                 |                 |

(continued)

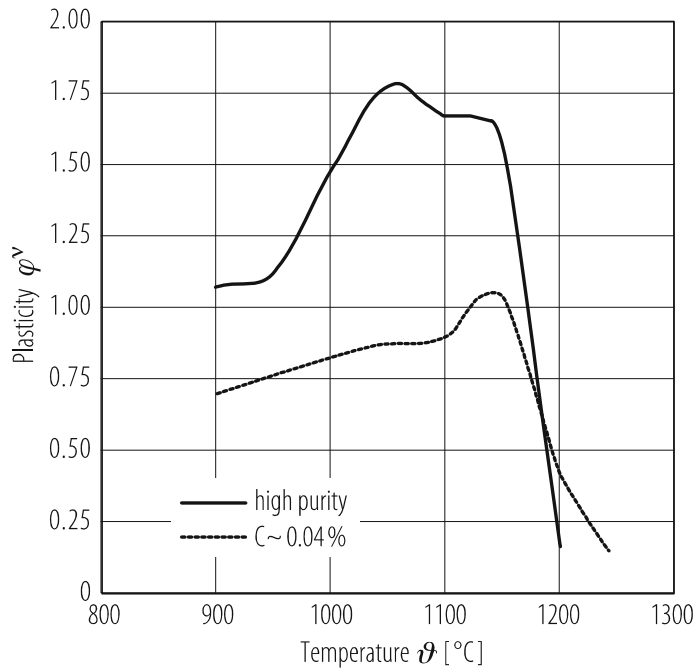
| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Effect of strain $K_\varphi$           |                 |                |                  |                 |                 |
| $m_2$                                  |                 | 0.38163        |                  |                 |                 |
| $m_4$                                  |                 | 0.00028        |                  |                 |                 |
| $m_5$                                  |                 | -0.00344       |                  |                 |                 |
| $m_7$                                  |                 | 1.39344        |                  |                 |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                |                  |                 |                 |
| $m_8$                                  |                 | 0.000078       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                       |                 | 900...1200     |                  |                 |                 |
| $\varphi$                              |                 | 0.03...0.8     |                  |                 |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.01...10      |                  |                 |                 |

|                                                                                                                                                                                |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    |



**Fig. 5.156** Flow stress curves of NiCr<sub>22</sub>Mo<sub>9</sub>Nb by hot and cold forming.

### Plasticity in torsion



**Fig. 5.157** Hot plasticity of NiCr<sub>22</sub>Mo<sub>9</sub>Nb as a function of the temperature.

### Physical properties

| Temperature<br>$\theta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                           | 9.8                                       | 415.0                                   | 12.18                                                                    | 8440                                   | 209                          |
| 100                          | 11.3                                      | 427.0                                   | 12.51                                                                    | 8408.3                                 |                              |
| 200                          | 13.1                                      | 442.1                                   | 12.93                                                                    | 8374.5                                 |                              |
| 300                          | 15.0                                      | 457.1                                   | 13.35                                                                    | 8338.6                                 |                              |
| 400                          | 16.9                                      | 472.2                                   | 13.77                                                                    | 8300.5                                 |                              |
| 500                          | 18.7                                      | 487.2                                   | 14.19                                                                    | 8260.3                                 |                              |
| 600                          | 20.6                                      | 502.3                                   | 14.61                                                                    | 8218.0                                 |                              |
| 700                          | 22.5                                      | 517.3                                   | 15.03                                                                    | 8173.5                                 |                              |
| 800                          | 24.3                                      | 532.4                                   | 15.45                                                                    | 8127.0                                 |                              |
| 900                          | 26.2                                      | 547.4                                   | 15.87                                                                    | 8078.3                                 |                              |
| 1000                         | 28.1                                      | 562.5                                   | 16.29                                                                    | 8027.4                                 |                              |
| 1100                         | 29.9                                      | 577.5                                   | 16.71                                                                    | 7974.5                                 |                              |
| 1200                         | 31.8                                      | 592.6                                   | 17.13                                                                    | 7919.4                                 |                              |

**Symbols and abbreviations**

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| AMS             | aerospace material standards                                          |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| BS              | British standards                                                     |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, mechanical and physical properties of NiCr<sub>21</sub>Mo

## 5.5 Heat resistant Nickel – Chromium – alloys

### Designation

|             |         |               |          |            |
|-------------|---------|---------------|----------|------------|
| UNS number: | N 08825 | Chem. symbol: | NiCr21Mo | EN number: |
|-------------|---------|---------------|----------|------------|

### Composition (EN) [Weight-%]

| C      | Si    | Mn    | P      | S      | Cr                  | Mo                  | Ni                  | V | Nb | Ti                  | Fe   | Co    | Cu                  | Al    | B | Zr |
|--------|-------|-------|--------|--------|---------------------|---------------------|---------------------|---|----|---------------------|------|-------|---------------------|-------|---|----|
| <0.025 | <0.50 | <1.00 | <0.025 | <0.015 | 19.5<br>...<br>23.5 | 2.50<br>...<br>3.50 | 38.0<br>...<br>46.0 |   |    | 0.60<br>...<br>1.20 | Bal. | <1.00 | 1.50<br>...<br>3.00 | <0.20 |   |    |

### International comparison of standards

|                       |               |                |                |
|-----------------------|---------------|----------------|----------------|
| ISO                   |               | China          |                |
| ISO 6207              | ISO 6208      | H01420         | T 15007 (1994) |
| ISO 9723              | ISO 9725      |                |                |
| Material number (DIN) |               | DIN            |                |
| 2.4858                |               | DIN 17744      | DIN 17750      |
|                       |               | DIN 17752      |                |
| Japan                 |               | United Kingdom |                |
| NCF 825               | D 3531 (2003) | NA 16          | BS 3072 (1989) |
|                       |               | BS 3074        | BS 3076        |
| USA                   |               |                |                |

|             |              |            |            |              |
|-------------|--------------|------------|------------|--------------|
| ASME        |              | ASTM       |            | UNS standard |
| ASME SB-163 | ASME SB-366  | ASTM B 163 | ASTM B 366 | N 08825      |
| ASME SB-423 | ASME SB-425  | ASTM B 423 | ASTM B 425 |              |
| ASME SB 564 | ASME SB-775, | ASTM B 564 | ASTM B 775 |              |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material           | Hot deformation |                | Cold deformation |                        |                 |
|-----------------------------|-----------------|----------------|------------------|------------------------|-----------------|
|                             | cast state      | deformed state | annealed (an)    | skin past rolled (skr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]         |                 | 326.6          | 787.3            | 867.6                  |                 |
| A                           |                 | 19279.837      | 1563.932         | 1563.195               |                 |
| Effect of temperature $K_9$ |                 |                |                  |                        |                 |
| $m_1$                       |                 | −0.00359       | −0.00103         | −0.00103               |                 |

(continued)



| State of material                      | Hot deformation |                | Cold deformation |                        |                 |
|----------------------------------------|-----------------|----------------|------------------|------------------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | skin past rolled (skr) | cold drawn (cd) |
| Effect of strain $K_\varphi$           |                 |                |                  |                        |                 |
| $m_2$                                  |                 | 0.35704        | 0.34010          | 0.29850                |                 |
| $m_4$                                  |                 | 0.00870        | 0.00924          | 0.00931                |                 |
| $m_5$                                  |                 | 0.00126        |                  |                        |                 |
| $m_7$                                  |                 | −0.74652       |                  |                        |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                        |                 |
| $m_3$                                  |                 |                | 0.01084          | 0.01132                |                 |
| $m_8$                                  |                 | 0.000087       |                  |                        |                 |
| Range of validity                      |                 |                |                  |                        |                 |
| $\vartheta$ [°C]                       |                 | 900...1200     | 20...300         | 20...300               |                 |
| $\varphi$                              |                 | 0.03 ... 0.30  | 0.03 ... 1.50    | 0.03 ... 1.50          |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.1...50       | 0.01...100       | 0.01...100             |                 |

|                                                                                                                                                                                |                                                                                                            |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                                                                                    | [DOI: <a href="#">978-3-642-14174-4_2</a> ]                                                                |

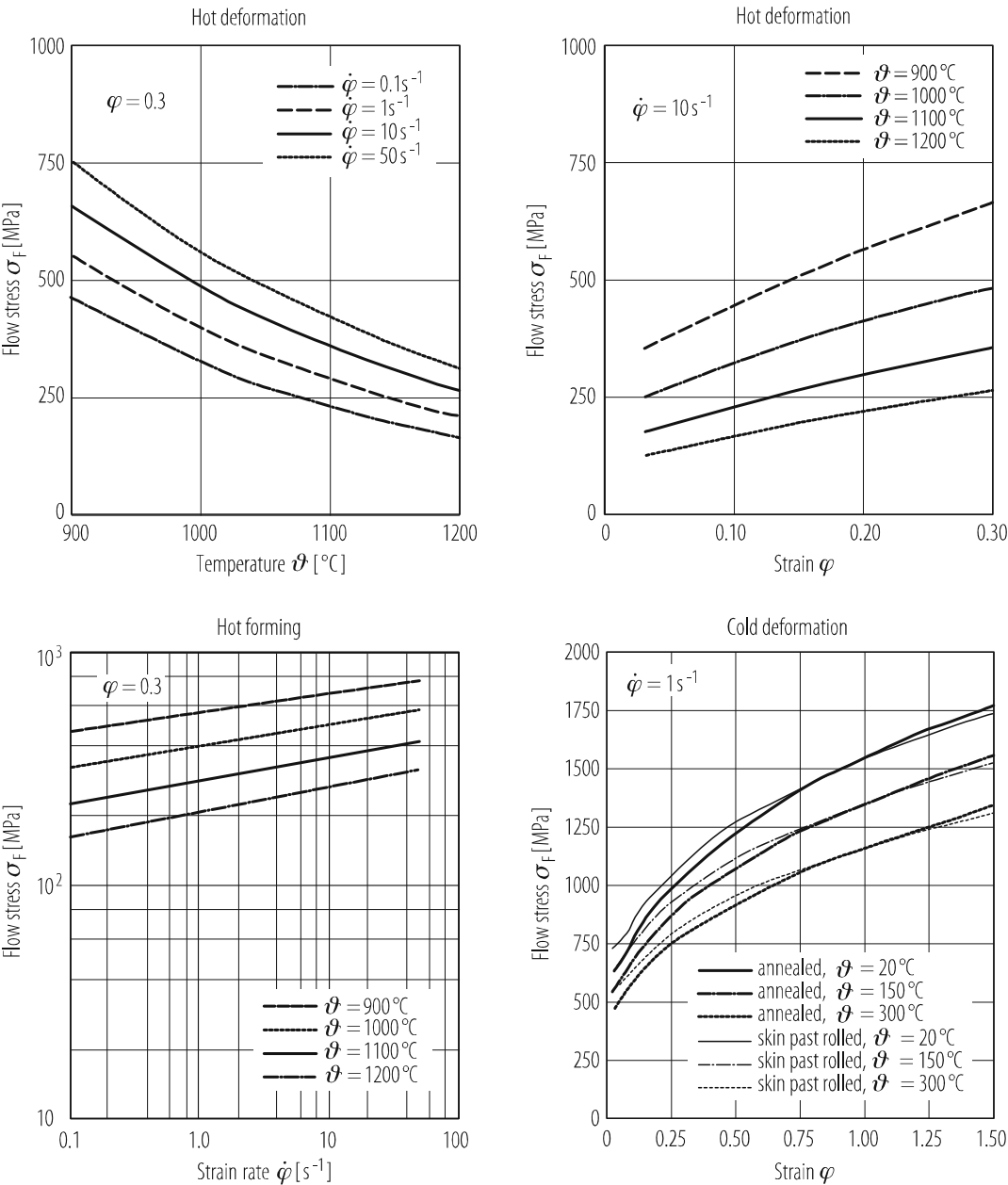


Fig. 5.158 Flow stress curves of NiCr21Mo by hot and cold forming.

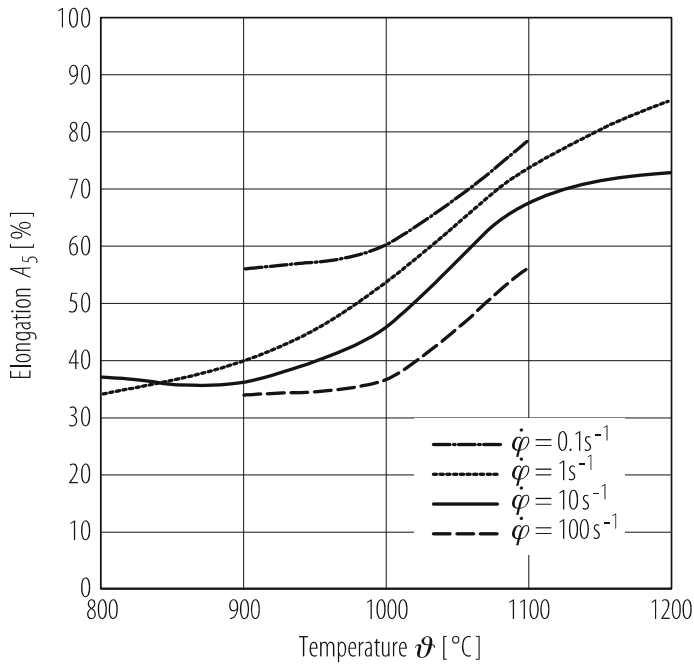
Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |         |        | Tensile strength $\Delta R_m$ [MPa] |         |        |
|-------------------|---------------------------------|---------|--------|-------------------------------------|---------|--------|
|                   | $A_0$                           | $A$     | $n_1$  | $B_0$                               | $B$     | $n_2$  |
| soft annealed     | 450..550                        | 71.6132 | 0.6346 | 550. . .650                         | 52.9739 | 0.6859 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |        |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|--------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$  | $n_4$   |                            |
| soft annealed     | 45...55                                 | 35.9695 | 0.1454 | -9.7369 | <40                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test



**Fig. 5.159** Hot plasticity of NiCr21Mo as a function of the temperature and deformation rate

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 15.2                 | 461.6              | 13.00                                   | 8580                        |                 |
| 100              | 15.9                 | 467.9              | 14.00                                   | 8544.0                      | 212             |
| 200              | 17.3                 | 476.0              | 14.80                                   | 8503.8                      | 207             |
| 300              | 18.9                 | 484.2              | 15.10                                   | 8463.4                      | 202             |
| 400              | 20.4                 | 492.6              | 15.50                                   | 8420.4                      | 196             |
| 500              | 22.2                 | 501.1              | 15.70                                   | 8377.9                      | 188             |
| 600              | 23.9                 | 509.7              | 16.30                                   | 8328.3                      | 181             |

(continued)

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 700                             | 25.6                                      | 518.5                                   | 16.80                                                                    | 8277.3                                 | 172                          |
| 800                             | 27.3                                      | 527.4                                   | 17.30                                                                    | 8223.8                                 | 163                          |
| 900                             | 29.1                                      | 536.5                                   | 17.70                                                                    | 8170.0                                 | 152                          |
| 1000                            | 30.4                                      | 545.8                                   |                                                                          | 8230.5                                 | 142                          |
| 1100                            | 32.0                                      | 555.2                                   |                                                                          | 8195.3                                 | 132                          |
| 1200                            | 33.7                                      | 564.8                                   |                                                                          | 8160.1                                 | 122                          |

Temperature dependence of the mean specific heat capacities of 2.4634 NiCo20Cr15MoTiAl was used

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| BS                  | British standards                                                     |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of NiCr<sub>60-15</sub>

## 5.5 Heat resistant Nickel – Chromium – alloys

### Designation

|             |               |               |                  |            |
|-------------|---------------|---------------|------------------|------------|
| UNS number: | <b>N06004</b> | Chem. symbol: | <b>NiCr60-15</b> | EN number: |
|-------------|---------------|---------------|------------------|------------|

### Composition (DIN) [Weight-%]

| C     | Si          | Mn    | P      | S      | Cr          | Co    | Ni    | Cu    | Al    | Ti | Fe          |
|-------|-------------|-------|--------|--------|-------------|-------|-------|-------|-------|----|-------------|
| <0.15 | 0.50...2.00 | <2.00 | <0.020 | <0.015 | 14.0...19.0 | <1.00 | >59.0 | <0.50 | <0.30 |    | 19.0...25.0 |

### International comparison of standards

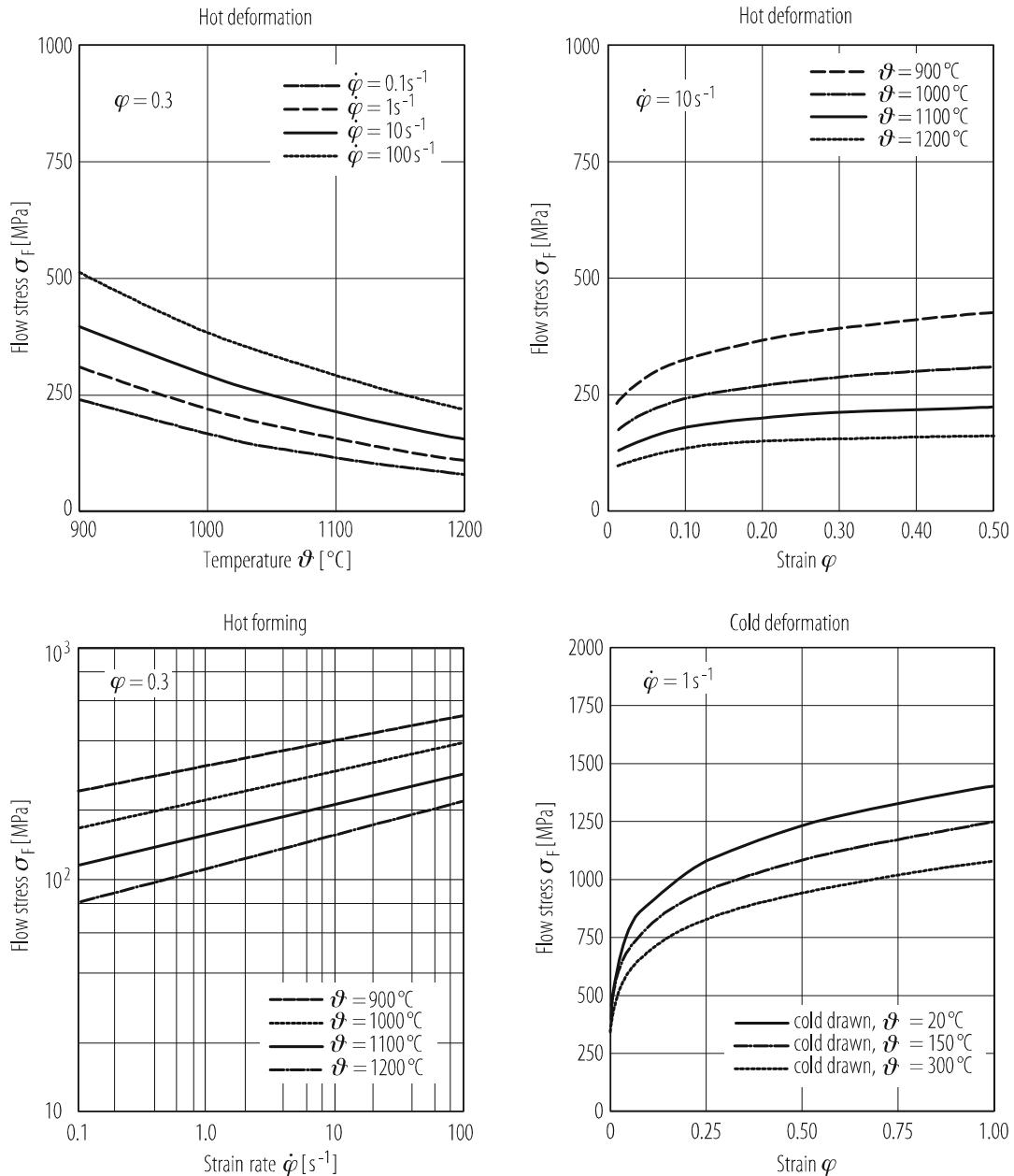
|                       |           |                  |                   |
|-----------------------|-----------|------------------|-------------------|
| Euronorm              |           | ISO              |                   |
| Material number (DIN) |           | DIN              |                   |
| 2.4867                |           | DIN 17470 (1982) | DIN 17742 (1983)  |
| United Kingdom        |           | Russia           |                   |
| RESISTOHM alloy 605   |           | Ch15N60          | GOST 10994 (1974) |
| USA                   |           |                  |                   |
| Spec.                 |           | UNS standard     |                   |
| Nichrome              | alloy 605 | N06004           |                   |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                           | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 241.0          |                  |                 | 919.1           |
| A                                         |                 | 7598.681       |                  |                 | 1437.764        |
| Effect of temperature $K_{\theta}$        |                 |                |                  |                 |                 |
| $m_1$                                     |                 | −0.00314       |                  |                 | −0.00096        |
| Effect of strain $K_{\varphi}$            |                 |                |                  |                 |                 |
| $m_2$                                     |                 | 0.24172        |                  |                 | 0.18985         |
| $m_4$                                     |                 | 0.00162        |                  |                 | −0.00103        |
| $m_5$                                     |                 | −0.00102       |                  |                 |                 |
| $m_7$                                     |                 | 0.45775        |                  |                 |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |                 |                 |
| $m_3$                                     |                 |                |                  |                 | 0.01092         |
| $m_8$                                     |                 | 0.000122       |                  |                 |                 |
| Range of validity                         |                 |                |                  |                 |                 |
| $\theta$ [°C]                             |                 | 900...1200     |                  |                 | 20...300        |
| $\varphi$                                 |                 | 0.03...0.50    |                  |                 | 0.03...1.00     |
| $\dot{\varphi}$ [1/s]                     |                 | 0.01...150     |                  |                 | 0.01...50       |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.160** Flow stress curves of NiCr60–15 by hot and cold forming

**Mechanical properties after cold deformation**

| State of material | Yield stress $\Delta R_p$ [MPa] |          |        | Tensile strength $\Delta R_m$ [MPa] |         |        |
|-------------------|---------------------------------|----------|--------|-------------------------------------|---------|--------|
|                   | $A_0$                           | $A$      | $n_1$  | $B_0$                               | $B$     | $n_2$  |
| soft annealed     | 280...330                       | 162.3964 | 0.3926 | 600...650                           | 31.3919 | 0.6953 |
|                   |                                 |          |        | Vickers hardness $\Delta H_V$       |         |        |
|                   |                                 |          |        | $B_0$                               | $B$     | $n_2$  |
| soft annealed     |                                 |          |        | 170...190                           | 21.0995 | 0.4713 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |        |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|--------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$  | $n_4$   |                            |
| hot rolled        | 30...35                                 | 28.6857 | 0.0246 | -7.8208 | <80                        |
| soft annealed     | 32...38                                 | 23.6911 | 0.0813 | -4.8215 | <75                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

**Physical properties**

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 13.3                 | 460.6              | 13.39                                   | 8200                        |                 |
| 100              | 14.4                 | 466.9              | 13.69                                   | 8166.3                      |                 |
| 200              | 15.7                 | 475.0              | 14.07                                   | 8130.8                      |                 |
| 300              | 17.0                 | 483.2              | 14.44                                   | 8093.4                      |                 |
| 400              | 18.3                 | 491.5              | 14.81                                   | 8054.2                      |                 |
| 500              | 19.6                 | 500.0              | 15.19                                   | 8013.2                      |                 |
| 600              | 20.9                 | 508.6              | 15.56                                   | 7970.3                      |                 |
| 700              | 22.2                 | 517.4              | 15.94                                   | 7925.6                      |                 |
| 800              | 23.4                 | 526.3              | 16.31                                   | 7879.0                      |                 |
| 900              | 24.7                 | 535.4              | 16.68                                   | 7830.6                      |                 |
| 1000             | 26.0                 | 544.6              | 17.06                                   | 7780.4                      |                 |
| 1100             | 27.3                 | 554.0              | 17.43                                   | 7728.3                      |                 |
| 1200             | 28.6                 | 563.5              | 17.81                                   | 7674.4                      |                 |

**Symbols and abbreviations**

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| ISO            | international organisation for standardization |
| $R_m$          | tensile strength                               |
| $R_p$          | yield stress                                   |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\Delta H_v$   | vickers hardness                               |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |



# Flow stress, mechanical and physical properties of NiCr<sub>80-20</sub>

## 5.5 Heat resistant Nickel – Chromium – alloys

### Designation

|             |               |               |                  |            |
|-------------|---------------|---------------|------------------|------------|
| UNS number: | <b>N06003</b> | Chem. symbol: | <b>NiCr80-20</b> | EN number: |
|-------------|---------------|---------------|------------------|------------|

### Composition (EN) [Weight-%]

| C     | Si          | Mn    | P      | S      | Cr          | Co    | Ni    | Cu    | Al    | Ti | Fe    |
|-------|-------------|-------|--------|--------|-------------|-------|-------|-------|-------|----|-------|
| <0.15 | 0.50...2.00 | <1.00 | <0.020 | <0.015 | 19.0...21.0 | <1.00 | >75.0 | <0.50 | <0.50 |    | <1.00 |

### International comparison of standards

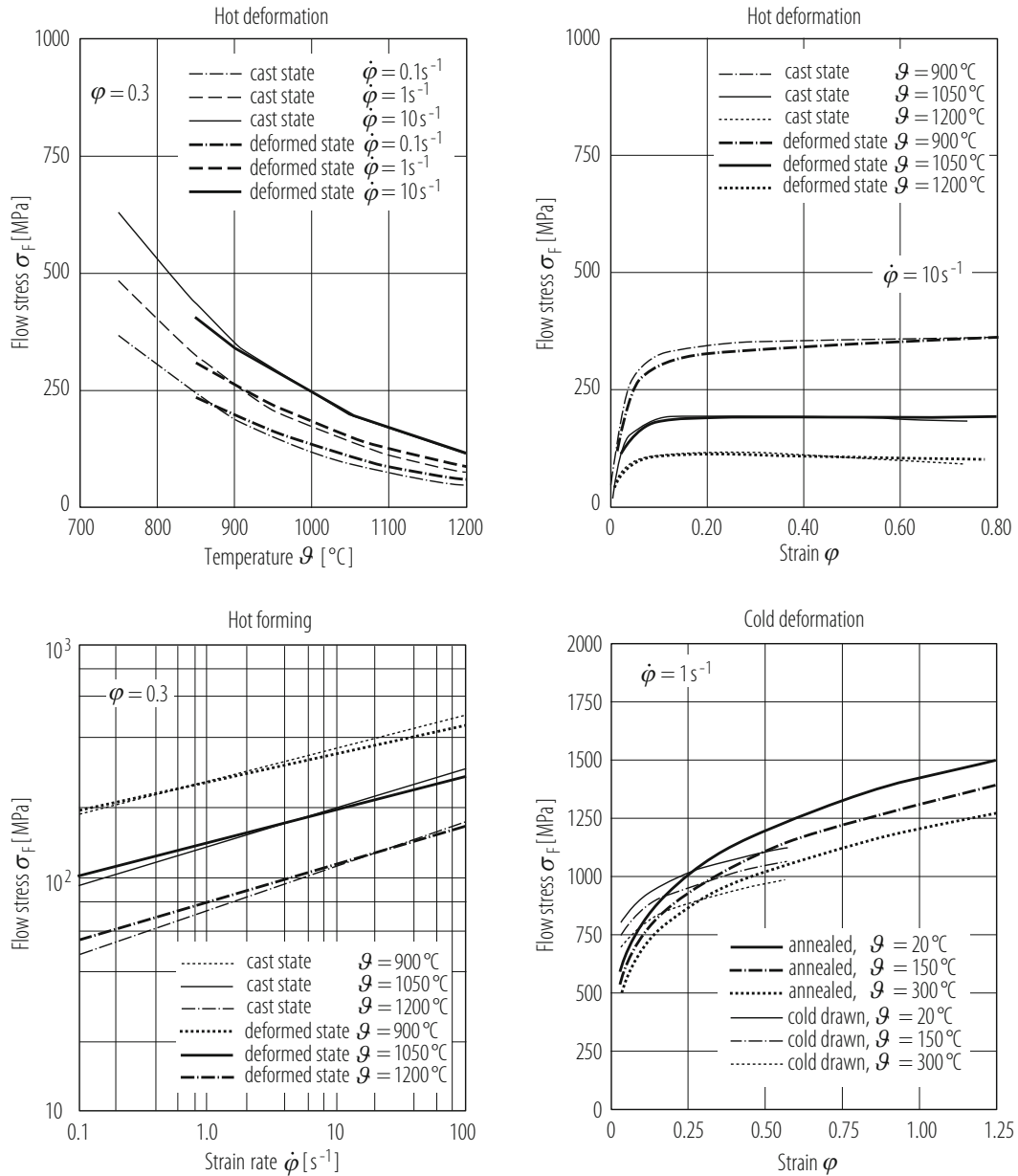
|                       |        |               |                   |
|-----------------------|--------|---------------|-------------------|
| Euronorm              | ISO    |               |                   |
| EN 17742              |        |               |                   |
| Material number (DIN) | DIN    |               |                   |
| 2.4869                |        | DIN 17470     | DIN 17472         |
| United Kingdom        | Russia |               |                   |
| Thermax 75            | Spec.  | Ch20N80       | GOST 10994 (1974) |
| USA                   |        |               |                   |
| ASME                  |        | ASTM          | UNS standard      |
| ASME 5676             |        | ASTM B 344-01 | N06003            |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                           | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       | 226.3           | 216.2          | 825.4            |                 | 930.8           |
| A                                         | 10208.031       | 8208.031       | 1437.764         |                 | 1219.864        |
| Effect of temperature $K_{\theta}$        |                 |                |                  |                 |                 |
| $m_1$                                     | −0.00373        | −0.00353       | −0.00059         |                 | −0.00050        |
| Effect of strain $K_{\varphi a3}$         |                 |                |                  |                 |                 |
| $m_2$                                     | 0.10291         | 0.10191        | 0.23981          |                 | 0.12780         |
| $m_4$                                     | −0.01136        | −0.01136       | −0.00129         |                 | 0.00084         |
| $m_5$                                     | −0.00175        | −0.00175       |                  |                 |                 |
| $m_7$                                     | 0.94114         | 0.92114        |                  |                 |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |                 |                 |
| $m_3$                                     |                 |                | 0.00952          |                 | 0.01104         |
| $m_8$                                     | 0.000157        | 0.000137       |                  |                 |                 |
| Range of validity                         |                 |                |                  |                 |                 |
| $\theta$ [°C]                             | 750...1200      | 850...1200     | 20...300         |                 | 20...300        |
| $\varphi$                                 | 0.03 ... 0.80   | 0.03 ... 0.80  | 0.03 ... 1.25    |                 | 0.03 ... 0.50   |
| $\dot{\varphi}$ [1/s]                     | 0.001...100     | 0.01...150     | 0.01...50        |                 | 0.01...50       |

| Hot deformation:                                                                                                                                                      | Cold deformation                                                                                        |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                  | [Equation (2.25), Chapter 2.3.2.2.2]                                                                    |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                            | [DOI: 978-3-642-14174-4_2]                                                                              |



**Fig. 5.161** Flow stress curves of NiCr<sub>80-20</sub> by hot and cold forming

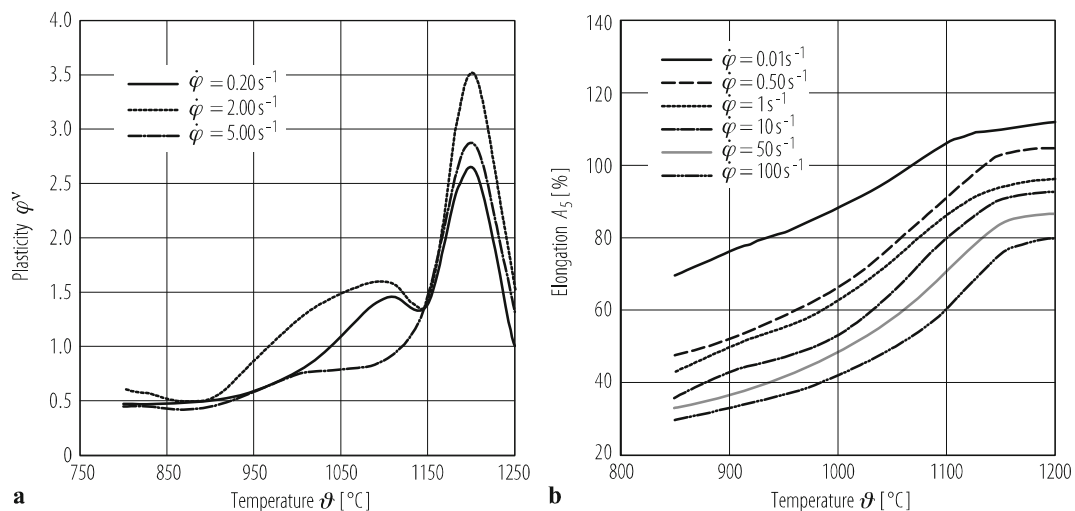
### Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |         |        | Tensile strength $\Delta R_m$ [MPa] |         |        |
|-------------------|---------------------------------|---------|--------|-------------------------------------|---------|--------|
|                   | $A_0$                           | $A$     | $n_1$  | $B_0$                               | $B$     | $n_2$  |
| soft annealed     | 300...350                       | 94.3310 | 0.5488 | 700...800                           | 15.0415 | 0.8760 |
|                   |                                 |         |        | Vickers hardness $\Delta H_v$       |         |        |
|                   |                                 |         |        | $B_0$                               | $B$     | $n_2$  |
| soft annealed     |                                 |         |        | 170...190                           | 14.8603 | 0.6381 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |        |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|--------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$  | $n_4$   |                            |
| hot rolled        | 30...35                                 | 21.7167 | 0.1356 | -5.7442 | <80                        |
| soft annealed     | 32...38                                 | 22.2106 | 0.1098 | -3.3887 | <75                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

