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Metal Forming Data

Part 1
Ferrous Alloys

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Part 1

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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 steels 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 steel grades 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 170 steel grades 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

VIII/C1 Metal Forming Data

Part 1: Ferrous Alloys

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Deformation behaviour of steels

Non-alloy, alloy quality and special steels

Material number	Symbol	Page in Book
1.0038	S235JRG2	87
1.0128	S275JRC	91
1.0300	C4D	95
1.0301	C10	99
1.0332	DD11	103
1.0335	DD13	108
1.0338	DC04	112
1.0401	C15	116
1.0402	C22	120
1.0429	L290MB	125
1.0445	H300BD	129
1.0481	P295GH	133
1.0489	H280LA	137
1.0501	C35	141
1.0503	C45	146
1.0518	C56D	151
1.0528	C30	155
1.0535	C55	159
1.0570	S355J2G3	163
1.0586	C50D	167
1.0601	C60	171
1.0603	C67	175
1.0605	C75	179
1.0615	C70D	183
1.0616	C86D	187
1.0620	C78D	192
1.0715	11SMn30	196
1.0718	11SMnPb30	200

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Material number	Symbol	Page in Book
1.0721	10S20	204
1.0810	M 350-50A	208
1.0815	M 700-50A	212
1.0873	DC06	217
1.0974	S340M	221
1.0977	S355NC	225
1.0978	S380MC	229
1.0980	S420MC	233
1.0982	S460MC	237
1.1154	C42D2	241
1.1159	G46Mn4	246
1.1167	36Mn5	250
1.1242	C72D2	254
1.1274	C100S	258
1.1545	C105U	263
1.1555	C120U	267

Tool steels, wear resistant steels and bearing steels

Material number	Symbol	Page in Book
1.2063	145CrV6	272
1.2080	X210Cr12	276
1.2108	90CrSi5	280
1.2208	31CrV2	284
1.2235	80CrV2	288
1.2344	X40CrMoV5-1	292
1.2360	X50CrMoV8-1-1	296
1.2363	X100CrMoV5-1	300
1.2365	X32CrMoV3-3	304
1.2419	105WCr6	308
1.2436	X210CrW12	312
1.2516	120WV4	316
1.2549	50WCrV8	320
1.2562	142WV13	324
1.2581	X30WCrV9-3	328

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Material number	Symbol	Page in Book
1.2601	X165CrMoV12	332
1.2713	55NiCrMoV6	336
1.2764	X19NiCrMo4	340
1.2767	X45NiCrMo4	344
1.3207	S10-4-3-10	348
1.3243	S6-5-2-5	352
1.3247	HS2-9-1-8	356
1.3318	S12-1-2	360
1.3333	S3-3-2	364
1.3343	S6-5-2	368
1.3355	S18-0-1	372
1.3401	X120Mn12	376
1.3505	100Cr6	380

Stainless steels

Material number	Symbol	Page in Book
1.3964	X2CrNiMnMoNNb-21-16-5-3	384
1.4001	X7Cr14	388
1.4006	X12Cr13	392
1.4017	X6CrNi17-1	396
1.4021	X20Cr13	400
1.4034	X46Cr13	404
1.4104	X14CrMoS17	408
1.4112	X90CrMoV18	412
1.4116	X50CrMoV15	416
1.4301	X5CrNi18-10	420
1.4305	X10CrNiS18-9	424
1.4306	X2CrNi19-11	428
1.4310	X10CrNi18-8	432
1.4331	X2CrNi21-10	436
1.4401	X5CrNiMo17-12-2	440
1.4403	X5CrNiMo19-11	444
1.4404	X2CrNiMo17-12-2	448
1.4406	X2CrNiMoN17-11-2	452

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Material number	Symbol	Page in Book
1.4418	X4CrNiMo16-5-1	456
1.4429	X2CrNiMoN17-13-	460
1.4430	X2CrNiMo19-12	464
1.4439	X2CrNiMoN17-13-3	468
1.4462	X2CrNiMoN22-5-3	473
1.4506	X5NiCrMoCuTi20-18	477
1.4510	X3CrTi17	481
1.4512	X2CrTi12	485
1.4541	X6CrNiTi18-10	489
1.4548	X5CrNiCuNb17-4-4	494
1.4556	X2CrNiNb24-12	498
1.4567	X3CrNiCu18-9	502
1.4568	X7CrNiAl17-7	506
1.4571	X6CrNiMoTi17-12-2	510
1.4576	X5CrNiMoNb19-12	515

Heat resistant and high-temperature resisting steels

Material number	Symbol	Page in Book
1.4713	X10CrAlSi7	519
1.4718	X45CrSi9-3	523
1.4724	X10CrAlSi13	527
1.4742	X10CrAlSi18	531
1.4762	X10CrAlSi24	535
1.4767	CrAl20-5	539
1.4820	X12CrNi26-5	543
1.4821	X15CrNiSi25-4	547
1.4828	X15CrNiSi20-12	551
1.4829	X12CrNi22-12	555
1.4841	X15CrNiSi25-21	559
1.4845	X12CrNi25-21	563
1.4864	X12CrNiSi35-16	567
1.4871	X53CrMnNiN21-9	571
1.4873	X45CrNiW18-9	575
1.4876	X10CrNiTiAl32-21	579

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Material number	Symbol	Page in Book
1.4903	X10CrMoVNb9-1	583
1.4923	X22CrMoV12-1	587
1.4941	X6CrNiTiB18-10	591
1.4986	X7CrNiMoBNb16-16	595

Alloy special steels: High strength weldable structural steels

Material number	Symbol	Page in Book
1.8902	S420N	771
1.8925	S890QL1	775
1.8970	L385H	779
1.8972	L415MB	783
1.8977	L485MB	787
1.8988	S690QL1	791

Alloy special steels: Structural steels

Material number	Symbol	Page in Book
1.5021	48Si7	599
1.5024	46Si7	603
1.5026	56Si7	607
1.5112	10MnSi5	611
1.5122	37MnSi5	615
1.5217	20MnV6	619
1.5223	42MnV7	623
1.5231	38MnSiVS5	627
1.5415	16Mo3	631
1.5528	22MnB5	635
1.5662	X8Ni9	639
1.5714	16NiCr4	643
1.5752	15NiCr13	647
1.5918	17CrNi6-6	651
1.6358	X2NiCoMo18-9-5	655
1.6368	15NiCuMoNb5	659
1.6545	30NiCrMo2-2	663

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Material number	Symbol	Page in Book
1.6582	GS-34CrNiMo6	667
1.6587	18CrNiMo7-6	671
1.7016	17Cr3	675
1.7033	34Cr4	679
1.7035	41Cr4	683
1.7103	67SiCr5	687
1.7106	56SiCr7	691
1.7108	60SiCr5	695
1.7321	20MoCr4	723
1.7131	16MnCr5	699
1.7147	20MnCr5	703
1.7218	25CrMo4	707
1.7220	34CrMo4	711
1.7225	42CrMo4	715
1.7264	20MoCr5	719
1.7335	13CrMo4-5	727
1.7380	10CrMo9-10	731
1.7389	GX12CrMo10-1	735
1.7390	X15CrMo5-1	739
1.7707	30CrMoV9	743
1.7715	14MoV6-3	747
1.7779	20CrMoV13-5	751
1.7950	10MnCrMoV5-5-5-2	755
1.8075	10CrSiMoV7	759
1.8159	51CrV4	763
1.8550	34CrAlNi7	767

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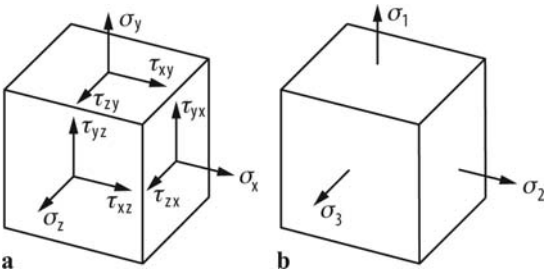
1 Deformation behaviour of steel

Introduction and Definitions

1.1 Flow stress

For a precise characterization of deformation processes, the mechanical stress in the deformation zone is assigned to the directions of a three-dimensional cartesian coordinate system. At the sectional planes of each direction x, y and z, one normal stress component, for example σ_x in the case of the yz-plane, and two shear stresses, for example τ_{zx} and τ_{yx} in the case of the yz-plane, occur (Fig. 1.1a). If the coordinates are chosen parallel to the directions of the largest normal stresses, the stress state can be solely described by the normal stress parameters, as the values of the shear stresses are now zero. In this case the normal stresses σ_1, σ_2 and σ_3 are called principal stresses (Fig. 1.1b). Depending on the principal stress values, stresses can be positive (tensile stress) or negative (compression stress).

Fig. 1.1.
(a) Normal stresses σ and shear stresses τ in a coordinate system at any position. (b) Main stresses in a coordinate system with axes parallel to the main axes.



According to Tresca's material flow hypothesis, a plastic flow (i.e. the beginning of the deformation process) occurs if a certain difference (stress gap) exists between the strongest and the smallest principal stress ($\sigma_1 > \sigma_2 > \sigma_3$) [1.1]:

$$\sigma_1 - \sigma_3 =: \sigma_F. \tag{1.1}$$

σ_F is the flow stress, a very important material parameter at deformation processes. Tresca's flow conjecture says that it is irrelevant whether the plastic flow is caused by compression or tensile stresses, as long as a stress gap $\sigma_F \neq 0$ exists.

The influence of the midrange principal stress σ_2 on the flow stress σ_F is generally not considered. Yet, according to investigations of Lode [1.2], von Mises [1.3], Roš and Eichinger [1.4] such an influence exists in reality, and it is incorporated into the deformation energy hypotheses. According to von Mises [1.3], Huber [1.5] and Hencky [1.6] the flow stress σ_F is then given as

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$$\sigma_F = \sqrt{\frac{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)}{2}}, \tag{1.2}$$

which in the case of principal normal stresses σ_1, σ_2 and σ_3 leads to

$$\sigma_F = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}. \tag{1.2a}$$

Lode [1.2, 1.7] considered the influence of the midrange principal stress σ_2 by

$$\sigma_1 - \sigma_3 =: n_\gamma \sigma_F, \tag{1.3}$$

with n_γ an auxiliary parameter that contains σ_2 by

$$n_\gamma = \frac{2}{\sqrt{3 + \upsilon^2}}, \qquad \upsilon = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3} = \pm \left| \frac{\sigma_2 - \frac{\sigma_1 + \sigma_3}{2}}{\frac{\sigma_1 - \sigma_3}{2}} \right|. \tag{1.4}$$

At uniaxial strain υ has the value ± 1 (flow condition according to Tresca). It can be easily calculated that the Lohe conditions comply with the flow condition according to von Mises for every σ_2. For hot and cold strip rolling, σ_2 was found to be the arithmetic mean value of the two other principal stresses σ_1 and σ_3. Thus the flow stress has a value of

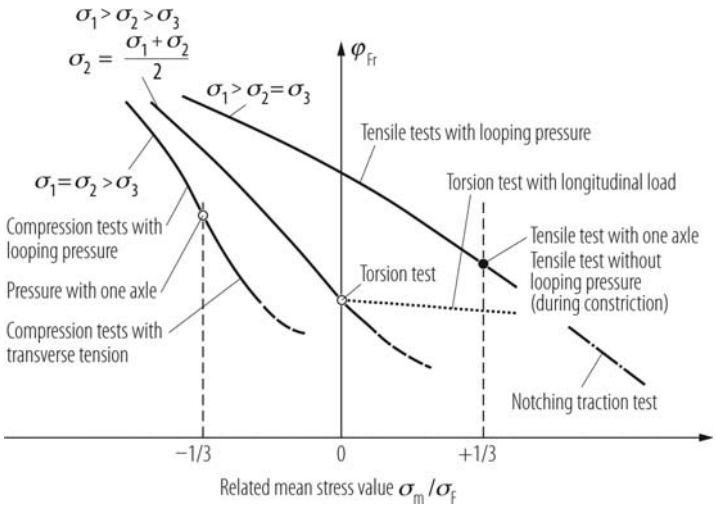
$$\sigma_F = \frac{2}{\sqrt{3}}(\sigma_1 - \sigma_3) = 1,155 \cdot \sigma_{F-\text{Tresca}} \tag{1.5}$$

1.2 Plasticity

Every deformation process requires a plasticity of the material, i.e. the ability to change its form under the influence of moderate external forces (which generate a tension inside the material) without damaging the material cohesion. At a critical deformation degree the materials ability for plastical deformation comes to an end. The deformation degree when first cracks will appear is defined as plasticity φ_{Fr}. The specific plasticity of a material is determined by the deformation conditions such as temperature, deformation rate and the residual hardening of the material after an earlier deformation process. In contrast to the flow stress σ_F, the plasticity φ_{Fr} depends strongly on the stress state (Fig. 1.2). At cold deformations the distribution of the total deformation on the single passes affects the plasticity φ_{Fr}. This should be noticed especially for brittle materials when high deformation degrees near the plasticity limit have to be realized, as longitudinal or transversal cracks can appear in such cases.

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Fig. 1.2.
Influence of the stress type on the plasticity in correlation to the related mean stress value σ_m/σ_F [1.8]. $\sigma_m = 1/3\cdot(\sigma_1 + \sigma_2 + \sigma_3)$



1.3 Deformation behavior

There is no unique definition for the term deformation behavior. The term refers to a material's behavior under plastic deformation. Good deformation behavior generally means: when a low external force is applied, the material changes its geometrical form without cracks, with an smooth and precise surface as well as with a high yield and long durability of the deformation devices. Figure 1.3 gives an overview of the parameters which determine the deformation behavior of a material. They can be divided into four groups: metallurgical-physical conditions of material processing; thermodynamical conditions at deformation; stress state at deformation; deformation process and deformation device. Many of the parameters presented in Fig. 1.3 depend on or affect each other.

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Fig. 1.3.
Parameters that influence the deformation behavior.

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1.4 Methods to determine the deformation behavior

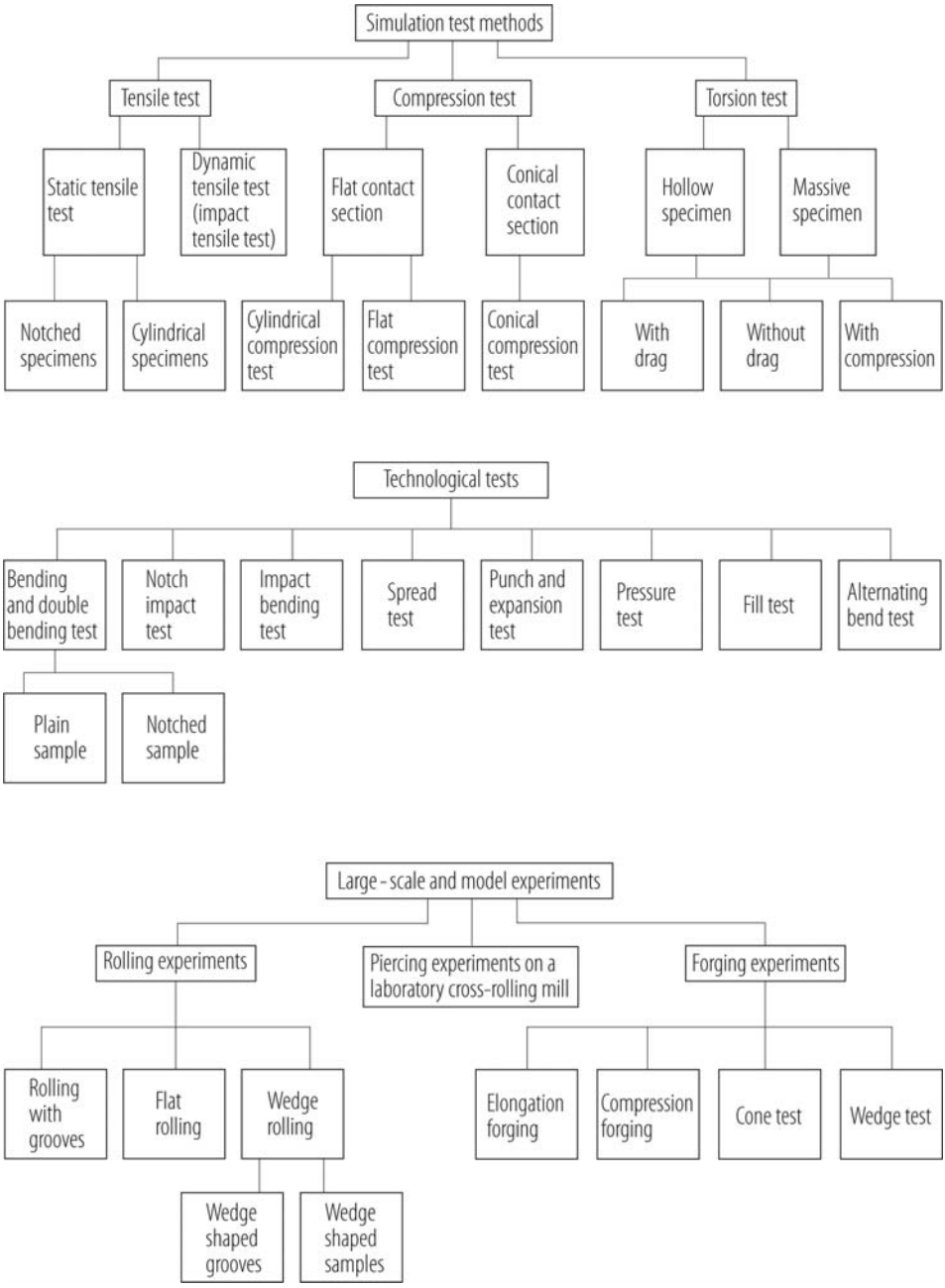
1.4.1 Overview and specifications

The following methods are available for the determination of the deformation behavior (Fig. 1.4):

- *Simulation test methods* such as tensile, compression and torsion tests investigate the influence of the deformation condition parameters (temperature, deformation degree and deformation rate) on the flow stress and partly also on the deformation behavior (if the related mean stress value depends on the deformation process).
- *Technological test methods* such as tensile, compression, bending, transverse bending and bulging tests are mostly used for quality control. They deliver data which allow qualitative estimates for specific process technologies, mostly at cold deformation. Technological test methods supply mostly parameters which depend on the sample form, and their objective is to investigate the general applicability of process technologies as well as the aptitude of semi-finished products for further processing. Besides standard procedures there also exist a large number of not unstandardized tests in order to meet the requirements of specialized production processes.
- Adaptation of deformation conditions that are common for industrial deformation processes for smaller deformation devices (in consideration of the rules of process similarity). In general, the results can be easily transferred to technical processes, although this is often a time and material consuming process which additionally only allows a limited generalization.