### Plasticity in torsion and tensile test



**Fig. 5.162** Hot plasticity of NiCr<sub>80-20</sub> as a function of the temperature and deformation rate. (a) Torsion test (b) Tensile test

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 15.2                 | 420.4              | 13.39                                   | 8200                        | 200             |
| 100              | 16.6                 | 426.2              | 13.69                                   | 8166.3                      |                 |
| 200              | 18.4                 | 433.6              | 14.07                                   | 8130.8                      |                 |
| 300              | 20.2                 | 441.1              | 14.44                                   | 8093.4                      |                 |
| 400              | 22.0                 | 448.7              | 14.81                                   | 8054.2                      |                 |
| 500              | 23.8                 | 456.4              | 15.19                                   | 8013.2                      |                 |
| 600              | 25.6                 | 464.3              | 15.56                                   | 7970.3                      |                 |
| 700              | 27.4                 | 472.3              | 15.94                                   | 7925.6                      |                 |
| 800              | 29.2                 | 480.4              | 16.31                                   | 7879.0                      |                 |
| 900              | 31.0                 | 488.7              | 16.68                                   | 7830.6                      |                 |
| 1000             | 32.8                 | 497.1              | 17.06                                   | 7780.4                      |                 |
| 1100             | 34.5                 | 505.7              | 17.43                                   | 7728.3                      |                 |
| 1200             | 36.3                 | 514.4              | 17.81                                   | 7674.4                      |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\Delta Hv$         | vickers hardness                                                      |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of NiCr<sub>10</sub>

## 5.5 Heat resistant Nickel – Chromium – alloys

### Designation

|             |               |        |            |
|-------------|---------------|--------|------------|
| UNS number: | Chem. symbol: | NiCr10 | EN number: |
|-------------|---------------|--------|------------|

### Composition (DIN) [Weight-%]

| C           | Si          | Mn          | P      | S      | Cr          | Mo | Ni    | V           | Nb | Ti          | Others |
|-------------|-------------|-------------|--------|--------|-------------|----|-------|-------------|----|-------------|--------|
| 0.10...0.15 | 0.30...0.60 | 0.20...0.40 | <0.045 | <0.030 | 9.00...11.0 |    | >87.0 | 0.90...1.10 |    | 0.50...0.70 |        |

### International comparison of standards

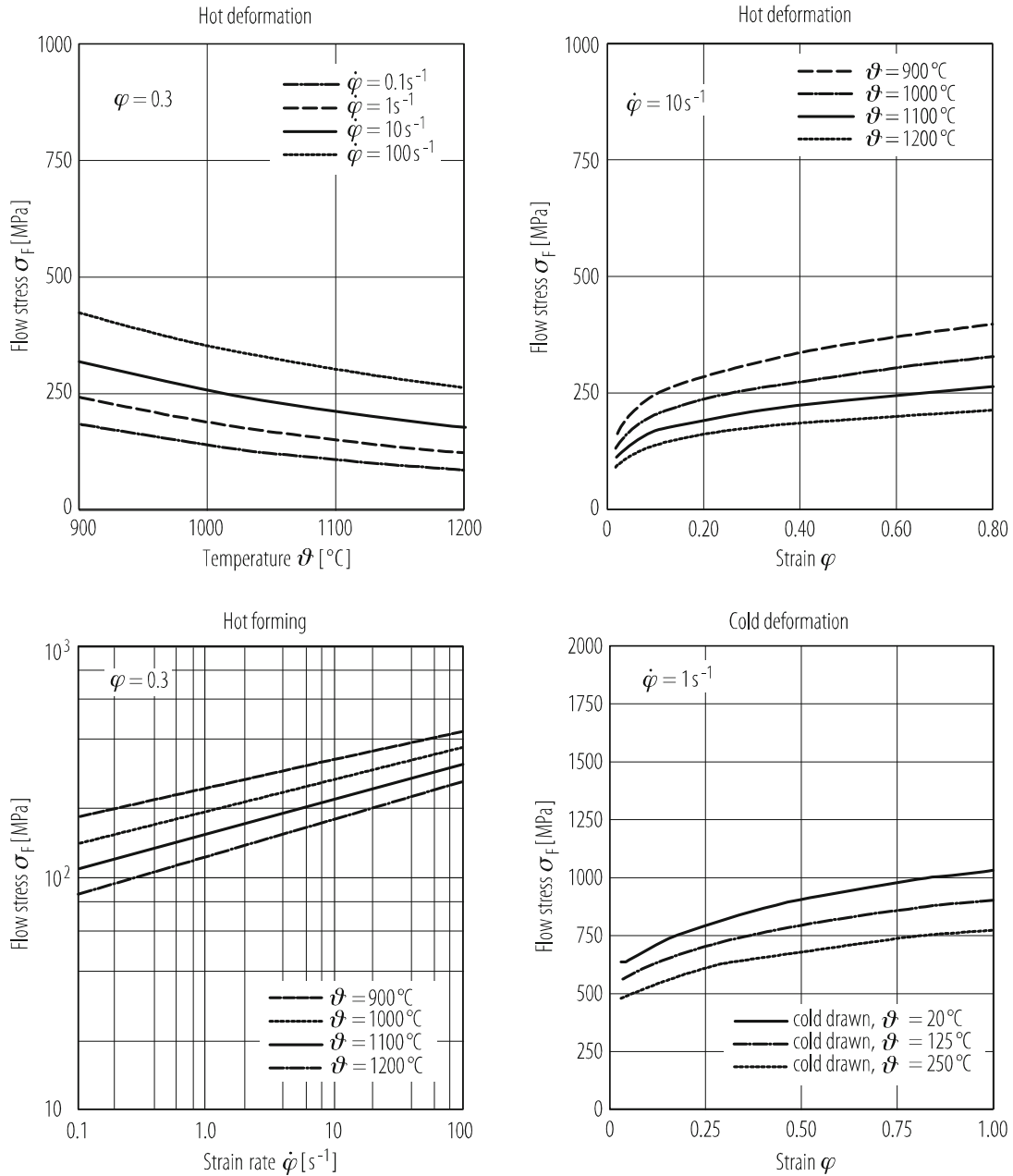
|                       |                   |
|-----------------------|-------------------|
| Euronorm              | ISO               |
|                       | ISO 9001          |
| Material number (DIN) | DIN               |
| 2.4870                | DIN 17742         |
| France                | Russia            |
|                       | NCh9              |
|                       | GOST 10994 (1974) |
| USA                   |                   |
| ASME                  | ASTM              |
|                       | ASTM B 443        |
|                       | UNS standard      |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 | 203.6          |                  |                 | 713.6           |
| A                                      |                 | 2303.760       |                  |                 | 1045.362        |
| Effect of temperature $K_{\theta}$     |                 |                |                  |                 |                 |
| $m_1$                                  |                 | −0.00218       |                  |                 | −0.00125        |
| Effect of strain $K_{\phi}$            |                 |                |                  |                 |                 |
| $m_2$                                  |                 | 0.23027        |                  |                 | 0.19300         |
| $m_4$                                  |                 | −0.00180       |                  |                 | 0.00614         |
| $m_5$                                  |                 | −0.00038       |                  |                 |                 |
| $m_7$                                  |                 | 0.22745        |                  |                 |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                |                  |                 | 0.01138         |
| $m_8$                                  |                 | 0.000137       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\theta$ [°C]                          |                 | 900...1200     |                  |                 | 20...250        |
| $\phi$                                 |                 | 0.03...0.80    |                  |                 | 0.03...1.00     |
| $\dot{\phi}$ [1/s]                     |                 | 0.10...100     |                  |                 | 0.01...100      |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.163** Flow stress curves of NiCr<sub>10</sub> by hot and cold forming.

**Mechanical properties after cold deformation**

| State of material | Yield stress $\Delta R_p$ [MPa] |     |       | Tensile strength $\Delta R_m$ [MPa] |         |        |
|-------------------|---------------------------------|-----|-------|-------------------------------------|---------|--------|
|                   | $A_0$                           | $A$ | $n_1$ | $B_0$                               | $B$     | $n_2$  |
| soft annealed     |                                 |     |       | 550. . .650                         | 35.3161 | 0.6262 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$   | $n_4$    |                            |
| soft annealed     | 35. . .45                               | 86.4287 | −0.1334 | −11.0868 | <80                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

**Physical properties**

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 17.4                 |                    |                                         |                             |                 |
| 100              | 18.9                 |                    |                                         |                             |                 |
| 200              | 20.7                 |                    |                                         |                             |                 |
| 300              | 22.6                 |                    |                                         |                             |                 |
| 400              | 24.5                 |                    |                                         |                             |                 |
| 500              | 26.4                 |                    |                                         |                             |                 |
| 600              | 28.2                 |                    |                                         |                             |                 |
| 700              | 30.1                 |                    |                                         |                             |                 |
| 800              | 32.0                 |                    |                                         |                             |                 |
| 900              | 33.8                 |                    |                                         |                             |                 |
| 1000             | 35.7                 |                    |                                         |                             |                 |
| 1100             | 37.6                 |                    |                                         |                             |                 |
| 1200             | 39.4                 |                    |                                         |                             |                 |

**Symbols and abbreviations**

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASME                | American society of mechanical engineers                              |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| EN             | Euronorm                                       |
| GOST           | gosudarstvennyy standart (state standard)      |
| ISO            | international organisation for standardization |
| $R_m$          | tensile strength                               |
| $R_p$          | yield stress                                   |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |



# Flow stress, plasticity and physical properties of NiCr<sub>20</sub>AlSi

## 5.5 Heat resistant Nickel – Chromium – alloys

### Designation

|             |               |               |                   |            |
|-------------|---------------|---------------|-------------------|------------|
| UNS number: | <b>N07080</b> | Chem. symbol: | <b>NiCr20AlSi</b> | EN number: |
|-------------|---------------|---------------|-------------------|------------|

### Composition (EN) [Weight-%]

| C     | Si          | Mn    | P      | S      | Cr          | Al          | Ni    | Cu    | Co    | Ti | Fe    |
|-------|-------------|-------|--------|--------|-------------|-------------|-------|-------|-------|----|-------|
| <0.05 | 0.50...2.00 | <0.70 | <0.020 | <0.015 | 19.0...21.0 | 2.50...4.00 | >73.0 | <0.10 | <1.00 |    | <1.00 |

### International comparison of standards

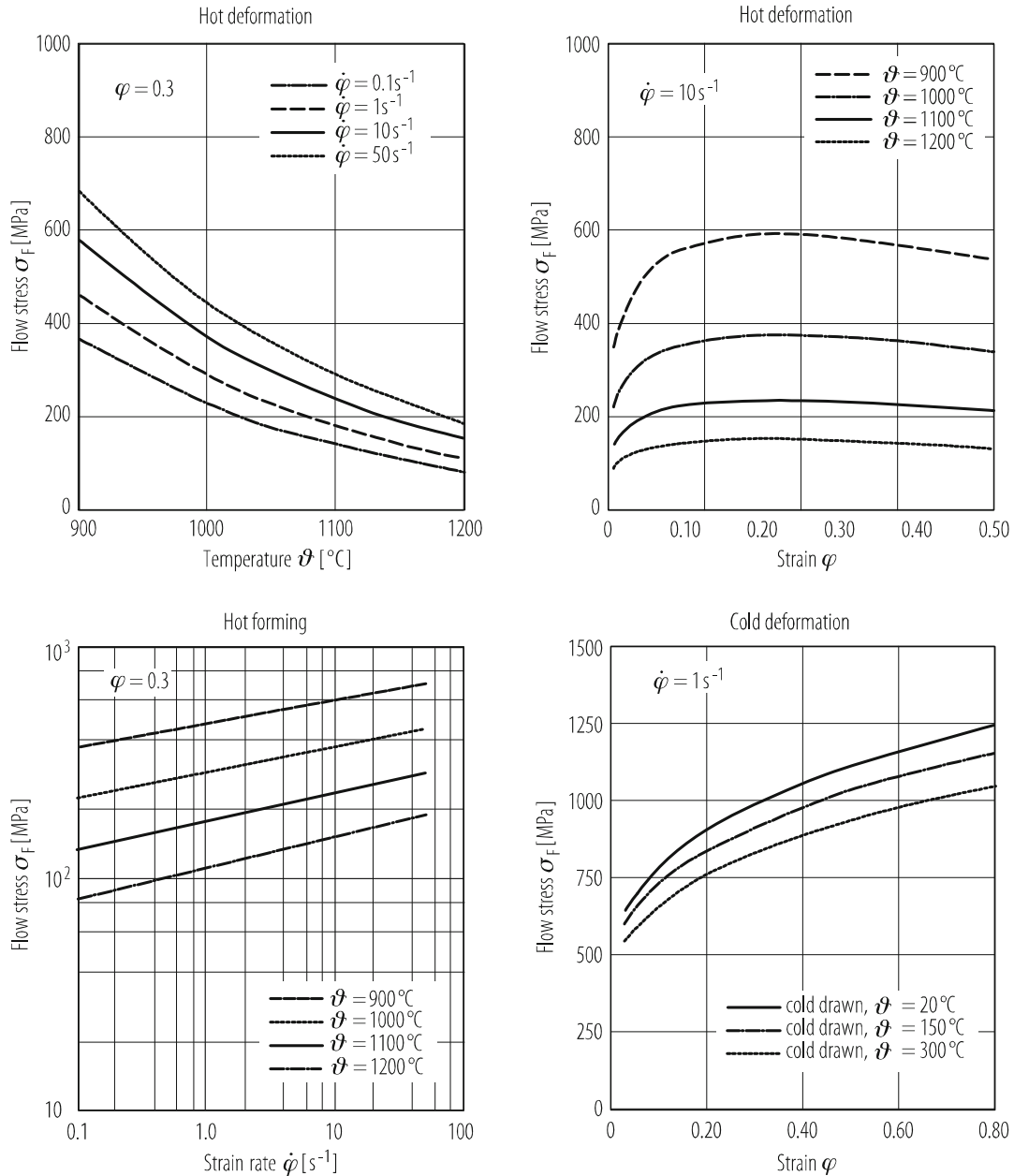
| Euronorm              |          | ISO            |              |
|-----------------------|----------|----------------|--------------|
| EN 10302              | EN 10269 |                |              |
| Material number (DIN) |          | DIN            |              |
| 2.4872                |          | DIN 17742      | DIN 17480    |
| France                |          | United Kingdom |              |
| AFNOR NC 20 TA        |          | BS 20          | HR 401       |
| USA                   |          |                |              |
| ASME                  |          | ASTM           | UNS standard |
|                       |          | ASTM B637 - 12 | N07080       |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

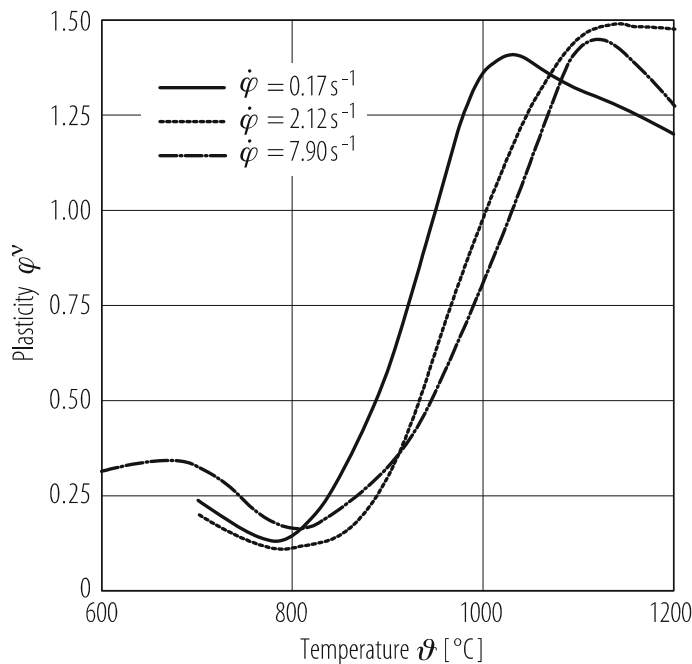
| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 | 319.6          | 803.4            |                 |                 |
| A                                      |                 | 52401.998      | 1323.505         |                 |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                  |                 |                 |
| $m_1$                                  |                 | −0.00473       | −0.00062         |                 |                 |
| Effect of strain $K_{\phi}$            |                 |                |                  |                 |                 |
| $m_2$                                  |                 | 0.24974        | 0.24012          |                 |                 |
| $m_4$                                  |                 | 0.00126        | 0.00432          |                 |                 |
| $m_5$                                  |                 | −0.00021       |                  |                 |                 |
| $m_7$                                  |                 | −0.42843       |                  |                 |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.00995          |                 |                 |
| $m_8$                                  |                 | 0.000111       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\theta$ [°C]                          |                 | 900...1200     | 20...300         |                 |                 |
| $\phi$                                 |                 | 0.03...1.00    | 0.03...0.80      |                 |                 |
| $\dot{\phi}$ [1/s]                     |                 | 0.1...50       | 0.01...50        |                 |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.164** Flow stress curves of NiCr<sub>20</sub>AlSi by hot and cold forming.

Plasticity in torsion



**Fig. 5.165** Hot plasticity of NiCr<sub>20</sub>AlSi as a function of the temperature and deformation rate.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 14                   | 460.6              |                                         | 8000                        |                 |
| 100              |                      | 466.9              |                                         |                             |                 |
| 200              |                      | 475.0              |                                         |                             |                 |
| 300              |                      | 483.2              |                                         |                             |                 |
| 400              |                      | 491.5              |                                         |                             |                 |
| 500              |                      | 500.0              |                                         |                             |                 |
| 600              |                      | 508.6              |                                         |                             |                 |
| 700              |                      | 517.4              |                                         |                             |                 |
| 800              |                      | 526.3              |                                         |                             |                 |
| 900              |                      | 535.4              |                                         |                             |                 |
| 1000             |                      | 544.6              |                                         |                             |                 |
| 1100             |                      | 554.0              |                                         |                             |                 |
| 1200             |                      | 563.5              |                                         |                             |                 |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| AFNOR           | Association Française de Normalisation                                |
| ASME            | American society of mechanical engineers                              |
| ASTM            | American society for testing and materials                            |
| BS              | British standards                                                     |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, plasticity and physical properties of Zn<sub>99.95</sub>

## 5.6 Zinc and Zinc alloys

### Designation

|             |               |                              |
|-------------|---------------|------------------------------|
| UNS number: | <b>Z15001</b> | Chem. symbol: <b>Zn99.95</b> |
|-------------|---------------|------------------------------|

### Compustion (EN) [Weight-%]

| Zn     | Pb     | Sn     | Fe     | Cd     | Cu     |
|--------|--------|--------|--------|--------|--------|
| >99.95 | <0.015 | <0.001 | <0.007 | <0.005 | <0.001 |

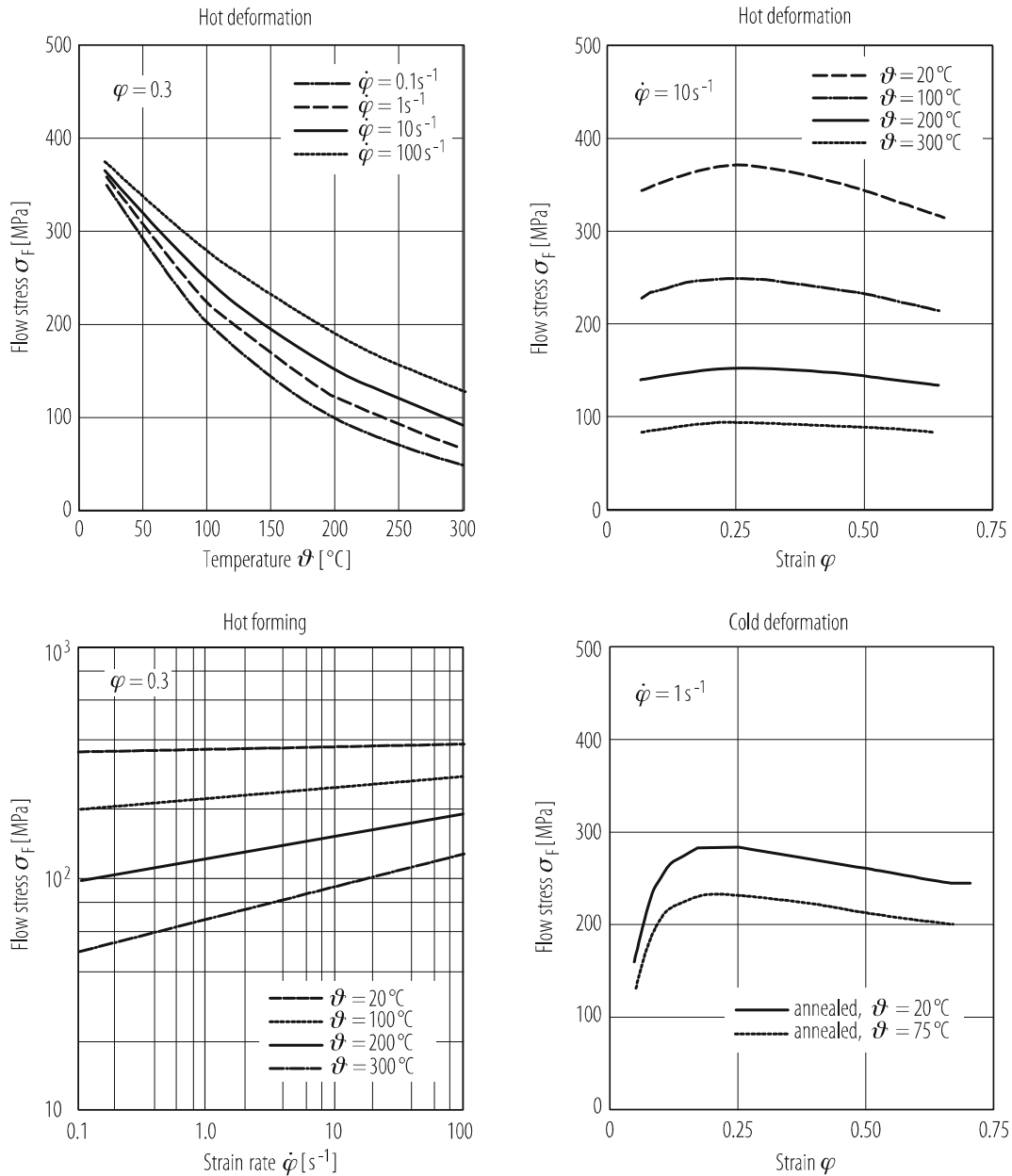
### International comparison of standards

| Euronorm              |            | ISO            |
|-----------------------|------------|----------------|
| EN 1982: 2008 2       |            | ISO 9000 3     |
| Material number (DIN) |            | United Kingdom |
| 2.2035                | DIN 1706   | BS 3436(86)    |
| China                 |            |                |
| CNS H 3004            |            |                |
| USA                   |            |                |
| ASTM                  |            | UNS standard   |
| ASTM B833 - 09        | ASTM A1055 | Z15001         |
| ASTM A1055M           |            |                |

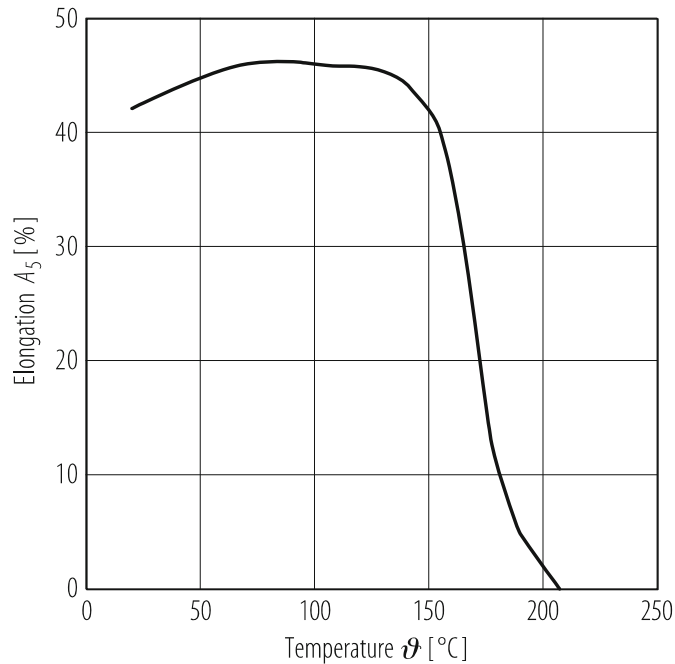
It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                     | Hot deformation |                | Cold deformation |                 |                 |
|---------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                       | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                   |                 | 111.1          | 293.9            |                 |                 |
| A                                     |                 | 859.173        | 257.011          |                 |                 |
| Effect of temperature $K_\theta$ :    |                 |                |                  |                 |                 |
| $m_1$                                 |                 | −0.00612       | −0.00361         |                 |                 |
| Effect of strain $K_\phi$ :           |                 |                |                  |                 |                 |
| $m_2$                                 |                 | 0.38578        | −0.32864         |                 |                 |
| $m_4$                                 |                 | 0.02102        | −0.07079         |                 |                 |
| $m_5$                                 |                 | 0.00047        |                  |                 |                 |
| $m_7$                                 |                 | −1.20248       |                  |                 |                 |
| Effect of strain rate $K\dot{\phi}$ : |                 |                |                  |                 |                 |
| $m_3$                                 |                 |                | 0.06774          |                 |                 |
| $m_8$                                 |                 | 0.000472       |                  |                 |                 |
| Range of validity                     |                 |                |                  |                 |                 |
| $\theta$ [°C]                         |                 | 0...300        | 0...75           |                 |                 |
| $\phi$                                |                 | 0.10...0.70    | 0.05...0.70      |                 |                 |
| $\dot{\phi}$ [1/s]                    |                 | 0.1...100      | 0.1...100        |                 |                 |



**Fig. 5.166** Flow stress curves of Zn<sub>99.95</sub> by hot and cold forming.

**Plasticity in tensile test****Fig. 5.167** Plasticity of Zn<sub>99.95</sub> as a function of the temperature.**Physical properties**

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}/K$ ] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                              | 115.0                                     | 388.3                                   | 30                                                                       | 7130.7                                 | 103                          |
| 50                              | 113.8                                     | 390.1                                   |                                                                          | 7111.2                                 |                              |
| 100                             | 111.9                                     | 392.9                                   | 32                                                                       | 7079.2                                 |                              |
| 150                             | 110.0                                     | 396.1                                   |                                                                          | 7047.6                                 |                              |
| 200                             | 108.1                                     | 379.6                                   | 34                                                                       | 7016.5                                 |                              |
| 250                             | 106.2                                     | 403.4                                   |                                                                          | 6985.8                                 |                              |
| 300                             | 104.3                                     | 407.3                                   | 36                                                                       | 6955.5                                 |                              |
| 350                             | 102.4                                     | 411.5                                   |                                                                          | 6925.7                                 |                              |
| 400                             | 100.5                                     | 415.9                                   | 38                                                                       | 6896.3                                 |                              |

**Symbols and abbreviations**

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| EN             | Euronorm                                       |
| ISO            | international organisation for standardization |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |



# Flow stress, plasticity and physical properties of Zn<sub>1</sub>

## 5.6 Zinc and Zinc alloys

### Designation

|             |                          |
|-------------|--------------------------|
| UNS number: | Chem. symbol: <b>Zn1</b> |
|-------------|--------------------------|

### Compustion (EN) [Weight-%]

| Zn   | Pb | Sn | Fe | Cd | Ti            | Cu            | Al     | Mg |
|------|----|----|----|----|---------------|---------------|--------|----|
| Bal. |    |    |    |    | 0.07 ... 0.12 | 0.08 ... 0.20 | 0.0015 |    |

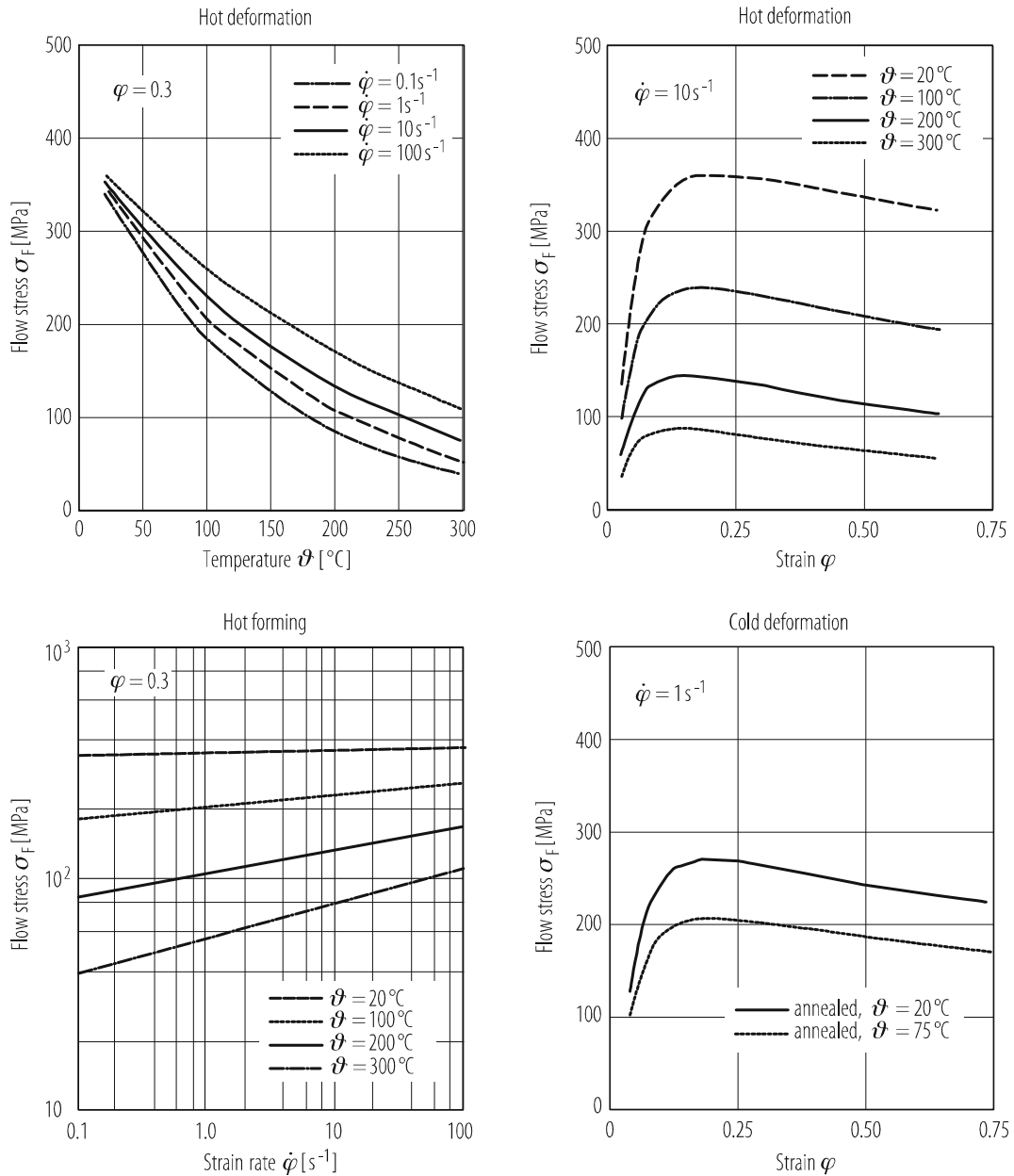
### International comparison of standards

|             |                |
|-------------|----------------|
| Euronorm    | ISO            |
| EN AW-7020  | EN 573         |
| DIN         | ISO 301        |
| DIN 1725    |                |
| Japan       | Russia         |
| USA         |                |
| ASTM        | UNS standard   |
| ASTM B240   | ASTM B833 - 09 |
| ASTM A1055M | ASTM A1055     |

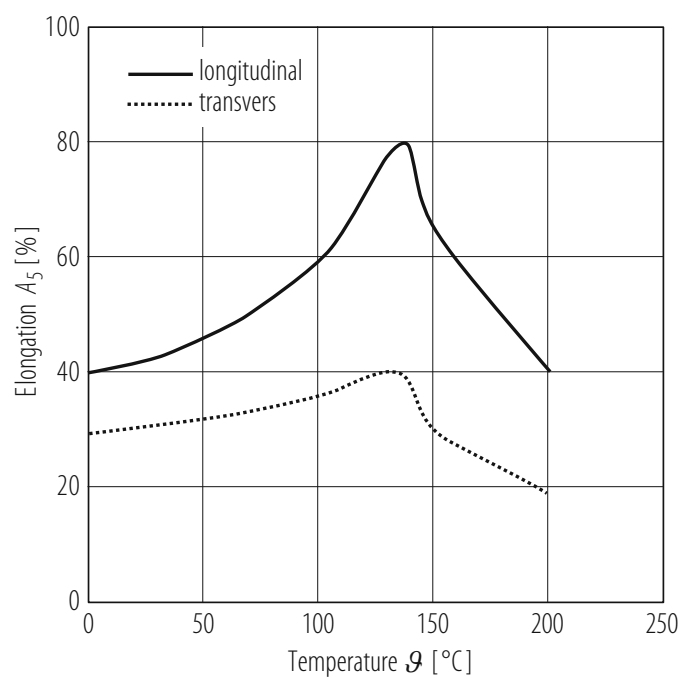
It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |                 |                 |
|-------------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                           | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 223.3          | 294.6            |                 |                 |
| A                                         |                 | 354.944        | 242.148          |                 |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                  |                 |                 |
| $m_1$                                     |                 | -0.00558       | -0.00479         |                 |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                  |                 |                 |
| $m_2$                                     |                 | -0.22491       | -0.32052         |                 |                 |
| $m_4$                                     |                 | -0.05031       | -0.06328         |                 |                 |
| $m_5$                                     |                 | -0.00384       |                  |                 |                 |
| $m_7$                                     |                 | 0.00356        |                  |                 |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |                 |                 |
| $m_3$                                     |                 |                | 0.08053          |                 |                 |
| $m_8$                                     |                 | 0.000500       |                  |                 |                 |
| Range of validity                         |                 |                |                  |                 |                 |
| $\theta$ [°C]                             |                 | 0 ... 300      | 0 ... 75         |                 |                 |
| $\varphi$                                 |                 | 0.10 ... 0.70  | 0.05 ... 0.70    |                 |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.8 ... 100    | 0.8 ... 100      |                 |                 |



**Fig. 5.168** Flow stress curves of Zn<sub>1</sub> by hot and cold forming.

**Plasticity in tensile test****Fig. 5.169** Plasticity of Zn 1 as a function of the temperature.**Physical properties**

| Temperature<br>$\theta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}/K$ ] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                           | 115.0                                     | 388.3                                   | 30                                                                       | 7130.7                                 | 103                          |
| 50                           | 113.8                                     | 390.1                                   |                                                                          | 7111.2                                 |                              |
| 100                          | 111.9                                     | 392.9                                   | 32                                                                       | 7079.2                                 |                              |
| 150                          | 110.0                                     | 396.1                                   |                                                                          | 7047.6                                 |                              |
| 200                          | 108.1                                     | 379.6                                   | 34                                                                       | 7016.5                                 |                              |
| 250                          | 106.2                                     | 403.4                                   |                                                                          | 6985.8                                 |                              |
| 300                          | 104.3                                     | 407.3                                   | 36                                                                       | 6955.5                                 |                              |
| 350                          | 102.4                                     | 411.5                                   |                                                                          | 6925.7                                 |                              |
| 400                          | 100.5                                     | 415.9                                   | 38                                                                       | 6896.3                                 |                              |

Physical properties of 2.2035 Zn 99.95 was used

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress and physical properties of ZnAl<sub>4</sub>

## 5.6 Zinc and Zinc alloys

### Designation

|             |               |                                       |
|-------------|---------------|---------------------------------------|
| UNS number: | <b>Z33520</b> | Chem. symbol: <b>ZnAl<sub>4</sub></b> |
|-------------|---------------|---------------------------------------|

### Composition (EN) [Weight-%]

| Zn   | Pb | Sn     | Fe     | Cd | Σ Pb + Cd | Cu    | Al          | Mg          |
|------|----|--------|--------|----|-----------|-------|-------------|-------------|
| Bal. |    | <0.001 | <0.075 |    | <0.011    | <0.10 | 3.90...4.30 | 0.02...0.05 |

### International comparison of standards

|                        |            |                |               |
|------------------------|------------|----------------|---------------|
| Euronorm               |            | ISO            |               |
| EN 1774                |            | ISO 301        |               |
| Material number (DIN): |            | DIN            |               |
| 2.2140                 |            | DIN 1743       |               |
| France                 |            | United Kingdom |               |
| Z – A4G                | NF A55-010 | Alloy A        | BS 1004       |
| Z –A4                  | NF A55-010 |                |               |
| Japan                  |            | Russia         |               |
| JIS H2201              | JIS H5201  | CA4            | GOST 25140-93 |
|                        | JIS H5301  | CA40           | GOST 25140-93 |
| USA                    |            |                |               |
| ASTM                   |            | UNS standard   |               |
| ASTM B 86-11           |            | Z33520         |               |
| ASTM B 240             |            |                |               |

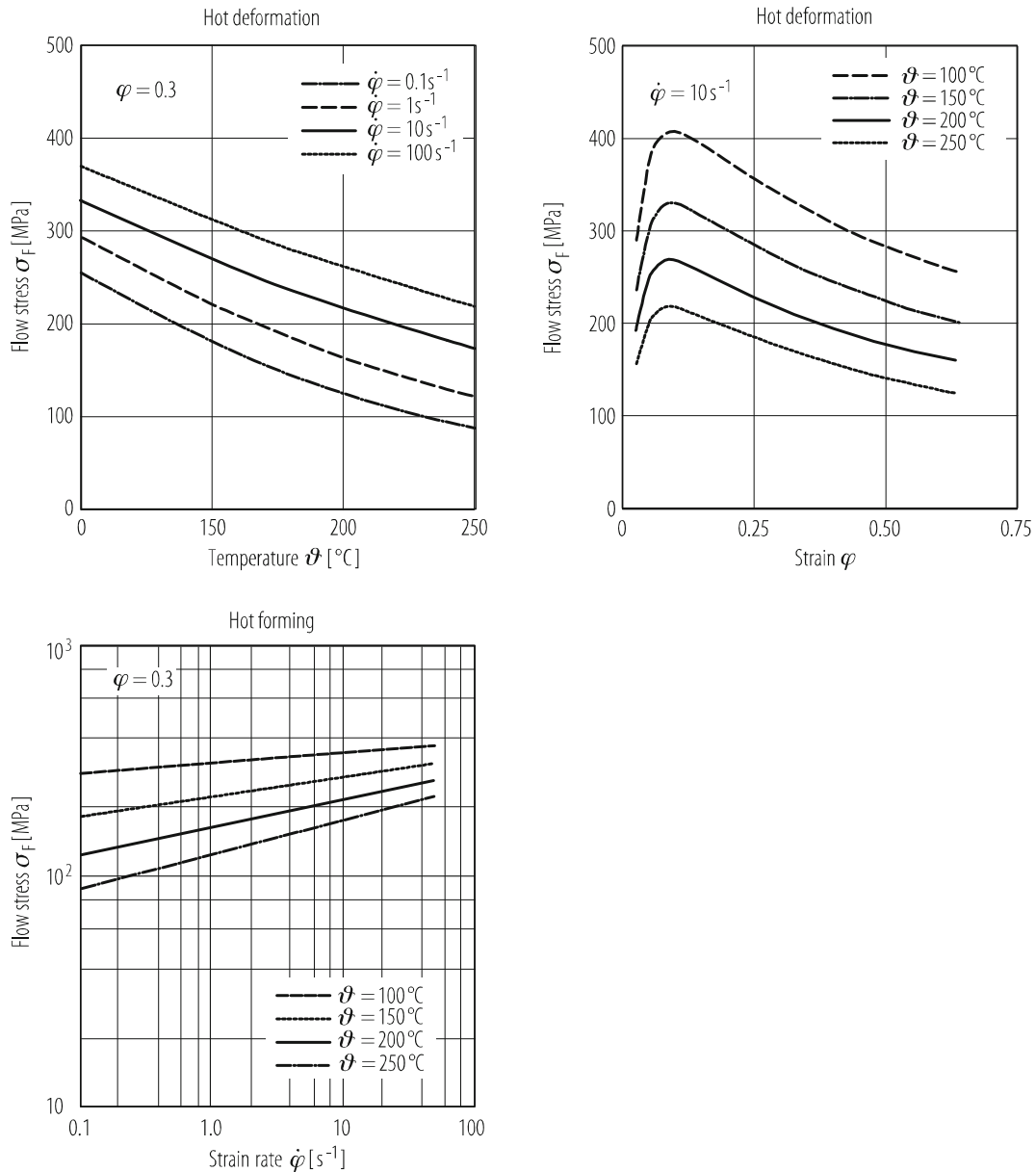
It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                    | Hot deformation |                | Cold deformation |                 |                 |
|--------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                      | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                  |                 | 403.5          |                  |                 |                 |
| A                                    |                 | 429.693        |                  |                 |                 |
| Effect of temperature $K_{\theta}$ : |                 |                |                  |                 |                 |
| $m_1$                                |                 | -0.00541       |                  |                 |                 |
| Effect of strain $K_{\varphi}$ :     |                 |                |                  |                 |                 |
| $m_2$                                |                 | -0.30119       |                  |                 |                 |
| $m_4$                                |                 | -0.03165       |                  |                 |                 |
| $m_5$                                |                 | -0.00147       |                  |                 |                 |
| $m_7$                                |                 | -0.21511       |                  |                 |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                |                  |                 |                 |
| $m_8$                                  |                 | 0.000594       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                       |                 | 100 ... 250    |                  |                 |                 |
| $\varphi$                              |                 | 0.05 ... 0.70  |                  |                 |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.1 ... 50     |                  |                 |                 |



**Fig. 5.170** Flow stress curves of ZnAl<sub>4</sub> by hot forming.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 113.0                | 400.0              | 27.7                                    | 6600.0                      | 127.5           |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| BS              | British standards                                                     |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| GOST            | gosudarstvennyy standart (state standard)                             |
| ISO             | international organisation for standardization                        |
| JIS             | Japanese industrial standards                                         |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress and physical properties of ZnAl<sub>4</sub>Cu<sub>1</sub>

## 5.6 Zinc and Zinc alloys

### Designation

|             |               |                                                     |
|-------------|---------------|-----------------------------------------------------|
| UNS number: | <b>Z33520</b> | Chem. symbol: <b>ZnAl<sub>4</sub>Cu<sub>1</sub></b> |
|-------------|---------------|-----------------------------------------------------|

### Compustion (EN) [Weight-%]

| Zn   | Pb | Sn     | Fe     | Cd | Σ Pb + Cd | Cu          | Al         | Mg          |
|------|----|--------|--------|----|-----------|-------------|------------|-------------|
| Bal. |    | <0.001 | <0.075 |    | <0.011    | 0.60...1.00 | 3.90..4.30 | 0.02...0.05 |

### International comparison of standards

| Euronorm              |              | ISO            |               |
|-----------------------|--------------|----------------|---------------|
| EN1774                |              | ISO 301        |               |
| Material number (DIN) |              | DIN            |               |
| 2.2141                |              | DIN 1743       |               |
| France                |              | United Kingdom |               |
| Z – A4U1G             | NF A55 - 010 | Alloy B        | BS 1004       |
| Z – A4U1              | NF A55 - 102 |                |               |
| Japan                 |              | Russia         |               |
| Class 1               | JIS H5201    | CA4M1          | GOST 25140-93 |
| Class 1               | JIS H5301    | CA4M1o0        | GOST 25140-93 |
| USA                   |              |                |               |
| ASTM                  |              | UNS standard   |               |
| ASTM B 240            | ASTM B 86-10 | Z33520         |               |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

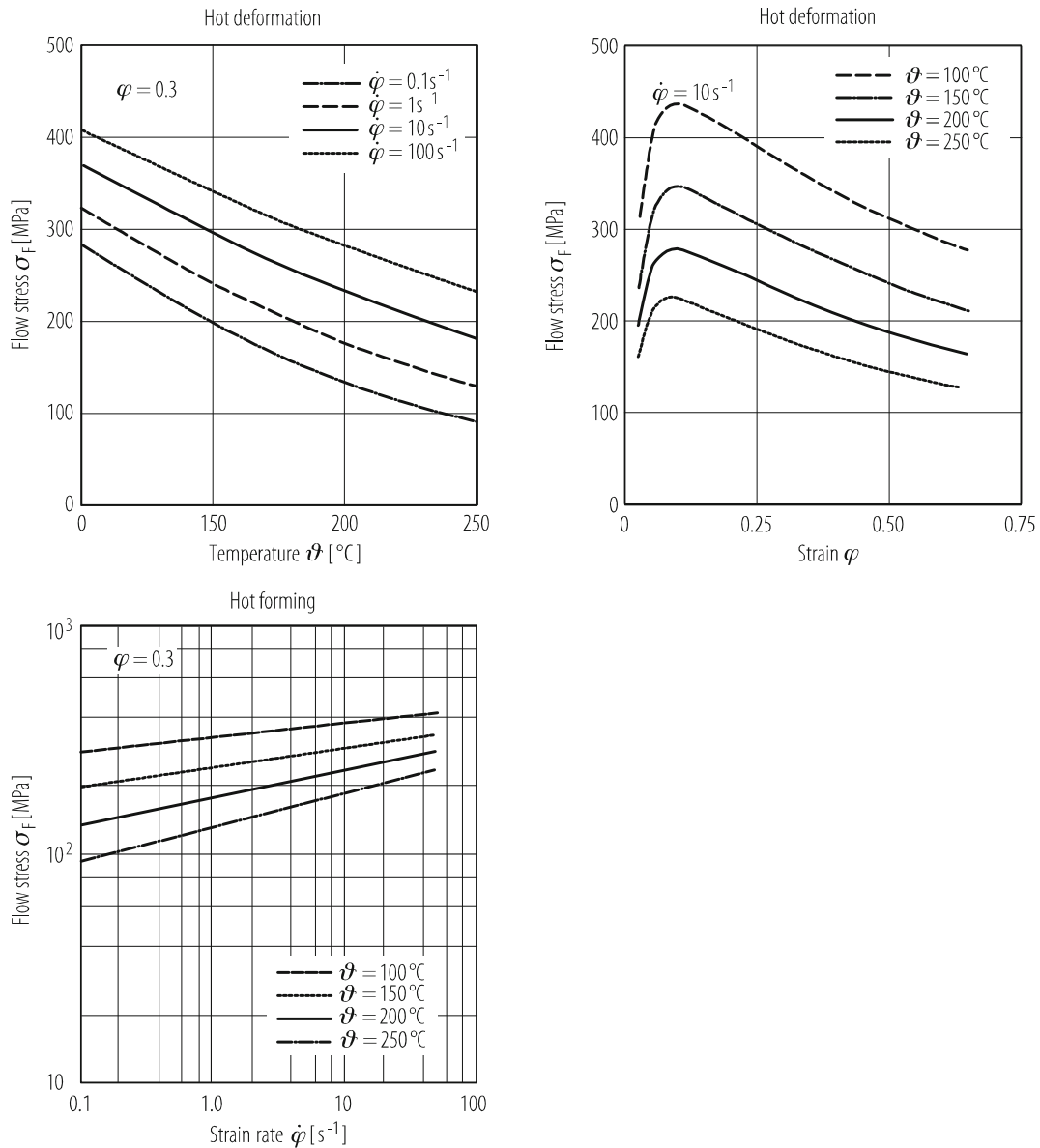
### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 | 434.5          |                  |                 |                 |
| A                                      |                 | 585.098        |                  |                 |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                  |                 |                 |
| $m_1$                                  |                 | −0.00567       |                  |                 |                 |
| Effect of strain $K_{\phi}$            |                 |                |                  |                 |                 |
| $m_2$                                  |                 | −0.19530       |                  |                 |                 |
| $m_4$                                  |                 | −0.02568       |                  |                 |                 |
| $m_5$                                  |                 | −0.00177       |                  |                 |                 |
| $m_7$                                  |                 | −0.43157       |                  |                 |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                |                  |                 |                 |
| $m_8$                                  |                 | 0.000593       |                  |                 |                 |

(continued)



| State of material     | Hot deformation |                | Cold deformation |                 |                 |
|-----------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                       | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| Range of validity     |                 |                |                  |                 |                 |
| $\vartheta$ [°C]      |                 | 100. . . 250   |                  |                 |                 |
| $\varphi$             |                 | 0.05 . . 0.70  |                  |                 |                 |
| $\dot{\varphi}$ [1/s] |                 | 0.1 . . 50     |                  |                 |                 |



**Fig. 5.171** Flow stress curves of  $\text{ZnAl}_4\text{Cu}_1$  by hot forming.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 110.0                | 400.0              | 27.4                                    | 6700.0                      | 128             |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| BS              | British standards                                                     |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| GOST            | gosudarstvennyy standart (state standard)                             |
| ISO             | international organisation for standardization                        |
| JIS             | Japanese industrial standards                                         |
| NF              | France normalisation                                                  |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress of $\text{ZnCu}_1\text{Ti}_{0.1}$

## 5.6 Zinc and Zinc alloys

### Designation

|             |               |                                 |
|-------------|---------------|---------------------------------|
| UNS number: | <b>Z41320</b> | Chem. symbol: <b>ZnCu1Ti0.1</b> |
|-------------|---------------|---------------------------------|

### Compustion (EN) [Weight-%]

| Zn   | Pb | Cu   | Al     | Mg | Ti          |
|------|----|------|--------|----|-------------|
| Bal. |    | ~1.0 | <0.015 |    | 0.07...0.12 |

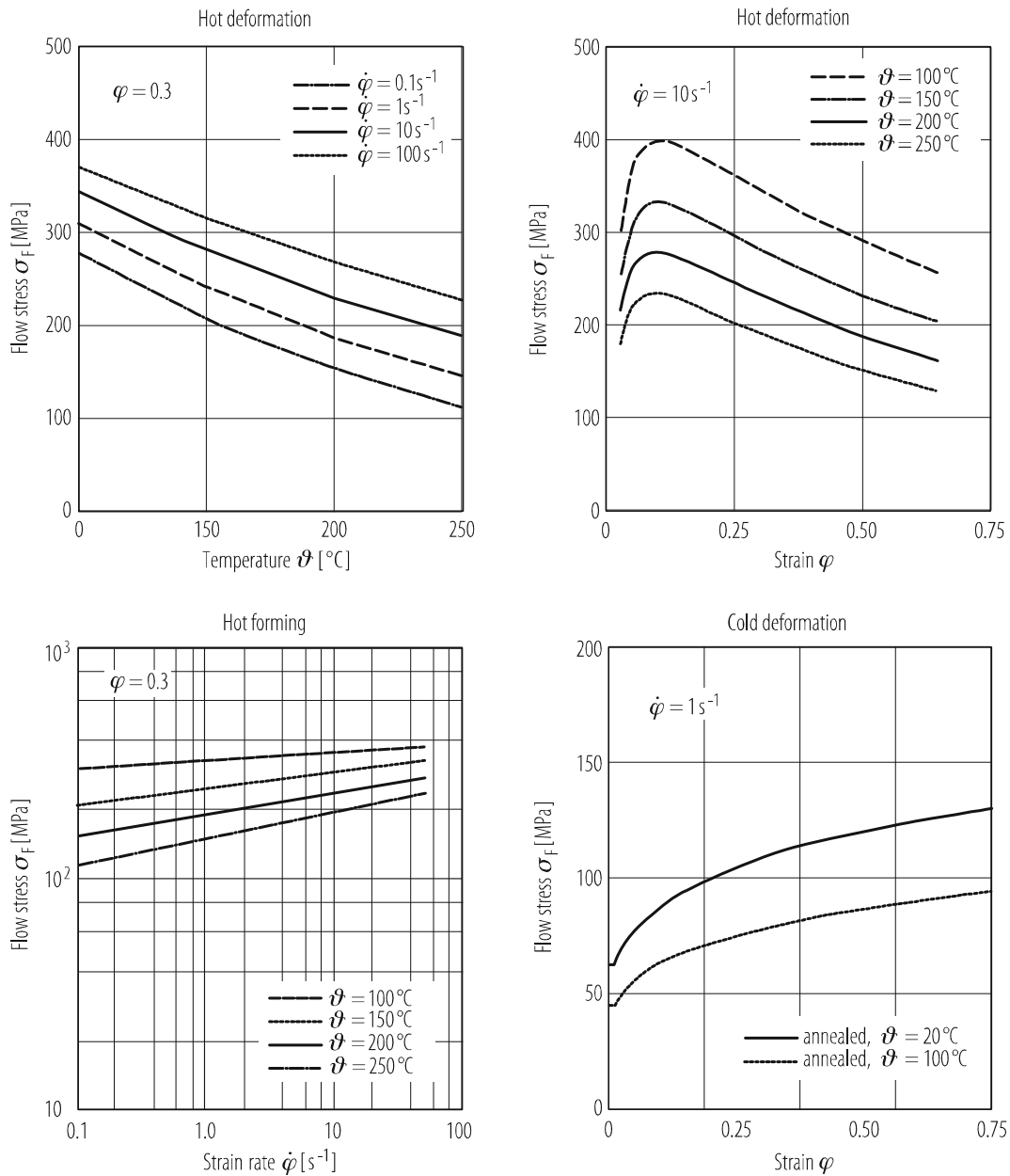
### International comparison of standards

|                        |                  |
|------------------------|------------------|
| Euronorm               | ISO              |
| EN 988                 |                  |
| Material number (DIN): | DIN              |
| 2.2203                 | DIN 17770 (1990) |
| Japan                  | Russia           |
| USA                    |                  |
| ASTM                   | UNS standard     |
| ASTM B69 - 11          | Z41320           |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 | 397.2          | 83.5             |                 |                 |
| A                                      |                 | 549.341        | 122.371          |                 |                 |
| Effect of temperature $K_\theta$       |                 |                |                  |                 |                 |
| $m_1$                                  |                 | -0.00438       | -0.00412         |                 |                 |
| Effect of strain $K_\varphi$           |                 |                |                  |                 |                 |
| $m_2$                                  |                 | -0.12694       | 0.19955          |                 |                 |
| $m_4$                                  |                 | -0.02085       | 0.00175          |                 |                 |
| $m_5$                                  |                 | -0.00245       |                  |                 |                 |
| $m_7$                                  |                 | -0.51730       |                  |                 |                 |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.06114          |                 |                 |
| $m_8$                                  |                 | 0.000456       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\theta$ [°C]                          |                 | 100...250      | 20...100         |                 |                 |
| $\varphi$                              |                 | 0.05...0.80    | 0.05...1.00      |                 |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.1...50       | 0.1...250        |                 |                 |



**Fig. 5.172** Flow stress curves of  $\text{ZnCu}_1\text{Ti}_{0.1}$  by hot and cold forming.

**Symbols and abbreviations**

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |

# Flow stress, plasticity and physical properties of Pb<sub>99.98</sub>

## 5.7 Lead

### Designation

|             |               |                               |
|-------------|---------------|-------------------------------|
| UNS number: | <b>L50050</b> | Chem. symbol: <b>Pb 99.98</b> |
|-------------|---------------|-------------------------------|

### Composition (EN) [Weight-%]

| Pb     | Ag      | As     | Bi    | Cu     | Fe     | Sb     | Sn     | Sn     |
|--------|---------|--------|-------|--------|--------|--------|--------|--------|
| >99.95 | <0.0015 | <0.002 | <0.03 | <0.015 | <0.002 | <0.005 | <0.002 | <0.002 |

### International comparison of standards

| Euronorm               |              | CAS number      |
|------------------------|--------------|-----------------|
| EN 12659               | EN 12588     | CAS 7439-92-1   |
| Material number (DIN): |              | DIN             |
| 2.3030                 | 2.3040       | DIN 1719        |
| France                 |              | United Kingdom  |
| Pb 99.97 raffine'      | NF A55 - 105 | Chemical lead A |
| Pb 99.97 raffine'      | NF A55 - 105 | BS 334          |
| Japan                  |              | Russia          |
|                        |              | S2              |
|                        |              | GOST 3778 - 77  |
| USA                    |              |                 |
| ASTM                   |              | UNS standard    |
| ASTM B 29-03           |              | L50050          |
| ASTM B 749 - 03        |              |                 |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

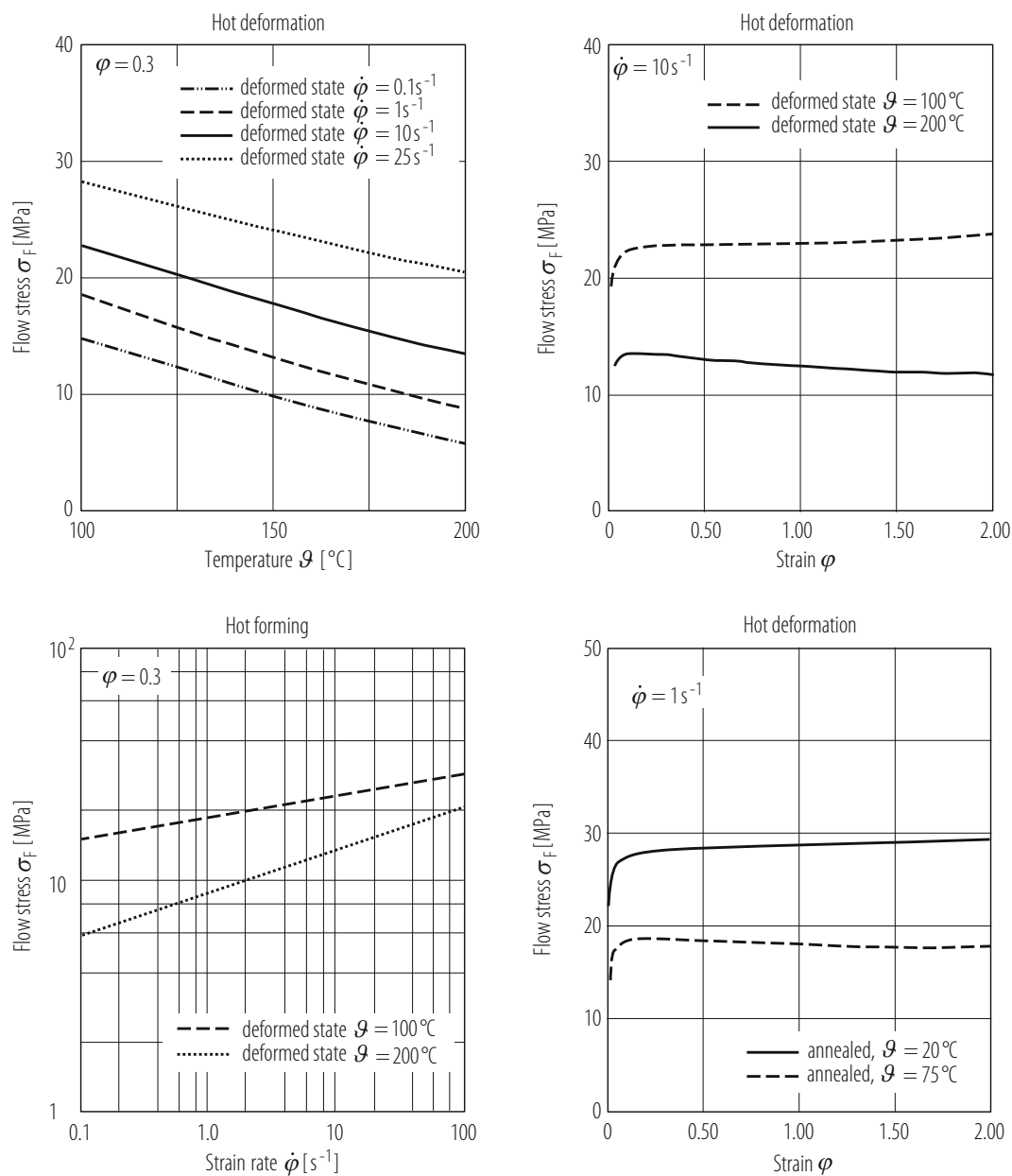
### Flow curves

| State of material                  | Hot deformation |                | Cold deformation |               |                 |
|------------------------------------|-----------------|----------------|------------------|---------------|-----------------|
|                                    | cast state      | deformed state | hot rolled (hr)  | annealed (an) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                |                 | 22.23          |                  | 28.62         |                 |
| A                                  |                 | 39.094         |                  | 33.568        |                 |
| Effect of temperature $K_{\theta}$ |                 |                |                  |               |                 |
| $m_1$                              |                 | -0.00693       |                  | -0.00693      |                 |
| Effect of strain $K_{\varphi}$     |                 |                |                  |               |                 |
| $m_2$                              |                 | 0.01832        |                  | 0.00583       |                 |
| $m_4$                              |                 | -0.00322       |                  | -0.00322      |                 |
| $m_5$                              |                 | -0.00206       |                  | -0.00206      |                 |
| $m_7$                              |                 | 0.09964        |                  | 0.02996       |                 |

(continued)

| State of material                      | Hot deformation |                | Cold deformation |               |                 |
|----------------------------------------|-----------------|----------------|------------------|---------------|-----------------|
|                                        | cast state      | deformed state | hot rolled (hr)  | annealed (an) | cold drawn (cd) |
| Effect of strain rate $K\dot{\varphi}$ |                 |                |                  |               |                 |
| $m_3$                                  |                 |                |                  | 0.000923      |                 |
| $m_8$                                  |                 | 0.000923       |                  |               |                 |
| Range of validity                      |                 |                |                  |               |                 |
| $\vartheta$ [°C]                       |                 | 20...250       |                  | 20...100      |                 |
| $\varphi$                              |                 | 0.01...2.00    |                  | 0.01...2.00   |                 |
| $\dot{\varphi}$ [1/s]                  |                 | 0.4...250      |                  | 0.4...100     |                 |

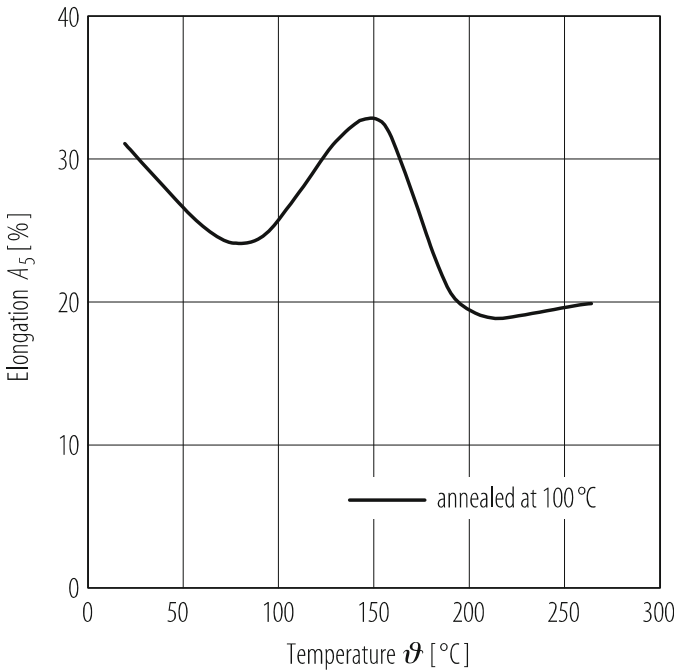
| Hot deformation:                                                                                                                                                               | Hold deformation                                                                                                                                                               |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          |



**Fig. 5.173** Flow stress curves of Pb<sub>99.98</sub> by hot and cold forming.



Plasticity in tensile test



**Fig. 5.174** Plasticity of Pb<sub>99.98</sub> as a function of the temperature.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [10 <sup>-6</sup> /K]        | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 35.4                 | 128.2              | 28.3                                    | 11346.3                     | 16.0            |
| 50               | 34.9                 | 129.1              |                                         | 11317.9                     |                 |
| 100              | 34.2                 | 130.4              | 29.2                                    | 11270.7                     |                 |
| 150              | 33.5                 | 131.7              |                                         | 11223.7                     |                 |
| 200              | 33.0                 | 132.8              | 30.3                                    | 11176.9                     |                 |
| 250              | 32.5                 | 133.9              |                                         | 11130.3                     |                 |
| 300              | 32.0                 | 134.8              | 31.3                                    | 11083.9                     |                 |

Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| BS              | British standards                                                     |
| CAS             | chemical abstracts service                                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| EN             | Euronorm                                       |
| GOST           | gosudarstvennyy standart (state standard)      |
| ISO            | international organisation for standardization |
| NF             | France normalisation                           |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |

# Flow stress, plasticity and physical properties of Mo<sub>99.95</sub>

## 5.7 Lead

### Designation

|             |               |                              |
|-------------|---------------|------------------------------|
| UNS number: | <b>R03600</b> | Chem. symbol: <b>Mo99.95</b> |
|-------------|---------------|------------------------------|

### Composition (EN) [Weight-%]

| Nb | Ta | Mo     | W | Fe   | Ti | C     | H <sub>2</sub> | N <sub>2</sub> | O <sub>2</sub> |
|----|----|--------|---|------|----|-------|----------------|----------------|----------------|
|    |    | >99.95 |   | 0.01 |    | 0.005 | 0.001          | 0.001          | 0.005          |

### International comparison of standards

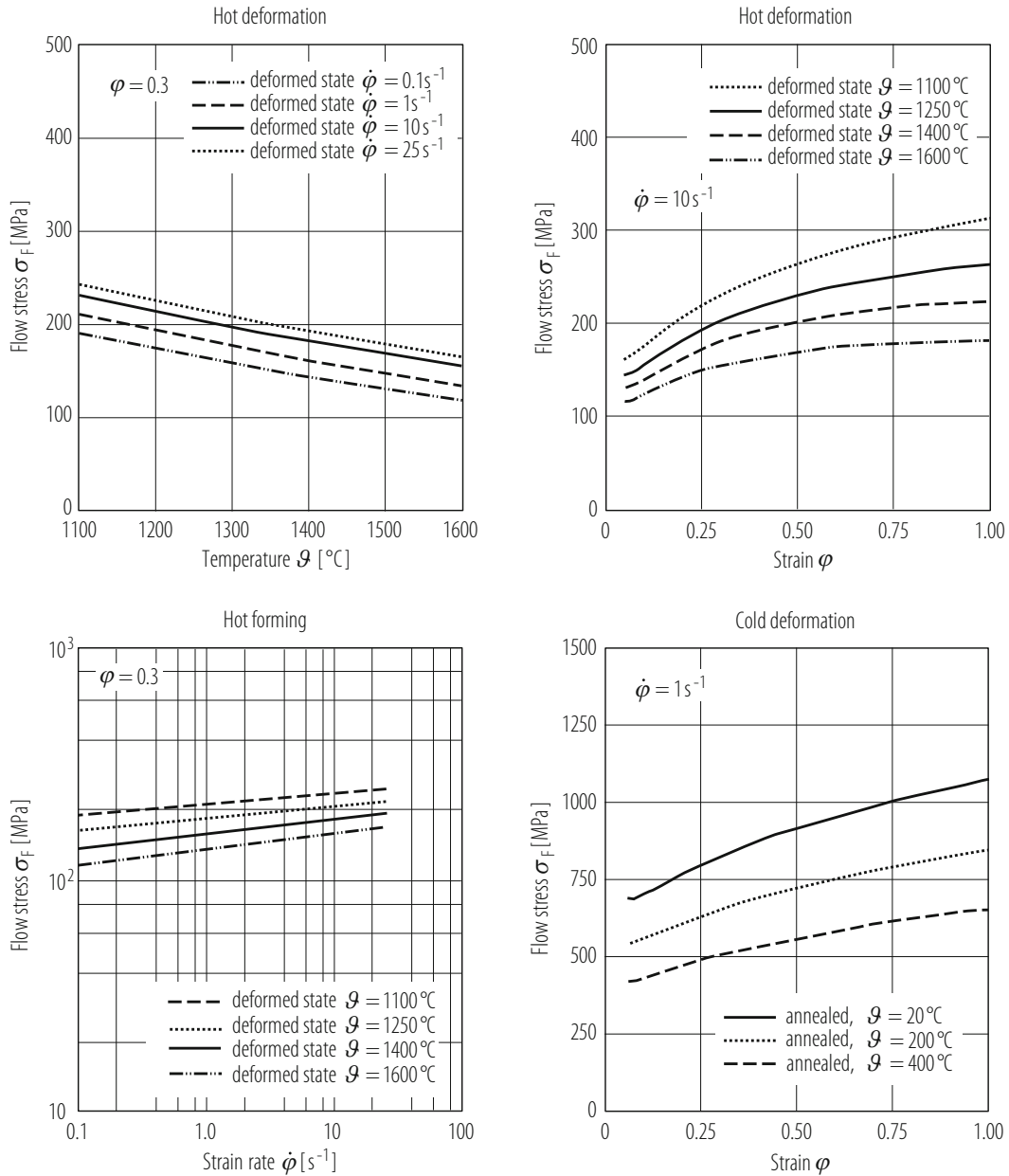
| Euronorm         |                  | Material                               |
|------------------|------------------|----------------------------------------|
| EN ISO 9001:2008 | EN ISO/IEC 17025 | Mo 99.95 % (type 360)<br>vacuum melted |
| EN 15510         | EN 61303         |                                        |
| CAS number       |                  | DIN                                    |
| CAS 7439-98-7    |                  | DIN 6852                               |
|                  |                  | DIN 6854                               |
|                  |                  | DIN 6855-11                            |
| USA              |                  | UNS standard                           |
| ASTM             |                  | R03600                                 |
| ASTM B387        | ASTM B386        |                                        |
| ASTM F364        | ASTM F289        |                                        |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