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Fig. 1.4.
Test methods for the deformation behavior.



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The following requirements are imposed on both test methods and their results:

- Determination of reproducible parameters for the definition of the plasticity and the flow stress of the material.
- Coverage of a broad testing range for the plasticity, deformation temperature and deformation rate (preferably $0.01 \leq \varphi \leq 3.0$, $20°C \leq \vartheta \leq 1500°C$, $10^{-3}\ s^{-1} \leq \dot{\varphi} \leq 10^{3}\ s^{-1}$).
- Imitation of deformation parameters and deformation programs that are common in large-scale deformation processes.
- Simple and economical application as well as their applicability for process control.

The test methods meet these demands only in parts. Table 1.1 shows a summary of deformation rates, deformation degrees and pause times between two successive deformation steps for common deformation processes. The degree of deformation φ pertains to the degree of deformation that is customarily realized in a single pass and was calculated based on section variations during deformation.

Table 1.1.
Deformation rates, deformation degrees and pause times of deformation processes.

Deformation process	Strain rate [s^{-1}]	Individual degree of forming	Pause time [s]
Push bench	10…300	0.01…0.30	0.70…0.025
Stretch reducing mill	50…900	0.05…0.09	0.20…0.005
Continous tube rolling mill	4.0…70	0.02…0.40	2.50…0.40
Automatic mill	40…200	0.10…0.70	8.0…5.0
Punching press	0.40…20	0.30…0.70	
Cross rolling mill	1.0…9.0	0.70…1.70	
Extruding press	1.0…400	1.0…4.60	
Blooming and slabbing	0.15…30	0.04…0.60	10…2.50
Blanks and profiles	2.0…70	0.10…0.70	8.0…0.50
Hot strip	0.50…500	0.10…0.55	
Roughing line	0.50…7.0		70…6.0
Finishing line	15…500		4.0…0.25
Heavy plate mill	1.00…80	0.05…0.60	20…4.00
Light section steel and wire	0.80…3000	0.10…0.70	
Roughing line	0.80…20		40…5.00
Intermediate line	15…700		5.00…0.25
Finishing line	125…3000		0.15…0.006
Cold rolled strip mill	70…2500	0.008…0.50	
Cold upsetting press	1.00…60	0.15…1.50	

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In continuous forming processes, if a total or partial dehardening of the material occurs between two passes, the hardening effect from the preceding pass may have to be considered. Therefore, modern simulation tools for forming behavior are required to realize such deformation degree-time distributions, possibly with variable temperature and/or forming rates, for example in order to simulate the forming conditions in the finishing line of a hot strip. This test methodology is increasingly gaining importance, since not only information about the force and work requirements about partially dehardened grain structure conditions are required, but also about the grain structure development through recovery and recrystallization onto which transformation and precipitation processes can be superimposed.

The pause time is reduced from 5…15 s for edge passes of a blooming line and during the turn of a slab to less than 0.01 s in the last stands of a wire rolling block. The dependence of the pause time on the forming speed is almost identical for different continuous rolling line types. Deformation degree-time distributions with pause times of more than 0.15 s can be performed in compression tests as well as in torsion tests up to the maximum possible forming speed of the test machine. The pause time of servo hydraulic test machines is determined by the switching time of the multi-step servo valves, while in torsion plastometers it depends on the switching time of the electromagnetic coupling. For plastometers, significant reductions of these times can not be expected in the near future, since in contrast to continuous rolling facilities the masses in motion (tools, sample clamping) must be braked during the pause time and then again accelerated.

In interrupted compression or torsion tests, the influence of very small pause times on the stress-strain curve as well as on hardening and dehardening distributions can be investigated. However, in many cases this is not possible at forming rates that are technically common. This holds primarily for the finishing line area.

1.4.2 Simulation test method

Because of the good measurability and controllability of deformation parameters at well defined laboratory conditions, the compression test, the tensil tests and the torsion test are most commonly used. But also technological test methods deliver useful (mostly qualtitative) conclusions about the influence of temperature and material properties on the plasticity. Modern test systems allow the simulation of deformation conditions specified in Table 1.2.

Table 1.2.
Working ranges of simulation processes.

Deformation process	Strain rate [s^{-1}]	Individual degree of forming	Pause time [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…100	0.01…1.70	0.06…>100

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The working ranges for plots of torsion and flat compression tests are those of the test facilities in operation at the Institute for Metal Forming of the TU Bergakademie Freiberg (Fig. 1.5). They come from the technical data of the torsion plastometer TPM 38. The technical specifications of the servo hydraulic test system SHM 400 and of the multifunctional simulation and test system Gleeble HDS-V40 are summarized in Table 1.3.

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

Technical specification	Servo hydraulic testing system SHM 400	GLEEBLE HDS-V40
Testing force [kN]	400 (static); 320 (dynamic)	400 (vertical); 50 (horizontal)
Testing speed [mm/s]	0…480	0.1…1700
Lift [mm]	±50	
Drive power [kW]	75	
Control	force, distance or forming degree	
Load	at rest, increasing or vibrating	
Strain rate [s^{-1}]	max. 40 in cylinder upsetting test	max. 100
Deformation temperature [°C]	20…1250	20 … 1800
Sample heating	in upsetting tool (separate furnace); inductively with programmed control	upsetting test and tensile test conductive heating
Heating/cooling rate [K/s]	max. 10 / 3	5…1000 / 1…330
Number of forming cycles	max. 10	max. 25
Minimum downtime between two forming steps [s]	0.20	0.15
Testing methods	*upsetting test*: cylinder, cone, hollow cylinder, flat compression; *tensile test*: round, flat samples; *bending test*	*upsetting test*: cylinder, cone, flat; *tensile test*: round, flat samples; *multiaxial deformation*

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Fig. 1.5.
Testing systems. (Above left) Gleeble HDS-V40. (Above right) Servo hydraulic SHM 400. (Left) Torsion plastometer TPM 38.







The operating range of torsion tests in Table 1.4 is based on the conversion of the shear stress and shear rate into the corresponding compression parameter per Nadai-Mises. In the flat test, a maximum degree of deformation of about 1.60 can be applied. This covers the range of standard reductions in most longitudinal and cross rolling processes, while for extrusion pressing only the lowest ranges of the operationally applied elongation rate can be achieved. In the torsion test, there is no technical limit with respect to the degree of deformation, which is dictated solely by the plasticity of the material. Both test processes have in common that the maximum deformation rate is substantially below that of standard continuous rolling processes, especially for the area of finishing lines.

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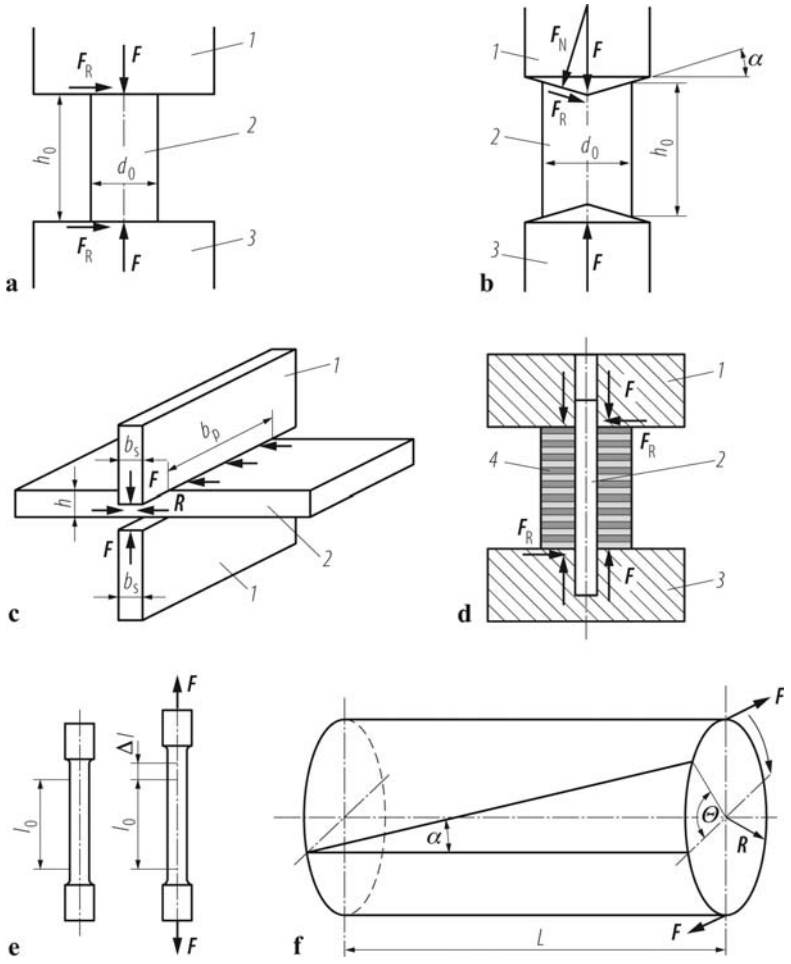
Table 1.4.
Technical parameters of torsion plastometers [1.12].

Sample size [mm]	Ø 6.0 x 12.0…15.0
Drive power [kW]	2
Nominal moment [Nm]	23.5
Permissible overload	7
Rotational speed [min^{-1}]	10 … 2000
Minimum/maximum rotation angle [°]	5 / 60000
Min. downtime between two forming steps [s]	0.10
Testing temperature [°C]	20…1200
Strain rate [s^{-1}]	< 25
Max. number of forming cycles	24

Fig. 1.6 summarizes the most important laboratory test methods fort the determination of the deformation behavior. Table 1.5 shows the equations to calculate parameter characteristics of the deformation behavior. It should be mentioned that several equations are available for the calculation of the deformation degree at torsion test. All of them base on the theory of plasticity, but their results can differ especially at higher shearing stresses. The authors use the translation after Nadai-Mises, because this method yields consistent results for characteristic points of hot flow curves that are found in compression and/or torsion test.

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



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Table 1.5.

Equation for the calculation of parameters that characterize the deformation behavior [1.13] and comparison of the testing procedures for the determination of yield stress and plasticity [1.14].

	Compression test	Torsion test	Tensile test
Flow stress σ_F	$\sigma_F = \dfrac{\sigma_w}{1 + \dfrac{\mu}{3}\dfrac{d_x}{h_x}}$	$\sigma_F = \sqrt{3}\tau$ (v. Mises) $\sigma_F = 2\tau$ (Tresca)	$\sigma_F = \dfrac{F}{\Delta\, l_x} = (1+\varepsilon)^{-1}\dfrac{F}{\Delta l_0}$ (uniform elongation)
Strain φ	$\varphi = \ln\dfrac{h_x}{h_0}$	$\varphi = \dfrac{\sqrt{3}}{4}\gamma^*$ (v. Mises) $\varphi = \dfrac{2}{\sqrt{3}}\ln\left(\dfrac{3\gamma^*}{8} + \sqrt{\dfrac{9}{64}\gamma^{*2} + 1}\right)$ (Nadai-v. Mises)	$\varphi = \ln\dfrac{l_x}{l_0} = \ln(1+\varepsilon)$ (uniform elongation)
Strain rate $\dot{\varphi}$	$\dot{\varphi} \approx \dfrac{\Delta\varphi}{\Delta t} = \dfrac{v}{h_x}$	$\dot{\varphi}_{NM} = \dfrac{d\varphi}{dt} = \dfrac{\partial\varphi}{\partial\dot{\gamma}}\cdot\ddot{\gamma} = \dfrac{\sqrt{3}\pi R\dot{n}}{L\sqrt{\gamma^2+4}}$	$\dot{\varphi} \approx \dfrac{\Delta\varphi}{\Delta t} = \dfrac{v}{l_x}$
Symbols	F - compression force; A - area; $\sigma_w = F/A$ - deform. stress; μ - friction value; v - compression rate; d_x, h_x - sample size.	M_D - torque; R - sample radius; $\tau = 3\, M_D\, (2\pi\, R^3)^{-1}$ - shear stress; L - gauge length; Θ - torsion angle; $\gamma = R/L\ \Theta$- shearing strain; n - number of rotations.	F - tensile force; A_0 - section before trial; A_x - section during trial; l_0 - gauge length; l_x - length during trial; $\varepsilon = \Delta l/l_0$ - elongation; v - test speed.

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Table 1.5. (continued)

	Compression test	Torsion test	Tensile test
Advantages/ Disadvantages	+ forming by compressive stresses similar to most longitudinal rolling; + simple test procedure; + high forming rate in ballistic test; – friction between sample and tool; – friction correction to stress-strain curve necessary; – with bulging of the sample (i.e. $\varphi \geq$ 0.35 undefined stress conduit); – buckling of slender samples – fracture degree of deformation can only be determined for brittle materials – absolute values depend on sample size and shape.	+ simultaneous determination of yield stress, plasticity and forming behavior; + free of friction; + simulation of technical deformation-time distributions without cross section change of the sample; + determination of first cracking from longitudinal stress distribution; – several sets of equations for calculating yield stress, degree of deformation and forming rate; – homogeneous forming over L/D = 1.5…2.5; – longitudinal stresses lead to cross section changes in non-alloy C steels at $\varphi \geq 3.0$; – $\dot{\varphi} \approx 30\ s^{-1}$.	+ simultaneous determination of strength and plasticity values with small limit degrees of deformation; + free of friction; + fast determination of stress-strain curve through stretch limit determination of cold formed samples at RT; – multi-axis stress conduit from constriction (for hot/cold forming at $\varphi \geq$ 0.30/0.20); – no simulation of technical deformation-time distributions due to low fracture degree of deformation; – deformation by tension stress does not correspond to any technical forming process.

The last line of Table 1.5 describes advantages and disadvantages of the most important test methods. Although the torsion test for the determination of the behavior at hot and cold deformation has been widely accepted, it should be noted that no technical deformation process operates with mere shear stresses. Additionally, the stress and deformation distribution inside the sample and across the section are inhomogeneous.

1.4.3 Technological tests

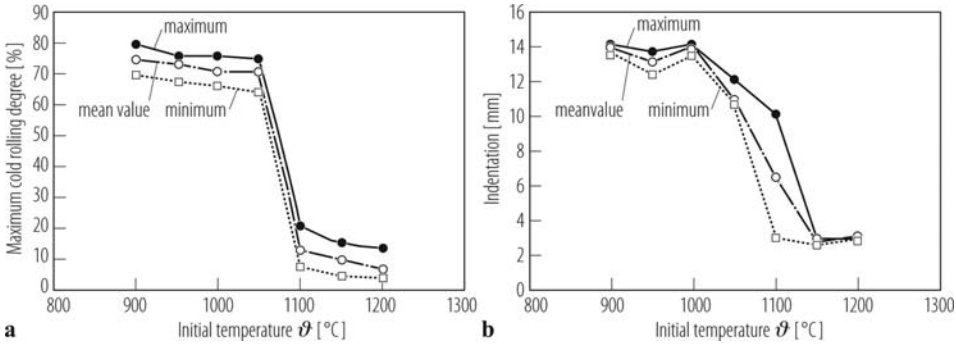
1.4.3.1 Deep drawing test

In [1.15], the existence of a relationship between the deep drawing test according to Erichsen and the largest possible reduction at cold rolling of ferritic steels with a thickness between 2.0

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and 5.0 mm was shown (Fig. 1.7). High values of the deep drawing test suggest a good plasticity at cold rolling, low values characterize brittle behavior. In the deep drawing test according to Erichsen (DIN 50 101, 50 102) a strong clamped sheet or strip is bulged by a ball-shaped die until the first crack appears. The test result, the so called Erichsen-cupping, is the length of die stroke until tear-off. It has to be higher than the minimum values postulated in the standards. Additionally, it is possible to evaluate anisotropies 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 a texture of the sheet, which is hence less suitable for deep drawing. Also, the surface porosity allows conclusions about the grain size. Materials with big grains can not be further processed; and they mostly do not have the required values for deep drawing.

Fig. 1.7.
(a) Correlation between maximum degree of cold rolling (up to the occurrence of cracks) and hot deformation temperature. Steel: X10CrAlSi24; Rolling schedule 5.0 → 4.0 → 2.5 → 2.0 mm; Heat treatment: air cooling → 800°C / 30 min → air cooling. (b) Correlation between indentation and deformation temperature. Steel: X10CrAlSi24; same rolling conditions as in Fig. 1.7a.



1.4.3.2 Cold rolling test

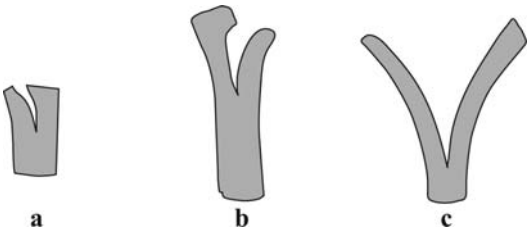
With the exception of flat compression tests (where the plasticity can only be determined under very special conditions) none of the described test methods operates with the stress state ($\sigma_1 = -\sigma_3$, $\sigma_2 = (\sigma_1 + \sigma_3)/2$) and straining state ($\varphi_1 = -\varphi_3$, $\varphi_2 = 0$) that occur at strip rolling. Hence it was tested if it is possible to determine the critical deformation degree at cold rolling with high reliability [1.16], which lead to the following method for the determination of plasticity at cold rolling.

The strips are rolled without lubrication at a constant reduction of 10% and a constant deformation rate until the maximum deformation capacity (i.e. appearance of the first crack) is reached [1.16]. Fig. 1.8 shows some samples at maximum deformation capacity. The strips are cooled down in water to room temperature in order to eliminate a potential influence of the deformation heat on the result. As a disadvantage of this method, a relatively wide scattering band has to be accepted especially at low deformation degrees (up to 50%). This is party caused by micro cracks that can not be visually detected, and it could hence be avoided

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by a inductive crack detection. Yet, the number of test runs would extremely increase due to the vast multiplicity of parameters to be investigated. In order to transfer the results to technical processes, the procedure has to follow the criteria of similarity (equal temperature and deformation rate, equal roll gap ratio and equal friction conditions).

Fig. 1.8.
Crack formation of sheet samples (steel X10CrAlSi24) after rolling. (a) h_0 = 7.2, ϑ_r = 1080°C, ε_{fr} = 22%. (b) h_0 = 4.8, ϑ_r = 1180°C, ε_{fr} = 66%. (c) h_0 = 7.2, ϑ_r = 880°C, ε_{fr} = 67%.



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2 Flow stress of steel

Introduction and Definitions

2.1 Influence of the chemical composition

2.1.1 Hot working

The effect of alloying and accompanying elements on the flow stress during hot forming can be reduced to a few major factors. The hardening effect of dissolved elements depends on the relative atom size difference δ , the relative shear modulus difference η and the concentration of the elements C_{Ei}:

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

A flow stress increase caused by solid solution hardening is limited by the fact that there is a direct relationship between the solubility of the impurity atoms and their specific hardening effect: if ϑ and η are high, the solubility is low (and vice versa) [2.1]. Fig. 2.1 summarizes the material specific parameters for the flow stress at hot deformation.

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Fig. 2.1.
Material related parameters on flow stress at hot deformation. (a) Material: σ_F **is a function of the material specific activation energy at hot deformation** Q**. Three graphs for different homologue deformation temperatures** $(T_d/T_m)_1 < (T_d/T_m)_2 < (T_d/T_m)_3$ **are shown. (b) Purity: A rising content of impurities in solution yields a higher** σ_F **compared to the flow stress of the pure metal. (c) Phase composition: At the same deformation conditions** $(\vartheta, \varphi, \dot{\varphi})$**,** σ_F **depends on the phase composition** (α, γ) $\vartheta_1 < \vartheta_2 < \vartheta_3$ **due to differences of the lattice constant and the phase diffusion coefficient. (d) Stacking fault energy: Hot flow curves for materials with high stacking fault energy (dynamical recovery) and low stacking fault energy (dynamical recrystallisation). (e) Microstructure before deformation: At the same chemical composition the flow stress of an as-cast structure is lower by a factor of approx. 0.70…0.95 compared to as-rolled structures. In general the maximum of** σ_F **appears at higher deformation degrees for as-cast structures and is not very pronounced.**

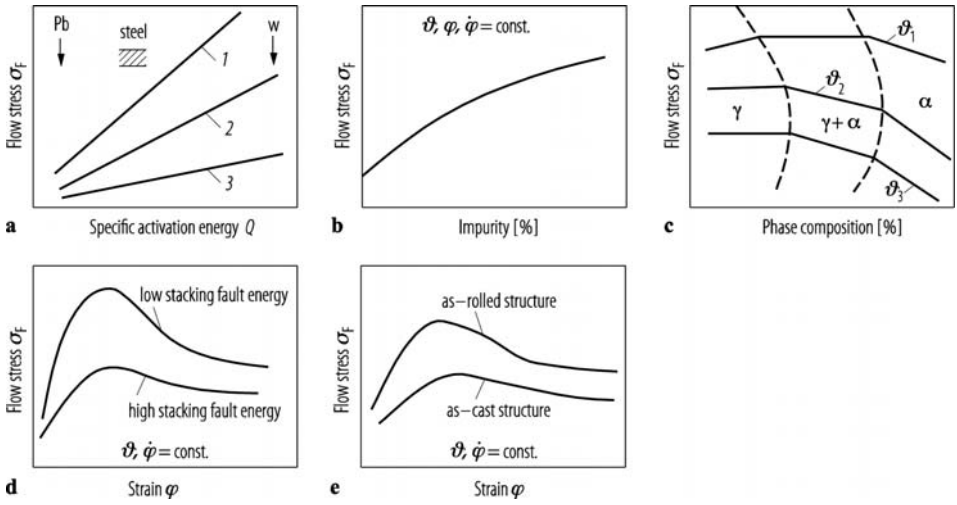


Table 2.1 lists data on the atomic radius and shear modulus of various alloying and accompanying elements of steels [2.2, 2.3, 2.4]. By hot tensile tests at temperatures between 800 and 1300°C Židek determined the influence of the carbon-, chromium-, manganese-, nickel-, molybdenum- and silicon-content on the flow stress. In each case only one element was varied [2.5]. According to this study, molybdenum causes higher flow stresses over the complete temperature range, followed by manganese, chromium and nickel. On the other hand a higher carbon content leads to reduced flow stresses. Quantitatively these results correspond precisely to the sequence that can be expected according to the atom radii and the shear modulus differences. Similar statements were given by Tamura et al [2.20] with manganese alloyed steels. (Fig. 2.2). The decrease of flow stress due to a higher carbon content was only confirmed at lower deformation rates.

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Fig. 2.2.
(a) Correlation between flow stress and carbon content at $\dot{\varphi}$ = 21 s^{-1}, ε = 0.30. (b) Influence of the alloying elements Cr, Cu, Mn, Mo, Ni and Si at 900°C, $\dot{\varphi}$ = 21 s^{-1}, ε = 0.30. (c) Influence of the alloying elements at 900°C, $\dot{\varphi}$ = 21 s^{-1}, ε = 0.30. (c) Influence of the microalloying elements Nb, Ti and V at 900°C, $\dot{\varphi}$ = 21 s^{-1}, ε = 0.30.

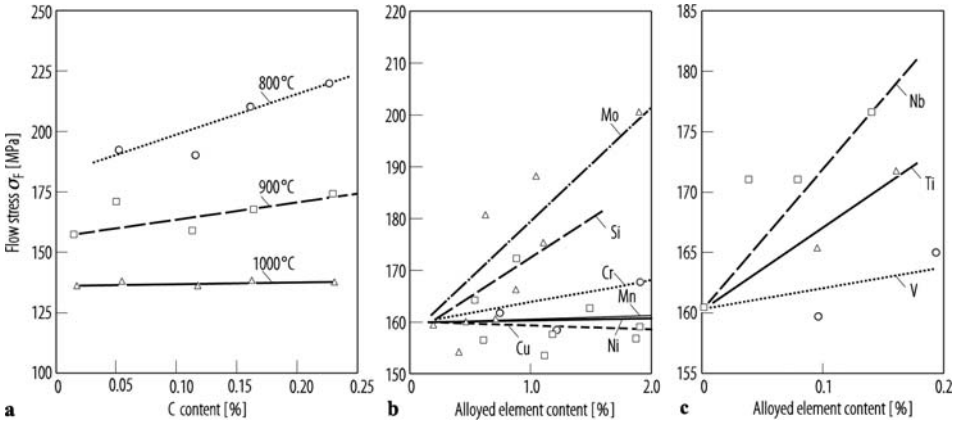


Table 2.1.
Atomic radius and shear modulus of alloying elements of steels [2.2, 2.3, 2.4].

Element	Atomic radius [kX]	Atomic radius difference to iron [%]	Shear modulus [GPa]	Shear modulus difference to iron [%]
Iron	1.27	0	82.6	0
Carbon	0.77	−39.4		
Manganese	1.30	2.36	66.8	−18.1
Silicon	1.17	−7.87	39.2	−52.0
Chromium	1.28	0.79	86.8	6.13
Nickel	1.24	−2.36	76.0	−6.86
Molybdenum	1.40	10.2	125.6	53.9
Titanium	1.46	15.0	45.6	−44.1
Vanadium	1.35	6.30	50.6	−38.0
Niobium	1.47	15.7	37.5	−54.0
Copper	1.28	0.79	84.3	3.31
Aluminium	1.43	12.6	26.2	−67.9

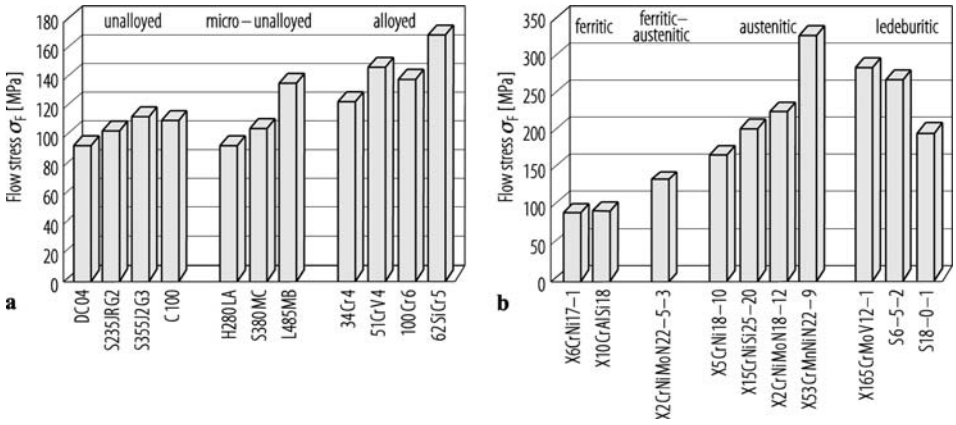
Furthermore the flow stress of steels is affected by components of metals and nonmetals as carbide, nitrides and sulphides (which increase or decrease the strength), by modification of the phase condition and by modification of the liquidus and solidus temperature. Yet, it should be remarked that these factors depend on each other. Fig. 2.3 shows a comparison of

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the flow stresses of unalloyed, alloyed, and high alloyed steel grades at $\vartheta = 1000°C$, $\varphi = 0.10$ and $\dot{\varphi} = 10\ s^{-1}$ (σ_{FO} value) with each other. From the data, the following conclusions can be drawn:

- Unalloyed steels (structural steels, quality steels and special steels, including unalloyed tool steels) show a flow stress σ_{FO} basic value between 90 and 110 MPa, depending on the carbon content, the percentages of accompanying elements and the allowable inclusions.
- The flow stress of micro-alloyed steels is defined by the manganese content as well as the micro-alloyant contents. It ranges between 95 and 140 MPa, or in part higher, for Cr and Ni alloyed steels in the case of the above mentioned conditions of deformation.
- Chromium, manganese, molybdenum, tungsten and vanadium have a flow stress increasing effect especially on alloyed steels. The flow stress basic value σ_{FO} of the latter group of steels ranges between 105 and 180 MPa, depending on the alloying content which is highly variable.
- Ferritic Cr-, Cr-Al-, and Cr-Si-steels do not differ in their σ_{FO} value from carbon steels of identical carbon content.
- Austenitic Cr-Ni- and Cr-Ni-Ti-steels show a flow stress basic value σ_{FO} of 160…180 MPa. lt is increased if nitrogen is added. Among the group of austenitic steels, the flow stress is highest in Cr-Mn-austenites.
- The σ_{FO} value in ledeburitic steels (high-carbon chrome-alloyed tool steels, high-speed steels) is in the order of 200 MPa.

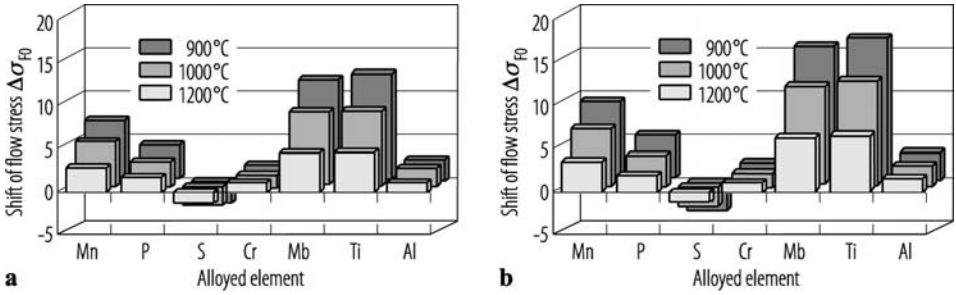
Fig. 2.3.
Influence of chemical composition of the flow stress in (a) unalloyed, micro-alloyed, alloyed and (b) highly alloyed steels.



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Fig. 2.4. shows how variations in the chemical composition, which are permitted by the standards, affect the flow stress difference for the upper and lower boundary composition of steel H380LA. Three temperatures and two deformation rates at a deformation degree of 0.10 can be observed. In this case, mainly the content of microalloying elements is responsible for the flow stress differences, followed by manganese.

Fig. 2.4.
(a) Shifting of the flow stress $\Delta\sigma_{FO}$ by variation of the chemical composition (steel H380LA) at $\dot{\varphi}$ = 10 s^{-1}. (b) Shifting of the flow stress $\Delta\sigma_{FO}$ by variation of the chemical composition (steel H380LA) at $\dot{\varphi}$ = 100 s^{-1}.



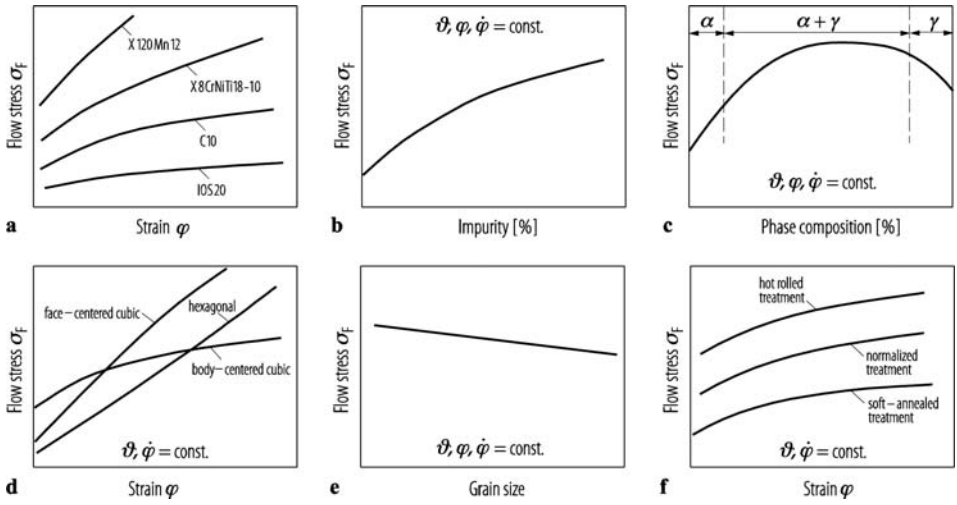
2.1.2 Cold deformation

2.1.2.1 General remarks

For most of the alloys the influence of material related parameters on the flow stress at cold deformation (Fig. 2.5) is very similar to hot deformation, but there naturally are quantitative as qualitative differences.

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Fig. 2.5.
Material related parameters on flow stress at cold deformation. (a) Material: At the same deformation and heat treatment conditions, a strong correlation exists between flow stress and material. (b) Purity: A higher content of impurities in solution leads to an increase of σ_F compared to the flow stress of the pure metal. (c) Phase composition: Variation of the phase composition causes different flow stresses. (d) Crystal structure: The flow stress characteristics is decisively affected by the crystal structure. Face-centred cubic and hexagonal metals have the highest hardening exponent, body-centred cubic metals have the lowest hardening exponents. (e) Grain size: A higher grain size reduces the flow stress. This complies with the Hall-Petch Relationship. (f) Heat treatment condition: Both the absolute value of flow stress and the hardening behavior strongly depend on the heat treatment conditions.



For ferrous materials, only binary Fe-Ni-alloys and deeply decarburized silicized dynamo steel grades can be named as examples for flow stress increase by dissolved elements, since the solubility limit for carbon is very low at room temperature. Carbon is bound in carbides. Nickel, with a slight atomic radius and shear modulus difference to iron, requires a concentration of approx. 50% for a flow stress increase of approx. 100 MPa at 20°C and a forming degree of 0.10. For silicon with its high shear modulus difference of −52%, the same value is reached for a concentration of approx. 1.5%.

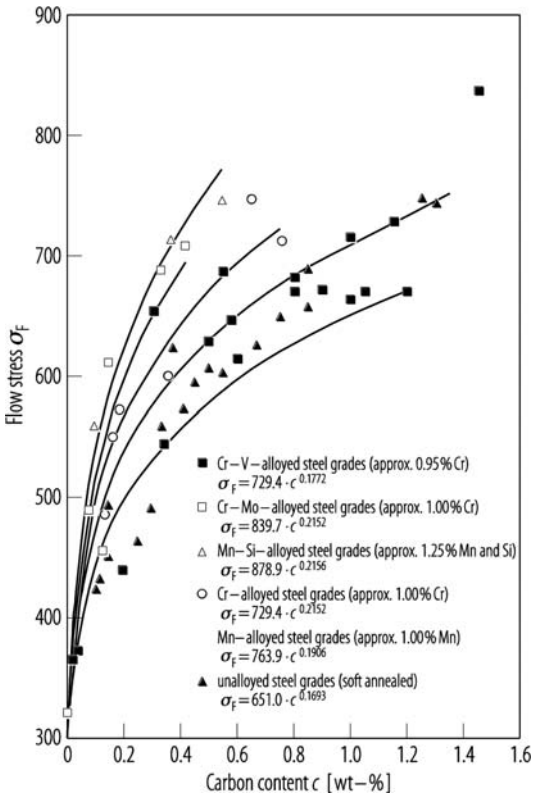
If carbides, nitrides or other compounds are precipitated in steels, their behavior combines with that of the matrix. Particles embedded in fine dispersion pose obstacles to moving dislocations and therefore have an indirect hardening effect. As is shown in Fig. 2.6, the flow stress of soft-annealed unalloyed and alloyed steels increases with increasing carbon content. Unalloyed C-steels have the slowest increase, and Mn-Si grades have the steepest one. Manganese and silicon are solved in solid solution. As is well known, solid solution

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hardening is stronger than precipitation hardening, which is demonstrated by the curves for Cr-, Cr-V- and Cr-Mo-alloyed steels. The following flow stresses are obtained for steels with approx. 0.40% C at 20°C and a forming degree of 0.10 with $\dot{\varphi} = 10\ s^{-1}$:

- unalloyed C steel: 557.0 MPa;
- Cr-alloyed steel (approx. 0.75% Cr): 603.8 MPa;
- Cr-V-alloyed steel with approx. 0.1% V: 620.1 MPa;
- Cr-Mo-alloyed steel with approx. 0.4% Mo:689.0 MPa
- Mn-alloyed steel with approx. 1.0% Mn: 641.4 MPa
- Mn-Si-alloyed steel with approx. 1.0% Mn and Si: 721.3 MPa.