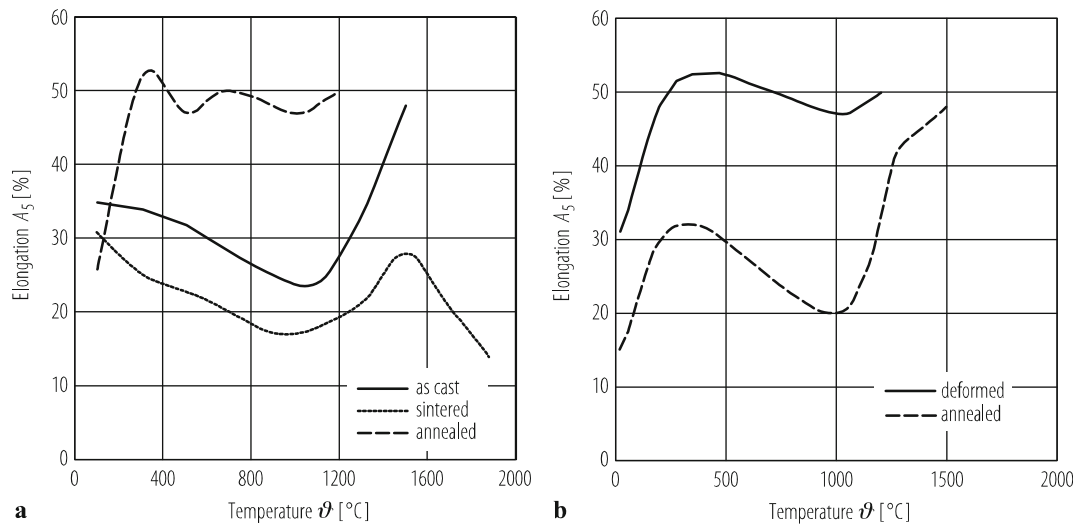
| State of material                      | Hot deformation |                | Cold deformation |               |                 |
|----------------------------------------|-----------------|----------------|------------------|---------------|-----------------|
|                                        | cast state      | deformed state | hot rolled (hr)  | annealed (an) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 | 162.2          |                  | 698.3         |                 |
| A                                      |                 | 889.812        |                  | 1078.353      |                 |
| Effect of temperature $K_8$            |                 |                |                  |               |                 |
| m <sub>1</sub>                         |                 | −0.00073       |                  | −0.00131      |                 |
| Effect of strain $K_\phi$              |                 |                |                  |               |                 |
| m <sub>2</sub>                         |                 | 0.47516        |                  | 0.24859       |                 |
| m <sub>4</sub>                         |                 | 0.02192        |                  | 0.01641       |                 |
| m <sub>5</sub>                         |                 | −0.00063       |                  |               |                 |
| m <sub>7</sub>                         |                 | 0.10383        |                  |               |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |               |                 |
| m <sub>3</sub>                         |                 |                |                  |               |                 |
| m <sub>8</sub>                         |                 | 0.000040       |                  |               |                 |
| Range of validity                      |                 |                |                  |               |                 |
| $\vartheta$ [°C]                       |                 | 1100...1600    |                  | 20...400      |                 |
| $\phi$                                 |                 | 0.05...0.9     |                  | <1.00         |                 |
| $\dot{\phi}$ [1/s]                     |                 | 0.25...25      |                  | 2             |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.175** Flow stress curves of Mo<sub>99.95</sub> by hot and cold forming.

## Plasticity in tensile test



**Fig. 5.176** Plasticity of Mo<sub>99.95</sub> as a function of the temperature. a.+b.) Influence of different material condition;

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus   |                      |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-------------------|----------------------|
|                  |                      |                    |                                         |                             | powder metallurgy | molten electron-beam |
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}/K$ ]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]         |                      |
| 20               | 141.4                | 292.4              | 5.1                                     | 10212.1                     | 322               | 322                  |
| 100              | 137.1                | 297.8              | 5.19                                    | 10199.2                     | 315               | 318                  |
| 200              | 132.0                | 304.3              | 5.28                                    | 10182.6                     | 311               | 314                  |
| 300              | 127.2                | 311.2              | 5.39                                    | 10165.7                     | 306               | 310                  |
| 400              | 122.7                | 318.4              | 5.48                                    | 10148.2                     | 300               | 306                  |
| 500              | 118.5                | 325.7              | 5.59                                    | 10130.3                     | 294               | 301                  |
| 600              | 114.7                | 333.3              | 5.68                                    | 10112.0                     | 289               | 297                  |
| 700              | 111.1                | 341.0              | 5.77                                    | 10093.2                     | 282               | 292                  |
| 800              | 107.9                | 349.0              | 5.87                                    | 10073.9                     | 276               | 288                  |
| 900              | 105.0                | 357.1              |                                         | 10054.2                     | 270               | 284                  |
| 1000             | 102.5                | 365.3              |                                         | 10034.0                     | 265               | 275                  |
| 1100             | 100.2                | 373.8              |                                         | 10013.4                     | 258               | 275                  |
| 1200             | 98.3                 | 382.4              |                                         | 9992.3                      | 254               | 268                  |
| 1300             | 96.6                 | 391.2              |                                         | 9970.7                      | 248               | 263                  |
| 1400             | 95.3                 | 400.3              |                                         | 9948.7                      | 237               | 255                  |
| 1500             | 94.3                 | 409.3              |                                         | 9926.3                      | 222               | 247                  |
| 1600             | 93.7                 | 418.6              |                                         | 9903.4                      | 208               | 238                  |
| 1700             | 93.3                 | 421.6              |                                         | 9880.0                      | 193               | 231                  |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| CAS             | chemical abstracts service                                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| IEC             | international electrotechnical commission                             |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | Density                                                               |

# Flow stress, mechanical and physical properties of Nb<sub>99.8</sub>

## 5.8 Niobium and Niobium alloys

### Designation

|             |               |                              |
|-------------|---------------|------------------------------|
| UNS number: | <b>R04200</b> | Chem. symbol: <b>Nb 99.8</b> |
|-------------|---------------|------------------------------|

### Composition (EN) [Weight-%]

| Nb    | Ta   | Mo | W | Fe   | Ti | C     | H <sub>2</sub> | N <sub>2</sub> | O <sub>2</sub> |
|-------|------|----|---|------|----|-------|----------------|----------------|----------------|
| 99.86 | 0.02 | W  |   | 0.05 |    | 0.005 | 0.001          | 0.03           | 0.02           |

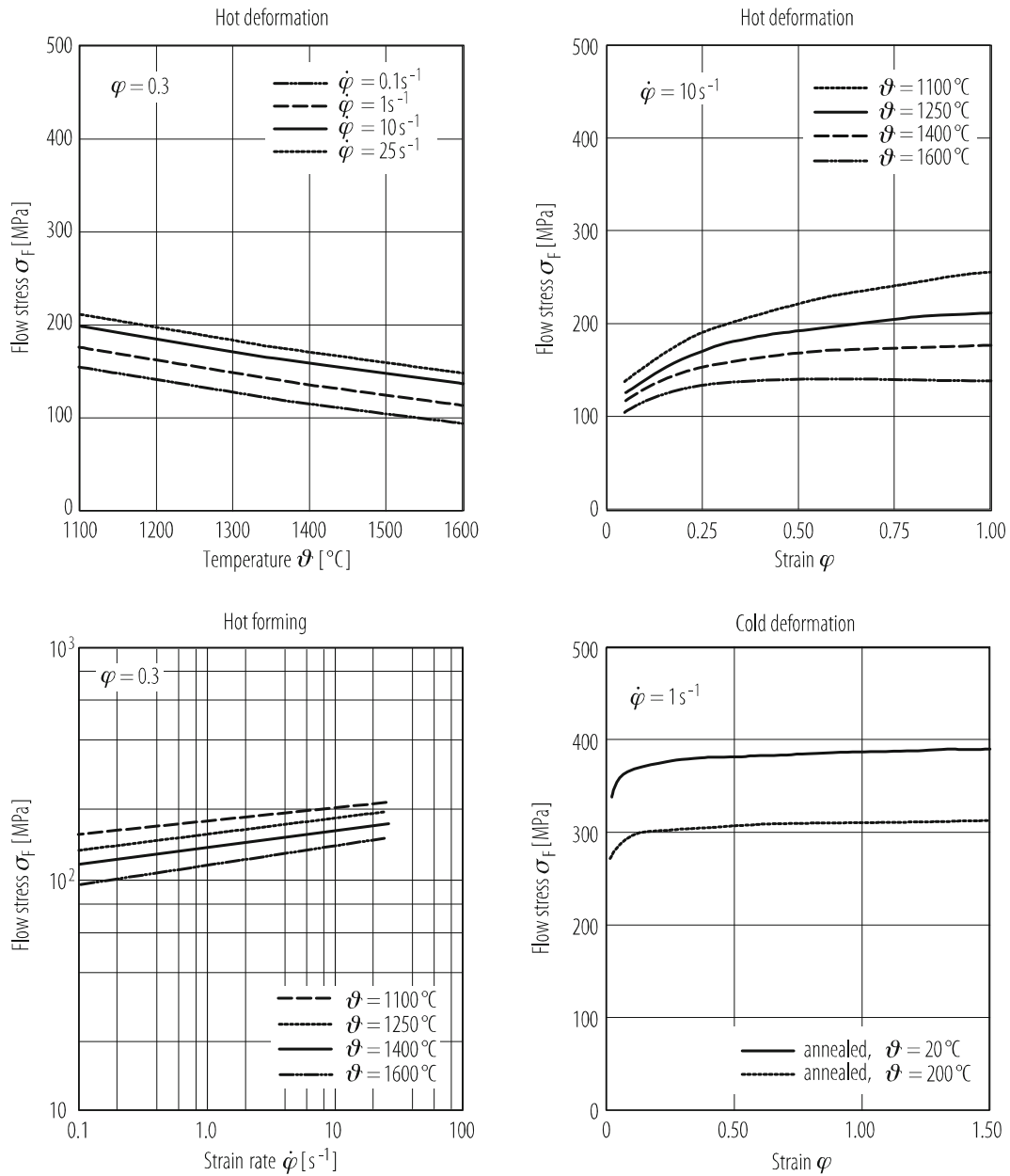
### International comparison of standards

| Euronorm      |           | Material                               |              |
|---------------|-----------|----------------------------------------|--------------|
| EN 729-3      | EN 60204  | Nb 99.8 % (R04200) type 1 – Ta ≤ 0.1 % | EN ISO 10993 |
|               |           |                                        | EN ISO 9001  |
| CAS number    |           | DIN                                    |              |
| CAS 7440-03-1 |           | DIN 1654-5                             | DIN 24340    |
| USA           |           | UNS standard                           |              |
| ASTM          |           |                                        |              |
| ASTM B392     | ASTM B393 | R04200                                 |              |
| ASTM B394     | ASTM B391 |                                        |              |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

| State of material                      | Hot deformation |                | Cold deformation |               |                 |
|----------------------------------------|-----------------|----------------|------------------|---------------|-----------------|
|                                        | cast state      | deformed state | hot rolled (hr)  | annealed (an) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 | 145.7          |                  | 381.7         |                 |
| A                                      |                 | 642.839        |                  | 398.568       |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                  |               |                 |
| $m_1$                                  |                 | −0.00058       |                  | −0.00123      |                 |
| Effect of strain $K_{\phi}$            |                 |                |                  |               |                 |
| $m_2$                                  |                 | 0.43045        |                  | 0.01521       |                 |
| $m_4$                                  |                 | 0.01440        |                  | −0.00164      |                 |
| $m_5$                                  |                 | −0.00110       |                  |               |                 |
| $m_7$                                  |                 | 0.41048        |                  |               |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |               |                 |
| $m_3$                                  |                 |                |                  | 0.01412       |                 |
| $m_8$                                  |                 | 0.000052       |                  |               |                 |
| Range of validity                      |                 |                |                  |               |                 |
| $\theta$ [°C]                          |                 | 1000...1600    |                  | 20...200      |                 |
| $\phi$                                 |                 | 0.05...1.0     |                  | 0.04...1.20   |                 |
| $\dot{\phi}$ [1/s]                     |                 | 0.25...25      |                  | 0.1...25      |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.177** Flow stress curves of Nb<sub>99.8</sub> by hot and cold forming.



Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |         |         | Validity $\varepsilon$ [%] |
|-------------------|---------------------------------|---------|---------|----------------------------|
|                   | $A_0$                           | $A$     | $n_I$   |                            |
|                   | $A_0$                           | $A$     | $n_I$   |                            |
| annealed          | 550 590                         | 49.0499 | 0.53444 | <50                        |

Yield stress:

$$R_p = A_0 + A \cdot \varepsilon^{n_I}$$

[Equation (4.1), Chapter 5.1.4]

[DOI: 978-3-642-14174-4\_5]

Plasticity by tensile test

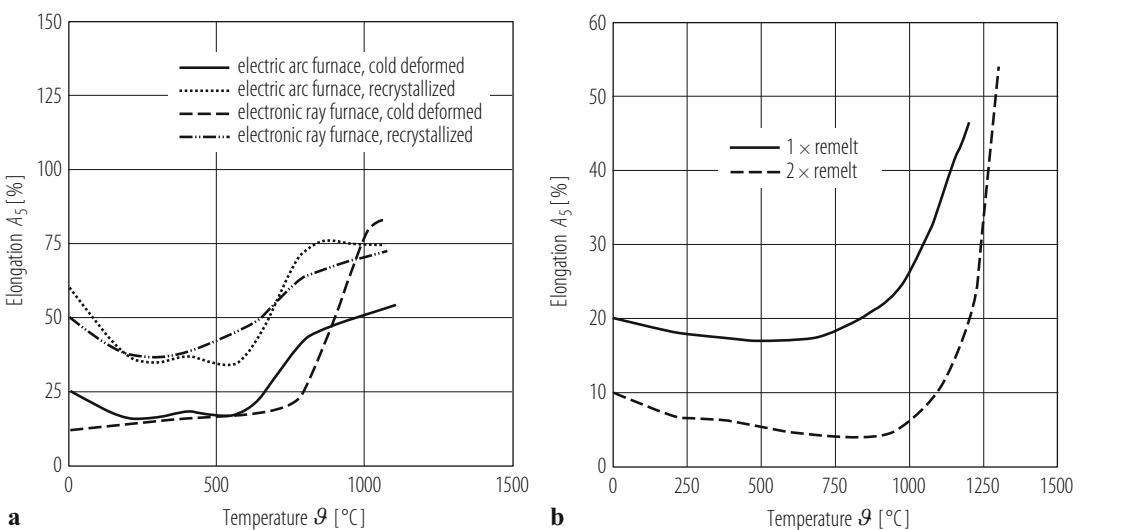


Fig. 5.178 Plasticity of Nb99.8 as a function of the temperature. a.+b.) Influence of different production

Physical properties

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [10 <sup>-6</sup> /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus |      |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------|----------------------------------------|-----------------|------|
|                                 |                                           |                                         |                                                                                |                                        | defomed         | cast |
| 20                              | 53.7                                      | 270.8                                   |                                                                                | 8574.2                                 | 103             | 110  |
| 100                             | 54.7                                      | 272.1                                   |                                                                                | 8558.5                                 | 103             | 109  |
| 200                             | 56.0                                      | 273.7                                   |                                                                                | 8538.3                                 | 103             | 109  |
| 300                             | 57.2                                      | 275.4                                   | 7.31                                                                           | 8517.4                                 | 103             | 109  |
| 400                             | 58.4                                      | 277.2                                   | 7.39                                                                           | 8495.8                                 | 103             | 108  |
| 500                             | 59.6                                      | 279.2                                   | 7.47                                                                           | 8473.6                                 | 103             | 108  |
| 600                             | 60.8                                      | 281.3                                   | 7.56                                                                           | 8450.7                                 | 104             | 108  |
| 700                             | 62.0                                      | 283.5                                   | 7.64                                                                           | 8427.2                                 | 104             | 109  |
| 800                             | 63.2                                      | 285.8                                   | 7.72                                                                           | 8403.0                                 | 105             | 109  |
| 900                             | 64.3                                      | 288.2                                   | 7.80                                                                           | 8378.1                                 | 105             | 110  |

(continued)

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus |      |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|-----------------|------|
|                                 |                                           |                                         |                                                                          |                                        | defomed         | cast |
| 1000                            | 65.4                                      | 290.6                                   | 7.88                                                                     | 8352.6                                 | 105             | 108  |
| 1100                            | 66.5                                      | 293.2                                   |                                                                          | 8326.4                                 | 104             | 108  |
| 1200                            | 67.6                                      | 296.0                                   |                                                                          | 8299.5                                 | 103             | 107  |
| 1300                            | 68.7                                      | 298.8                                   |                                                                          | 8272.0                                 | 102             | 107  |
| 1400                            | 69.8                                      | 301.7                                   |                                                                          | 8243.8                                 | 100             | 107  |
| 1500                            | 70.8                                      | 304.7                                   |                                                                          | 8214.9                                 | 98              | 106  |
| 1600                            | 71.9                                      | 307.8                                   |                                                                          | 8185.4                                 | 96              | 105  |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| CAS                 | chemical abstracts service                                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress and plasticity of NbZr<sub>1</sub>

## 5.8 Niobium and Niobium alloys

### Designation

|             |               |                            |
|-------------|---------------|----------------------------|
| UNS number: | <b>R04261</b> | Chem. symbol: <b>NbZr1</b> |
|-------------|---------------|----------------------------|

### Composition (EN) [Weight-%]

| Nb       | Ta | Mo | Zr   | Fe   | Ti | C     | H <sub>2</sub> | N <sub>2</sub> | O <sub>2</sub> |
|----------|----|----|------|------|----|-------|----------------|----------------|----------------|
| ca. 98,5 |    |    | ~1,0 | 0.05 |    | 0.005 | 0.001          | 0.03           | 0.02           |

### International comparison of standards

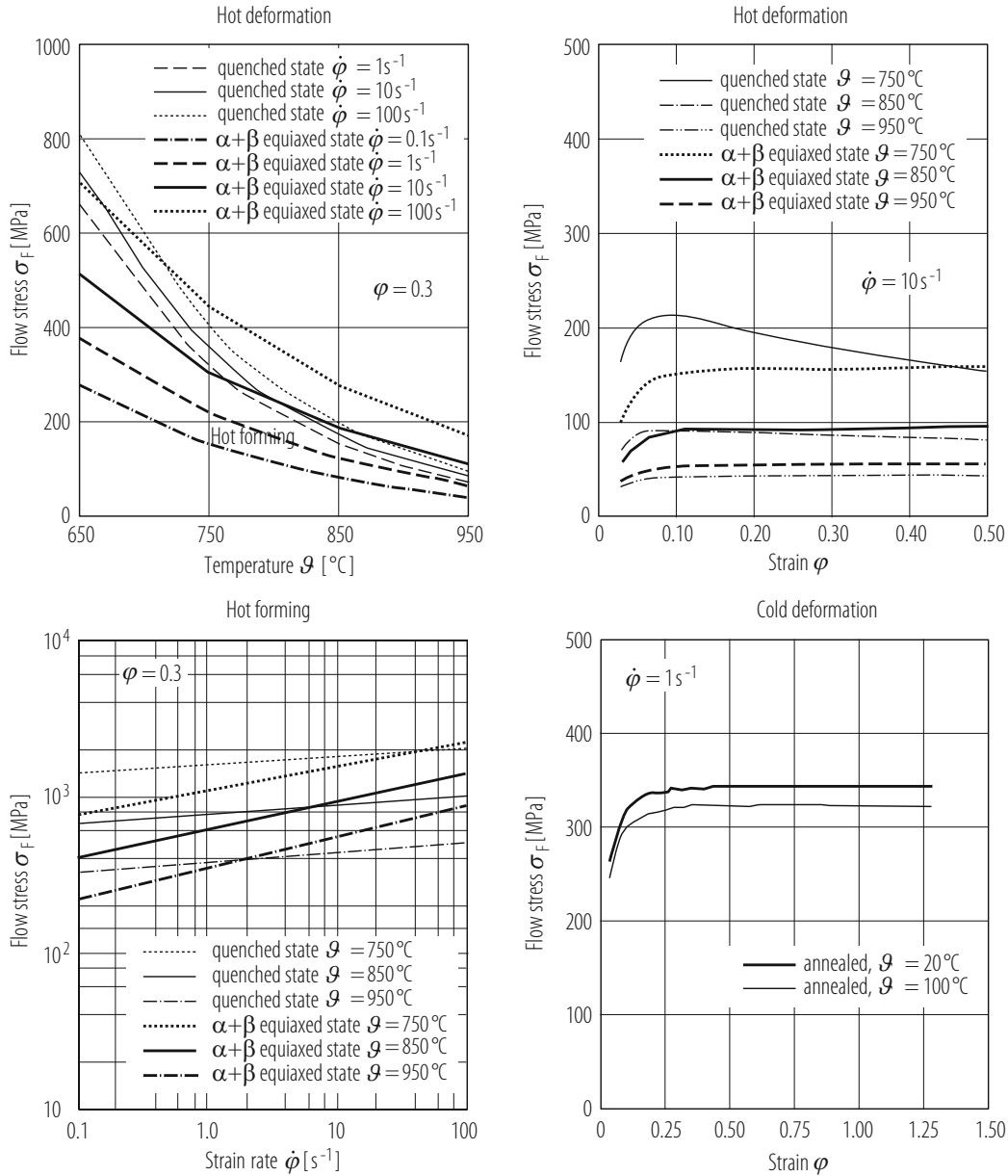
| Euronorm   |           | Material              |                       |
|------------|-----------|-----------------------|-----------------------|
| EN 10002-1 |           | NbZr1 (R04251) type 3 | NbZr1 (R04261) type 4 |
| DIN        |           | Russia                |                       |
| DIN 1654-5 |           |                       |                       |
| USA        |           |                       |                       |
| ASTM       |           | UNS standard          |                       |
| ASTM B392  | ASTM B393 | R04261                |                       |
| ASTM B394  | ASTM B391 |                       |                       |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

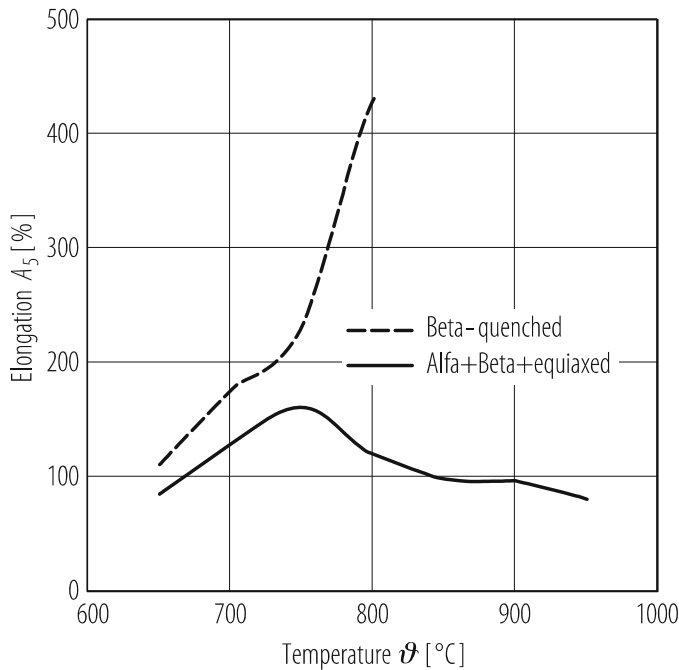
| State of material                         | Hot deformation |                         | Cold deformation |               |                 |
|-------------------------------------------|-----------------|-------------------------|------------------|---------------|-----------------|
|                                           | quenched        | $\alpha+\beta$ equiaxed | hot rolled (hr)  | annealed (an) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       | 140.28          | 117.31                  |                  | 317.6         |                 |
| A                                         | 56596.363       | 5068.094                |                  | 354.106       |                 |
| Effect of temperature $K_{\theta}$        |                 |                         |                  |               |                 |
| $m_1$                                     | -0.00886        | -0.00582                |                  | -0.00078      |                 |
| Effect of strain $K_{\varphi}$            |                 |                         |                  |               |                 |
| $m_2$                                     | -0.49005        | -0.33105                |                  | -0.01861      |                 |
| $m_4$                                     | -0.03250        | -0.03441                |                  | -0.01362      |                 |
| $m_5$                                     | 0.00601         | 0.00083                 |                  |               |                 |
| $m_7$                                     | -2.97017        | 0.25083                 |                  |               |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                         |                  |               |                 |
| $m_3$                                     |                 |                         |                  |               |                 |
| $m_8$                                     | 0.000067        | 0.000208                |                  |               |                 |
| Range of validity                         |                 |                         |                  |               |                 |
| $\theta$ [°C]                             | 650...950       | 650...950               |                  | 20...100      |                 |
| $\varphi$                                 | 0.05...0.50     | 0.05...0.50             |                  | 0.05...1.30   |                 |
| $\dot{\varphi}$ [1/s]                     | 0.001...100     | 0.001...100             |                  | 1             |                 |

| Hot deformation:                                                                                                                                                      | Cold deformation                                                                                        |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                  | [Equation (2.25), Chapter 2.3.2.2.2]                                                                    |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                            | [DOI: 978-3-642-14174-4_2]                                                                              |



**Fig. 5.179** Flow stress curves of NbZr<sub>1</sub> by hot and cold forming.

Plasticity in tensile test



**Fig. 5.180** Hot plasticity of NbZr<sub>1</sub> as a function of the temperature.

Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |

# Flow stress of NbTa<sub>7.5</sub>

## 5.8 Niobium and Niobium alloys

### Designation

|             |               |                                         |
|-------------|---------------|-----------------------------------------|
| UNS number: | <b>R04261</b> | Chem. symbol: <b>NbTa<sub>7.5</sub></b> |
|-------------|---------------|-----------------------------------------|

### Composition (EN) [Weight-%]

| Nb     | Ta  | Mo | W | Fe   | Ti | C     | H <sub>2</sub> | N <sub>2</sub> | O <sub>2</sub> |
|--------|-----|----|---|------|----|-------|----------------|----------------|----------------|
| ca. 92 | 7.8 |    |   | 0.05 |    | 0.005 | 0.001          | 0.03           | 0.02           |

### International comparison of standards

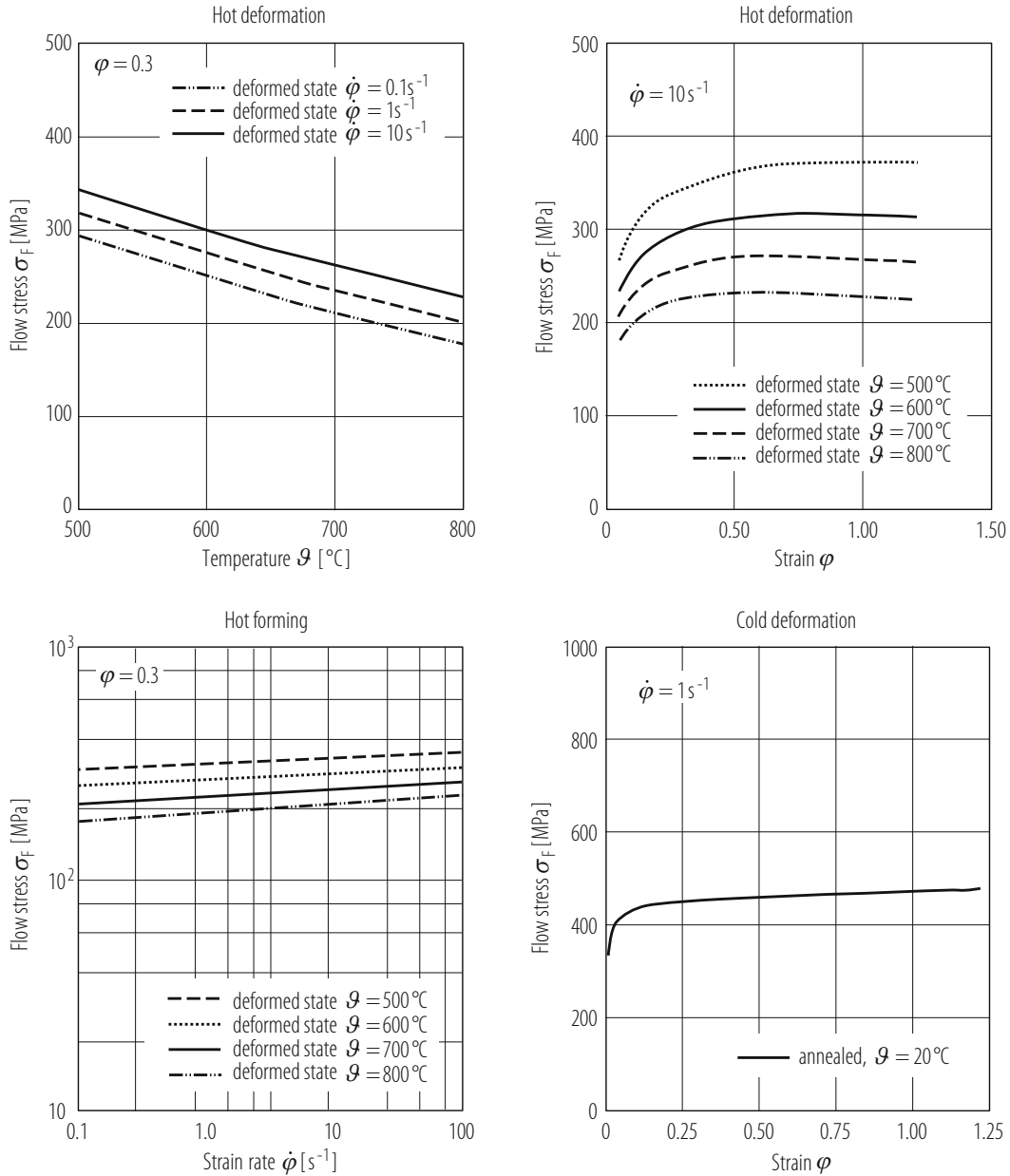
|           |              |
|-----------|--------------|
| Euronorm  | ISO          |
| Japan     | Russia       |
| USA       |              |
| ASTM      | UNS standard |
| ASTM B392 | ASTM B393    |
| ASTM B394 | ASTM B391    |
|           | R04261       |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |               |                 |
|----------------------------------------|-----------------|----------------|------------------|---------------|-----------------|
|                                        | cast state      | deformed state | hot rolled (hr)  | annealed (an) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 | 199.76         |                  | 439.00        |                 |
| A                                      |                 | 892.828        |                  | 473.549       |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                  |               |                 |
| $m_1$                                  |                 | -0.00141       |                  |               |                 |
| Effect of strain $K_{\phi}$            |                 |                |                  |               |                 |
| $m_2$                                  |                 | 0.19824        |                  | 0.03211       |                 |
| $m_4$                                  |                 | 0.00113        |                  | -0.00111      |                 |
| $m_5$                                  |                 | -0.00056       |                  |               |                 |
| $m_7$                                  |                 | -0.05414       |                  |               |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |               |                 |
| $m_3$                                  |                 |                |                  | 0.00395       |                 |
| $m_8$                                  |                 | 0.000067       |                  |               |                 |
| Range of validity                      |                 |                |                  |               |                 |
| $\vartheta$ [°C]                       |                 | 500...800      |                  | 20            |                 |
| $\phi$                                 |                 | 0.05...1.40    |                  | 0.04...1.20   |                 |
| $\dot{\phi}$ [1/s]                     |                 | 0.2...10       |                  | 0,1 ... 10    |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                   |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                               |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                         |