Fig. 2.6.
Flow stress at $\varphi = 0.1$ of soft-annealed unalloyed and alloyed steel grades vs. carbon content at a forming temperature of 20°C and a forming rate of 10 s^{-1}.



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The strongest flow stress increase is caused by molybdenum due to its atomic radius difference of +10% and its shear modulus difference of +54% together with the high hardness value of molybdenum carbides (approx. 1500 HV). For instance, 0.3% Mo under the above forming conditions cause a flow stress increase of almost 140 MPa in steel grade 15Mo3 compared to the soft annealed steel C15. The influence of the alloying elements can be described by power functions if the microstrucutral state and forming conditions are constant. Thus, the flow stress of semi-ferritic, ferritic, martensitic and ledeburitic chromium steels shows an similar dependence on the carbon content. The influence of the chromium content (13 or 17%, respectively) is felt only with pearlitic steels, i.e. above approx. 0.20% C.

2.1.2.2 Heat treatment state

For identical forming conditions, the absolute value of the flow stress and its dependence on the forming degree are significantly influenced by the heat treatment state. Fig. 2.7 illustrates the influence of the heat treatment state on the cold flow curve of steel grade 125Cr1. The normalized state has the highest flow stress and hardening tendency. With increasing carbide embedding, i. e. soft annealing and annealing to spherical cementite (ASC), both flow stress and hardening tendency decrease. The flow stress can be further reduced by cold forming prior to ASC, as can be seen in Table 2.2. This simultaneously leads to improved formability. Patenting, which is employed to obtain an easily cold-formable sorbitic microstructure, increases the flow stress by 40% to 100% compared to the soft annealed state at the same carbon content and forming conditions. For high-alloy ferritic and austenitic steel grades, the heat treatment predominantly affects the grain size. With increasing grain size, i.e. higher annealing temperature and/or longer annealing time, the flow stress is reduced. For example, the flow stress σ_F for steel grade X10CrAlSi18 is reduced from 651.5 MPa after a heat treatment of 800°C/1h/air to 614.8 MPa for 1100°C/1h/air, while the grain size changes from 6090 to 17200 μm^2.

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Fig. 2.7.
Influence of heat treatment state on the flow stress of 125Cr1 at a forming temperature of 20°C and a forming rate of 10 s^{-1}.

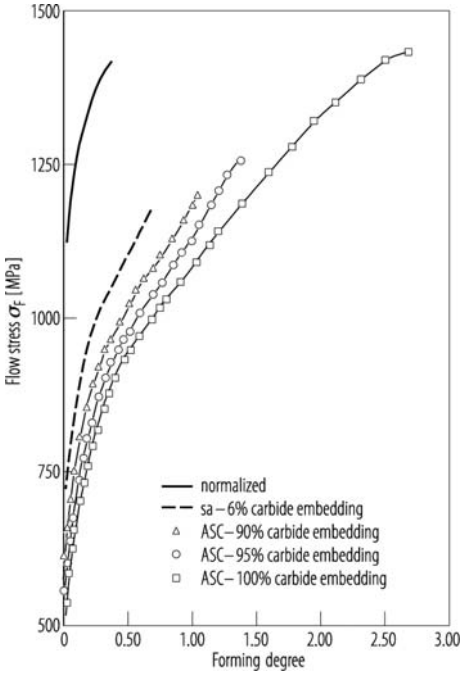


Table 2.2.
Influence of cold forming on the flow stress.

Steel grade	σ_F [MPa] after heat treatment	σ_F [MPa] after cold forming + ASC
35B2	701.1	654.2
38Cr2	821.3	726.7
41Cr4	790.6	709.6

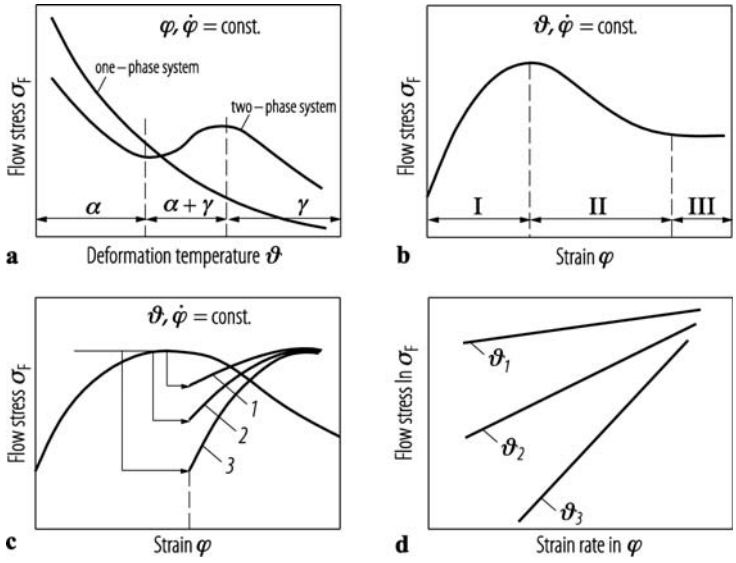
2.2 Influence of forming conditions

2.2.1 Hot forming

Fig. 2.8 shows the influence of the deformation conditions on the flow stress of steels. The most important parameters will be discussed in the following.

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Fig. 2.8.
Material related variables that influence the flow stress at hot deformation. (a) Deformation temperature: In the one-phase system, the flow stress exponentially decreases with higher temperatures. If several phases exist, σ_F increases. This unsteadiness is material related. **(b) Deformation degree:** The flow stress characteristics depends on material and deformation conditions. A hot flow curve consists of three sectors: I - hardening sector (σ_F increases at higher deformation degrees); II - sector of dynamical softening (σ_F decreases at higher deformation degrees); III - steady state sector (σ_F is independent from the deformation degree). **(c) Interpass times between two deformation steps:** If the total deformation is realized in two deformation steps, a recovery in parts (1,2) or a complete recovery (3) can occur in the time between the steps. **(d) Deformation rate:** In a double logarithmic diagram, σ_F depends linearly on the deformation rate. Three curves for different deformation temperatures $\vartheta_1 < \vartheta_2 < \vartheta_3$ are shown.

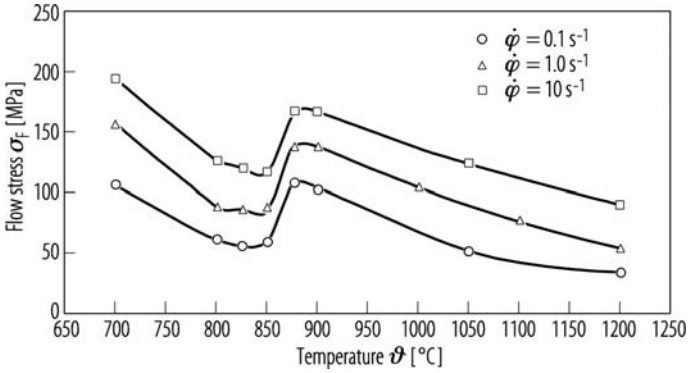


2.2.1.1 Influence of the deformation temperature

The point of maximum stress in the stress-strain curve of steel DD11 versus the deformation temperature for three strain rates can be seen in Fig. 2.9. The continuous flow stress decrease with rising temperatures is interrupted by an unsteadiness between 800 and 850°C, where the γ-α-transformation takes place. At 900°C the structure consists of 100% austenite, at 870°C it consists of 63% austenite and 37% ferrite, and at 750°C it consists of 96% ferrite and 4% austenite [2.21].

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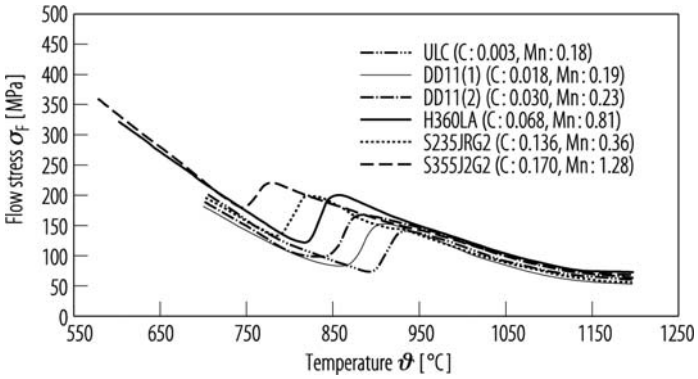
Fig. 2.9.
Stress strain curve maximum versus temperature in steel grade DD11.



The strain hardening behavior, which leads to a reduction in flow stress, is different in the two phases. While the influence of structure transformation on the absolute value is relatively low in unalloyed and low-alloy steels, there may be considerable differences in the case of highly alloyed grades.

The unsteadiness of the temperature values caused by the α-γ-transformation depends on the chemical steel composition, which is shown in Fig. 2.10. Also, the influence of the alloying elements carbon and manganese in weldable construction steels can be seen.

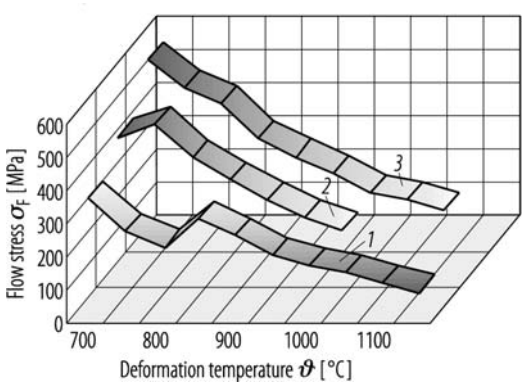
Fig. 2.10.
Transformation range of weldable construction steels at $\dot{\varphi} = 1\ s^{-1}$, $\varphi = 0.42$.



The flow stress of the steel X165CrMoV12-1 decreases between 700 and 800°C if it is directly heated up to its test temperature (Fig. 2.11). At 800°C its structure consists of ferrite and about 30% ferriferous mixed carbides of the alloyants. The ferrite becomes austenite and the carbides are increasingly dissolved between 800 and 860°C. The α-γ-transformation and the austenite enrichment with carbon, which leads to mixed crystal hardening, raise the flow stress between 800 and 850°C by approx. 100 MPa. Above 860°C, the flow stress of the austenite/carbide structure decreases.

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Fig. 2.11.
Influence of the heating method on the flow stress in X165CrMoV12-1. *1* - heating up to deformation temperature. *2* - heating up to austenitizing temperature 1050°C and cooling down to deformation temperature. *3* - heating up to austenitizing temperature 1200°C and cooling down to deformation temperature.



If the material is austenitized before hot deformation, the austenite is in a steady condition even at lower temperatures due to the supercooling effect, which means that the influence of the temperature on the flow stress of austenite exists even up to the Ar_3 temperature. The latter temperature Ar_3 is approx. 780°C if the austenitizing temperature is 1050°C and the cooling rate is 15…20 K/min [2.22]. Structure transformation is not yet finished at 700°C. The austenite condition is still steady at 700°C if austenitization takes place at 1200°C, because the Ar_3 temperature further decreases due to the coarse grain that are formed in that case. Fig. 2.11 reveals that the different structures that exist at 750…800°C basically double the flow stress values.

2.2.1.2 Influence of strain

The flow stress of steel grade X15CrNiSi25-20 versus the strain is illustrated in Fig. 2.12 for the temperature range between 500 and 1100°C at a strain rate of 2 s^{-1}. The flow stress increases and the material becomes strain-hardened with increasing strain at deformation temperatures between 500 and 600°C. A typical hot stress-strain curve composed of three segments can be seen above 700°C:

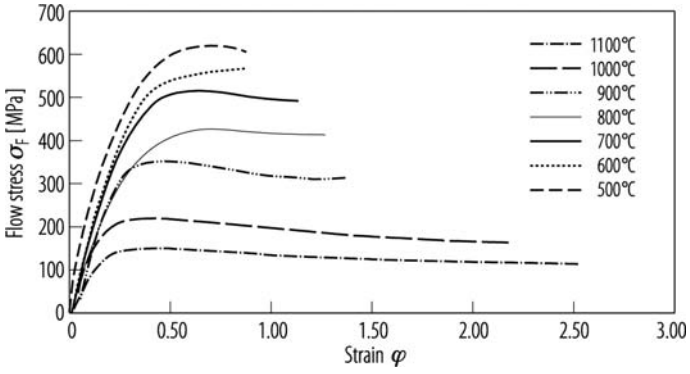
- The flow stress rises up to its maximum with increasing strain from its initial value $\varphi = 0$, which depends on the temperature and the strain rate. The rise becomes steeper as the strain rate increases and the deformation temperature decreases, a fact which is also true for the strain at the stress-strain curve maximum point (which is $\varphi = 0.37$ at 1100°C and $\varphi = 0.70$ at 800°C).
- Dynamic softening starts at the stress-strain curve maximum point and leads to a significant reduction in the flow stress as the strain increases. The dynamic softening is favored by rising strain rates and diminishing deformation temperatures, but it is important to note that high temperatures limit strain hardening in the case of hot deformation.

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The dynamic softening continues down to a flow stress level which depends on the temperature and the strain rate, but which is higher than the flow stress starting level in the respective deformation situation. The strain at which the dynamic softening is complete also depends on the temperature and the rate of the strain. Decreasing temperatures and rising strain rates increase the strain.

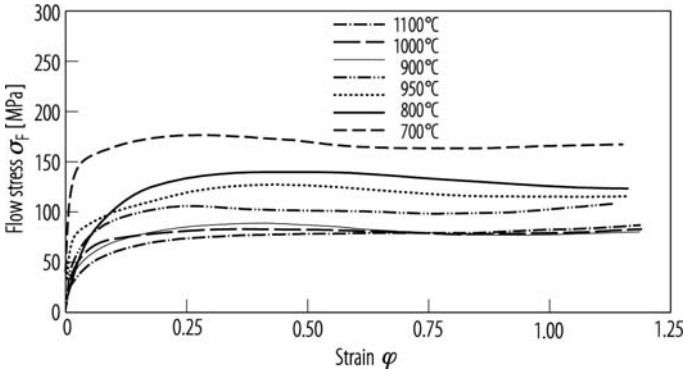
– Above the strain at which the dynamic softening is complete, there is a steady state region of the stress-strain curve in which the flow stress of the material is independent of the strain.

Fig. 2.12.
Stress-strain curves of X15CrNiSi25-20 at a strain rate of $\dot{\varphi} = 2\ s^{-1}$.



The stress-strain curve of micro-alloyed steels H280LA to S420MC for 800 or 800 and 850°C is below that for 850 or 900°C, which is due to the α-γ-transformation. It is accompanied by a qualitative change in the stress-strain curve profile and a decrease in dynamic softening (Fig. 2.13).

Fig. 2.13.
Stress-strain curves of H280LA at its austenizing temperature of 1120°C.

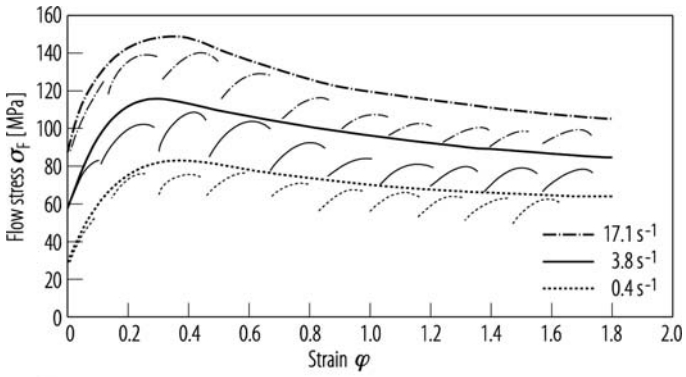


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Hot deformation is characterized by simultaneous hardening and softening, which are also dependent on time. If conditions are appropriate, static softening occurs in the intervals between two successive shaping steps. Contrary to deformations at high rolling speeds with very short intervals between roll passes, interval periods > 2 seconds lead to a complete material softening at temperatures above 900°C in the case of unalloyed and alloyed steels. Micro-alloyed and high-alloyed steels loose their hardness only partly or insignificantly.

Fig. 2.14 presents flow curves of steel S255N for three deformation rates. The total deformation degree of ≈ 1.70 was realized in 10 passes, the interpass times were 0.01, 0.044 and 0.375 s, which are prevailing at continuous tube processing. As can be seen in a comparison between continuous and more step flow curves, both curves have the typical characteristics of hot flow curves. The deformation begins with a hardening, followed by dynamical softening. After completing the dynamical softening, the flow stress is independent from the deformation degree and is only affected by temperature and deformation rate. The static softening in the short interpass times leads neither to a qualitatively different flow curve characteristics nor to essentially reduced absolute flow stress values. Hence continuous deformation processes can be based on hot flow curves whose deformation degree (start and finish) can be related to the total deformation degree for the actual temperature and deformation rate of one deformation step.

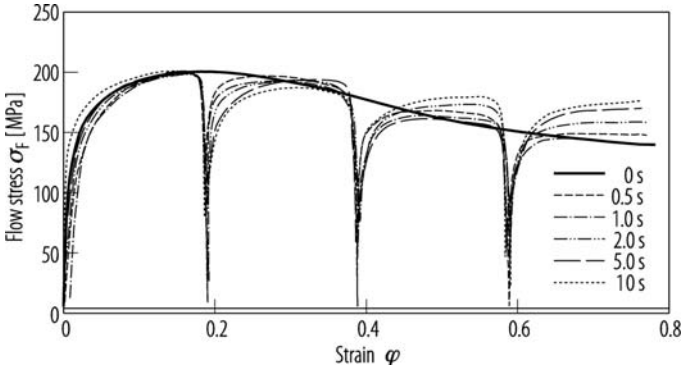
Fig. 2.14.
Continuous and more step flow curves of steel S255N for different pause times.



If, besides softening, precipitation processes run during the pause time between two passes, these lead to a considerable increase of flow stress with increasing number of passes. This can be seen in Fig. 2.15 for steel X210Cr12 which was rolled at 1000°C in four passes ($\varphi = 0.185$, $\varphi_{total} = 0.74$) with pause times between 0.50 and 10 s.

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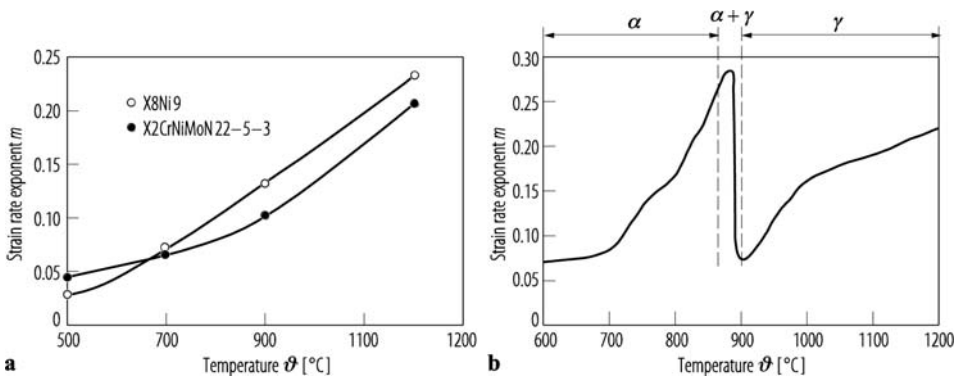
Fig. 2.15.
Effect of the pause time (between 0.5 and 10 s) on the flow stress for steel X210Cr12 at 1000°C and a deformation rate of 1.0 s^{-1}.



2.2.1.3 Influence of the strain rate

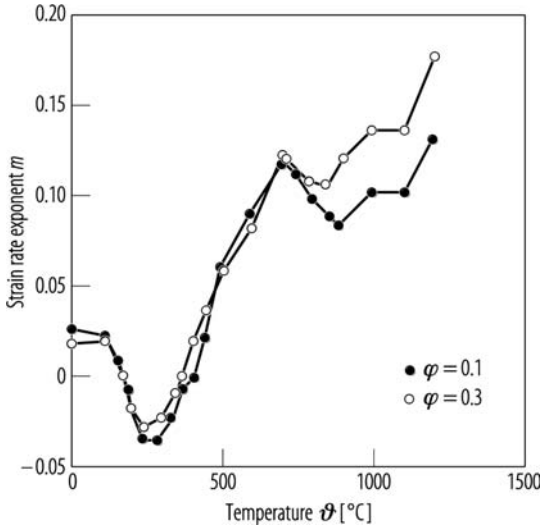
Increasing strain rates raise the flow stress at constant temperatures and a constant strain, which can be seen in Fig. 2.16 for steel X2CrNiMoN22-5-3. The strain rate exponent, which expresses the flow stress with rising strain rate, increases with increasing temperatures from 0.0261 at 500°C to 0.2324 at 1200°C in the case of the above steel grade. The continuous increase between room temperature and 1200°C is disturbed by unsteadinesses in the blue-brittle range and at the γ-α-transformation (Fig. 2.17), an influence of the deformation degree seems to exist in the austenite range only.

Fig. 2.16.
(a) Strain rate exponent as a function of the temperature for 2 different steel grades. (b) Strain rate exponent as a function of the temperature for DC06, with temperatures Ar_1 = 883.1°C and Ar_3 = 895.6°C.



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Fig. 2.17.
Strain rate exponent as a function of the temperature for the steel S235JRG2 for different strains φ = 0.1, 0.3.

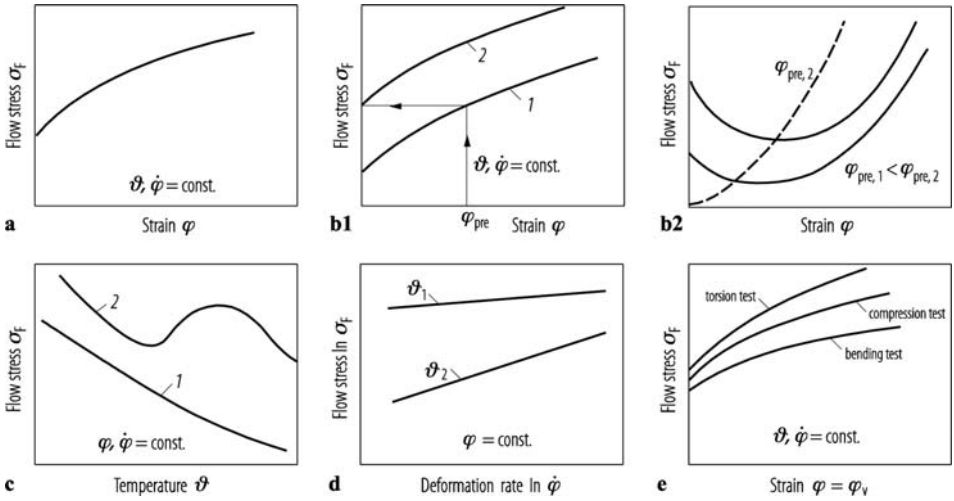


2.2.2 Cold Forming

Fig. 2.18 gives an overview of the influence of material related parameters on the flow stress at cold steel deformation. Deformation degree, deformation rate and temperature will be discussed more in more detail.

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Fig. 2.18.
Material related parameters on the flow stress at cold deformation. (a) Deformation degree: An increase of the flow stress σ_F as a result of hardening occurs until the plasticity limit is reached. In a double logarithmic diagram, a linear correlation between flow stress σ_F and deformation degree φ exists for certain ranges of the deformation degree (b) Pre-forming degree: at constant load, pre-hardening leads to an increase of the flow stress σ_F. *1* - soft-annealed; *2* - preformed with φ_{pre}. A change of loading (f.i. tension vs. compression) leads to a mechanical hysteresis (Bauschinger-Effect) (c) Temperature: In the single phase range the flow stress σ_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 σ_F and deformation rate exists, although the slope is much smaller than at hot deformation. (e) Determination method: Despite a translation into reference stresses and reference deformation degree, the flow stress depends on the investigation method such as torsion test, compression test and bending test.

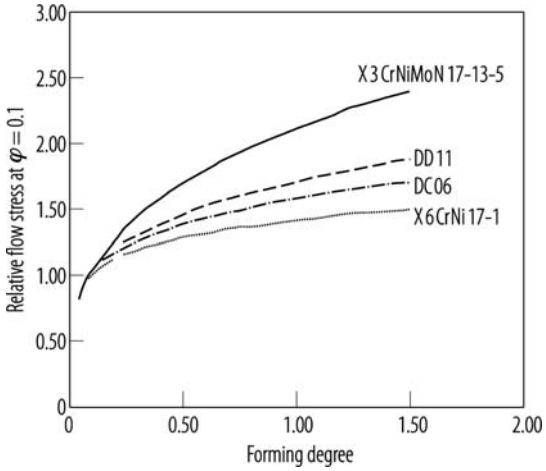


2.2.2.1 Forming degree

Cold forming leads to hardening until the deformation capability of the material is exhausted. Strongest hardening is observed for cubic face centered materials [2.6] i.e. austenitic steel grades. All other unalloyed, alloyed and high-alloy steel grades, which have a cubic body centered lattice in the cold forming range, harden less strongly (Fig. 2.19). For austenitic steel grades, an increase of the forming degree from 0.10 to approx. 0.30 leads to a flow stress increase by 50%. For the same effect, the forming degree has to be increased to approx. 0.90 with ferritic steel grades, since the cubic body centered lattice of these has a less pronounced hardening tendency.

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Fig. 2.19.
Hardening during cold forming for different steel grades.



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

$$\sigma_F = \sigma_F(\varphi = 1.0) \cdot \varphi^n, \quad \dot{\varphi}, \vartheta = \text{const.} \tag{2.2}$$

For many materials and material states, the hardening exponent n is not a constant but a function of the forming degree [2.7, 2.8]. In rough approximation, two flow curve ranges can be observed in which the hardening exponent is constant ("double-n-behavior" [2.7]). If upsetting tests are used to determine the flow curve, flow curves with one hardening range are obtained for unalloyed carbon steel grades (depending on the heat treatment state) and alloyed structural steel grades. Flow curves with two hardening ranges are characteristic for unalloyed carbon steel grades (depending on the heat treatment state), alloyed case-hardening and heat-treatable steel grades and for corrosion-resistant ferritic chromium and austenitic chromium-nickel steel grades. If the material has two hardening ranges, the hardening exponent value at the beginning of deformation (up to forming degrees of approx. 0.15…0.20 for steels) is a multiple of the value for higher forming degrees.

2.2.2.2 Forming rate

According to Alder and Philips [2.9], the equation

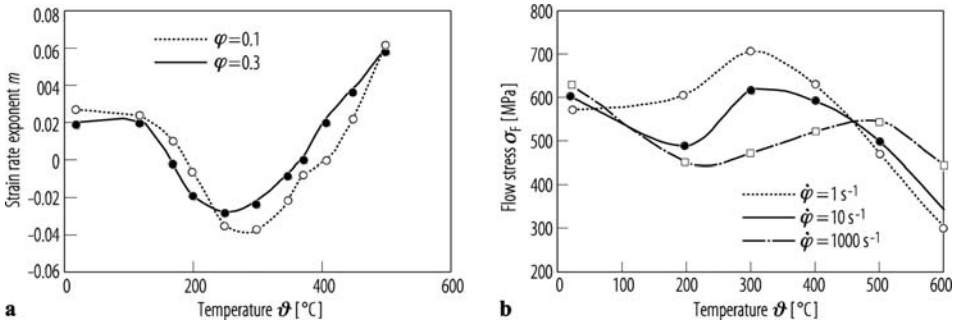
$$\sigma_{F,1} = \sigma_{F,2} \cdot \left(\frac{\varphi_1}{\varphi_2}\right)^m \tag{2.3}$$

holds for cold forming as well. The speed exponent m, which depends on the material and material state, continuously grows with increasing forming temperature if no phase transitions and precipitation processes take place in the material. Since unalloyed and low-alloy steel grades show a tendency towards blue brittleness between 150°C and 350°C, which is accompanied by hardening and a deterioration of the plastic properties, the influence of the forming

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rate on the flow stress can reverse in this temperature range: the speed exponent m turns negative. In addition, since the temperature range of blue brittleness also depends on the forming rate (Fig. 2.20a) [2.10], the exponent m can vary both its value and sign at higher cold forming temperatures. Even at room temperature, the flow stress grows only up to a certain limit with increasing forming rate, while a F reduction with increasing forming rate takes place due to the higher heat of deformation at higher forming degrees. The increase of the flow stress in the blue brittle range depends on the deformation rate (Fig. 2.20b).

Fig. 2.20.
(a) Strain rate exponent m of steel S235JRG2 as a function of the temperature. (b) Influence of the forming rate on the flow stress of the steel DC01.

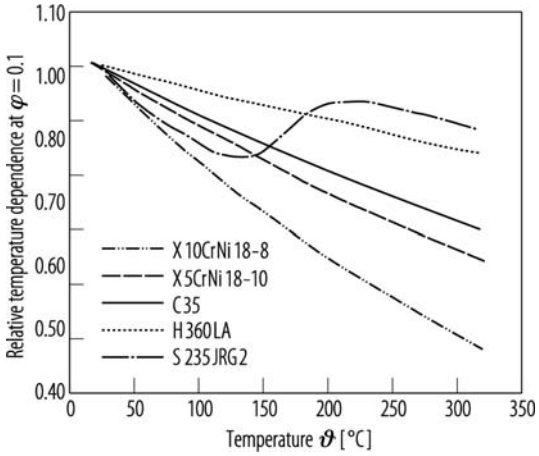


2.2.2.3 Forming temperature

For the product range under investigation, flow stress reduction with increasing temperature at constant forming degree and forming rate occurs almost exclusively for high- carbon, alloyed as well as austenitic and ferritic steel grades (Fig. 2.21). For all other steel grades, the continuous flow stress reduction with increasing temperature is interrupted by the speed-dependent blue brittleness range. The flow stress in this temperature range can be higher than at room temperature for low-carbon steels. With increasing forming rate, the interruption of the temperature-related flow stress reduction by a local maximum due to blue brittleness moves to higher temperatures. At the same time, the maximum becomes flatter (see S235JRG2 in Fig. 2.21) or disappears completely. For austenitic steels, the strong reduction of the flow stress with increasing temperature is explained by the dissolution of the deformation martensite.

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Fig. 2.21.
Temperature dependence of the flow stress for various steel grades between 20°C und 320°C.



2.3 Modelling

2.3.1 Influence of the chemical composition

The following assumptions hold for hot forming of non-alloyed and low alloy steels:

- the alloying elements are completely dissolved in austenite, their hardening is hence provided by their difference in atomic radii compared to iron;
- the alloying elements do not enter into any chemical compounds with one another (intermetallic compounds);
- the yield stress change by an alloying element can be expressed by an exponential function (Table 2.2);
- the material condition is homogeneous;
- the material is isotropic in terms of its plastic properties.

For the yield stress of this steel group at defined forming conditions, one can write [2.11]

$$\sigma_F = \sigma_{F,\text{pure iron}} + \sum A_i \cdot C_i^{B_i} \tag{2.4}$$

$\sigma_{F,\text{pure iron}}$ is the flow stress of pure iron at 1000°C, $\varphi = 0.10$, $\dot{\varphi} = 10\ s^{-1} = 86.6$ MPa. A_i is the flow stress increase by the element i compared to pure iron with a content of 1.00 mass%, C_i is the content of the element i (in mass%), and B_i is the exponent of the alloy hardening by the element i. The coefficients A and B were determined for 14 alloying and companion elements of the above mentioned steel group. The assumptions on which the modelling is based have a physical background:

- Only elements with an atomic radius that differs from iron by a most 15% are dissolved. When these elements have a cubic face centered phase, they dissolve very well in the cubic face centered host crystal lattice of the γ-iron. This applies for the alloying elements Mn,

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Ni, Cu and Co. The cubic body centered metals Cr, W, Mo and V are within the 15% boundary. However, they form carbides. Carbon deviates from this rule, it is not substituted but is arranged in interstitial sites.

- The tendency to form intermetallic compounds with steel is relative low. Only niobium, titanium and high chrome contents (> 20%) can form such phases with steel.
- The constants for equation (2.4) were determined with highly deformed steels. One can hence assume that the material is homogeneous and may be considered as being quasi-isotropic.

Besides the chemical composition, the grain structure condition determines the flow stress. It is known that the flow stress of cast grain structures with equal forming conditions is lower than the flow stress of unformed grain structures, where it is additionally dependent on the direction.

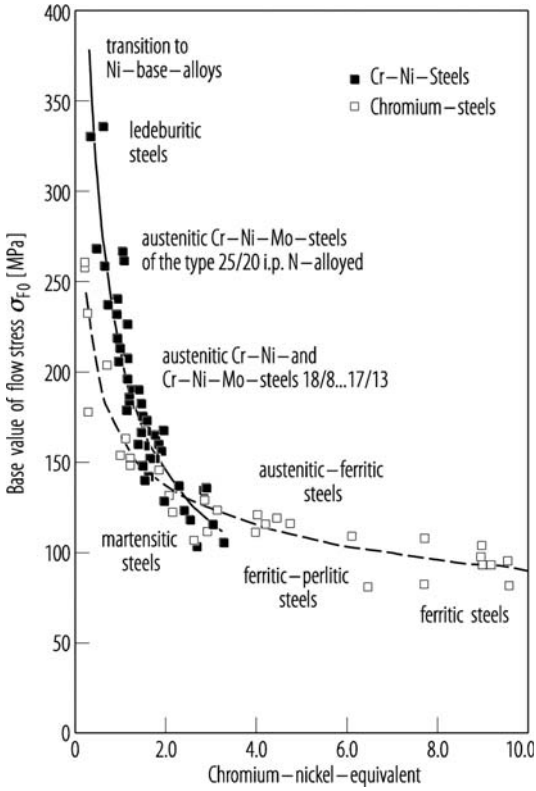
Table 2.3.
Characterization of flow stress of unalloyed and low alloyed steels by an exponential function. σ_F – 1.00% denotes the flow stress at 1.00% element content, and R_{xy} ist the correlation coefficient.

Steel grades	σ_F - 1.00% [MPa]	Exponent n_i	R_{xy}	Range of validity [%]			
				C	Mn	Si	Other
Carbon	117.2	0.06333	0.9733	0.03…1.30	0.10…0.80	0.02…0.50	
Manganese	125.7	0.05486	0.9627	0.05…0.90	0.70…1.30	0.10…0.30	
Manganese-silicon	120.5	0.05127	0.9989	0.20…0.65	0.90…1.40	0.70…1.40	
Chromium	124.2	0.06541	0.9967	0.15…0.90	0.50…0.80	0.05…0.40	Cr: 0.80…1.20
Chromium-vanadium	145.2	0.06074	0.9816	0.30…1.15	0.70…1.10	0.15…0.35	Cr: 0.80…1.20 V: 0.07…0.12

For highly alloyed chrome and chrome-nickel steels, the grain structure state can be characterized according to the Schaeffler diagram by the chrome-nickel equivalent. Considering two variations with equal chrome-nickel equivalent, a steel with a homogeneous austenite grain structure will have a higher flow stress than a steel whose austenitic matrix still contains (Fe, Cr)-carbides (Fig. 2.22). The difference increases with increasing carbide proportion. With the increase in the two-phase occurrence (austenitic-ferritic) with CrNi-steels and ferritic-perlitic with Cr-steels, the flow stresses approach each other. Fig. 2.22 again confirms the earlier conclusion that mixed-crystal dissolved elements have a greater effect on the hardening in hot forming than precipitated crystals do.

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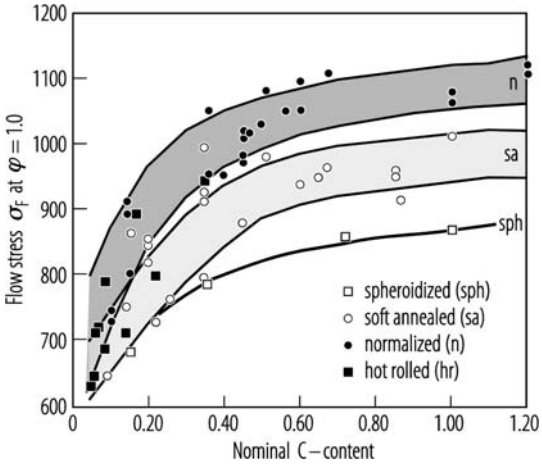
Fig. 2.22.
Influence of the grain structure on the base value of the flow stress σ_{F0} of high alloy Cr-Ni-steels and Cr-steels.



The results obtained for hot forming of steels are also transferable to nonferrous metals as well as to cold forming: the influence of the alloy contents on the flow stress can be described for various grain structure conditions by exponential functions which are valid for specific forming conditions. As Fig. 2.23 shows, the absolute value of the flow stress as well as its increase with rising C-content are significantly influenced by the beat treatment condition.