**Fig. 5.181** Flow stress curves of NbTa<sub>7.5</sub> by hot and cold forming.

**Symbols and abbreviations**

| Short form      | Full form                                      |
|-----------------|------------------------------------------------|
| $\sigma_F$      | flow stress                                    |
| $\varphi$       | strain                                         |
| $\dot{\varphi}$ | strain rate                                    |
| ASTM            | American society for testing and materials     |
| EN              | Euronorm                                       |
| ISO             | international organisation for standardization |
| $T, \vartheta$  | temperature                                    |
| UNS             | unified numbering system                       |



# Flow stress, mechanical and physical properties of Ta<sub>99.9</sub>

## 5.9 Tantalum

### Designation

|             |               |                                        |
|-------------|---------------|----------------------------------------|
| UNS number: | <b>R05200</b> | Chem. symbol: <b>Ta<sub>99.9</sub></b> |
|-------------|---------------|----------------------------------------|

### Composition (EN) [Weight-%]

| Nb   | Ta   | Mo | W | Fe   | Ti | C | H <sub>2</sub> | N <sub>2</sub> | O <sub>2</sub> |
|------|------|----|---|------|----|---|----------------|----------------|----------------|
| 0.12 | 99.9 |    |   | 0.03 |    |   | 0.001          | 0.031          | 0.003          |

### International comparison of standards

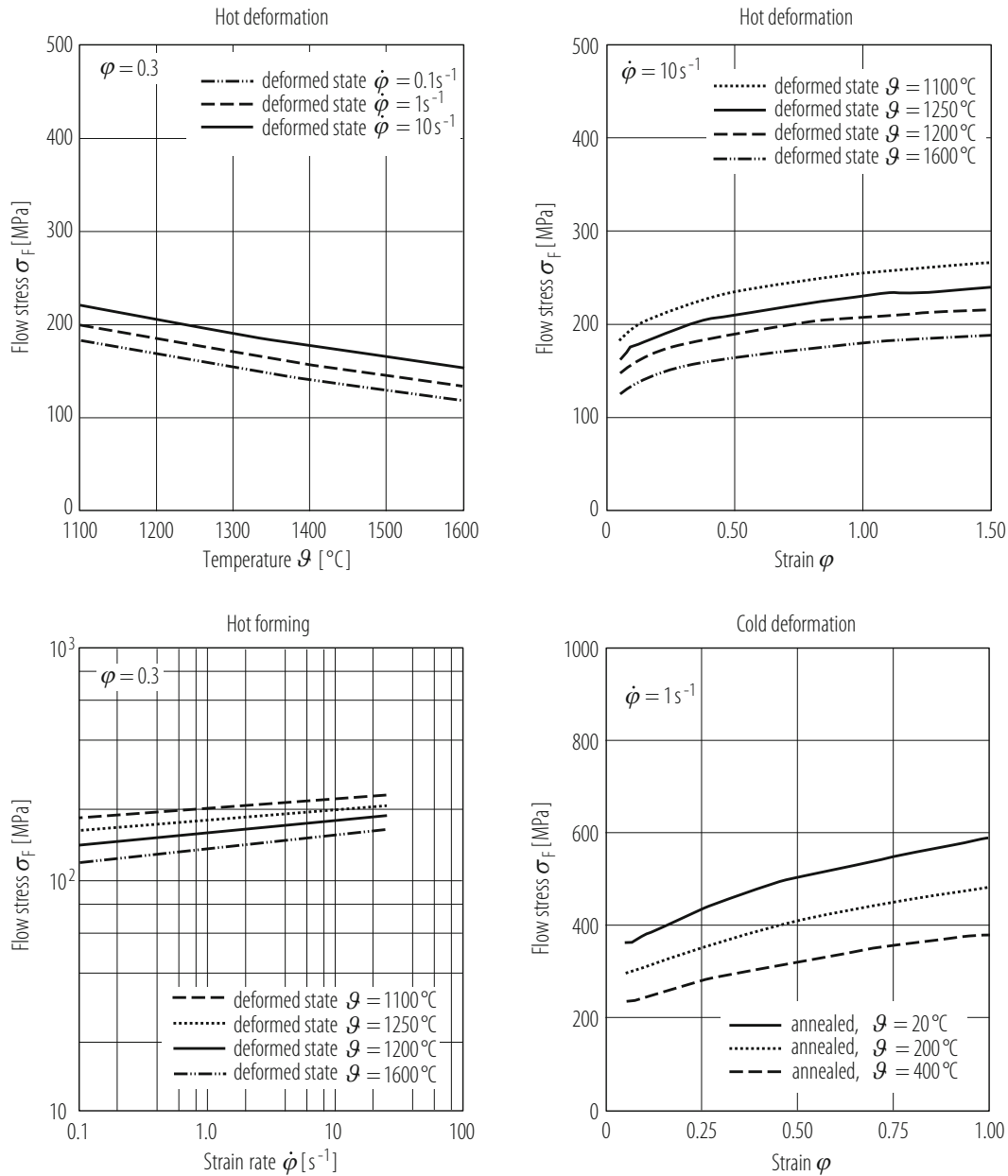
| Euronorm    |           | Material                         |
|-------------|-----------|----------------------------------|
| EN ISO 9001 |           | Ta 99.9 % (R05200) vacuum melted |
| CAS number  |           | ISO                              |
| 7440-25-7   |           | EN ISO 10993                     |
|             |           | EN ISO 1207                      |
| USA         |           |                                  |
| ASTM        |           | UNS standard                     |
| ASTM B364   | ASTM B365 | R05200                           |
| ASTM B708   | ASTM B521 |                                  |
| ASTM F560   |           |                                  |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |               |                 |
|-------------------------------------------|-----------------|----------------|------------------|---------------|-----------------|
|                                           | cast state      | deformed state | hot rolled (hr)  | annealed (an) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 179.8          |                  | 412.0         |                 |
| A                                         |                 | 568.278        |                  | 594.404       |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                  |               |                 |
| $m_1$                                     |                 | -0.00081       |                  | -0.00116      |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                  |               |                 |
| $m_2$                                     |                 | 0.13286        |                  | 0.24781       |                 |
| $m_4$                                     |                 | 0.00246        |                  | 0.01428       |                 |
| $m_5$                                     |                 | 0.00004        |                  |               |                 |
| $m_7$                                     |                 | -0.04111       |                  |               |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |               |                 |
| $m_3$                                     |                 |                |                  | 0.03672       |                 |
| $m_8$                                     |                 | 0.000037       |                  |               |                 |
| Range of validity                         |                 |                |                  |               |                 |
| $\vartheta$ [°C]                          |                 | 1100...1600    |                  | 20...400      |                 |
| $\varphi$                                 |                 | 0.05...0.9     |                  | <1.0          |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.1...16       |                  | <1000         |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.182** Flow stress curves of Ta<sub>99,9</sub> by hot and cold forming.

## Mechanical properties after cold deformation

| State of material | Tensile strength $\Delta R_m$ [MPa] |         |         | Validity $\varepsilon$ [%] |
|-------------------|-------------------------------------|---------|---------|----------------------------|
|                   | $B_0$                               | $B$     | $n_2$   |                            |
| annealed          | 370 ... 410                         | 41.2021 | 0.49485 | <60                        |

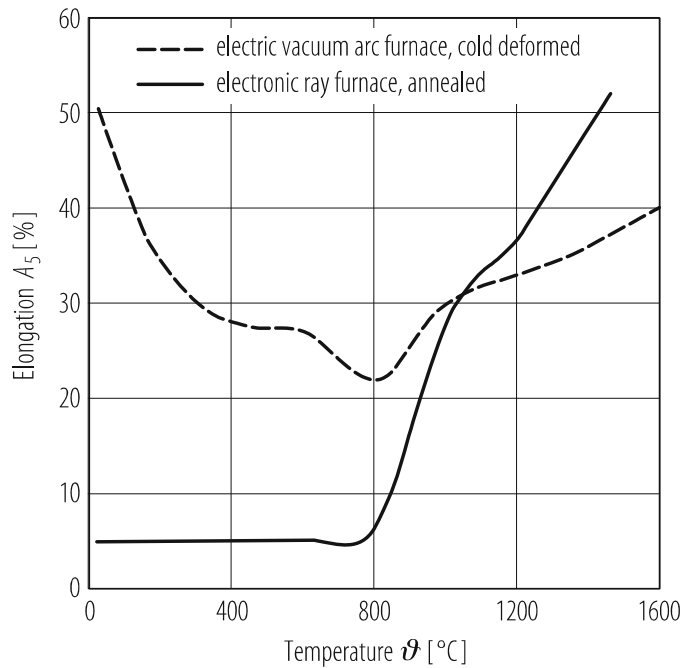
Tensile strength:

$$R_m = B_0 + B \cdot \varepsilon^{n_2}$$

[Equation (4.2), Chapter 5.1.4]

[DOI: [978-3-642-14174-4\\_5](https://doi.org/10.1007/978-3-642-14174-4_5)]

## Plasticity in tensile test



**Fig. 5.183** Plasticity of Ta<sub>99.9</sub> as a function of the temperature.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 53.2                 | 146.4              |                                         | 16146.1                     | 175             |
| 100              | 53.5                 | 146.9              |                                         | 16123.3                     | 173             |
| 200              | 53.9                 | 147.6              |                                         | 16094.5                     | 171             |
| 300              | 54.4                 | 148.2              |                                         | 16065.3                     | 169             |
| 400              | 54.8                 | 148.9              |                                         | 16035.7                     | 167             |
| 500              | 55.3                 | 149.6              |                                         | 16005.6                     | 165             |
| 600              | 55.7                 | 150.2              |                                         | 15975.1                     | 164             |
| 700              | 56.2                 | 150.8              |                                         | 15944.2                     | 162             |

(continued)

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 800              | 56.7                 | 151.4              |                                         | 15912.8                     | 161             |
| 900              | 57.2                 | 152.1              |                                         | 15881.1                     | 160             |
| 1000             | 57.7                 | 152.7              |                                         | 15848.9                     | 158             |
| 1100             | 58.3                 | 153.2              |                                         | 15816.2                     | 157             |
| 1200             | 58.8                 | 153.8              |                                         | 15783.2                     | 156             |
| 1300             | 59.3                 | 154.4              |                                         | 15749.7                     | 155             |
| 1400             | 59.9                 | 155.0              |                                         | 15715.8                     | 153             |
| 1500             | 60.5                 | 155.5              |                                         | 15681.5                     | 152             |
| 1600             | 61.1                 | 156.0              |                                         | 15646.8                     | 150             |

### Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| CAS                 | chemical abstracts service                                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches institut für normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of uranium

## 5.10 Uranium

### Designation

|             |                 |
|-------------|-----------------|
| UNS number: | Chem. symbol: U |
|-------------|-----------------|

### Composition (EN) [Weight-%]

| U    | Mn     | Ni     | Cu      | Cr      | Co     | H <sub>2</sub> | N <sub>2</sub> | O <sub>2</sub> |
|------|--------|--------|---------|---------|--------|----------------|----------------|----------------|
| 99.8 | 0.0012 | 0.0012 | 0.00074 | 0.00072 | 0.0001 | 0.0047         | 0.0041         | 0.176          |

### International comparison of standards

| Euronorm        |                 | ISO          |             |
|-----------------|-----------------|--------------|-------------|
|                 |                 | EN ISO 13849 | EN ISO 9001 |
| DIN             |                 | Russia       |             |
| DIN 51524       |                 |              |             |
| USA             |                 | UNS standard |             |
| ASTM            |                 |              |             |
| ASTM C1204 - 02 | ASTM C1462 - 00 |              |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |               |                 |
|-------------------------------------------|-----------------|----------------|------------------|---------------|-----------------|
|                                           | cast state      | deformed state | hot rolled (hr)  | annealed (an) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 11.4           |                  | 995.1         |                 |
| A                                         |                 | 64569.665      |                  | 1633.598      |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                  |               |                 |
| $m_1$                                     |                 | -0.00889       |                  | -0.00411      |                 |
| Effect of strain $K_{\varphi}$ :          |                 |                |                  |               |                 |
| $m_2$                                     |                 | 0.05785        |                  | 0.26394       |                 |
| $m_4$                                     |                 | -0.00238       |                  | 0.00938       |                 |
| $m_5$                                     |                 | -0.00003       |                  |               |                 |
| $m_7$                                     |                 | -0.03081       |                  |               |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |               |                 |
| $m_3$                                     |                 |                |                  | 0.04361       |                 |
| $m_8$                                     |                 | 0.000177       |                  |               |                 |
| Range of validity                         |                 |                |                  |               |                 |
| $\vartheta$ [°C]                          |                 | 800...1000     |                  | 20...300      |                 |
| $\varphi$                                 |                 | 0.02...1.00    |                  | <1.0          |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.25...100     |                  | 0.25...25     |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                                                 |

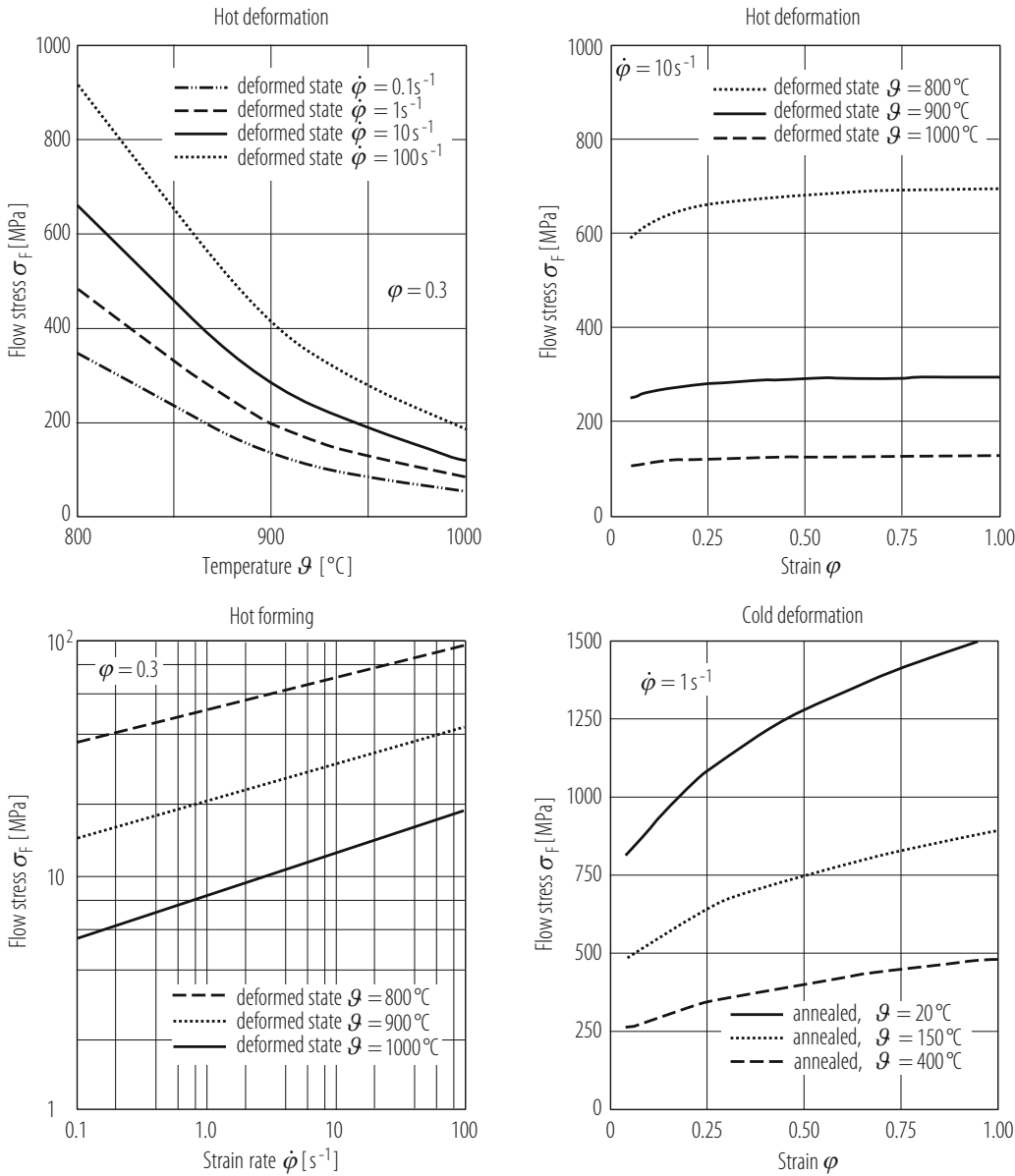


Fig. 5.184 Flow stress curves of U by hot and cold forming.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ GPa]        |
| 25               | 27.6                 | 116.0              |                                         | 19050                       |                 |

## Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, mechanical and physical properties of W<sub>99.95</sub>

## Tungsten

### Designation

|             |               |                             |
|-------------|---------------|-----------------------------|
| UNS number: | <b>R07005</b> | Chem. symbol: <b>W99.95</b> |
|-------------|---------------|-----------------------------|

### Composition (EN) [Weight-%]

| Nb | Ta | Mo | W      | Fe    | Ti | C     | H <sub>2</sub> | N <sub>2</sub> | O <sub>2</sub> |
|----|----|----|--------|-------|----|-------|----------------|----------------|----------------|
|    |    |    | >99.95 | 0.004 |    | 0.008 | 0.001          | 0.003          | 0.003          |

### International comparison of standards

| Euronorm       |             | Material                            |
|----------------|-------------|-------------------------------------|
| EN ISO 636     | EN ISO 9001 | W 99.95 %<br>powder-metallurgically |
| CAS number     |             | DIN                                 |
| CAS 7440-33-7  |             | DIN1045-1                           |
| USA            |             |                                     |
| ASTM           |             | UNS standard                        |
| ASTM B760      | ASTM F288   | R07005                              |
| ASTM B631 - 93 |             |                                     |

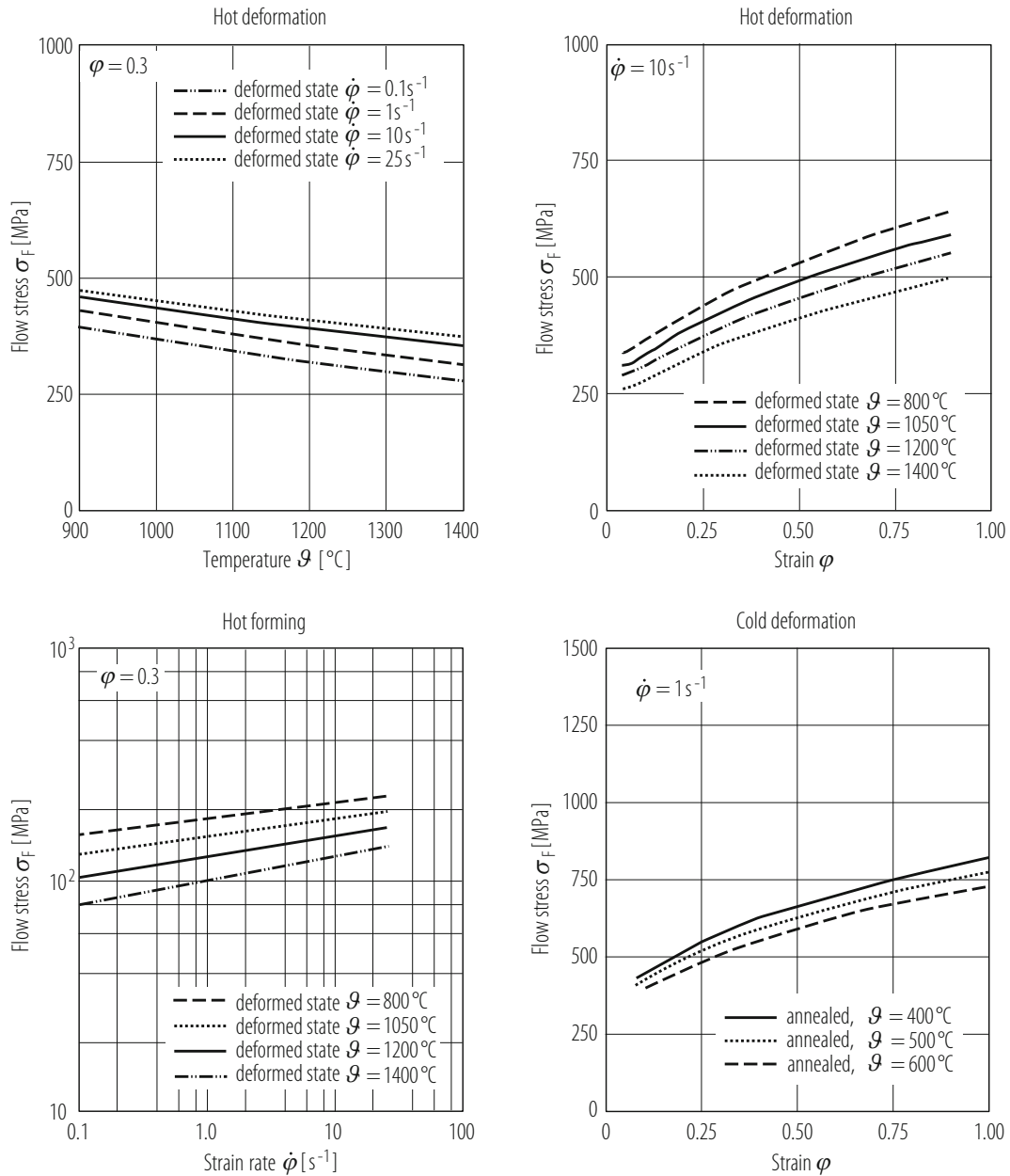
It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |               |                 |
|-------------------------------------------|-----------------|----------------|------------------|---------------|-----------------|
|                                           | cast state      | deformed state | hot rolled (hr)  | annealed (an) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 309.0          |                  | 1061.8        |                 |
| A                                         |                 | 962.949        |                  | 1677.131      |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                  |               |                 |
| m <sub>1</sub>                            |                 | -0.00062       |                  | -0.00134      |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                  |               |                 |
| m <sub>2</sub>                            |                 | 0.27627        |                  | 0.3092        |                 |
| m <sub>4</sub>                            |                 | 0.01286        |                  | 0.02816       |                 |
| m <sub>5</sub>                            |                 | 0.00005        |                  |               |                 |
| m <sub>7</sub>                            |                 | 0.06898        |                  |               |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |               |                 |
| m <sub>3</sub>                            |                 |                |                  |               |                 |
| m <sub>8</sub>                            |                 | 0.000037       |                  |               |                 |
| Range of validity                         |                 |                |                  |               |                 |
| $\theta$ [°C]                             |                 | 900...1400     |                  | 400...600     |                 |
| $\varphi$                                 |                 | 0.05...0.9     |                  | <1.00         |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.25...25      |                  | 2             |                 |



| Hot deformation:                                                                                                                                                               | Cold deformation                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                          | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                      |



**Fig. 5.185** Flow stress curves of W99.95 by hot and cold forming.

### Mechanical properties after cold deformation

| State of material | Tensile strength $\Delta R_m$ [MPa] |         |         | Validity $\varepsilon$ [%] |
|-------------------|-------------------------------------|---------|---------|----------------------------|
|                   | $B_0$                               | B       | $n_2$   |                            |
| annealed          | 110 145                             | 0.02942 | 2.24662 | <60                        |

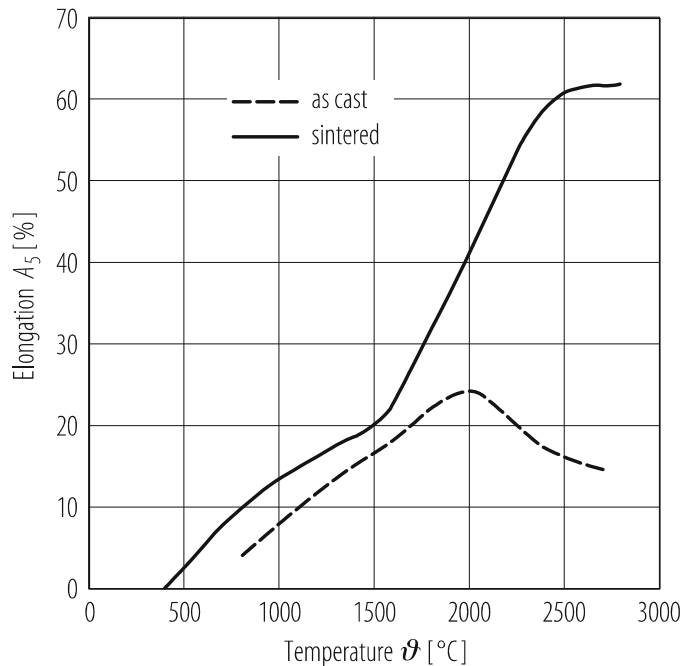
Tensile strength:

$$R_m = B_0 + B \cdot \varepsilon^{n_2}$$

[Equation (4.2), Chapter 5.1.4]

[DOI: [978-3-642-14174-4\\_5](https://doi.org/10.1007/978-3-642-14174-4_5)]

### Plasticity in tensile test



**Fig. 5.186** Plasticity of W99.95 as a function of the temperature.

### Physical properties

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus   |      |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|-------------------|------|
|                                 |                                           |                                         |                                                                          |                                        | powder metallurgy | cast |
| 20                              | 157.8                                     | 131.4                                   | 4.3                                                                      | 19247.5                                | 390               | 404  |
| 100                             | 152.6                                     | 131.6                                   |                                                                          | 19232.1                                | 385               | 400  |
| 200                             | 146.5                                     | 131.8                                   | 4.44                                                                     | 19211.5                                | 380               | 396  |
| 300                             | 140.9                                     | 132.1                                   |                                                                          | 19189.4                                | 376               | 393  |
| 400                             | 135.6                                     | 132.5                                   | 4.6                                                                      | 19165.8                                | 372               | 389  |
| 500                             | 130.7                                     | 132.9                                   |                                                                          | 19140.8                                | 368               | 385  |
| 600                             | 126.2                                     | 133.6                                   | 4.72                                                                     | 19114.3                                | 363               | 381  |
| 700                             | 122.2                                     | 133.7                                   |                                                                          | 19086.4                                | 349               | 377  |

(continued)

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus   |      |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|-------------------|------|
|                                 |                                           |                                         |                                                                          |                                        | powder metallurgy | cast |
|                                 |                                           |                                         |                                                                          |                                        | $E$ [GPa]         |      |
| 800                             | 118.5                                     | 134.2                                   | 4.86                                                                     | 19057.0                                | 354               | 374  |
| 900                             | 115.2                                     | 134.7                                   |                                                                          | 19026.1                                | 350               | 370  |
| 1000                            | 112.3                                     | 135.3                                   | 5.01                                                                     | 18993.7                                | 345               | 367  |
| 1100                            | 109.9                                     | 135.9                                   |                                                                          | 18959.9                                | 341               | 363  |
| 1200                            | 107.8                                     | 136.5                                   | 5.15                                                                     | 18924.6                                | 336               | 360  |
| 1300                            | 106.1                                     | 137.2                                   |                                                                          | 18887.9                                | 331               | 355  |
| 1400                            | 104.9                                     | 137.9                                   |                                                                          | 18849.6                                | 325               | 350  |
| 1500                            | 104.0                                     | 138.6                                   | 5.35                                                                     | 18810.0                                | 314               | 344  |
| 1600                            | 103.5                                     | 139.4                                   |                                                                          | 18768.8                                | 306               | 335  |
| 1700                            | 103.4                                     | 140.2                                   |                                                                          | 18726.2                                | 295               | 328  |

### Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches institut für normung) |
| $E$             | Young's modulus                                                       |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $R_m$           | tensile strength                                                      |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |
| $\alpha_m$      | average coefficient of linear expansion                               |
| $\lambda$       | thermal conductivity                                                  |
| $\rho$          | density                                                               |

# Flow stress, plasticity and physical properties of Sn<sub>99</sub>

## 5.11 Tin

### Designation

|             |               |                           |
|-------------|---------------|---------------------------|
| UNS number: | <b>L13910</b> | Chem. symbol: <b>Sn99</b> |
|-------------|---------------|---------------------------|

### Composition (EN) [Weight-%]

| Fe     | Pb    | Cu     | Sb    | Bi    | As    | S | Sn   | Imp. max. |
|--------|-------|--------|-------|-------|-------|---|------|-----------|
| <0.015 | <0.25 | <0.050 | <0.20 | <0.10 | <0.05 |   | Bal. | <0.30     |

### International comparison of standards

| Euronorm      |                | Material                |             |
|---------------|----------------|-------------------------|-------------|
| EN 29453      | EN 610         | Sn 99<br>(electrolytic) |             |
| DIN           |                | ISO                     |             |
| DIN 1707-100  | DIN/EN 29453   | EN ISO 9453             | EN ISO 9001 |
| Japan         |                | Russia                  |             |
| USA           |                |                         |             |
| ASTM          |                | UNS standard            |             |
| ASTM B23 - 00 | ASTM A630 - 03 | L13910                  |             |
|               | ASTM B545 - 97 |                         |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

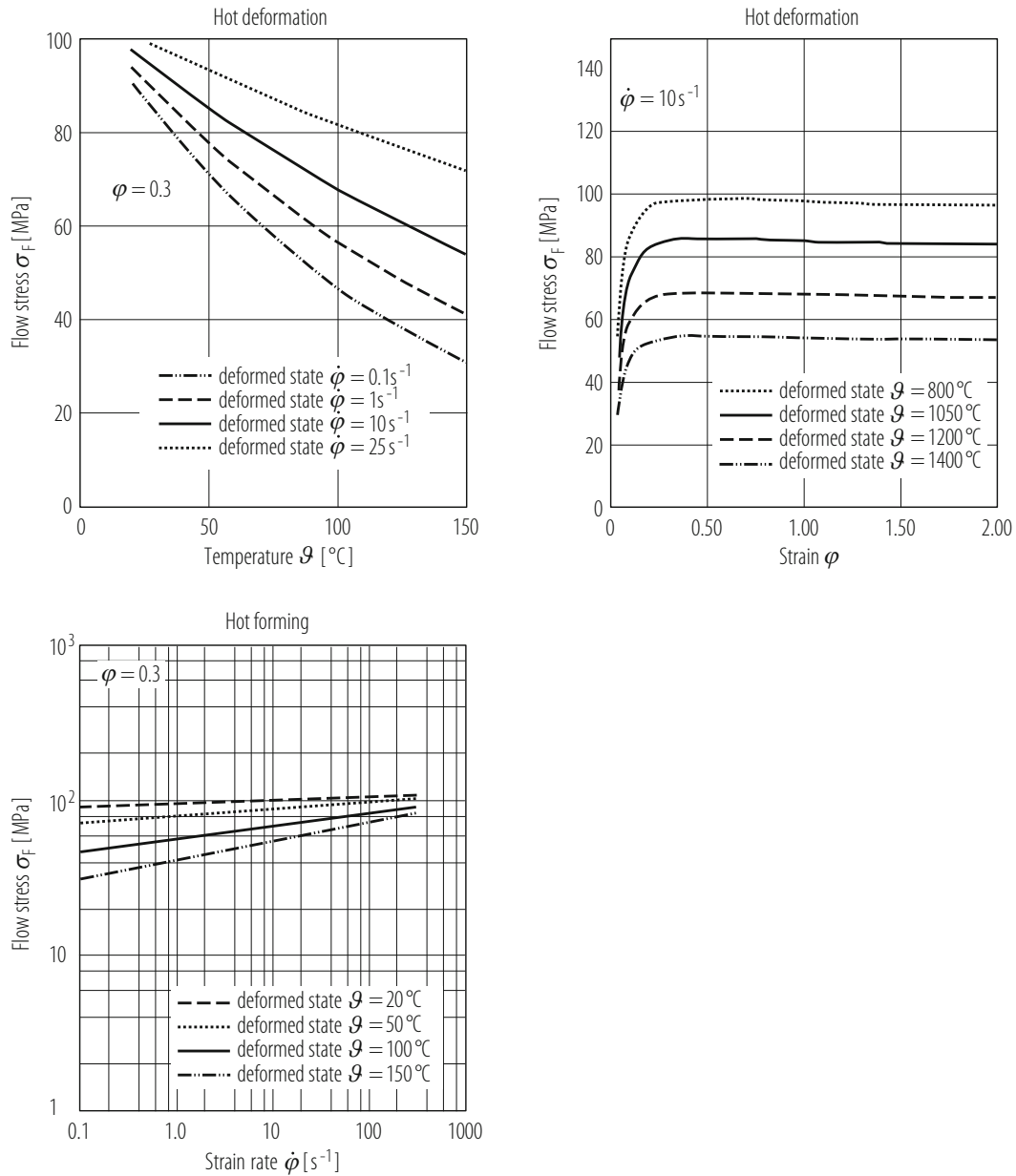
| State of material                         | Hot deformation |                | Cold deformation |               |                 |
|-------------------------------------------|-----------------|----------------|------------------|---------------|-----------------|
|                                           | cast state      | deformed state | hot rolled (hr)  | annealed (an) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 85.2           |                  |               |                 |
| A                                         |                 | 106.527        |                  |               |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                  |               |                 |
| m <sub>1</sub>                            |                 | −0.00643       |                  |               |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                  |               |                 |
| m <sub>2</sub>                            |                 | −0.09204       |                  |               |                 |
| m <sub>4</sub>                            |                 | −0.03495       |                  |               |                 |
| m <sub>5</sub>                            |                 | 0.00001        |                  |               |                 |
| m <sub>7</sub>                            |                 | 0.03696        |                  |               |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |               |                 |
| m <sub>3</sub>                            |                 |                |                  |               |                 |
| m <sub>8</sub>                            |                 | 0.000823       |                  |               |                 |
| Range of validity                         |                 |                |                  |               |                 |
| $\vartheta$ [°C]                          |                 | 20...150       |                  |               |                 |
| $\varphi$                                 |                 | 0.01...2.00    |                  |               |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.4...300      |                  |               |                 |

Hot deformation:

$$\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$$

[Equation (2.10), Chapter 2.3.2.1.1]

[DOI: [978-3-642-14174-4\\_2](https://doi.org/10.1007/978-3-642-14174-4_2)]



**Fig. 5.187** Flow stress curves of Sn<sub>99</sub> by hot forming.

Plasticity in tensile test

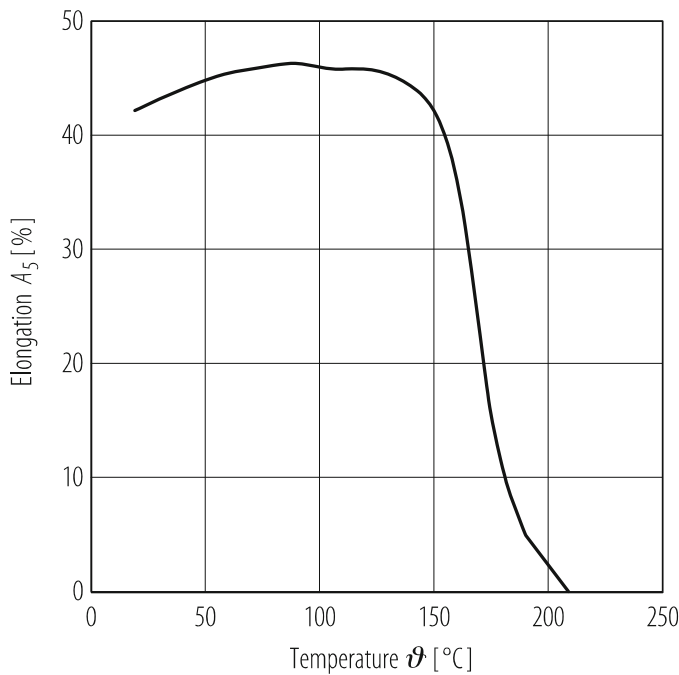


Fig. 5.188 Plasticity of Sn99 as a function of the temperature.