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Fig. 2.23.
Influence of the C-content of the flow stress for unalloyed C-steels and three heat treatment conditions.



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 contain the influence of the transformation conditions, the temperature ϑ, the strain φ and the strain rate $\dot{\varphi}$) or the hot deformation activation energy. Both methods are applicable to defined temperature ranges only.

2.3.2.1.1 Modelling by means of the thermodynamic factors

The mathematical modelling of the hot stress-strain curve is done by multiplying a material specific initial value by factors that express the influence of the conditions of deformation [2.12]:

$$\sigma_F = A \cdot K_\vartheta \cdot K_\varphi \cdot K_{\dot{\varphi}}. \tag{2.5}$$

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 events. And the influence of the strain rate is included by the temperature dependent proportionality between changes in strain and the flow stress.

Different model terms were tried out for the different thermodynamic factors K [2.13]:

$$\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot \dot{\varphi}^{m_3} (\text{term } 0), \tag{2.6}$$

$$\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot \dot{\varphi}^{m_3} \cdot e^{m_4/\varphi} (\text{term } 1), \tag{2.7}$$

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$$\sigma_F = A \cdot e^{m_1\vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1+\varphi)^{m_5\vartheta} \cdot e^{m_7\varphi} \cdot \dot{\varphi}^{m_8\vartheta} (\text{term } 2), \tag{2.8}$$

where A is a constant, m_1 to m_8 are exponents containing the influence of the deformation conditions on the flow stress and ϑ is the deformation temperature (in °C). The following comments can be made regarding the mathematical modelling of stress-strain curves as a function of the conditions of deformation:

- If flow stress changes are caused by precipitations or if the grain growth is not big, the temperature dependence K_ϑ can be expressed by a simple exponential function if the deformation occurs in a single-phase area:

$$K_\vartheta = e^{m_1\vartheta}. \tag{2.9}$$

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

$$K_\varphi = \varphi^{m_2} \cdot e^{m_4/\varphi}, \tag{2.10}$$

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

$$K_\varphi = \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1+\varphi)^{m_5\vartheta} \cdot e^{m_7\varphi}. \tag{2.11}$$

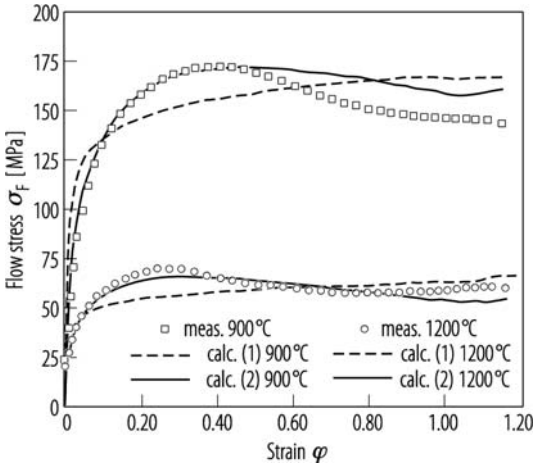
- Better agreement between measured and calculated flow stress is achieved if the power function for the strain rate $\dot{\varphi}$ contains a temperature dependent and a temperature independent exponent.

Term 0 traces back to Zjuzin [2.12], Hajduk and Elfmark [2.14] and is suitable for defining stress-strain curves in a single phase area 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 application scope is extended to a strain up to approx. 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 area 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 best suitable for the mathematical definition of stress-strain curves in engineering calculations [2.13, 2.15].

As pointed out earlier, stress-strain curve modelling can be applied to some temperature ranges only. Modelling for unalloyed, alloyed, and highly alloyed steels in accordance with term 2 was carried out for the entire temperature range between 500 and 1200°C, for the range between 500 and 800°C and for the usual hot deformation temperature range between 800 and 1200°C in order to get predictions of the limits. Softening is increasingly noticeable for all steels between 500 and 600°C. Fig. 2.24 shows how precisely the flow curve modelling according to equation (2.7) and (2.8) matches with the measured values for deformation temperatures between 800 and 1200°C. Normally the correlation coefficient at flow curve modelling according equation (2.8) is approx. 0.02 higher than with equation (2.7).

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Fig. 2.24.
Comparison between measured and calculated flow stress of the steel 20MnCr5 at a deformation rate of 1.0 s^{-1} and temperatures of 900°C and 1200°C, respectively. The calculation is based on either term 1 (equation (2.7)) or term 2 (equation (2.8)).



According to both terms, the flow stress decreases with higher temperatures. The flow stress modelling according to equation (2.8) reflects the flow stress variation with rising temperatures very precisely, while term 1 delivers an ascending flow stress for the complete range of deformation degrees. Term 2 also reflects the influence of dynamic recovery at 1200°C, while the mathematical model selected for term 1 does not incorporate the shifting of the flow curve maximum by the deformation conditions. It delivers only a mean curve both for the range of dynamic recovery and for the steady state zone.

The correlation between deformation speed and flow stress with increasing temperature rises faster in term 2. In comparison, term 1 leads to somewhat higher flow stress values at lower temperatures and to somewhat lower values at higher temperatures.

As for the correlation between deformation degree and flow stress, term 1 yields levelled results. At a low deformation degree, too high values for σ_F are calculated, near the flow curve maximum they are too low, and for high deformation degrees they are again too high. Hence, term 2 is exclusively used for flow curve modelling. Despite the high multiple determination of more than 0.9800 for term 2 at several deformation degrees, differences between measured and calculated curves can occur (more than 5% in singular cases). Normally the difference between measured and calculated values increase with reduced deformation temperature, increased deformation degree and increased deformation rate.

The stress-strain curves of steels without precipitation or transformation can be defined as constants for the temperature range between 600 and 1200°C. The constants are valid for the entire temperature range, see Fig. 2.25 for the steel X2CrNiMnMoNNb21-16-5-3. In the case of the unalloyed, low-alloyed, and micro-alloyed steels, the γ-α-transformation, which ends when perlite precipitation is finished at approx. 650°C for the selected test temperature range, occurs within the temperature span of 60–100 K. Nb and V carbides are precipitated between 620 and 900°C in the case of micro-alloyed steel grades. They have an impact on the strength removal and transformation behavior. In the case of highly alloyed steels, carbides, nitrides

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and/or carbonitrides may be precipitated, which certainly has an influence on the temperature dependence of the flow stress. The highest multiple determination of the regression calculation were obtained when the applicability limits of the models were identical with the transformation temperatures. If the γ-α-transformation temperature range is included in the stress-strain curve model, deviations between the measured and the calculated flow stress also occur in models based on term 2, as can be seen in Fig.2.26 for the ferrite-perlite (F + P) area and the austenite (A) area of steel DD11. The deviations are smaller if the modelling is carried out in a temperature range where only one phase exists. This method for flow curve modelling is used for all steels that show a microstructure transformation during hot deformation.

Fig. 2.25.
Flow stress for steel X2CrNiMnMoNNb21-16-5-3 in the temperature range from 600 to 1200°C at a deformation rate of 10 s^{-1}.

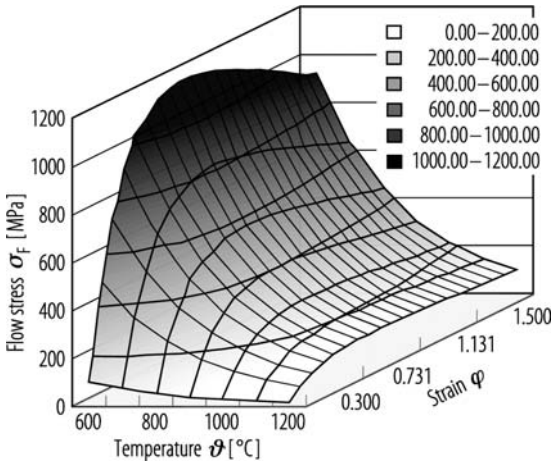
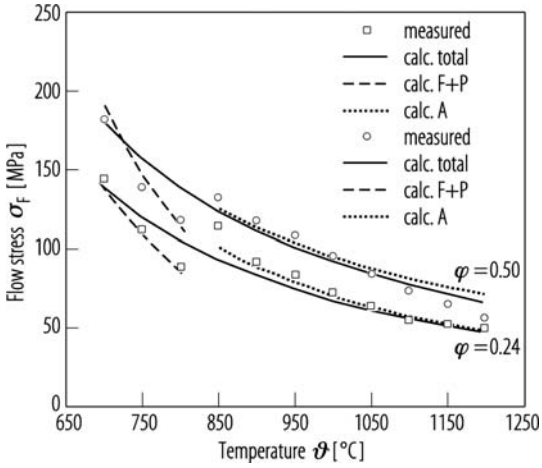


Fig. 2.26.
Stress-strain modelling for DD11 steel regarding the ferrite-perlite (F+P) and austenite (A) area



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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 und Hollomon [2.16]:

$$\dot{\varphi} = A \cdot \exp(-Q/RT) \cdot [\sinh(\alpha \cdot \sigma_F)]^n, \tag{2.12}$$

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

$$Q = -R \frac{\partial \ln \dot{\varphi}}{\partial (1/T)} \text{ for } \sigma_F = \text{const.} \tag{2.13}$$

According to equation (2.12), one can calculate the flow stress of the steady state range of the hot stress-strain curve. It assumes a linear relationship between the flow stress and the logarithm of the Zener-Hollomon parameter

$$Z = \dot{\varphi} \cdot \exp(Q/RT) \tag{2.14}$$

and requires that the activation energy of the hot forming is known.

Equation (2.12) is based on physical regularities. It seems to offer a number of advantages in flow stress calculation, as it considers the temperature and the rate impact on flow stress at the same time. The measured flow stress values found during the tests are in a relatively high agreement with the calculated results. However, the assumed linearity in equation (2.12) is no longer correct for stresses < 50 MPa, and the calculation is actually only valid for degrees of deformation that are a lot greater than in most applied technical hot forming processes. Hence numerous relationships have been developed from equation (2.12) in order to describe all ranges of the hot flow curve or to simplify it. Among those are, for example [2.17]

$$\sigma_F = A + B \cdot \ln Z, \tag{2.15}$$

where the constants A, B and the activation energy Q are determined as a function of the recorded stress-strain curves. Another approach ist given by [2.18]

$$\sigma_F = \sigma_{F,\max} \frac{\varphi}{\varphi_{\max}} \cdot \exp\left(1 - \frac{\varphi}{\varphi_{\max}}\right)^{C_\vartheta}, \varphi = const., \tag{2.16}$$

with C_ϑ a temperature dependent function.

Table 2.4 shows a comparison of measured and calculated values for the steel grade 100Cr6 (with activation energy $Q = 282314$ KJ mol^{-1}, strain $\varphi = 0.40$, strain rate $\dot{\varphi} = 0.20$ and 2.00 s^{-1} and with coefficients $A = -358.444$ and $B = 17.9257$). In this case, the activation energy represents a correction factor including all experimental inadequacies in addition to its own physical content. For low absolute flow stress values, there is no linear correlation between σ_F and ln Z, hence major deviations between the measured and the calculated values occur (see the value for 1200°C in Table 2.4). Equation (2.15) 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 dependent activation energies are compared with measured results in Fig. 2.27. The figure also shows how the linear interdependency between flow stress and the Zener-Hollomon parameter only holds for higher absolute flow stress values.

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Fig. 2.27.
Comparison of measured (symbol) and calculated (curve) flow stress results for the steel X165CrMoV12-1 for different strains φ = 0.1 and 0.4, temperatures ϑ = 900, 1000 and 1200°C.

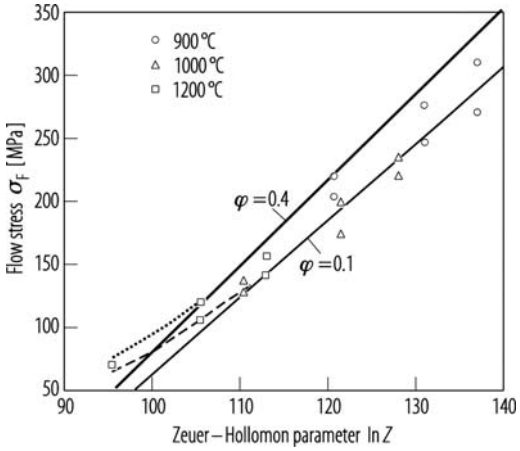


Table 2.4.
Comparison of measured and calculated flow stress σ_F for the steel 100Cr6.

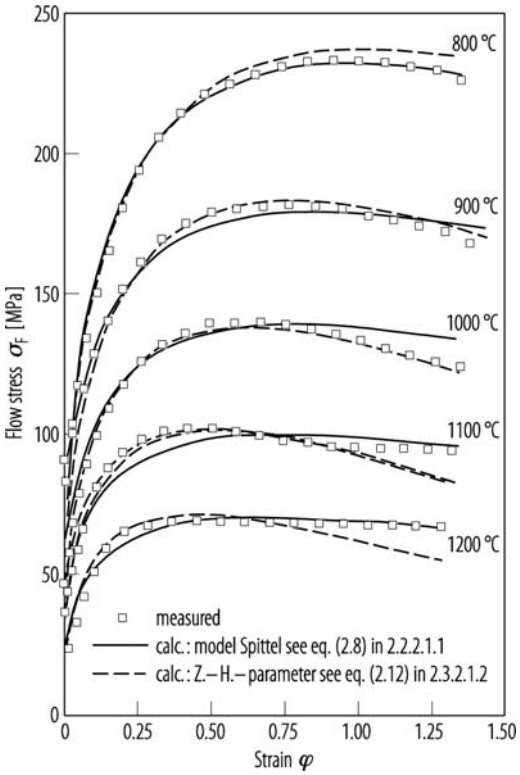
Temperature ϑ [°C]	σ_F [MPa] at $\dot{\varphi}$ = 0.20 s^{-1}		σ_F [MPa] at $\dot{\varphi}$ = 2.00 s^{-1}	
	measured	calculated	measured	calculated
800	185	180.3	220	221.5
850	158	155.0	190	196.3
900	130	131.9	162	173.2
950	105	110.6	152	151.9
1000	85	91.1	124	132.4
1050	68	73.0	108	114.3
1100	52	56.2	93	97.5
1150	40	40.6	76	81.9
1200	34	26.1	50	67.4

The use of equation (2.15) for the flow stress calculation is limited to single-phase areas. A further disadvantage regarding the equations (2.15) and (2.13) is the determination of the activation energy from test results that stretch, for example in their strain rate, over approximately four decades [2.19]. Such a wide range of test conditions is necessary for the determination of the activation energy with sufficient accuracy. Even small deviations from the "correct" value lead to major differences between measured and calculated values, as the activation energy exponentially enters the calculation.

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Both base models of stress-strain curves allow calculations with relatively small deviations between measured and calculated values (Fig. 2.28), if only a sufficient number of measured values is available in a wide range of forming conditions. This applies especially for models in which the activation energy is used, since it enters the model exponentially and all measurement accuracies precipitate into this parameter.

Fig. 2.28.
Comparison of calculated (curve) and measured (symbol) flow stress values of 15NiCuMoNb5 at a strain rate of 2.10 s^{-1} and different temperatures between 800 and 1200°C.



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2.3.2.2 Cold deformation

2.3.2.2.1 Effect of the deformation degree

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

$$\sigma_F = \sigma_{F,\varphi=1.0} \cdot \varphi^{n_1} \tag{2.17}$$

or by the Ludwik-equation

$$\sigma_F = \sigma_{F,A} + \Delta\sigma_{F,\varphi=1.0} \cdot \varphi^{n_2}, \tag{2.18}$$

where $\sigma_{F,\varphi=1.0}$ is the flow stress at $\varphi = 1.0$ MPa, $\sigma_{F,A}$ is the flow stress at $\varphi = 0$ MPa; $\Delta\sigma_{F,\varphi=1.0}$ is the hardening at $\varphi = 1.0$ MPa (which equals the flow increase between $\varphi = 0$ MPa and $\varphi = 1.0$ MPa) and n is the hardening exponent ($n_1 \neq n_2$). The correlations are valid for a constant temperature and deformation rate. For steel DD13, the constants $\sigma_{F,\varphi=1.0} = 705.6$ MPa, $n_1 = 0.24343$ and a multiple determination of 0.9910 were found for equation (2.17), while the flow curve determination was based of the tensile strength of cold rolled samples.

As $\sigma_F = 0$ for $\varphi = 0$, equation (2.17) is not suitable for low deformation degrees, for instance at skin pass rolling. Furthermore the equation does not consider the strength at the beginning of processing, which can be easily determined but is often a factor of uncertainty, for instance after heat treatments. These disadvantages can be avoided in equation (2.18), where the constants were found as $\sigma_{F,A} = 257.9$ MPa, $\Delta\sigma_{F,\varphi=1.0} = 467.8$ MPa, $n_2 = 0.52581$ and a multiple determination of 0.9500 for steel DD13. The low multiple determination for equation (2.18) is due to the fact that two deformation ranges exist at cold rolling of unalloyed and alloyed steels, and in both the hardening coefficient is constant ("double-n-behavior"). If this phenomenon is considered, we have

- $\varphi = 0.0\ldots0.20$: $\sigma_{F,A} = 259.0$ MPa, $\Delta\sigma_{F,\varphi=1.0} = 811.5$ MPa, $n_2 = 0.79424$, multiple determination 0.9964;
- $\varphi = 0.21\ldots1.50$: $\sigma_{F,A} = 259.0$ MPa, $\Delta\sigma_{F,\varphi=1.0} = 439.2$ MPa, $n_2 = 0.34673$, multiple determination 0.9876.

At beginning of deformation, the hardening is obviously nearly twice as high as at strong deformations.