Physical properties (β-Phase)

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [10 <sup>-6</sup> /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                              | 64.0                                      | 228.5                                   | 21.0                                                                           | 7296.4                                 |                              |
| 50                              | 61.8                                      | 231.2                                   | 23.5                                                                           | 7280.8                                 |                              |
| 100                             | 59.6                                      | 234.8                                   | 26.2                                                                           | 7254.3                                 | 75.5                         |
| 150                             | 59.5                                      | 238.5                                   | 28.9                                                                           | 7227.3                                 |                              |
| 200                             | 61.2                                      | 242.1                                   | 31.6                                                                           | 7199.8                                 | 121.6                        |

Average coefficient of linear expansion  $\alpha_m$  along crystal axes

Symbols and abbreviations

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| $c_{pm}$        | mean specific heat                                                    |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$             | Young's modulus                                                       |

(continued)

| Short form     | Full form                                      |
|----------------|------------------------------------------------|
| EN             | Euronorm                                       |
| ISO            | international organisation for standardization |
| $T, \vartheta$ | temperature                                    |
| UNS            | unified numbering system                       |
| $\alpha_m$     | average coefficient of linear expansion        |
| $\lambda$      | thermal conductivity                           |
| $\rho$         | density                                        |

# Flow stress and physical properties of Zr<sub>99.5</sub>

## 5.12 Zircon and Zircon alloy

### Designation

|             |               |                             |
|-------------|---------------|-----------------------------|
| UNS number: | <b>R60001</b> | Chem. symbol: <b>Zr99.5</b> |
|-------------|---------------|-----------------------------|

### Composition (EN) [Weight-%]

|      |       |       |       |
|------|-------|-------|-------|
| Zr   | Hf    | Al    | Fe    |
| 99.8 | 0.009 | 0.008 | 0.038 |

### International comparison of standards

|                          |                          |        |  |
|--------------------------|--------------------------|--------|--|
| CAS number               | Euronorm                 |        |  |
| 7440-67-7                | EN ISO 9001              |        |  |
| Japan                    | Russia                   |        |  |
| USA                      |                          |        |  |
| ASTM                     | UNS standard             |        |  |
| ASTM B493 / B493M - 08e1 | ASTM B658 / B658M - 11e1 | R60001 |  |
| ASTM B495 - 10           | ASTM B550 / B550M - 07   |        |  |

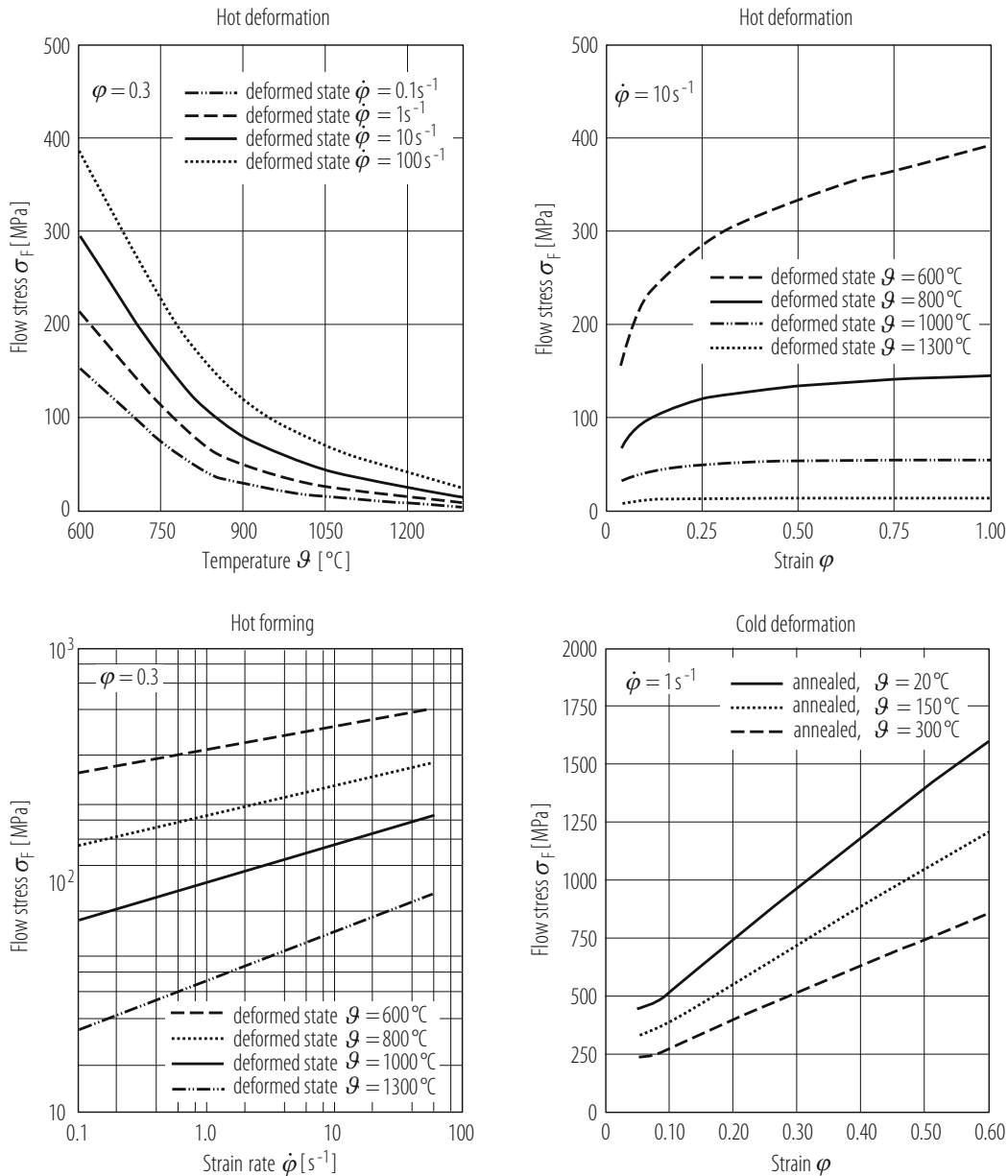
It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |               |                 |
|----------------------------------------|-----------------|----------------|------------------|---------------|-----------------|
|                                        | cast state      | deformed state | hot rolled (hr)  | annealed (an) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 | 42.3           |                  | 568.4         |                 |
| A                                      |                 | 5133.590       |                  | 2389.812      |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                  |               |                 |
| $m_1$                                  |                 | −0.00459       |                  | −0.00224      |                 |
| Effect of strain $K_{\phi}$            |                 |                |                  |               |                 |
| $m_2$                                  |                 | 0.26305        |                  | 0.82902       |                 |
| $m_4$                                  |                 | −0.00870       |                  | 0.04292       |                 |
| $m_5$                                  |                 | −0.00121       |                  |               |                 |
| $m_7$                                  |                 | 0.35153        |                  |               |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |               |                 |
| $m_3$                                  |                 |                |                  | 0.03769       |                 |
| $m_8$                                  |                 | 0.000245       |                  |               |                 |
| Range of validity                      |                 |                |                  |               |                 |
| $\theta$ [°C]                          |                 | 600...1300     |                  | 20...300      |                 |
| $\phi$                                 |                 | 0.03...1.00    |                  | <0.60         |                 |
| $\dot{\phi}$ [1/s]                     |                 | 0.25...60      |                  | 0.004...1000  |                 |



| Hot deformation:                                                                                                                                                      | Cold deformation                                                                                        |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                  | [Equation (2.25), Chapter 2.3.2.2.2]                                                                    |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                            | [DOI: 978-3-642-14174-4_2]                                                                              |



**Fig. 5.189** Flow stress curves of Zr<sub>99.5</sub> by hot and cold forming.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 21.9                 | 279.3              |                                         | 6474.1                      | 98.0            |
| 100              | 21.7                 | 284.9              |                                         | 6462.9                      |                 |
| 200              | 21.5                 | 291.3              |                                         | 6449.0                      |                 |
| 300              | 21.5                 | 297.8              | 5.8                                     | 6435.0                      |                 |
| 400              | 21.6                 | 304.2              |                                         | 6421.1                      |                 |
| 500              | 21.8                 | 310.5              |                                         | 6407.1                      |                 |
| 600              | 22.2                 | 316.7              |                                         | 6393.1                      |                 |
| 700              | 22.7                 | 322.7              |                                         | 6379.1                      |                 |
| 800              | 23.3                 | 328.5              |                                         | 6365.1                      |                 |
| 900              | 26.3                 | 327.0              |                                         | 6351.1                      |                 |
| 1000             | 28.2                 | 326.1              |                                         | 6337.1                      |                 |
| 1100             | 30.0                 | 326.0              |                                         | 6323.0                      |                 |
| 1200             | 31.7                 | 326.3              |                                         | 6309.0                      |                 |
| 1300             | 33.2                 | 327.2              |                                         | 6294.9                      |                 |
| 1400             | 34.6                 | 328.5              |                                         | 6280.9                      |                 |

## Symbols and abbreviations

| Short form      | Full form                                      |
|-----------------|------------------------------------------------|
| $\sigma_F$      | flow stress                                    |
| $\varphi$       | strain                                         |
| $\dot{\varphi}$ | strain rate                                    |
| ASTM            | American society for testing and materials     |
| CAS             | chemical abstracts service                     |
| $c_{pm}$        | mean specific heat                             |
| $E$             | Young's modulus                                |
| EN              | Euronorm                                       |
| ISO             | international organisation for standardization |
| $T, \vartheta$  | temperature                                    |
| UNS             | unified numbering system                       |
| $\alpha_m$      | average coefficient of linear expansion        |
| $\lambda$       | thermal conductivity                           |
| $\rho$          | density                                        |

# Flow stress of zircalloy 2

## 5.12 Zircon and Zircon alloy

### Designation

|             |               |                                  |
|-------------|---------------|----------------------------------|
| UNS number: | <b>R60802</b> | Chem. symbol: <b>Zircalloy 2</b> |
|-------------|---------------|----------------------------------|

### Composition (EN) [Weight-%]

| Zr   | Sn          | Fe          | Cr          | Ni          | O <sub>2</sub>  | N <sub>2</sub> |
|------|-------------|-------------|-------------|-------------|-----------------|----------------|
| Bal. | 1.30...1.60 | 0.07...0.20 | 0.05...0.15 | 0.03...0.08 | 1000...1300 ppm | <80 ppm        |

### International comparison of standards

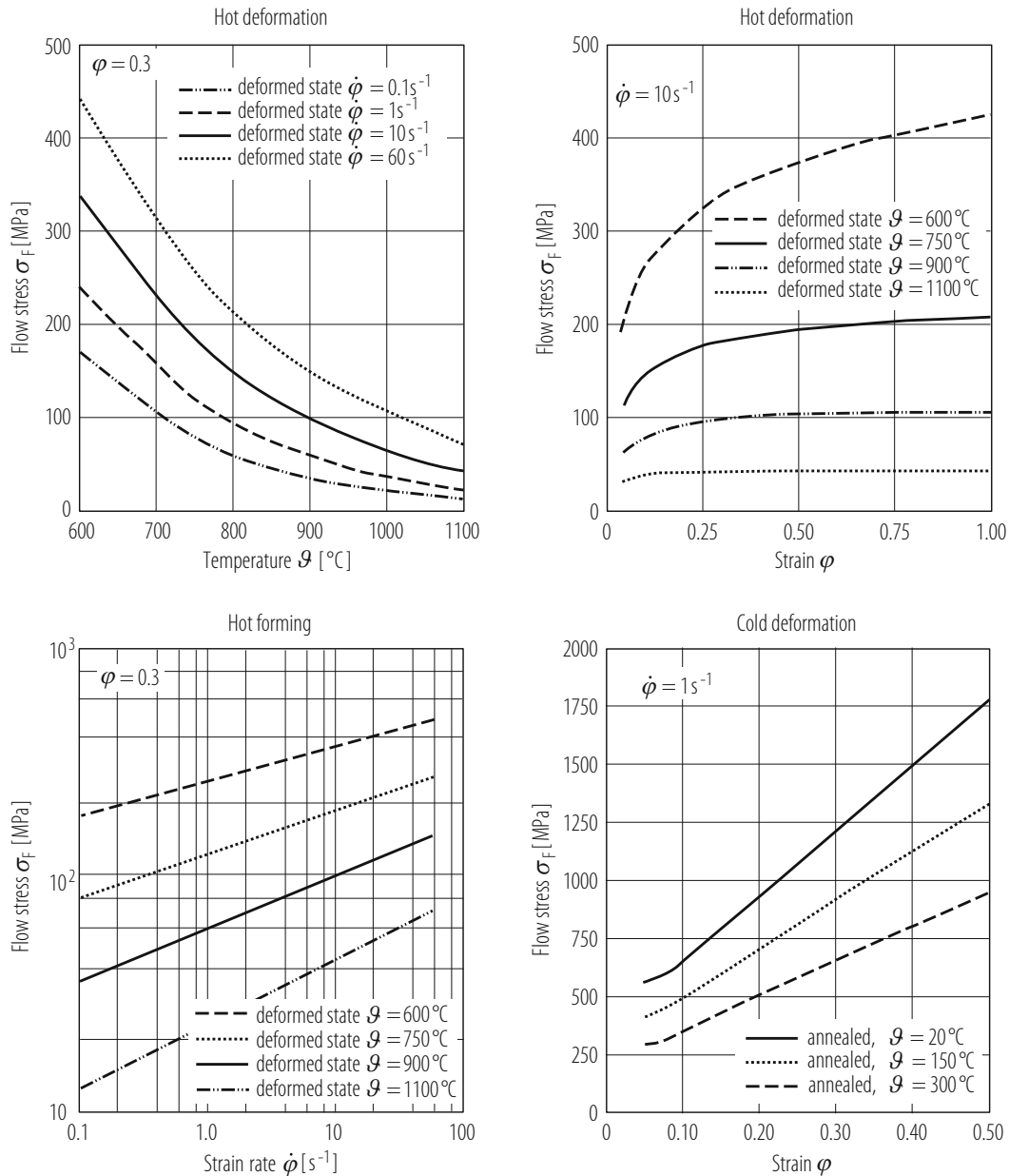
|                                     |              |
|-------------------------------------|--------------|
| Euronorm                            | CW           |
| VdTÜV-WB 480                        | CW106C       |
| DIN                                 | ISO          |
| DIN 1729-1                          | DIN 17666 2  |
| USA                                 | EN ISO 9001  |
| ASTM                                | UNS standard |
| ASTM B351 / B351M - 08 B 350/B 350M | R60802       |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |               |                 |
|-------------------------------------------|-----------------|----------------|------------------|---------------|-----------------|
|                                           | cast state      | deformed state | hot rolled (hr)  | annealed (an) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                       |                 | 53.5           |                  | 703.1         |                 |
| A                                         |                 | 5642.661       |                  | 3043.946      |                 |
| Effect of temperature $K_{\theta}$        |                 |                |                  |               |                 |
| $m_1$                                     |                 | -0.00435       |                  | -0.00226      |                 |
| Effect of strain $K_{\varphi}$            |                 |                |                  |               |                 |
| $m_2$                                     |                 | 0.33211        |                  | 0.84968       |                 |
| $m_4$                                     |                 | -0.00103       |                  | 0.04506       |                 |
| $m_5$                                     |                 | -0.00133       |                  |               |                 |
| $m_7$                                     |                 | 0.22771        |                  |               |                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |               |                 |
| $m_3$                                     |                 |                |                  | 0.03647       |                 |
| $m_8$                                     |                 | 0.000248       |                  |               |                 |
| Range of validity                         |                 |                |                  |               |                 |
| $\vartheta$ [°C]                          |                 | 600...1100     |                  | 20...300      |                 |
| $\varphi$                                 |                 | 0.03...1.00    |                  | <0.50         |                 |
| $\dot{\varphi}$ [1/s]                     |                 | 0.25...60      |                  | 0.004...1000  |                 |

| Hot deformation:                                                                                                                                                      | Cold deformation                                                                                        |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                  | [Equation (2.25), Chapter 2.3.2.2.2]                                                                    |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                            | [DOI: 978-3-642-14174-4_2]                                                                              |



**Fig. 5.190** Flow stress curves of Zircalloy 2 by hot and cold forming.

**Symbols and abbreviations**

| Short form      | Full form                                                             |
|-----------------|-----------------------------------------------------------------------|
| $\sigma_F$      | flow stress                                                           |
| $\varphi$       | strain                                                                |
| $\dot{\varphi}$ | strain rate                                                           |
| ASTM            | American society for testing and materials                            |
| DIN             | German institute for standardisation (Deutsches Institut Für Normung) |
| EN              | Euronorm                                                              |
| ISO             | international organisation for standardization                        |
| $T, \vartheta$  | temperature                                                           |
| UNS             | unified numbering system                                              |

# Flow stress, mechanical and physical properties of Ag<sub>99.9</sub>

## 5.13 Noble metals

### 5.13.1 Silver and Silver alloys

#### Designation

|             |               |                              |
|-------------|---------------|------------------------------|
| UNS number: | <b>P07020</b> | Chem. symbol: <b>Ag 99.9</b> |
|-------------|---------------|------------------------------|

#### Composition (DIN) [Weight-%]

| Ag        | Bi     | Cu     | Fe     | Pb     | Sb     | Other  | Total |
|-----------|--------|--------|--------|--------|--------|--------|-------|
| min. 99.9 | <0.002 | <0.015 | <0.035 | <0.003 | <0.002 | <0.043 | <0.10 |

#### International comparison of standards

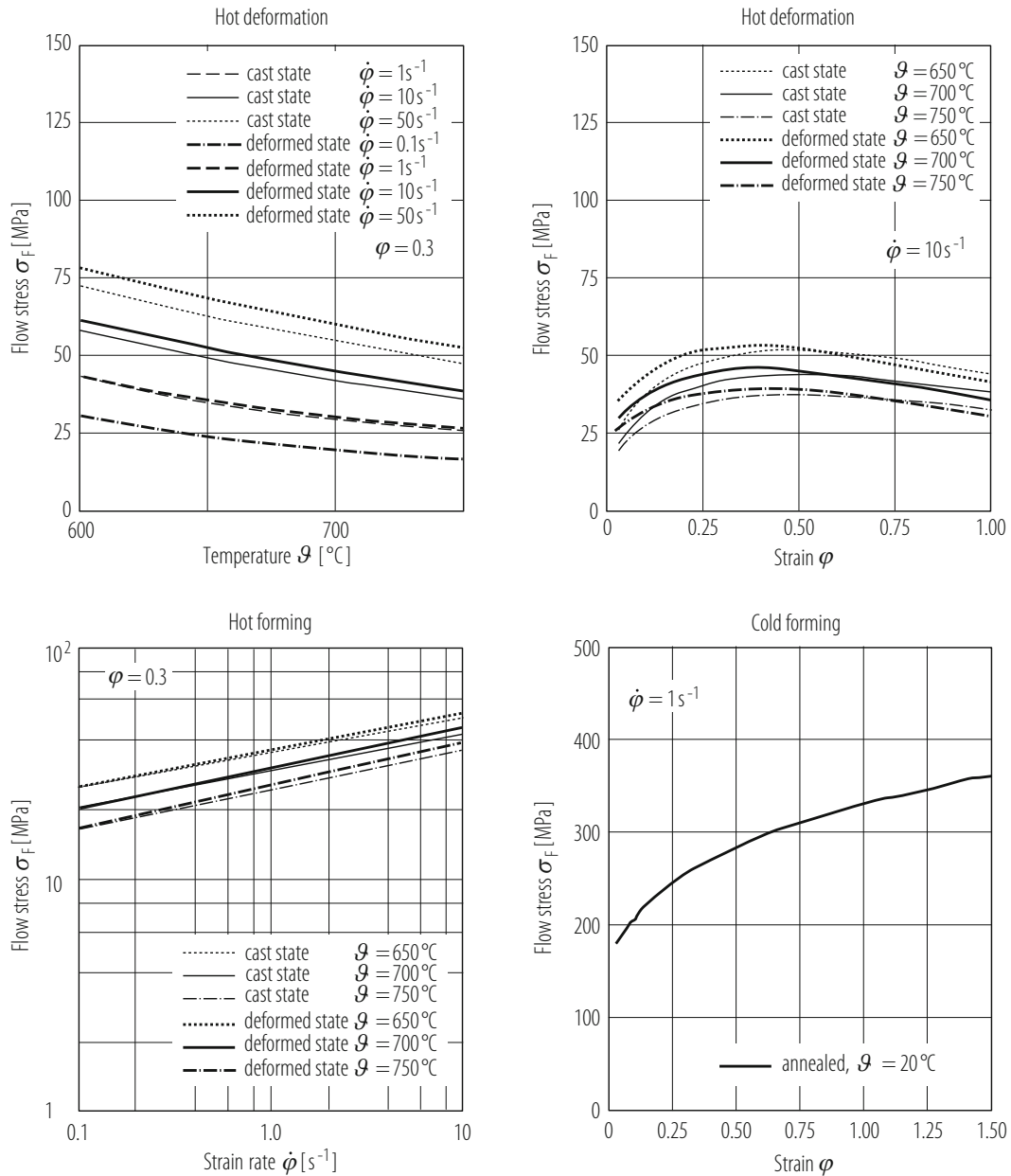
| CAS number       | DIN            |                |
|------------------|----------------|----------------|
| CAS 7440-22-4    | DIN 17 006     | DIN EN 485-2   |
| ISO              | United Kingdom |                |
| EN ISO 9001:2000 |                |                |
| Japan            | Russia         |                |
|                  | Sr 999         | GOST 6836 - 80 |
| USA              |                |                |
| ASTM             |                | UNS standard   |
| ASTM B413 - 97a  | P07020         |                |
| ASTM B742 - 90   |                |                |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    | 37.5            | 43.7           | 233.4            |                 |                 |
| A                                      | 916.946         | 808.336        | 328.874          |                 |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                  |                 |                 |
| $m_1$                                  | −0.00376        | −0.00362       |                  |                 |                 |
| Effect of strain $K_{\phi}$            |                 |                |                  |                 |                 |
| $m_2$                                  | 0.45973         | 0.40191        | 0.22339          |                 |                 |
| $m_4$                                  | 0.00582         | 0.00837        | 0.00569          |                 |                 |
| $m_5$                                  | 0.000236        | 0.00023        |                  |                 |                 |
| $m_7$                                  | −1.044615       | −1.09771       |                  |                 |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.04975          |                 |                 |
| $m_8$                                  | 0.000225        | 0.000249       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\theta$ [°C]                          | 600...750       | 600...750      | 20               |                 |                 |
| $\phi$                                 | 0.1...1         | 0.1...1        | 0.03...1.60      |                 |                 |
| $\dot{\phi}$ [1/s]                     | 0.1...50        | 0.1...50       | 0.0005...50      |                 |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                   |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                               |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                         |

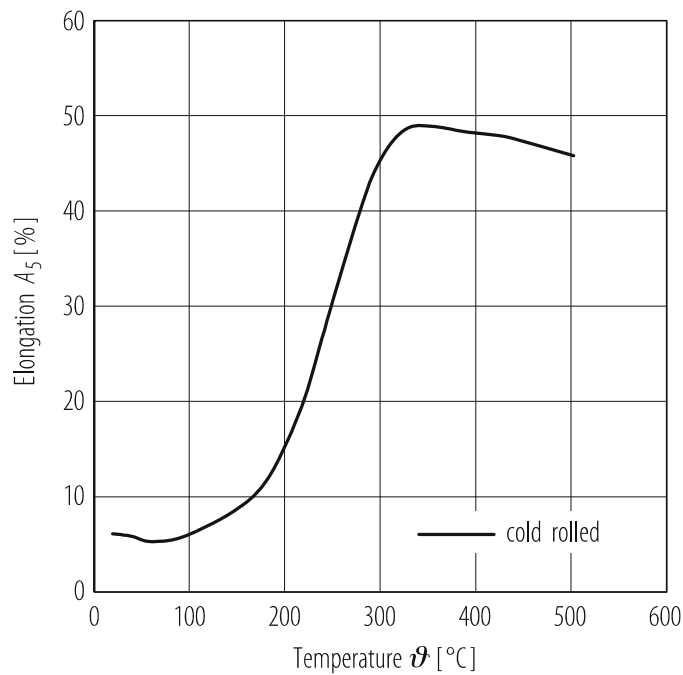


**Fig. 5.191** Flow stress curves of Ag<sub>99.9</sub> by hot and cold forming.

**Mechanical properties after cold deformation**

| State of material | Yield stress $\Delta R_p$ [MPa] |         |         | Tensile strength $\Delta R_m$ [MPa] |        |         |
|-------------------|---------------------------------|---------|---------|-------------------------------------|--------|---------|
|                   | $A_0$                           | $A$     | $n_1$   | $B_0$                               | $B$    | $n_2$   |
| annealed          | 80...120                        | 16.8363 | 0.61121 | 150...200                           | 2.4092 | 0.99539 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |         |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|---------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$   | $n_4$   |                            |
| annealed          | 45...50                                 | 48.9799 | -0.0185 | -9.1559 | <70                        |

**Plasticity in tensile test****Fig. 5.192** Plasticity of Ag 99.9 as a function of the temperature.**Physical properties**

| Temperature<br>$\vartheta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|---------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                              | 428.3                                     | 234.7                                   | 19.50                                                                    | 10489.8                                | 80                           |
| 100                             | 425.3                                     | 236.4                                   | 19.62                                                                    | 10448.6                                |                              |
| 200                             | 420.7                                     | 238.6                                   | 19.79                                                                    | 10394.0                                |                              |
| 300                             | 415.1                                     | 241.0                                   | 20.00                                                                    | 10336.0                                |                              |
| 400                             | 408.6                                     | 243.6                                   | 20.30                                                                    | 10274.5                                | 66.0                         |
| 500                             | 401.1                                     | 246.3                                   | 20.60                                                                    | 10209.7                                |                              |
| 600                             | 392.6                                     | 249.3                                   | 21.00                                                                    | 10141.4                                |                              |
| 700                             | 383.2                                     | 252.4                                   | 21.40                                                                    | 10069.6                                |                              |
| 800                             | 372.8                                     | 255.7                                   | 21.80                                                                    | 9994.5                                 | 45.0                         |
| 900                             | 361.4                                     | 259.1                                   | 22.40                                                                    | 9915.9                                 |                              |



## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| CAS                 | chemical abstracts service                                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of AgCu<sub>12.5</sub>

## 5.13 Noble metals

### 5.13.1 Silver and Silver alloys

#### Designation

|             |               |                                          |
|-------------|---------------|------------------------------------------|
| UNS number: | <b>P07932</b> | Chem. symbol: <b>AgCu<sub>12.5</sub></b> |
|-------------|---------------|------------------------------------------|

#### Composition [Weight-%]

| Ag          | Bi     | Cu   | Fe    | Pb    | Sb     | Other | Total |
|-------------|--------|------|-------|-------|--------|-------|-------|
| 87.0...89.0 | <0.005 | rest | <0.20 | <0.01 | <0.005 | <0.08 | <0.30 |

#### International comparison of standards

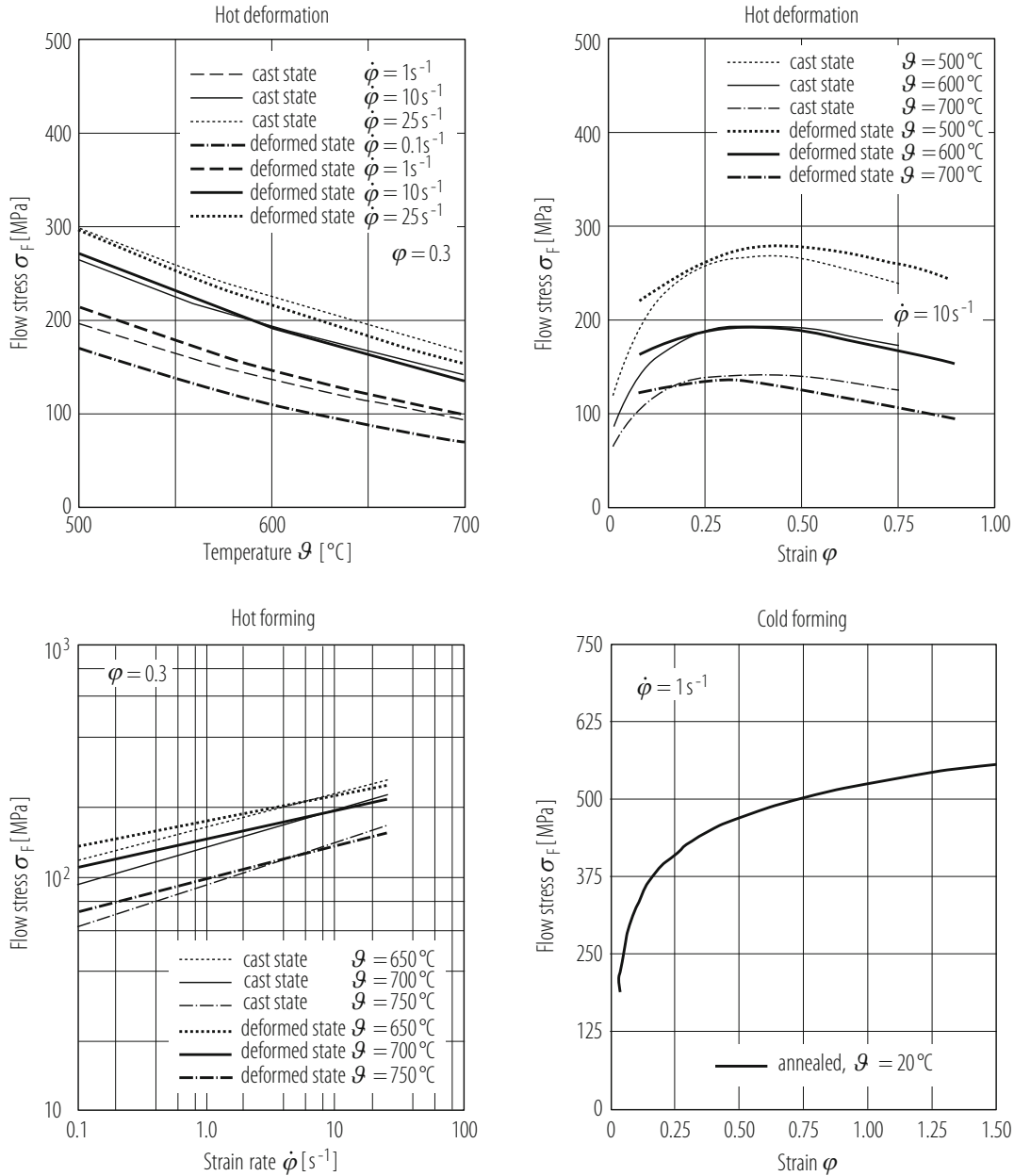
|          |               |                |                |
|----------|---------------|----------------|----------------|
| Euronorm |               | ISO            |                |
|          |               | ISO 9001:2000  |                |
| France)  |               | United Kingdom |                |
| Japan    |               | Russia         |                |
|          |               | SrM 875        | GOST 6836 - 80 |
| USA      |               |                |                |
| ASME     | ASTM          | UNS standard   |                |
|          | ASTM F72 - 06 | ASTM B693 - 91 | P07932         |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    | 129.9           | 144.7          | 362.1            |                 |                 |
| A                                      | 3099.760        | 4235.938       | 533.194          |                 |                 |
| Effect of temperature $K_\theta$       |                 |                |                  |                 |                 |
| $m_1$                                  | -0.00362        | -0.00311       |                  |                 |                 |
| Effect of strain $K_\phi$              |                 |                |                  |                 |                 |
| $m_2$                                  | 0.48882         | 0.86731        | 0.13227          |                 |                 |
| $m_4$                                  | 0.00506         | 0.0588         | -0.01699         |                 |                 |
| $m_5$                                  | -0.00047        | -0.00311       |                  |                 |                 |
| $m_7$                                  | -1.05454        | -0.57238       |                  |                 |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.03752          |                 |                 |
| $m_8$                                  | 0.00026         | 0.000203       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\theta$ [°C]                          | 500..700        | 500..700       | 20               |                 |                 |
| $\phi$                                 | 0.10...0.90     | 0.08...0.90    | 0.04...1.60      |                 |                 |
| $\dot{\phi}$ [1/s]                     | 0.1...25        | 0.1...25       | 0.001...50       |                 |                 |

| Hot deformation:                                                                                                                                                      | Cold deformation                                                                   |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                  | [Equation (2.25), Chapter 2.3.2.2.2]                                               |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                            | [DOI: 978-3-642-14174-4_2]                                                         |