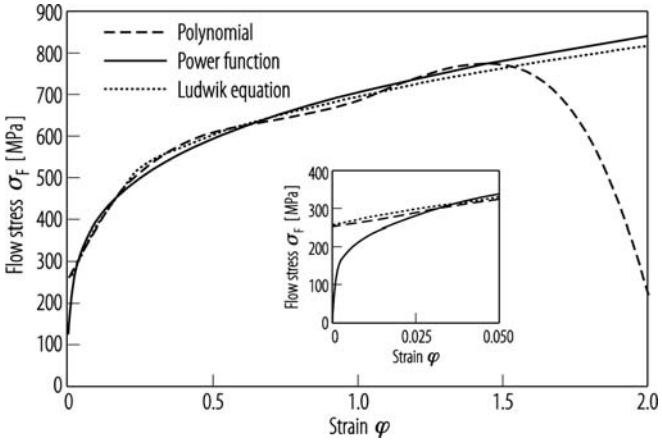
The cold flow curve at constant temperature is reflected by a polynomial function

$$\sigma_F = \sigma_{F,A} + C_1\varphi + C_2\varphi^2 + C_3\varphi^3 + C_4\varphi^4, \tag{2.19}$$

with $C_1,\ldots, C_4$ material related constants. It very well correlates measured and calculated values. Even though for $\varphi = 0$ the regression analysis delivers a finite value, this flow stress description causes no trouble, because it is only valid in the range of existing values for the deformation degree. An extrapolation beyond that range leads to drastical deviations between measured and calculated data, as the extrapolation is not based on physical laws (Fig. 2.29). Within the validity area of $\varphi = 0\ldots1.50$ for DD13, the constants were calculated as

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Fig. 2.29.
Description of the flow curve of steel DD13 by an exponential and a polynomial function (2.19) at room temperature.



	$\sigma_{F,A}$ [MPa]	C_1	C_2	C_3	C_4	multiple determination
DD13	257.9	1592.6	−2699.6	2136.0	−594.77	0.9983

The equations (2.16) to (2.18) only allow a rough estimation of flow curves, because they only include the influence of the deformation degree and, as a rule, were determined at room temperature and low deformation rates. This does not coincide with real deformation conditions within the deformation zone of cold deformation processes.

2.3.2.2.2 Influence of deformation degree, deformation temperature and deformation rate

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

$$\sigma_F = A \cdot K_\vartheta \cdot K_\varphi \cdot K_{\dot\varphi}. \tag{2.20}$$

K_ϑ, K_φ and $K_{\dot\varphi}$ are the correction functions for the influence of the deformation temperature, deformation degree and deformation rate, respectively. At hot deformation, equation (2.20) is identical with (2.5). For the thermodynamical factors K_ϑ, K_φ and $K_{\dot\varphi}$ exponential functions based on physical laws are used:

$$K_\vartheta = A_1 \cdot e^{m_1\vartheta}, K_\varphi = A_2 \cdot \varphi^{m_2} \cdot e^{m_4/\varphi}, K_{\dot\varphi} = A_3 \cdot \dot\varphi^{m_3}. \tag{2.21}$$

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

$$\sigma_F = \sigma_{F,0} \cdot A_1 \cdot A_2 \cdot A_3 \cdot e^{m_1\vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot\varphi^{m_3}. \tag{2.22}$$

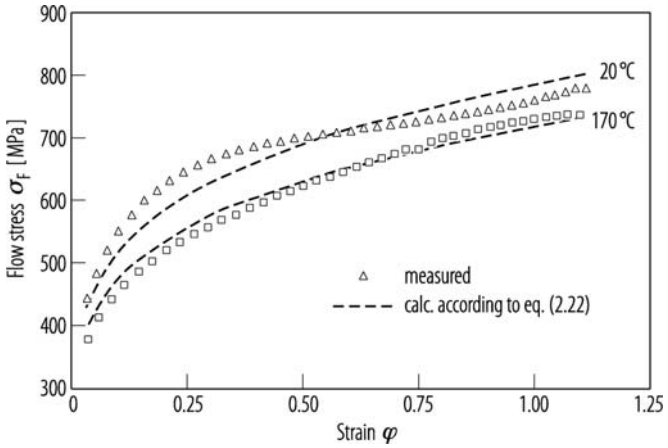
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The constants A_1, A_2 and A_3 result from the definition that $K_{\vartheta\,=\,20°C}$, $K_{\varphi\,=\,0.10}$ and $K_{\dot{\varphi}=10\,s^{-1}}$ are set as 1.000:

$$A_1 = e^{-20m_1}, A_2 = (0.10)^{-m_2} \cdot e^{-m_4/0.10}, A_3 = 10^{-m_3}. \quad (2.23)$$

Fig. 2.30 shows the correlation between the thermodynamical factors K_ϑ, K_φ and $K_{\dot{\varphi}}$ and deformation degree φ, deformation rate $\dot{\varphi}$ as deformation temperature ϑ for steel S235JRG2. The deformation degree is the main influence variable on the flow stress. An increase of the deformation rate from 10^{-3} s^{-1} to 100 s^{-1} leads to a flow stress raise by only ca. 19%, and a temperature increase of 20°C compared to ϑ = 170°C reduces σ_F by ca. 10.5%. Besides the deformation degree, also the material composition strongly influences the flow stress, as can be clearly seen in Fig. 2.30.

Fig. 2.30.
Comparison between measured and calculated flow stresses σ_F for steel S235JRG2 at temperatures 20°C and 170°C.



Hardening processes change with rising temperature, especially in the blue-brittleness range. In order to improve the precision of flow curve calculations at higher temperatures and deformation rates, it is hence useful to insert a temperature dependent factor in the functions K_φ and $K_{\dot{\varphi}}$. However, even considering the deformation heat, cold deformation occurs mostly at temperatures below the blue-brittle range, which is why flow curve calculations according to equation (2.22) are sufficient in this case and shall be used in Chapter 5 for all steel data sheets.

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3 Plasticity of steel

Introduction and Definitions

The plastic behaviour of metallic materials during hot deformation can be assessed objectively only if reliable information about their plasticity is available. The plasticity, being the strain level up to which a material can be deformed without cracking, permits to define the optimal temperatures and rate ranges for a shaping process. If hot deformation is used to achieve the maximum plasticity, a high yield, satisfactory surface finish and accuracy to size are required. In the case of primary deformations, i.e. deformation from the as-cast condition, a detailed knowledge of plasticity is essential, because it limits the strain potential.

3.1 Hot plasticity

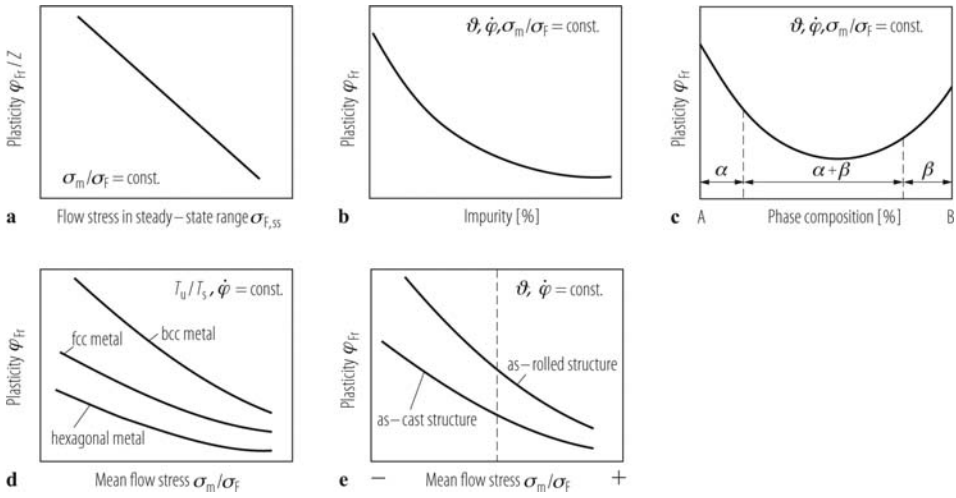
Fig. 3.1 and 3.2 summarize schematically the influence of material and process related factors on the plasticity at hot deformation. In the following chapters, the most important parameters will be discussed by means of typical examples.

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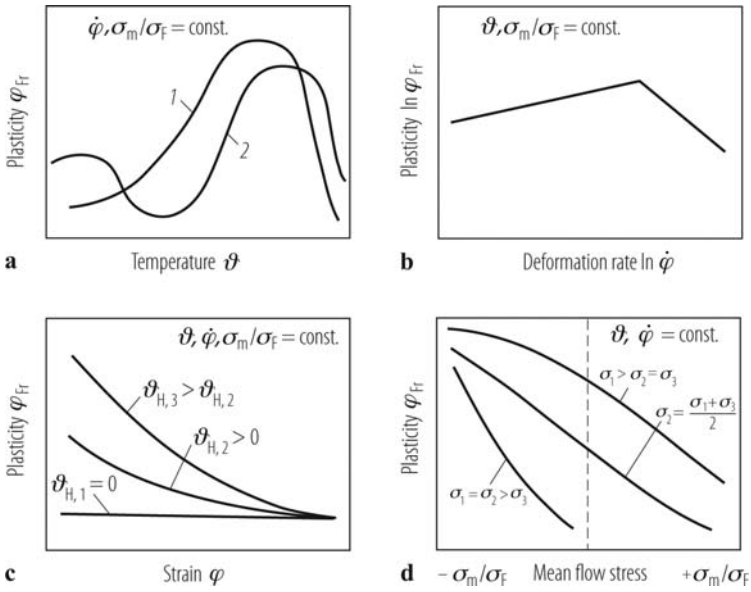
Fig. 3.1.

Influences of material related factors on the plasticity at hot deformation. (a) Material: In the single-phase range, the plasticity of steels is reduced with rising flow stress σ_F in the steady state range $\sigma_{F,ss}$. Z denotes the Zener-Hollomon-Parameter, σ_m/σ_F is the mean flow stress. (b) Purity: At equal deformation conditions, the plasticity deteriorates by impurities and admixtures. (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 of face-centred cubic and hexagonal metals (with deformation temperature T_u and solidus temperature T_s). (e) Initial structure: The plasticity of an as-cast structure lower by a factor 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 disperses heavily.



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Fig. 3.2.
Process related parameters at hot deformation. (a) Deformation temperature: At single-phase materials (1), the plasticity rises with higher temperatures up to 0.78…0.90 T_{melt} [K]. The continuous increase is interrupted by phase transformations and ranges with embrittlement (2). During phase transformations, super plasticity can appear. (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 might occur. (c) Holding time: If the strain up to the interruption is smaller than the deformation degree of the flow curve maximum, the plasticity increases The longer the holding time ϑ_H and the smaller the deformation degree before the interruption is, the steeper the increase. (d) Mean stress: The placticity is strongly influenced by the mean flow stress σ_m/σ_F and the ratio of the main normal stresses. Compression stresses yield a high plasticity, tensile stresses a lower plasticity.

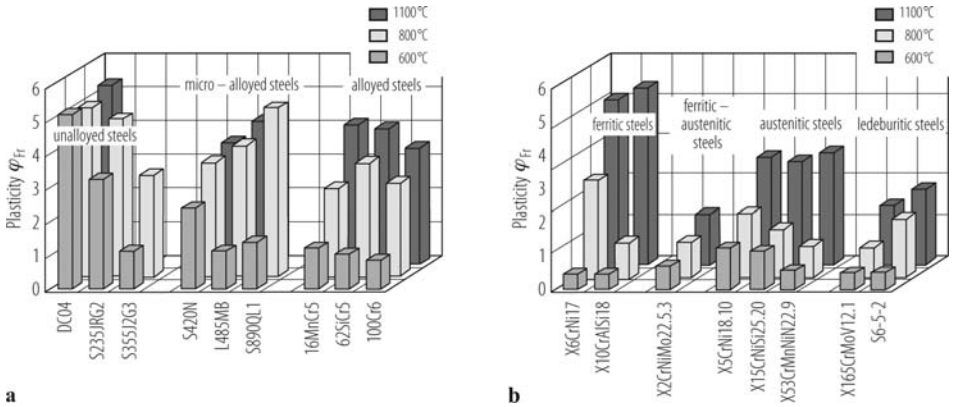


3.1.1 Influence of the material

As can be seen in Fig. 3.3, the plasticities φ_{Fr} of various steels strongly depend on the material groups and the steel grades for all three temperatures in consideration. Among the highly alloyed steels, ferritic grades have the highest and the two-phase ferritic-austenitic grade X2CrNiMoN22-5-3 has the lowest placitiy. The limited hot plasticity of ledeburitic steels is due to their hardly soluble carbides. While the influence of the chemical composition on hot plasticity becomes smaller at 1100°C, the plasticity decreases with increasing alloy content in the lower hot deformation range. Although each alloyant reacts differently, the hot plasticity generally decreases in unalloyed and alloyed steels with increasing alloying content.

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Fig. 3.3.
(a) Hot plasticity φ_{Fr} of unalloyed and alloyed steels (b) Hot plasticity φ_{Fr} of highly alloyed steels.



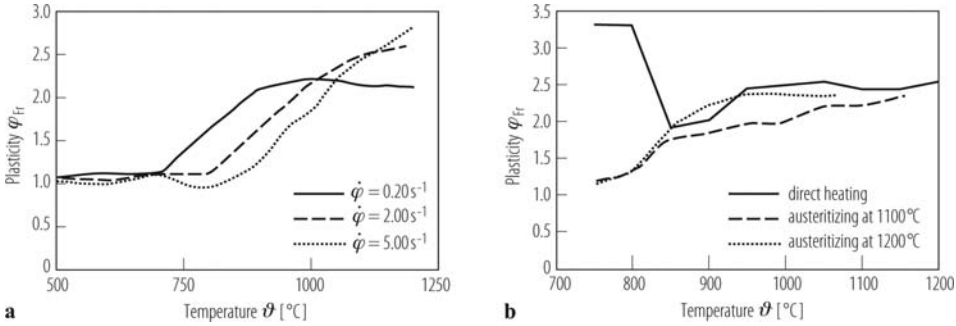
At temperatures below 600°C, a limited plasticity compared with the the plasticity under usual hot deformation conditions must generally be expected in all steels. Low-carbon grades DC01,…,DC04 are an exception, as they can be easily deformed even at 600°C.

3.1.2 Influence of temperature and strain rate

The plasticity of transformation-free steel grade X15CrNiSi 25-20 is shown in Fig. 3.4a for three strain rates in the temperature range between 500 and 1200°C. It increases continuously as the temperature rises. Increasing strain rates improve the plastic properties of the material above 1050°C. The plasticity of steels in which a α-γ- or γ-α-transformation occurs during deformation is determined by the temperature, but mainly by the phase condition. In the case of steel grade P295GH, the selected test method implies that the plasticity is drastically reduced between 650 and 700°C. The ferrite formation occurs at approx. 795°C and the perlite formation at 680°C.

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Fig. 3.4.
(a) Hot plasticity of X15CrNiSi25-20 as a function of the temperature at different strain rates 0.20, 2.00, 5.00 s^{-1}. (b) Influence of the heating method on the hot plasticity of X20Cr13 as a function of the temperature.



If cooling from the austenitic region takes place at a mean rate of 17.5 K/min, which was the rate in our tests, the transformation of the structure is complete at 655°C. The structure consists of 88% ferrite and 12% perlite. The plasticity of steel P295GH is restricted by the temperature level at which perlite, i.e. Fe_3C streaks, exists in the structure. The size and distribution of the carbides plays an important role in this context. Examining the plasticity of stainless grade X20Cr13 by heating the samples to the test temperature, maintaining the test temperature for 10 min and subsequently twisting the pieces results in the solid curve shown in Fig. 3.4b (direct heating up to deformation temperature). Austenite formation starts at 840°C and is complete at 930°C, in accordance with the time-temperature heat-up diagram. The globular carbides $(Fe,Cr)_{23}C_6$ are dissolved at 1030°C, from when on the structure consists of homogenous austenite. The high plasticity encountered at temperatures below 800°C is due to a ferritic matrix offering a better sliding capability than in the austenitic case. This implies that the occurrence of austenite in a structure leads to a reduction in hot plasticity and that globular carbides, contrary to streaky perlite, hardly influence the hot plasticity.

Austenitizing this steel at 1100 and 1200°C (dashed curves in Fig. 3.4b), which is the homogeneous austenite region, and cooling it down at 17.5 K/min to the test temperature leads to a plasticity above 850°C that only insignificantly differs from the values of the other methods. The differences can be attributed to coarser grain. On account of the supercooling effect during the γ-α-transformation, the transformation temperature is not even reached at 700°C at the above cooling rate, and the structure is austenite with separated globular carbides. This effect may lead to considerable differences in hot plasticity at identical temperatures. Such behavior is typical for rather highly alloyed perlitic grades (e.g. X20Cr13), martensitic grades (e.g. X90CrMoV18) and ledeburitic steels (e.g. X210CrW12, S6-5-1). In order to avoid wrong conclusions, it is therefore necessary to examine the hot plasticity in a temperature-time situation that is very similar to the practical situation to be assessed.

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3.1.3 Influence of the stress condition

The mean stress value

$$\sigma_m/\sigma_F := (\sigma_1 + \sigma_2 + \sigma_3)/\sigma_F \tag{3.1}$$

has a decisive impact on hot plasticity, as also the relationship between the mean normal stress values σ_1, σ_2 and σ_3 plays an important role. The plasticity is higher under compressive stress (negative related mean stress value) than under tensile stress. This basic dependence explains the difference in a material's deformation behavior when subjected to different shaping methods. The related mean stress value is nearly zero in a torsion test, which is usually employed for the determination of plasticity.

The influence of the mean stress value on the equivalent strain at fracture is confirmed when testing the steel S6-5-2 by several different methods (see Table 3.1). A constant hot plasticity was noticed in the cylinder upsetting test.

Table 3.1.
Strain at fracture for the steel S6-5-2.

	σ_m/σ_F	$\varphi_{800°C}$	$\varphi_{1000°C}$	$\varphi_{1200°C}$
Cylinder upsetting test	−0.33	> 1.80	> 1.80	> 1.80
Torsion test	≈ 0	2.121	1.402	1.355
Tensile test	+0.33	0.369	0.708	0.052
Notched tensile test	+0.65	0.165	0.303	0.506

3.2 Cold plasticity

3.2.1 Factors influencing cold plasticity

Besides the material itself and in particular its chemical composition and structural condition, the most important factors influencing cold plasticity are the stress condition during the deformation (expressed by the mean stress value σ_m/σ_F and the main normal stress interrelations), the temperature and a possibly existing pre-strain (i.e. pre-work hardness) [3.1, 3.2]. Many material and process factors of influence are interdependent, which 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 numerous cases.