**Fig. 5.193** Flow stress curves of AgCu<sub>12.5</sub> by hot and cold forming

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |         |         | Tensile strength $\Delta R_m$ [MPa] |        |         |
|-------------------|---------------------------------|---------|---------|-------------------------------------|--------|---------|
|                   | $A_0$                           | $A$     | $n_1$   | $B_0$                               | $B$    | $n_2$   |
| annealed          | 180...230                       | 12.5499 | 0.76644 | 280...320                           | 0.9670 | 1.31532 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$   | $n_4$    |                            |
| annealed          | 40...45                                 | 28.5638 | 0.09239 | −4.71346 | <90                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

Plasticity in tensile test

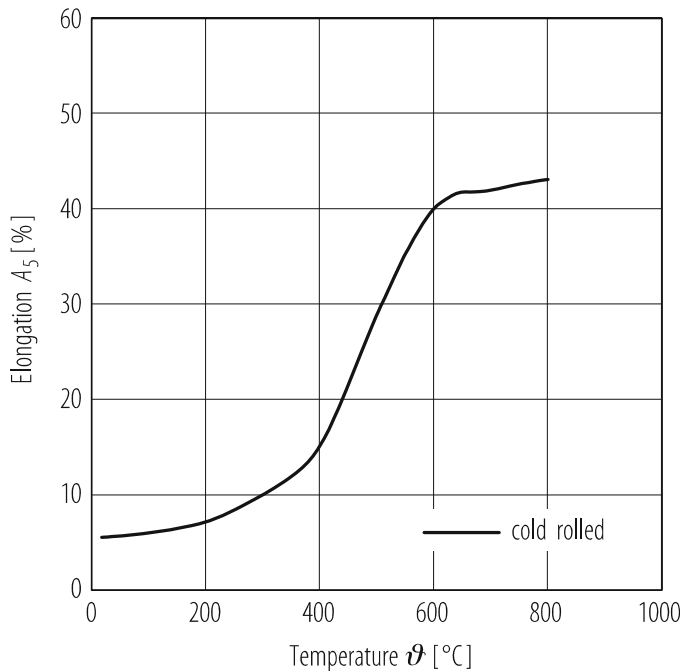


Fig. 5.194 Plasticity of AgCu<sub>12.5</sub> as a function of the temperature.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 410                  | 230                | 20                                      | 10343                       |                 |

## Symbols and abbreviations

| Short form          | Full form                                      |
|---------------------|------------------------------------------------|
| $\sigma_F$          | flow stress                                    |
| $\varphi$           | strain                                         |
| $\dot{\varphi}$     | strain rate                                    |
| $A_5$               | elongation to fracture                         |
| $A, B, C$ and $n_i$ | constants                                      |
| ASME                | American society of mechanical engineers       |
| ASTM                | American society for testing and materials     |
| $c_{pm}$            | mean specific heat                             |
| $E$                 | Young's modulus                                |
| GOST                | gosudarstvennyy standart (state standard)      |
| ISO                 | international organisation for standardization |
| $R_m$               | tensile strength                               |
| $R_p$               | yield stress                                   |
| $T, \vartheta$      | temperature                                    |
| UNS                 | unified numbering system                       |
| $\alpha_m$          | average coefficient of linear expansion        |
| $\lambda$           | thermal conductivity                           |
| $\rho$              | density                                        |

# Flow stress, mechanical and physical properties of AgNi<sub>20</sub>

## 5.13 Noble metals

### 5.13.1 Silver and Silver alloys

#### Designation

|             |                             |
|-------------|-----------------------------|
| UNS number: | Chem. symbol: <b>AgNi20</b> |
|-------------|-----------------------------|

#### Composition (EN) [Weight-%]

|     |     |
|-----|-----|
| Ag  | Ni  |
| ~80 | ~20 |

#### International comparison of standards

|                  |                   |              |
|------------------|-------------------|--------------|
| Euronorm         | DIN               |              |
| EN ISO 9001:2000 | DIN 46240 + 46241 |              |
| ISO              | United Kingdom    |              |
| EN ISO 13485     |                   |              |
| Japan            | Russia            |              |
| USA              |                   |              |
| ASME             | ASTM              | UNS standard |
| ASTM B961-08     | ASTM B628 - 98    |              |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                         | Hot deformation |                | Cold deformation |                 |                                 |
|-------------------------------------------|-----------------|----------------|------------------|-----------------|---------------------------------|
|                                           | cast state      | deformed state | annealed (an)    | hot rolled (hr) | produced powder metallurgy (pm) |
| $\sigma_{F0}$ [MPa]                       |                 | 27.0           | 354.1            | 410.0           | 144.4                           |
| A                                         |                 | 358.246        | 452.762          | 499.748         | 297.910                         |
| Effect of temperature $K_\theta$          |                 |                |                  |                 |                                 |
| $m_1$                                     |                 | -0.00277       |                  |                 |                                 |
| Effect of strain $K_\varphi$              |                 |                |                  |                 |                                 |
| $m_2$                                     |                 | 0.48655        | 0.16513          | 0.13657         | 0.40756                         |
| $m_4$                                     |                 | 0.00504        | 0.00508          | 0.0043          | 0.02143                         |
| $m_5$                                     |                 | -0.00138       |                  |                 |                                 |
| $m_7$                                     |                 | 0.39391        |                  |                 |                                 |
| Effect of strain rate $K_{\dot{\varphi}}$ |                 |                |                  |                 |                                 |
| $m_3$                                     |                 |                | 0.03628          | 0.03194         | 0.03194                         |
| $m_8$                                     |                 | 0.000221       |                  |                 |                                 |
| Range of validity                         |                 |                |                  |                 |                                 |
| $\vartheta$ [°C]                          |                 | 500...850      | 20               | 20              | 20                              |
| $\varphi$                                 |                 | 0.04...1.00    | 0.04...1.60      | 0.04...1.60     | 0.04...1.40                     |
| $\dot{\varphi}$ [1/s]                     |                 | 0,1 ... 25     | 0.01...50        | 0.01...50       | 0.01...50                       |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                   |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                               |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                         |

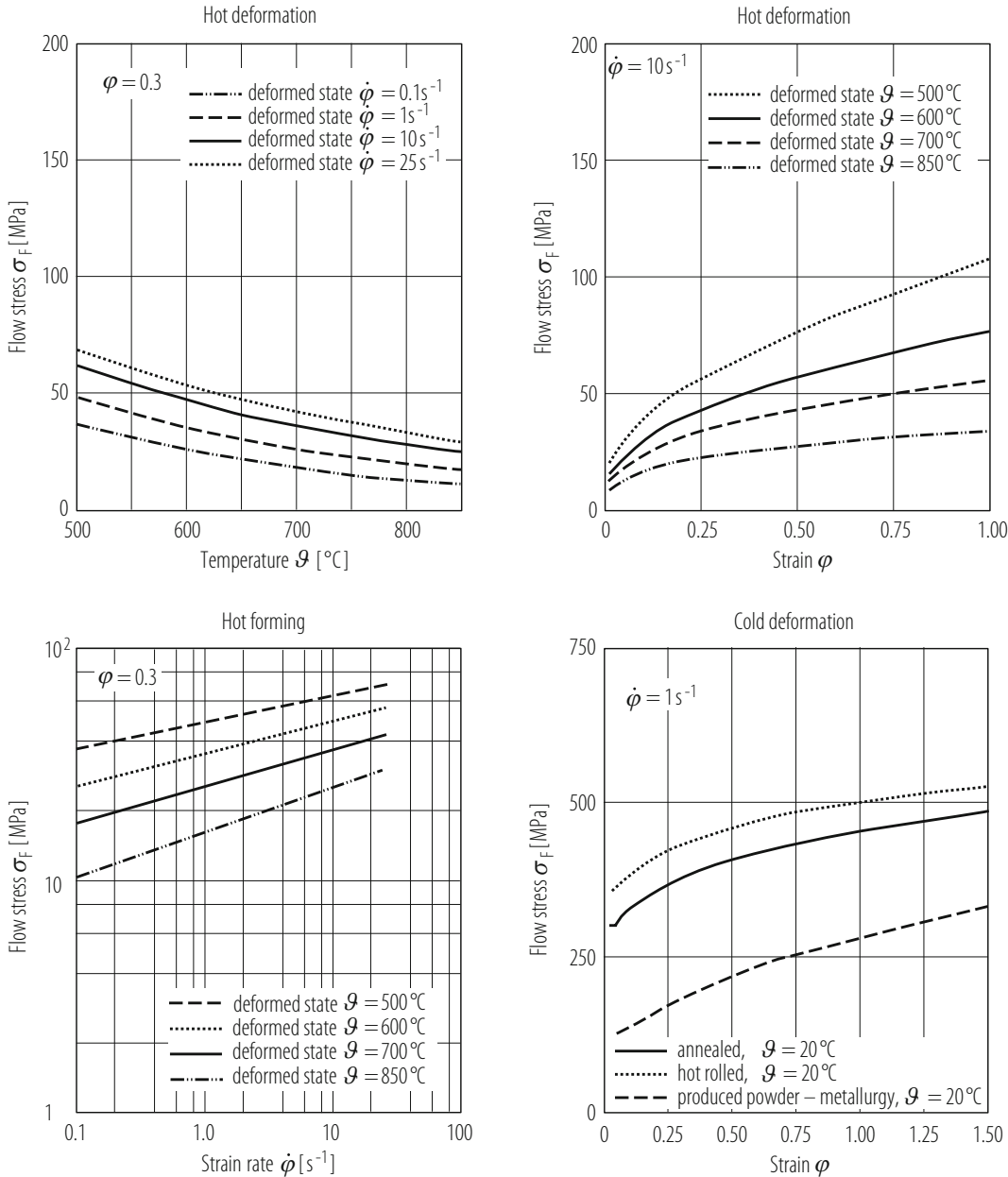


Fig. 5.195 Flow stress curves of AgNi20 by hot and cold forming.

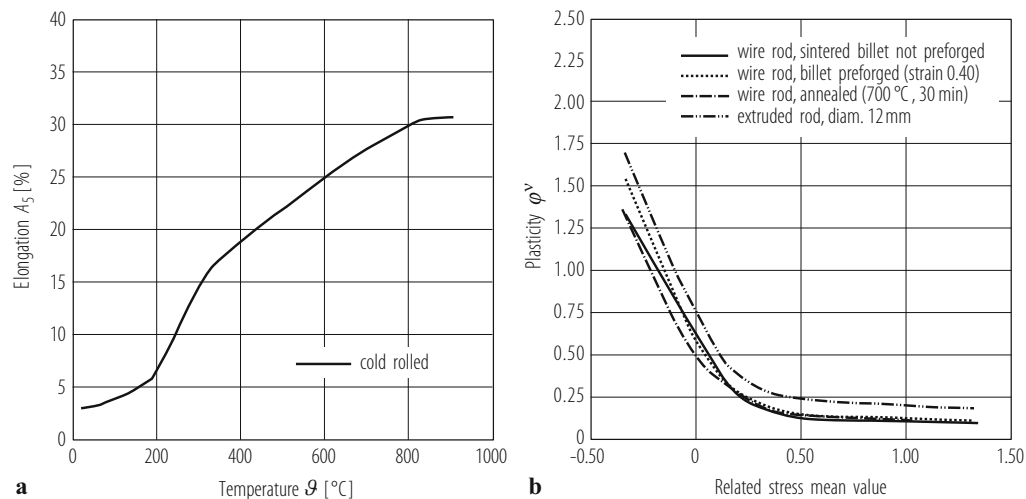
## Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |         |        | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|---------|--------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$     | $n_1$  | $B_0$                               | $B$     | $n_2$   |
| annealed          | 175...220                       | 27.2270 | 0.5579 | 280...325                           | 6.3413  | 0.82312 |
| annealed          |                                 |         |        | 200...250                           | 17.5986 | 0.57972 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |          |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|----------|----------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$    | $n_4$    |                            |
| annealed          | 30...35                                 | 52.4322 | −0.11182 | −9.54678 | <75                        |
| annealed          | 25...30                                 | 26.8533 | 0.00095  | −20.8384 | <85                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

## Plasticity in tensile test



**Fig. 5.196** Plasticity of AgNi<sub>20</sub> a) function of the temperature b) related stress mean value at 20°C.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 270.0                |                    |                                         | 10000.0                     | 98              |



## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| UNS                 | unified numbering system                                              |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| ASTM                | American society for testing and materials                            |
| ASME                | American society of mechanical engineers                              |
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $T, \vartheta$      | temperature                                                           |
| $R_p$               | yield stress                                                          |
| $R_m$               | tensile strength                                                      |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| $\lambda$           | thermal conductivity                                                  |
| $c_{pm}$            | mean specific heat                                                    |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\rho$              | density                                                               |
| $E$                 | Young's modulus                                                       |

# Flow stress, mechanical and physical properties of AgCdO<sub>10</sub>

## 5.13 Noble metals

### 5.13.1 Silver and Silver alloys

#### Designation

|             |                              |
|-------------|------------------------------|
| UNS number: | Chem. symbol: <b>AgCdO10</b> |
|-------------|------------------------------|

#### Composition (EN) [Weight-%]

|     |     |
|-----|-----|
| Ag  | CdO |
| ~90 | ~10 |

#### International comparison of standards

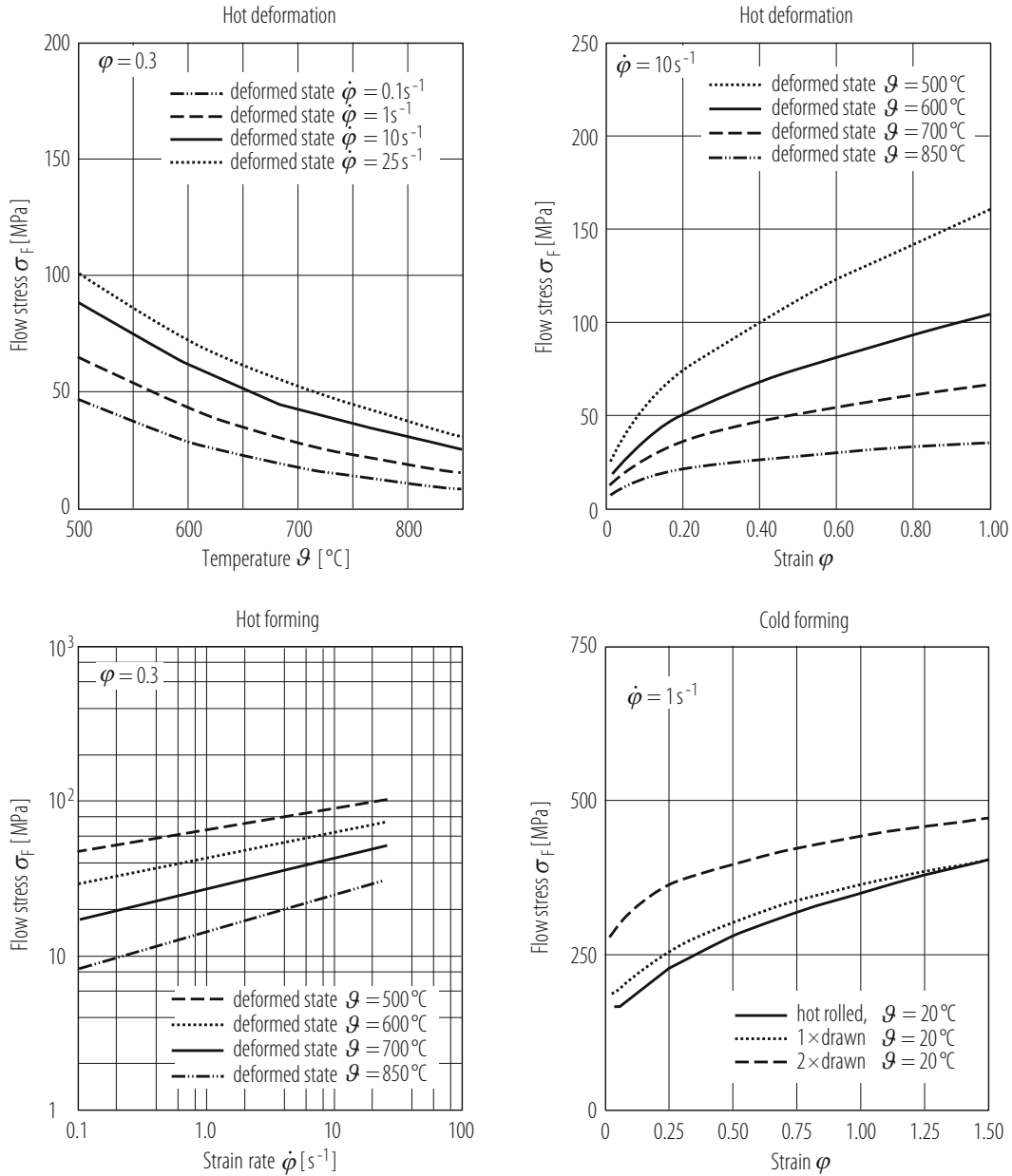
|                  |                 |                   |              |
|------------------|-----------------|-------------------|--------------|
| Euronorm         |                 | DIN               |              |
| EN 60715         | EN-60849        | DIN 46240 + 46241 | DIN EN 50178 |
| ISO              |                 | United Kingdom    |              |
| EN ISO 9001:2000 |                 |                   |              |
| Japan            |                 | Russia            |              |
| USA              |                 |                   |              |
| ASTM             |                 | UNS standard      |              |
| ASTM B440 - 12   | ASTM B781 - 93a | ASTM B712 - 93    |              |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | hot rolled (hr)  | 1x drawn (1*dr) | 2x drawn (2*dr) |
| $\sigma_{F0}$ [MPa]                    |                 | 31.9           | 205.7            | 234.3           | 349.3           |
| A                                      |                 | 911.079        | 347.224          | 360.076         | 442.568         |
| Effect of temperature $K_{\theta}$     |                 |                |                  |                 |                 |
| $m_1$                                  |                 | -0.00394       |                  |                 |                 |
| Effect of strain $K_{\phi}$            |                 |                |                  |                 |                 |
| $m_2$                                  |                 | 0.52823        | 0.35044          | 0.26924         | 0.15602         |
| $m_4$                                  |                 | 0.00514        | 0.01602          | 0.00883         | 0.00297         |
| $m_5$                                  |                 | -0.00141       |                  |                 |                 |
| $m_7$                                  |                 | 0.40228        |                  |                 |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.05349          | 0.04427         | 0.04034         |
| $m_8$                                  |                 | 0.000281       |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                       |                 | 500..850       | 20..150          | 20..150         | 20..150         |
| $\phi$                                 |                 | 0.04...1.00    | 0.06...1.80      | 0.05...1.70     | 0.04...1.60     |
| $\dot{\phi}$ [1/s]                     |                 | 0.1...25       | 0.01...10        | 0.01...10       | 0.01...50       |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                   |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                               |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                         |



**Fig. 5.197** Flow stress curves of AgCdO<sub>10</sub> by hot and cold forming.

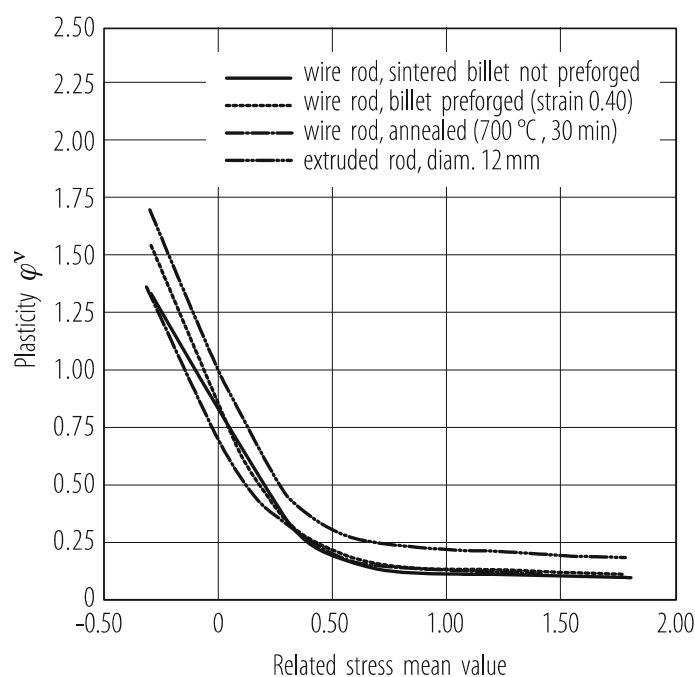
## Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |         |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|---------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$     | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| annealed          | 150. . . 170                    | 11.9440 | 0.69875 | 230. . . 280                        | 13.3346 | 0.56422 |
| annealed          |                                 |         |         | 230. . . 280                        | 44.6203 | 0.27872 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$   | $n_4$    |                            |
| annealed          | 26. . . 30                              | 17.3408 | 0.13804 | −3.4228  | <65                        |
| annealed          | 20. . . 30                              | 14.3826 | 0.0104  | −15.2815 | <85                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

## Plasticity in torsion test



**Fig. 5.198** Plasticity of AgCdO<sub>10</sub> as a function of the related stress mean value by 20°C.

## Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 295.0                |                    |                                         | 10200                       | 86              |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of Au<sub>99.99</sub>

## 5.13 Noble metals

### 5.13.2 Gold and Gold alloys

#### Designation

|             |         |                        |
|-------------|---------|------------------------|
| UNS number: | P 00020 | Chem. symbol: Au 99.99 |
|-------------|---------|------------------------|

#### Composition (EN) [Weight-%]

|       |    |
|-------|----|
| Au    | Ag |
| >99.9 |    |

#### International comparison of standards

| CAS number       |                 | DIN          |                |
|------------------|-----------------|--------------|----------------|
| CAS 7440-57-5    |                 | DIN 17860    | DIN 13972-2    |
| ISO              |                 | EN           |                |
| EN ISO 9001:2000 | EN ISO 17025    | DIN EN 12449 |                |
| Japan            |                 | Russia       |                |
|                  |                 | ZI 999       | GOST 6835 - 72 |
| USA              |                 |              |                |
| ASTM             |                 | UNS standard |                |
| ASTM B 562       | ASTM B 541 - 01 | P 00020      |                |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow stress

| State of material                       | Hot deformation |                | Cold deformation |                 |                 |
|-----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                         | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                     |                 |                | 178.5            |                 |                 |
| A                                       |                 |                | 293.577          |                 |                 |
| Effect of temperature $K_\theta$        |                 |                |                  |                 |                 |
| $m_1$                                   |                 |                |                  |                 |                 |
| Effect of strain $K_\varphi$            |                 |                |                  |                 |                 |
| $m_2$                                   |                 |                | 0.23905          |                 |                 |
| $m_4$                                   |                 |                | −00282           |                 |                 |
| $m_5$                                   |                 |                |                  |                 |                 |
| $m_7$                                   |                 |                |                  |                 |                 |
| Effect of strain rate $K_\dot{\varphi}$ |                 |                |                  |                 |                 |
| $m_3$                                   |                 |                | 0.03483          |                 |                 |
| $m_8$                                   |                 |                |                  |                 |                 |
| Range of validity                       |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                        |                 |                | 20               |                 |                 |
| $\varphi$                               |                 |                | 0.04 . . 1.60    |                 |                 |
| $\dot{\varphi}$ [1/s]                   |                 |                | 0.01 . . 50      |                 |                 |

|                                                                                    |
|------------------------------------------------------------------------------------|
| Cold deformation                                                                   |
| $\sigma_F = A \cdot \varphi^{m_2} \cdot e^{m_3/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.25), Chapter 2.3.2.2.2]                                               |
| [DOI: 978-3-642-14174-4_2]                                                         |

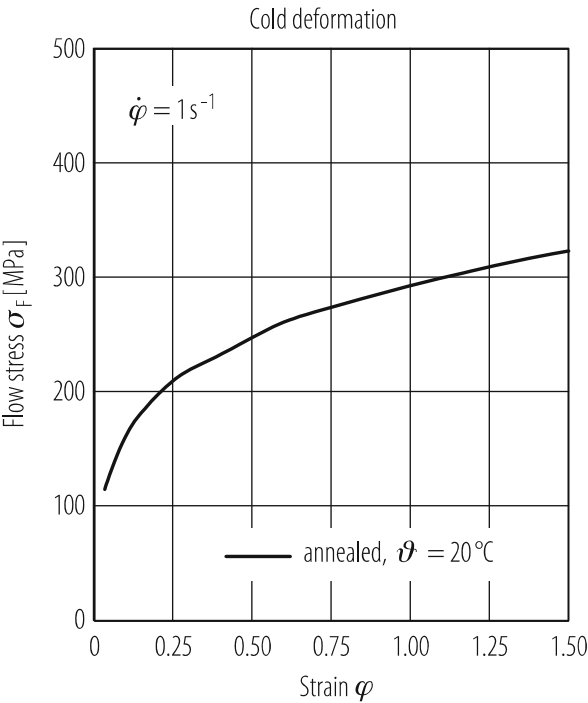


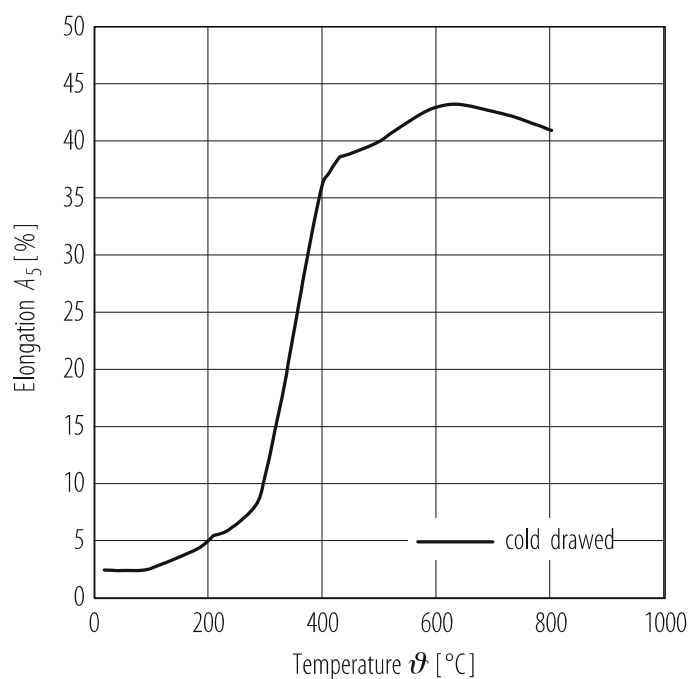
Fig. 5.199 Flow stress curves of Au99.9 cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |         |         | Tensile strength $\Delta R_m$ [MPa] |         |         |
|-------------------|---------------------------------|---------|---------|-------------------------------------|---------|---------|
|                   | $A_0$                           | $A$     | $n_1$   | $B_0$                               | $B$     | $n_2$   |
| soft annealed     | 50...60                         | 10.2829 | 0.65299 | 90...130                            | 10.0736 | 0.55925 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |          |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|----------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$    | $n_4$   |                            |
| soft annealed     | 45...38                                 | 73.6828 | −0.12354 | −.13646 | <70                        |

|                                         |                                         |                                                                   |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

**Plasticity in tensile test**

**Fig. 5.200** Plasticity of Au<sub>99.9</sub> as a function of the temperature. Initial test: deformed.

**Physical properties**

| Temperature<br>$\theta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                           | 317.4                                     | 130.0                                   | 14.15                                                                    | 19305.2                                | 82.5                         |
| 100                          | 311.1                                     | 130.3                                   | 14.32                                                                    | 19238.9                                |                              |
| 200                          | 303.6                                     | 130.8                                   | 14.51                                                                    | 19153.1                                |                              |
| 300                          | 296.4                                     | 131.5                                   |                                                                          | 19064.1                                |                              |
| 400                          | 289.6                                     | 132.3                                   | 14.96                                                                    | 18971.7                                | 72.0                         |
| 500                          | 283.2                                     | 133.4                                   |                                                                          | 18876.0                                |                              |
| 600                          | 277.1                                     | 134.6                                   | 15.49                                                                    | 18777.1                                |                              |
| 700                          | 271.4                                     | 135.9                                   |                                                                          | 18674.8                                |                              |
| 800                          | 266.0                                     | 137.5                                   | 16.12                                                                    | 18569.3                                | 56.0                         |
| 900                          | 261.0                                     | 139.2                                   |                                                                          | 18460.5                                |                              |
| 1000                         | 256.4                                     | 141.0                                   | 16.8                                                                     | 18348.4                                |                              |



## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A_5$               | elongation to fracture                                                |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $R_p$               | yield stress                                                          |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of AuAg<sub>32</sub>Cu<sub>5.5</sub>

## 5.13 Noble metals

### 5.13.2 Gold and Gold alloys

#### Designation

|             |               |                                                        |
|-------------|---------------|--------------------------------------------------------|
| UNS number: | <b>P00280</b> | Chem. symbol: <b>AuAg<sub>32</sub>Cu<sub>5.5</sub></b> |
|-------------|---------------|--------------------------------------------------------|

#### Composition [Weight-%]

|      |       |       |
|------|-------|-------|
| Au   | Ag    | Cu    |
| Bal. | ~32.0 | ~5.50 |

#### International comparison of standards

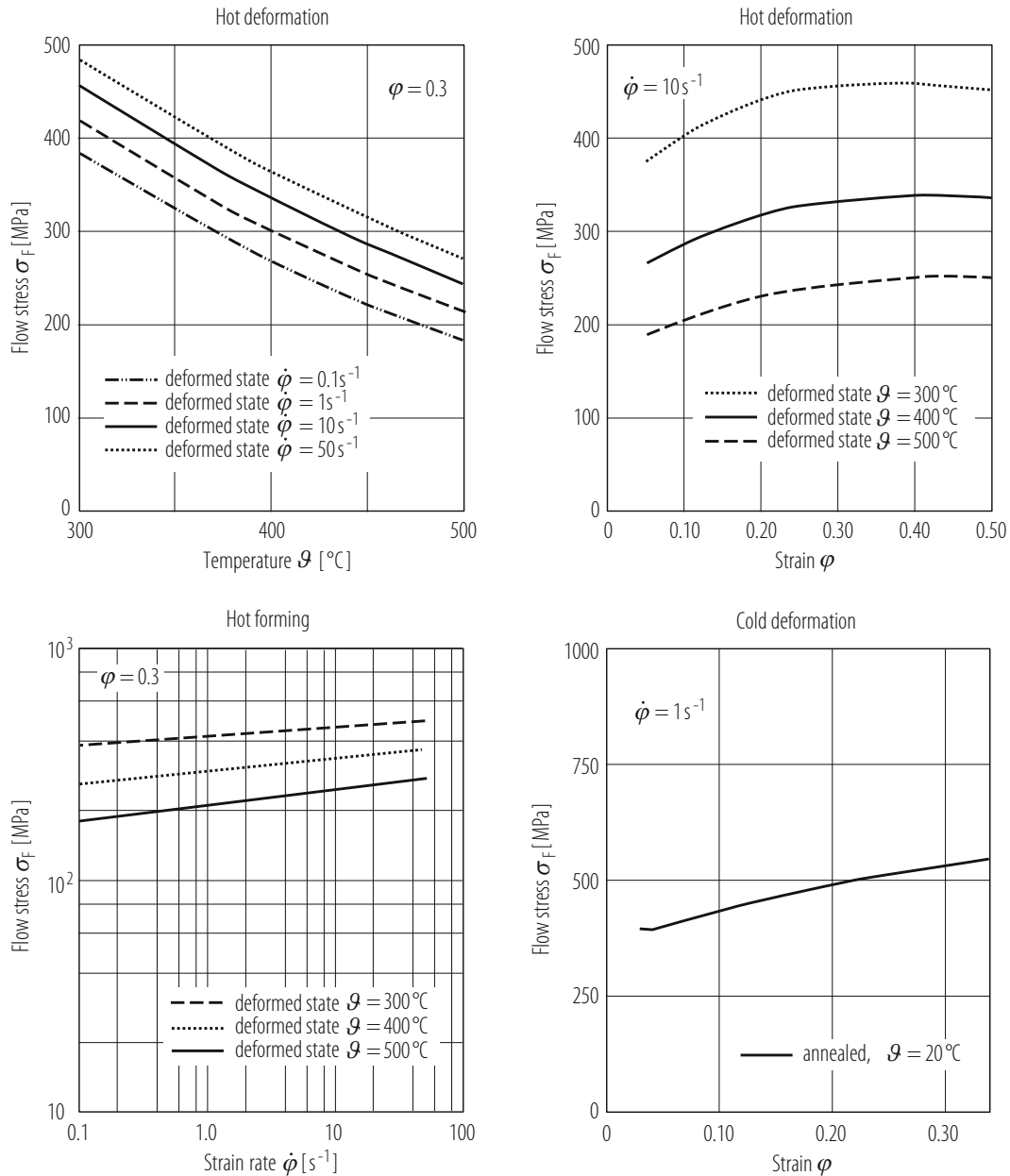
|                |                       |
|----------------|-----------------------|
| Euronorm       | ISO                   |
| France         | United Kingdom        |
| Japan          | Russia                |
| USA            |                       |
| ASTM           | UNS standard          |
| ASTM B477 - 97 | ASTM B476 - 01 P00280 |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                  | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]              |                 | (124,15)       | 476.1            |                 |                 |
| A                                |                 | 2361.400       | 704.494          |                 |                 |
| Effect of temperature $K_\theta$ |                 |                |                  |                 |                 |
| $m_1$                            |                 | -.00376        | -.00155          |                 |                 |
| Effect of strain $K_\phi$        |                 |                |                  |                 |                 |
| $m_2$                            |                 | 0.34021        | 0.22695          |                 |                 |
| $m_4$                            |                 | 0.01258        | 0.0076           |                 |                 |
| $m_5$                            |                 | 0.00129        |                  |                 |                 |
| $m_7$                            |                 | -.13173        |                  |                 |                 |
| Effect of strain rate $K_\phi$   |                 |                |                  |                 |                 |
| $m_3$                            |                 |                | 0.03722          |                 |                 |
| $m_8$                            |                 | 0.000126       |                  |                 |                 |
| Range of validity                |                 |                |                  |                 |                 |
| $\theta$ [°C]                    |                 | 300...500      | 20...250         |                 |                 |
| $\phi$                           |                 | 0.05...0.50    | 0.04...0.35      |                 |                 |
| $\dot{\phi}$ [1/s]               |                 | 0.1...50       | 1...50           |                 |                 |

| Hot deformation:                                                                                                                                                      | Cold deformation                                                                                        |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \theta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \theta}$ | $\sigma_F = A \cdot e^{m_1 \theta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                  | [Equation (2.25), Chapter 2.3.2.2.2]                                                                    |
| [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                                                                                 | [DOI: <a href="https://doi.org/10.1007/978-3-642-14174-4_2">978-3-642-14174-4_2</a> ]                   |



**Fig. 5.201** Flow stress curves of AuAg<sub>32</sub>Cu<sub>5.5</sub> by hot and cold forming.

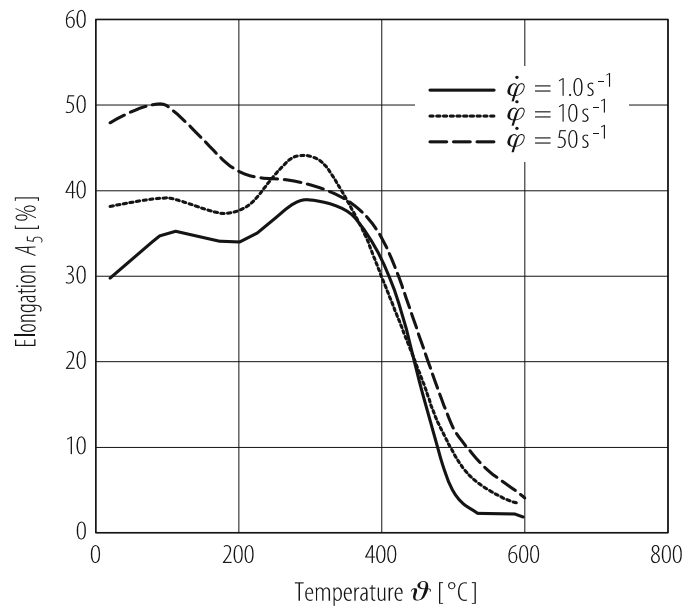
### Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |     |       | Vickers hardness $\Delta H_V$ |         |         |
|-------------------|---------------------------------|-----|-------|-------------------------------|---------|---------|
|                   | $A_0$                           | $A$ | $n_1$ | $B_0$                         | $B$     | $n_2$   |
| annealed          |                                 |     |       | 80...100                      | 17.2389 | 0.46369 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |          |         | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|----------|---------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$    | $n_4$   |                            |
| annealed          | 32...36                                 | 67.8819 | -0.15947 | -0.2841 | <75                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

### Plasticity in tensile test



**Fig. 5.202** Plasticity of AuAg<sub>32</sub>Cu<sub>5.5</sub> as a function of the temperature. Initial test: deformed.

### Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 54                   |                    |                                         | 14300                       |                 |

**Symbols and abbreviations**

| Short form          | Full form                                      |
|---------------------|------------------------------------------------|
| $\sigma_F$          | flow stress                                    |
| $\varphi$           | strain                                         |
| $\dot{\varphi}$     | strain rate                                    |
| $A_5$               | elongation to fracture                         |
| $A, B, C$ and $n_i$ | constants                                      |
| ASTM                | American society for testing and materials     |
| $c_{pm}$            | mean specific heat                             |
| $E$                 | Young's modulus                                |
| ISO                 | international organisation for standardization |
| $R_p$               | yield stress                                   |
| $T, \vartheta$      | temperature                                    |
| UNS                 | unified numbering system                       |
| $\Delta H_V$        | vickers hardness                               |
| $\alpha_m$          | average coefficient of linear expansion        |
| $\lambda$           | thermal conductivity                           |
| $\rho$              | density                                        |

# Flow stress, mechanical and physical properties of Pt<sub>99.99</sub>

## 5.13 Noble metals

### 5.13.3 Platinum and Platinum alloys

#### Designation

|             |        |                        |
|-------------|--------|------------------------|
| UNS number: | PO4995 | Chem. symbol: Pt 99.99 |
|-------------|--------|------------------------|

#### Composition (EN) [Weight-%]

|        |
|--------|
| Pt     |
| >99.99 |

#### International comparison of standards

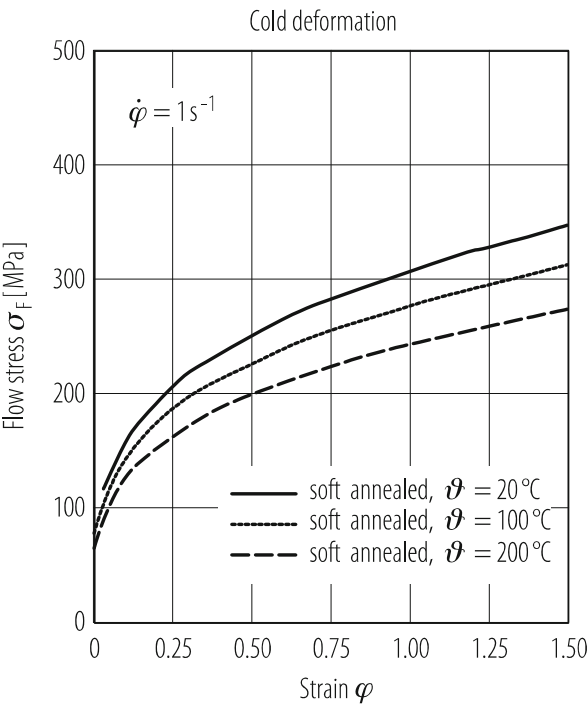
| Euronorm        |                | ISO             |             |
|-----------------|----------------|-----------------|-------------|
| EN 60751        |                | EN ISO 9001     | EN ISO14001 |
| CAS number      |                | DIN             |             |
| 7440-06-4       |                | DIN 43760       |             |
| Japan           |                | Russia          |             |
| USA             |                | UNS standard    |             |
| ASTM            |                | ASTM E2593 - 12 | PO4995      |
| ASTM E1159 - 98 | ASTM B561 - 94 |                 |             |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                      | Hot deformation |                | Cold deformation   |                 |                 |
|----------------------------------------|-----------------|----------------|--------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | soft annealed (sa) | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 |                | 172.76             |                 |                 |
| A                                      |                 |                | 315.989            |                 |                 |
| Effect of temperature $K_{\theta}$     |                 |                |                    |                 |                 |
| $m_1$                                  |                 |                | -0.00132           |                 |                 |
| Effect of strain $K_{\phi}$            |                 |                |                    |                 |                 |
| $m_2$                                  |                 |                | 0.28913            |                 |                 |
| $m_4$                                  |                 |                | 0.00124            |                 |                 |
| $m_5$                                  |                 |                |                    |                 |                 |
| $m_7$                                  |                 |                |                    |                 |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                    |                 |                 |
| $m_3$                                  |                 |                | 0.0325             |                 |                 |
| $m_8$                                  |                 |                |                    |                 |                 |
| Range of validity                      |                 |                |                    |                 |                 |
| $\vartheta$ [°C]                       |                 |                | 20 ... 150         |                 |                 |
| $\phi$                                 |                 |                | 0.03 ... 2.0       |                 |                 |
| $\dot{\phi}$ [1/s]                     |                 |                | 0.01 ... 100       |                 |                 |

|                                                                                                            |
|------------------------------------------------------------------------------------------------------------|
| Cold deformation                                                                                           |
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.25), Chapter 2.3.2.2.2]                                                                       |
| [DOI: 978-3-642-14174-4_2]                                                                                 |



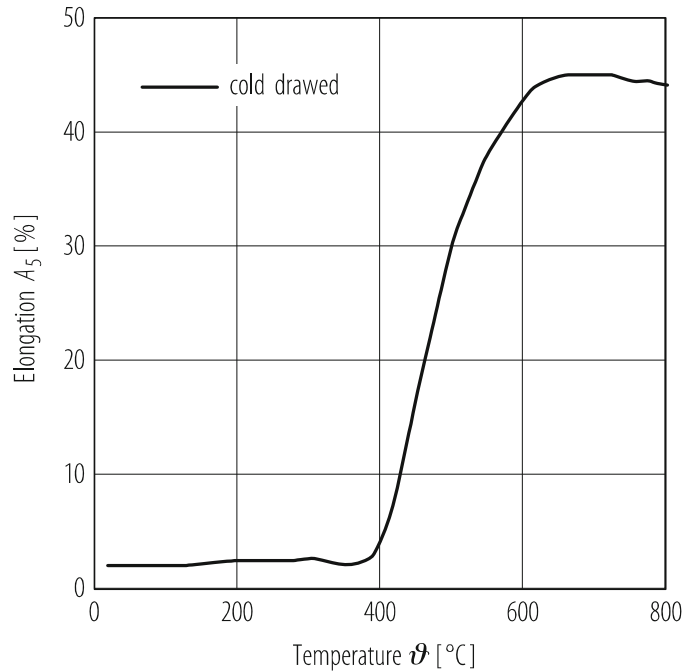
**Fig. 5.203** Flow stress curves of Pt99.99 by cold forming.

**Mechanical properties after cold deformation**

| State of material | Yield stress $\Delta R_p$ [MPa] |         |         | Tensile strength $\Delta R_m$ [MPa] |        |         |
|-------------------|---------------------------------|---------|---------|-------------------------------------|--------|---------|
|                   | $A_0$                           | $A$     | $n_1$   | $B_0$                               | $B$    | $n_2$   |
| annealed          | 50...70                         | 18.7535 | 0.64902 | 140...170                           | 5.4463 | 0.86452 |
| hardened          | 125...160                       | 24.6824 | 0.59664 | 230...270                           | 8.4453 | 0.74509 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$   | $n_4$    |                            |
| annealed          | 47...52                                 | 49.0912 | 0.00584 | −7.55578 | <80                        |
| hardened          |                                         |         |         |          |                            |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

**Plasticity in tensile test****Fig. 5.204** Plasticity of Pt<sub>99.99</sub> as a function of the temperature.**Physical properties**

| Temperature<br>$\theta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                           | 71.6                                      | 132.7                                   | 8.95                                                                     | 21506.6                                | 170                          |
| 100                          | 71.8                                      | 133.8                                   | 9.1                                                                      | 21445.4                                |                              |
| 200                          | 72.3                                      | 135.0                                   | 9.2                                                                      | 21370.5                                |                              |
| 300                          | 73.1                                      | 136.3                                   |                                                                          | 21297.3                                |                              |
| 400                          | 74.1                                      | 137.7                                   | 9.45                                                                     | 21225.9                                |                              |
| 500                          | 75.5                                      | 139.0                                   |                                                                          | 21156.2                                |                              |
| 600                          | 77.1                                      | 140.4                                   | 9.65                                                                     | 21088.2                                |                              |
| 700                          | 79.0                                      | 141.7                                   |                                                                          | 21021.9                                |                              |
| 800                          | 81.2                                      | 143.1                                   | 9.9                                                                      | 20957.4                                |                              |
| 900                          | 83.7                                      | 144.4                                   |                                                                          | 20894.6                                |                              |
| 1000                         | 86.4                                      | 145.8                                   | 10.15                                                                    | 20833.5                                |                              |

**Symbols and abbreviations**

| Short form          | Full form                                  |
|---------------------|--------------------------------------------|
| $\sigma_F$          | flow stress                                |
| $\varphi$           | strain                                     |
| $\dot{\varphi}$     | strain rate                                |
| $A_5$               | elongation to fracture                     |
| $A, B, C$ and $n_i$ | constants                                  |
| ASTM                | American society for testing and materials |
| CAS                 | chemical abstracts service                 |

(continued)



| Short form     | Full form                                                             |
|----------------|-----------------------------------------------------------------------|
| $c_{pm}$       | mean specific heat                                                    |
| DIN            | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$            | Young's modulus                                                       |
| EN             | Euronorm                                                              |
| ISO            | international organisation for standardization                        |
| $R_m$          | tensile strength                                                      |
| $R_p$          | yield stress                                                          |
| $T, \vartheta$ | temperature                                                           |
| UNS            | unified numbering system                                              |
| $\alpha_m$     | average coefficient of linear expansion                               |
| $\lambda$      | thermal conductivity                                                  |
| $\rho$         | density                                                               |

# Flow stress, mechanical and physical properties of PtRh<sub>10</sub>

## 5.13 Noble metals

### 5.13.3 Platinum and Platinum alloys

#### Designation

|             |                             |
|-------------|-----------------------------|
| UNS number: | Chem. symbol: <b>PtRh10</b> |
|-------------|-----------------------------|

#### Composition (EN) [Weight-%]

|     |     |
|-----|-----|
| Pt  | Rh  |
| ~90 | ~10 |

#### International comparison of standards

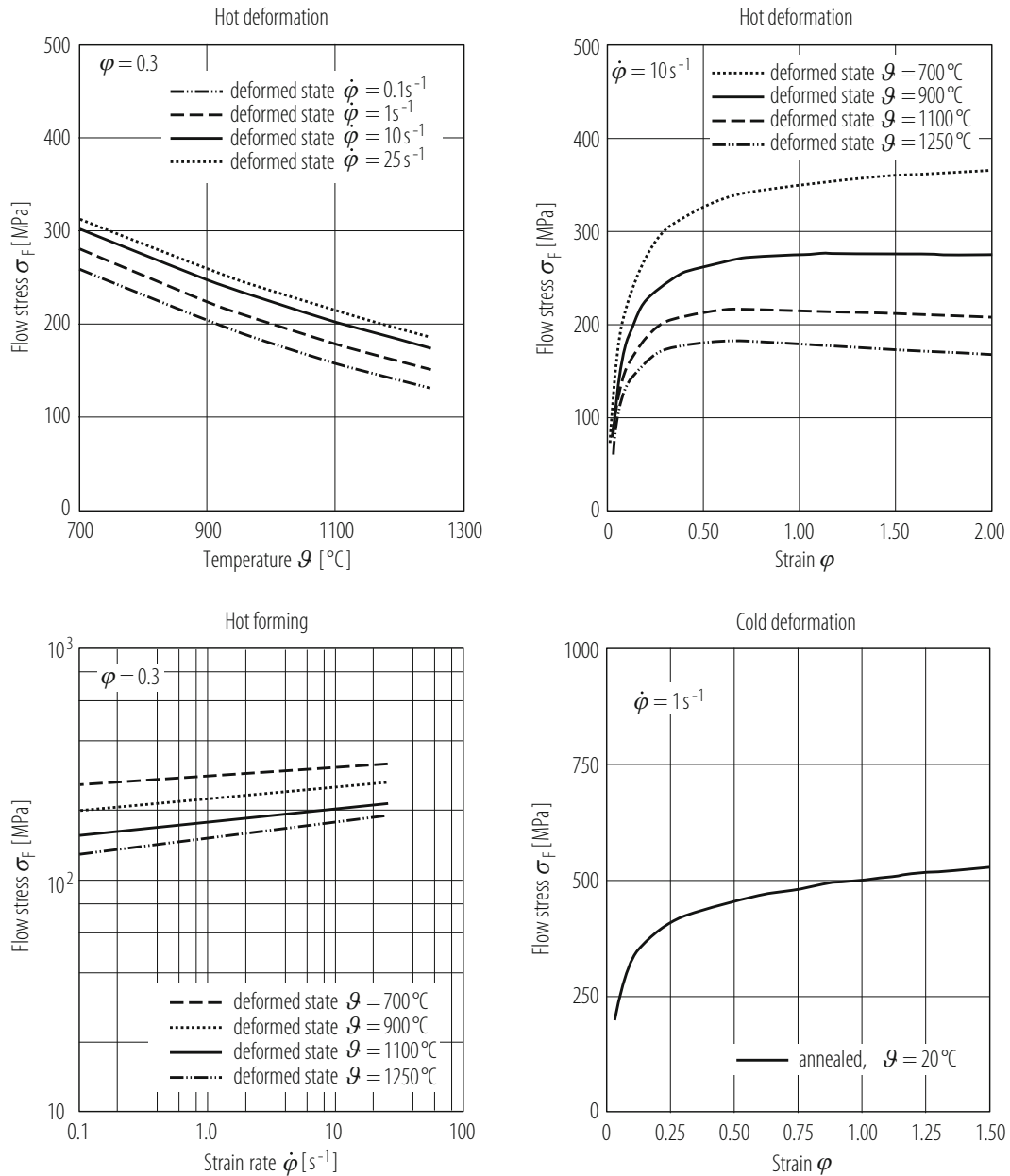
|                          |                 |            |
|--------------------------|-----------------|------------|
| Euronorm                 | DIN             |            |
| EN 60584                 | DIN 43 729      | DIN 43 710 |
| ISO                      | United Kingdom  |            |
| EN ISO 9001:2000         |                 |            |
| Japan                    | Russia          |            |
|                          | GOST 988        | GOST 8-585 |
| USA                      |                 |            |
| ASTM                     | UNS standard    |            |
| ASTM 988                 | ASTM E220 - 07  |            |
| ASTM E2181 / E2181M - 11 | ASTM E1159 - 98 |            |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

| State of material                    | Hot deformation |                | Cold deformation |                 |                 |
|--------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                      | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                  |                 | 167.1          | 363.7            |                 |                 |
| A                                    |                 | 806.787        | 509.721          |                 |                 |
| Effect of temperature $K_\theta$     |                 |                |                  |                 |                 |
| $m_1$                                |                 | −0.00099       |                  |                 |                 |
| Effect of strain $K_\phi$            |                 |                |                  |                 |                 |
| $m_2$                                |                 | 0.17908        | 0.11334          |                 |                 |
| $m_4$                                |                 | −0.02471       | −0.01622         |                 |                 |
| $m_5$                                |                 | −0.00049       |                  |                 |                 |
| $m_7$                                |                 | 0.04155        |                  |                 |                 |
| Effect of strain rate $K_\dot{\phi}$ |                 |                |                  |                 |                 |
| $m_3$                                |                 |                | 0.0372           |                 |                 |
| $m_8$                                |                 | 0.000051       |                  |                 |                 |
| Range of validity                    |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                     |                 | 700...1250     | 20               |                 |                 |
| $\phi$                               |                 | 0.10...2.00    | 0.04...1.60      |                 |                 |
| $\dot{\phi}$ [1/s]                   |                 | 0.1...25       | 0.1...10         |                 |                 |

| Hot deformation:                                                                                                                                                               | Cold deformation                                                                   |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| $\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1 + \varphi)^{m_5 \vartheta} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8 \vartheta}$ | $\sigma_F = A \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.10), Chapter 2.3.2.1.1]                                                                                                                                           | [Equation (2.25), Chapter 2.3.2.2.2]                                               |
| [DOI: 978-3-642-14174-4_2]                                                                                                                                                     | [DOI: 978-3-642-14174-4_2]                                                         |



**Fig. 5.205** Flow stress curves of PtRh<sub>10</sub> by hot and cold forming.

Mechanical properties after cold deformation

| State of material | Tensile strength $\Delta R_m$ [MPa] |         |         | Validity $\varepsilon$ [%] |
|-------------------|-------------------------------------|---------|---------|----------------------------|
|                   | $B_0$                               | $B$     | $n_2$   |                            |
| annealed          | 250...300                           | 14.3239 | 0.60118 | <60                        |

|                                         |
|-----------------------------------------|
| Tensile strength:                       |
| $R_m = B_0 + B \cdot \varepsilon^{n_2}$ |
| [Equation (4.2), Chapter 5.1.4]         |
| [DOI: 978-3-642-14174-4_5]              |

Plasticity in tensile test

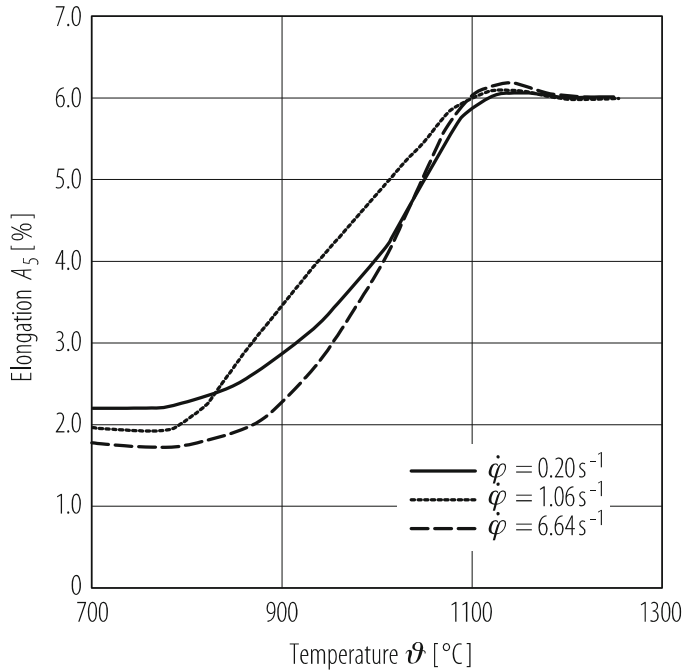


Fig. 5.206 Hot plasticity of PtRh10 as a function of the temperature and deformation rate.

Physical properties

| Temperature      | Thermal conductivity | Mean specific heat | Average coefficient of linear expansion | Density                     | Young's-modulus |
|------------------|----------------------|--------------------|-----------------------------------------|-----------------------------|-----------------|
| $\vartheta$ [°C] | $\lambda$ [W/m·K]    | $c_{pm}$ [J/kg·K]  | $\alpha_m$ [ $10^{-6}$ /K]              | $\rho$ [kg/m <sup>3</sup> ] | $E$ [GPa]       |
| 20               | 30.0                 |                    |                                         | 20600                       | 170             |
| 100              |                      |                    | 9.07                                    | 19960                       |                 |
| 200              |                      |                    | 8.97                                    | 19900                       |                 |
| 300              |                      |                    | 8.85                                    | 19850                       |                 |
| 400              |                      |                    | 8.93                                    | 19800                       |                 |
| 500              |                      |                    | 9.19                                    | 19740                       |                 |
| 600              |                      |                    | 9.28                                    | 19680                       |                 |
| 700              |                      |                    | 9.56                                    | 19610                       |                 |
| 800              |                      |                    | 9.68                                    | 19550                       |                 |
| 900              |                      |                    | 9.88                                    | 19490                       |                 |
| 1000             |                      |                    |                                         | 19420                       |                 |

## Symbols and abbreviations

| Short form          | Full form                                                             |
|---------------------|-----------------------------------------------------------------------|
| $\sigma_F$          | flow stress                                                           |
| $\varphi$           | strain                                                                |
| $\dot{\varphi}$     | strain rate                                                           |
| $A, B, C$ and $n_i$ | constants                                                             |
| ASTM                | American society for testing and materials                            |
| $c_{pm}$            | mean specific heat                                                    |
| DIN                 | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$                 | Young's modulus                                                       |
| EN                  | Euronorm                                                              |
| GOST                | gosudarstvennyy standart (state standard)                             |
| ISO                 | international organisation for standardization                        |
| $R_m$               | tensile strength                                                      |
| $T, \vartheta$      | temperature                                                           |
| UNS                 | unified numbering system                                              |
| $\alpha_m$          | average coefficient of linear expansion                               |
| $\lambda$           | thermal conductivity                                                  |
| $\rho$              | density                                                               |

# Flow stress, mechanical and physical properties of PtIr<sub>10</sub>

## 5.13 Noble metals

### 5.13.3 Platinum and Platinum alloys

#### Designation

|             |                             |
|-------------|-----------------------------|
| UNS number: | Chem. symbol: <b>PtIr10</b> |
|-------------|-----------------------------|

#### Composition (EN) [Weight-%]

|     |     |
|-----|-----|
| Pt  | Ir  |
| ~90 | ~10 |

#### International comparison of standards

|                      |                |
|----------------------|----------------|
| Euronorm             | DIN            |
| EN 9001              | EN ISO 14001   |
| ISO                  | United Kingdom |
| EN ISO 9001:2000     | ISO 14001      |
| Japan                | Russia         |
| USA                  |                |
| ASTM                 | UNS standard   |
| ASTM B684 - 97(2012) |                |

It should be noted that the chemical composition according to the standard applied in the table is not identical in all other national standards

#### Flow curves

|                                        | Hot deformation |                | Cold deformation |                 |                 |
|----------------------------------------|-----------------|----------------|------------------|-----------------|-----------------|
|                                        | cast state      | deformed state | annealed (an)    | hot rolled (hr) | cold drawn (cd) |
| $\sigma_{F0}$ [MPa]                    |                 |                | 520.0            |                 |                 |
| A                                      |                 |                | 680.453          |                 |                 |
| Effect of temperature $K_\theta$       |                 |                |                  |                 |                 |
| $m_1$                                  |                 |                |                  |                 |                 |
| Effect of strain $K_\phi$              |                 |                |                  |                 |                 |
| $m_2$                                  |                 |                | 0.17692          |                 |                 |
| $m_4$                                  |                 |                | 0.0066           |                 |                 |
| $m_5$                                  |                 |                |                  |                 |                 |
| $m_7$                                  |                 |                |                  |                 |                 |
| Effect of strain rate $K_{\dot{\phi}}$ |                 |                |                  |                 |                 |
| $m_3$                                  |                 |                | 0.03149          |                 |                 |
| $m_8$                                  |                 |                |                  |                 |                 |
| Range of validity                      |                 |                |                  |                 |                 |
| $\vartheta$ [°C]                       |                 |                | 20               |                 |                 |
| $\phi$                                 |                 |                | 0.04...1.60      |                 |                 |
| $\dot{\phi}$ [1/s]                     |                 |                | 0.01...50        |                 |                 |

|                                                                                    |
|------------------------------------------------------------------------------------|
| Cold deformation                                                                   |
| $\sigma_F = A \cdot \varphi^{m_2} \cdot e^{m_3/\varphi} \cdot \dot{\varphi}^{m_3}$ |
| [Equation (2.25), Chapter 2.3.2.2.2]                                               |
| [DOI: 978-3-642-14174-4_2]                                                         |

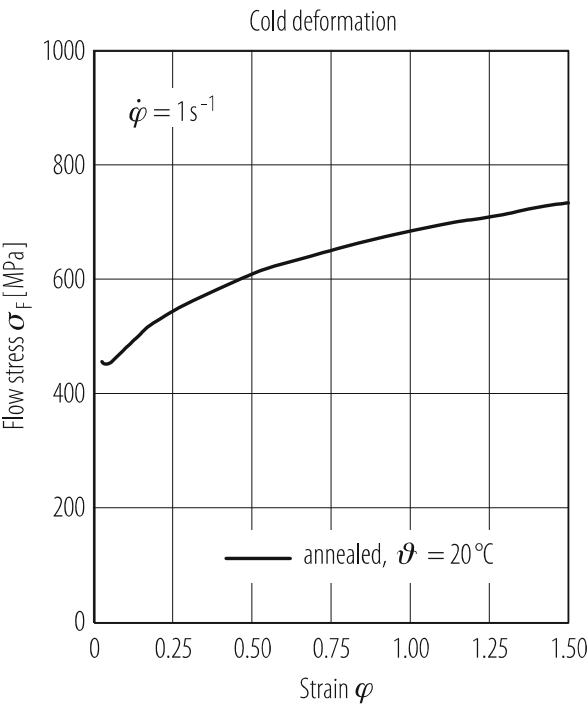


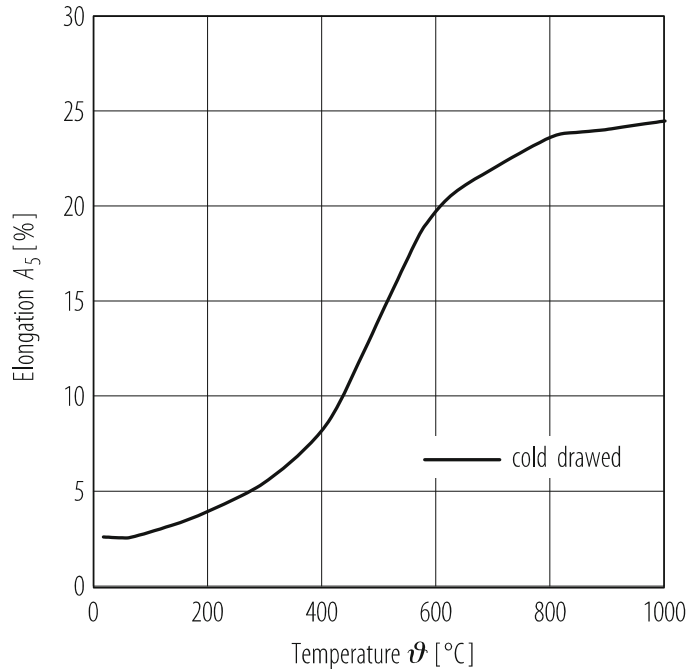
Fig. 5.207 Flow stress curves of PtIr10 by cold forming.

Mechanical properties after cold deformation

| State of material | Yield stress $\Delta R_p$ [MPa] |        |         | Tensile strength $\Delta R_m$ [MPa] |        |         |
|-------------------|---------------------------------|--------|---------|-------------------------------------|--------|---------|
|                   | $A_0$                           | $A$    | $n_1$   | $B_0$                               | $B$    | $n_2$   |
| annealed          | 270...310                       | 5.7823 | 0.92131 | 330...360                           | 5.7688 | 0.85525 |

| State of material | Elongation to fracture $\Delta A_5$ [%] |         |         |          | Validity $\varepsilon$ [%] |
|-------------------|-----------------------------------------|---------|---------|----------|----------------------------|
|                   | $C_0$                                   | $C$     | $n_3$   | $n_4$    |                            |
| annealed          | 25...30                                 | 21.3668 | 0.03075 | −5.92385 | <80                        |

| Yield stress:                           | Tensile strength:                       | Elongation to fracture                                            |
|-----------------------------------------|-----------------------------------------|-------------------------------------------------------------------|
| $R_p = A_0 + A \cdot \varepsilon^{n_1}$ | $R_m = B_0 + B \cdot \varepsilon^{n_2}$ | $A_5 = C_0 - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}$ |
| [Equation (4.1), Chapter 5.1.4]         | [Equation (4.2), Chapter 5.1.4]         | [Equation (4.3), Chapter 5.1.4]                                   |
| [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]              | [DOI: 978-3-642-14174-4_5]                                        |

**Plasticity in tensile test****Fig. 5.208** Plasticity of PtIr<sub>10</sub> as a function of the temperature.**Physical properties**

| Temperature<br>$\theta$ [°C] | Thermal conductivity<br>$\lambda$ [W/m·K] | Mean specific heat<br>$c_{pm}$ [J/kg·K] | Average coefficient<br>of linear expansion<br>$\alpha_m$ [ $10^{-6}$ /K] | Density<br>$\rho$ [kg/m <sup>3</sup> ] | Young's-modulus<br>$E$ [GPa] |
|------------------------------|-------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------|----------------------------------------|------------------------------|
| 20                           | 29.0                                      | 133.0                                   |                                                                          | 21450                                  | 220                          |
| 100                          |                                           |                                         | 8.70                                                                     | 21400                                  |                              |
| 200                          |                                           |                                         | 9.10                                                                     | 21640                                  |                              |
| 300                          |                                           |                                         | 9.40                                                                     | 21280                                  |                              |
| 400                          |                                           |                                         | 9.50                                                                     | 21220                                  |                              |
| 500                          |                                           |                                         | 9.60                                                                     | 21160                                  |                              |
| 600                          |                                           |                                         | 9.60                                                                     | 21100                                  |                              |
| 700                          |                                           |                                         | 9.90                                                                     | 21020                                  |                              |
| 800                          |                                           |                                         | 10.0                                                                     | 20960                                  |                              |
| 900                          |                                           |                                         | 10.1                                                                     | 20890                                  |                              |
| 1000                         |                                           |                                         | 10.3                                                                     | 20810                                  |                              |
| 1200                         |                                           |                                         | 10.6                                                                     | 20660                                  |                              |
| 1400                         |                                           |                                         | 11.0                                                                     | 20500                                  |                              |

**Symbols and abbreviations**

| Short form          | Full form                                  |
|---------------------|--------------------------------------------|
| $\sigma_F$          | flow stress                                |
| $\varphi$           | strain                                     |
| $\dot{\varphi}$     | strain rate                                |
| $A_5$               | elongation to fracture                     |
| $A, B, C$ and $n_i$ | constants                                  |
| ASTM                | American society for testing and materials |
| $c_{pm}$            | mean specific heat                         |

(continued)



| Short form     | Full form                                                             |
|----------------|-----------------------------------------------------------------------|
| DIN            | German institute for standardisation (Deutsches Institut Für Normung) |
| $E$            | Young's modulus                                                       |
| EN             | Euronorm                                                              |
| ISO            | international organisation for standardization                        |
| $R_m$          | tensile strength                                                      |
| $R_p$          | yield stress                                                          |
| $T, \vartheta$ | temperature                                                           |
| UNS            | unified numbering system                                              |
| $\alpha_m$     | average coefficient of linear expansion                               |
| $\lambda$      | thermal conductivity                                                  |
| $\rho$         | density                                                               |