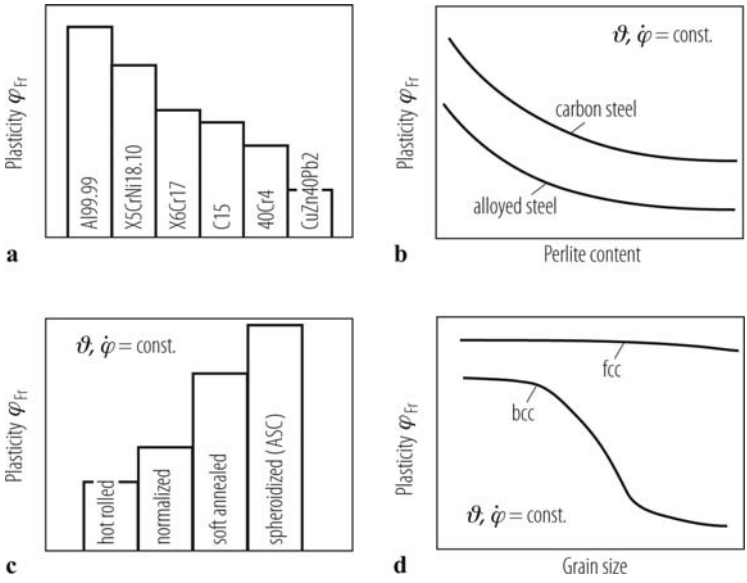
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3.2.2 Cold plasticity parameters

The influence of material and process related factors on plasticty at cold deformation is discussed in Fig. 3.5 and Fig. 3.6. In this publication the torsion test was used for the plasticity measurement at cold deformation, and the results were combined with results from tensile and notch impact tests as well as from deformation facilities.

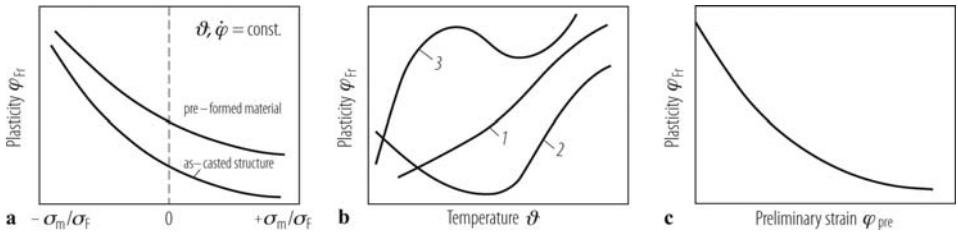
Fig. 3.5.

Influence of material related parameters on the plasticity at cold deformation. (a) Material: The plasticity at cold deformation strongly depends on the material properties. It can be widely affected by heat treatment (solution annealing, recrystallization annealing etc.). (b) Perlite content: A rising perlite content causes reduced cold plasticity (c) Heat treatment condition: Apart from annealing temperature and time or the re-heating and cooling rate, the heat treatment condition drastically affects cold plasticity. (d) Grain size: In face centred cubic (fcc) materials, the cold plasticity decreases less steeply with higher grain size. In body centred cubic (bcc) materials, the transition from ductile to brittle occurs in a small grain size range.



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Fig. 3.6.
Influence of process related parameters on the plasticity at cold deformation. (a) Initial structure: Pre-formed material conditions lead to a higher plasticity than materials with an as-casted structure. Also, as-casted structures are more sensitive to tensile stresses. (b) Deformation temperature: If the phase structure is constant, φ_{Fr} raises in the temperature range of cold deformation (curve *1*). At hot deformation this curve is continuous and uninterrupted unless phase transformations, precipitations and solution processes occur. For example a minimum exists for C-steels due to blue brittleness (curve *2*), and a local maximum appears at austenitic steels caused by martensite dissolution (curve *3*). (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 hardening), whereas the Bauschinger effect appears at alternating load.



Other than the process related factors named in Fig. 3.6, the related mean stress value σ_m/σ_F as well as the relation between the main normal stresses among each other have an essential effect on the plasticity, with high φ_{Fr} at compression stress and low φ_{Fr} at tensile stress, corresponding to the hot deformation in Fig. 3.2 (d).

Beside the differences in absolute value of the cold plasticity caused by the mean stress value, the multiplicity of test procedures entails different characteristic values. If standard test procedures including technological test methods for flat products, rods and tubes are used, the user of metallurgical products can get appropriate plasticity data.

Table 3.2 contains cold strain before rupture data for a number of plain carbon and highly alloyed steels. All data reflect the test results from several melts, sometimes even from several steel mills, for the indicated heat treatment condition. The scattering band is relatively narrow. A wider scattering band, caused by analysis variations, differing δ-ferrite contents, presence of transformation martensite and metallurgical factors (steelmaking method, ingot size), was only found for high-alloy austenitic cold heating steels. For ferritic steels, the scattering band is also widened by grain coarsening in addition to a reduction in cold plasticity (see X3CrTi17).

Table 3.2.
Strain before rupture φ_{Fr} of steels at room temperature.

Steel grade	Heat treatment	Strain at rupture
C15	As-rolled condition	0.929…0.971
	680°C/45 min/furnace	1.084…1.136
C60	680°C/45 min/furnace	0.884…0.913
C100	720°C/45 min/furnace	0.466…0.512
16MnCr5	720°C/45 min/furnace	0.986…1.047

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Table 3.2. (continued)

Steel grade	Heat treatment	Strain at rupture
100Cr6	As-rolled condition	0.230…0.290
	800°C/210 min/furnace	0.738…0.804
X7Cr14	780°C/120 min/air	0.733…1.127
X3CrTi17	1200°C/120 min/air	0.671…0.909
	1000°C/120 min/air	1.069…1.192
	800°C/120 min/air	1.426…1.464
X20Cr13	790°C/45 min/furnace	0.486…0.522
X5CrNi18-10	1020°C/30 min/water	0.844…1.302
X5CrNiMo17-12-2	1020°C/30 min/water	0.790…1.320
X3CrNiCu18-9	1020°C/30 min/water	0.943…0.985
X6CrNiTi18-10	1020°C/30 min/water	0.944…1.197

Changes in material condition lead to pronounced differences in the strain limit before rupture during cold torsion. For example, the soft annealing of C15 leads to a 15% increase compared to the hot rolled condition. And in unstabilized austenitic CrNiMo steels, cold deformation producing a necking of 10% lowers the strain limit before rupture from 1.038 to 0.936. Apart from the material's influence on cold plasticity, there is also a significant influence of the treatment conditions.

Table 3.3 characterizes the deformation behavior of steels. Beside the equivalent strain φ_{Fr} at fracture, it also contains parameters such as yield and tensile strength or elongation from tensile tests. It is remarkable that there is no correlation between the elongation (as a parameter for plasticity at tensile tests) and the deformation degree at fracture found in cold torsion tests at the same temperature.

Table 3.3.
Parameters of steel plasticity φ_{Fr} at room temperature.

Steel grade	Tensile test		Torsion test	
	Yield point R_p [MPa]	Tensile strength R_m [MPa]	Elongation A_5 [%]	Equiv. strain φ_{Fr} [-]
C 15 hot rolled	302	433	25	0.971
C 15 soft annealed	238	399	32	1.136
36Mn5 normalised	457	735	34	0.797
100Cr6 soft annealed	420	771	28	0.584
X20Cr13 soft annealed	396	712	25	0.732

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Table 3.3. (continued)

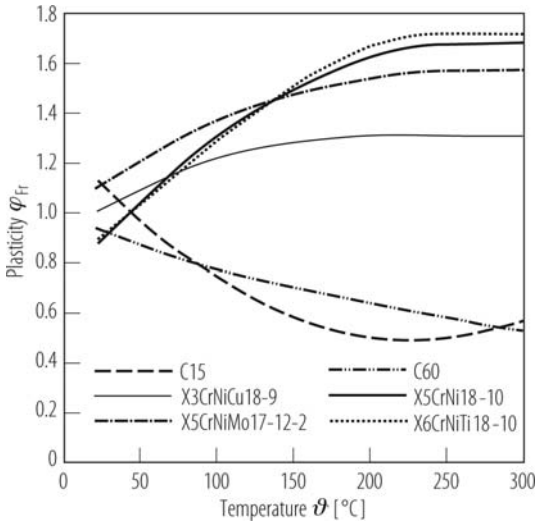
Steel grade	Tensile test		Torsion test	
	Yield point R_p [MPa]	Tensile strength R_m [MPa]	Elongation A_5 [%]	Equiv. strain φ_{Fr} [-]
X3CrTi17 recrystallised	260	453	39	1.200
X5CrNi18-10 austenitised	322	610	53	0.851
X5CrNiMo17-12-2 austenitised	330	626	54	0.789

Austenitic steels show high elongations in combination with a low deformation degree at fracture, while steel C15 has a very low elongation of 25%, but a high deformation degree at fracture. Even at nearly the same elongation very different equivalent strains at fracture can appear, which indicates the existence of a correlation between the microstructure of the materials and the three axial stress states at torsion test.

In general, the knowledge of plasticity at room temperature is not sufficient, as the deformation heat leads to a rising temperature by 50…250 K inside the deformed material, depending on the material, the reduction and the deformation process.

Fig. 3.7 shows the temperature dependence of the plasticity φ_{Fr} for C- steels and austenitic steels. In the range of blue brittleness, it decreases remarkably compared to room temperature. It then rises up to its maximum value near 0.80…0.85 T_s, where T_s is the absolute melting temperature. These basic characteristics were also found for alloyed steels such as case-hardening steels, heat-treatment steels and tool steels.

Fig. 3.7.
Plasticity φ_{Fr} of carbon and austenitic steels as a function of the temperature ϑ.

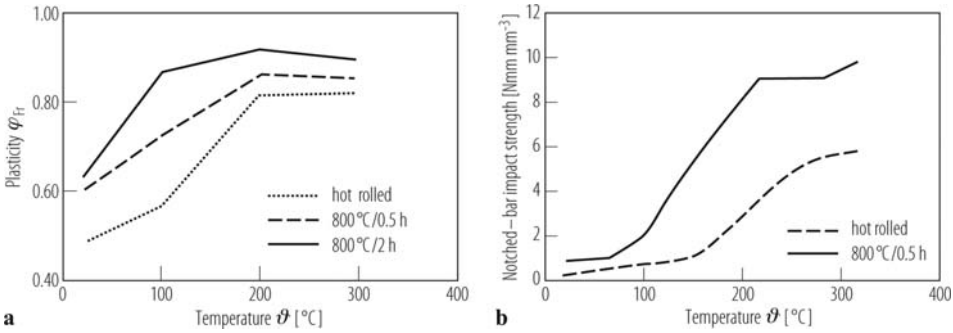


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The plasticity of austenitic steels rises with higher temperatures by dissolution of deformation martensite. The ascent depends on the Cr-Ni-equivalent, i.e. the austenite stability. In the range of the so-called "semi-hot deformation", the plasticity decreases again because of the lower softening rates at higher temperatures for these steels. If dynamic softening is applied, the plasticity improves again with rising temperatures.

Fig. 3.8 shows the characteristics of the equivalent strain at fracture φ_{Fr} and the notch impact toughness for different conditions and test temperatures of steel X10CrA1Si18. Qualitatively, the temperature dependence of both parameters is the same: both increase rapidly with rising temperature, while the elongation is reduced. A deformation to high quality tubes of this steel in hot rolled condition by the cold pilger rolling process is possible only at temperatures > 200°C and reductions > 50 %.

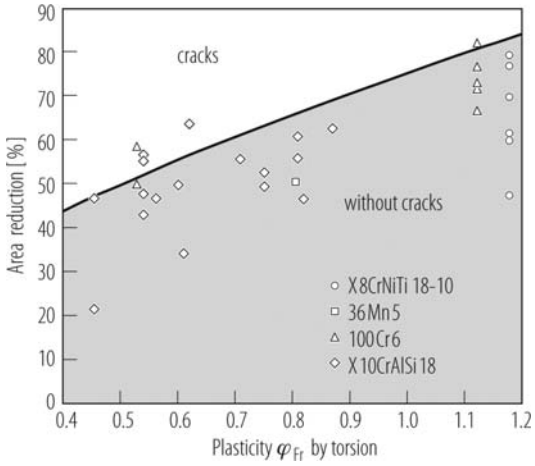
Fig. 3.8.
(a) Equivalent strain at fracture φ_{Fr} and (b) notch impact toughness versus test temperature ϑ for steel X10CrAlSi18.



The plasticity and the notched-bar impact strength accurately reflect the material behavior during plastic deformation in practice related conditions. The cold torsion test with a L/D-relation of 2.0…3.0 is a test alternative for cold plasticity, and it eliminates some disadvantages of the notch impact test. Fig. 3.9 shows the correlation between the area reduction and the equivalent strain at fracture for the cold pilger rolling process. Basically the area reduction increases with a higher deformation at fracture. If the pilger process starts above the line in the diagram, cracks with a length > 100 mm appear parallel to the tube axis, and at ferritic steels additionally transverse cracks occur.

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Fig. 3.9.
Correlation between the area reduction at cold pilger rolling and the equivalent strain φ_{Fr} in torsion tests.



3.3 Modelling of the plasticity by hot working

3.3.1 Modelling of the influence of the chemical composition

For unalloyed carbon steels in torsion tests, the influence of the carbon content c (in mass-%) on the hot plasticity φ_{Fr} at a fixed temperature can be expressed by

$$\varphi_{Fr} = A \cdot c^B \cdot e^{\frac{C+cD}{c}}, \tag{3.2}$$

with A, B, C and D constants. Fig. 3.10 shows the influence of alloying and accompanying elements on the hot plasticity of austenitic Cr-Ni-steels in correlation to their chemistry at cross rolling temperature. The plasticity was determined at the same deformation conditions for multiple heats, in some cases their chemical composition was outside the standardized analysis for Cr-Ni-steels. According to Nadai-Mises, the absolute value for the plasticity is obtained by multiplying the basic plasticity value at 1150°C with "influencing functions" for alloying and accompanying elements:

$$\varphi_{Fr} = \varphi_{Fr-0} \cdot K(\mathrm{Cr}) \cdot K(\mathrm{Ni}) \cdot K(\mathrm{Mn}) \cdot K(\mathrm{S}) \cdot K(\mathrm{Cu}) \cdot K(\mathrm{Mo}) \cdot K(\delta\text{–ferrite}), \tag{3.3}$$

with $\varphi_{Fr-0} = 2.7155$ (at $\vartheta = 1150°C$ and $\dot{\varphi} = 0.16\ s^{-1}$. The influence of the elements Cr, Ni and Mn on the plasticity is described by a complex power or exponential function, the effect of S, Mo, Cu and δ-ferrite by a simple power function in a linear multiple regression (see Table 3.4). Rising contents of δ-ferrite, S, Cu and Mo reduce the plasticity, elements such as Ni and Mn improve it. The optimum Cr-content is approx. 16.5%, which is also related to the δ-ferrite content.

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Fig. 3.10.
Plasticity of austenitic Cr-Ni-steels and boundary contents of different alloying and accompanying elements at cross rolling of thin-walled pierced tube billets.

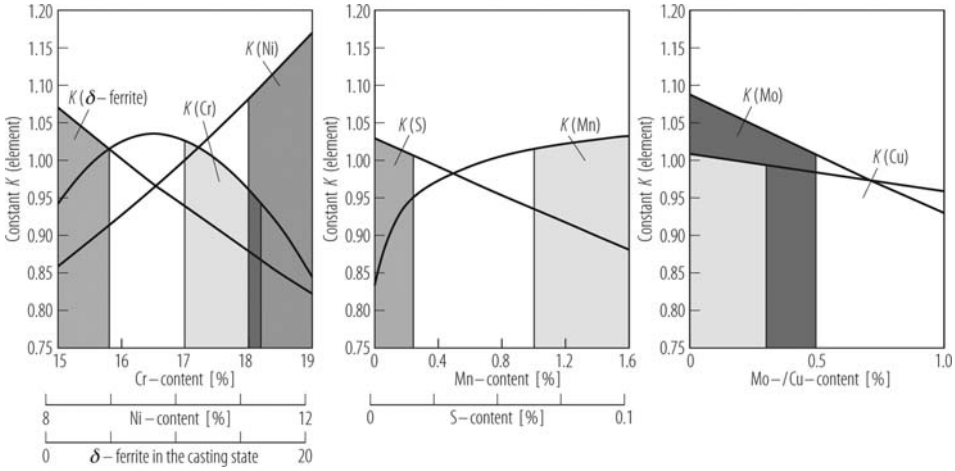


Table 3.4.
Constants for the calculation of plasticity of austenitic Cr-Ni-steels.

Element	Range of validity [%]	Equation for K_i	K_i = 1.00 at x [%]	Constants		
				A_i	B_i	C_i
Mn	0.20…1.60	$A_i \exp(B_i[\%\mathrm{Mn}]) \cdot [\%\mathrm{Mn}]^{C_i}$	0.70	1.0289	−0.0136	0.0533
S	0.01…0.10	$A_i \exp(B_i[\%\mathrm{S}])$	0.02	1.0322	−1.5851	–
Cr	14.0…19.0	$A_i \exp(B_i[\%\mathrm{Cr}]) \cdot [\%\mathrm{Cr}]^{C_i}$	17.50	$6.4205 \cdot 10^{-16}$	−1.1735	19.3974
Ni	8.0…13.0	$A_i \exp(B_i[\%\mathrm{Ni}]) \cdot [\%\mathrm{Ni}]^{C_i}$	10.00	$5.9948 \cdot 10^{-7}$	−1.0377	10.7289
Mo	0.10…0.30	$A_i \exp(B_i[\%\mathrm{Mo}])$	0.30	1.0883	−0.1572	–
Cu	0.10…0.30	$A_i \exp(B_i[\%\mathrm{Cu}])$	0.20	1.0107	−0.0534	–
δ-ferrite	1.00…23	$A_i \exp(B_i[\%\delta - \mathrm{ferrite}])$	5.00	1.0677	−0.0131	–

The diagram also contains ranges of elements and δ-ferrite where cross rolling of thin-walled Cr-Ni-steel pierced tube billets gave very good output quality [3.3]. A qualitative coherence between the results of torsion tests and the material behavior at cross rolling can be clearly seen. The lowest scrap was produced at alloying contents with the best plasticity. In [3.4] is reported how the temperature dependence of the number of rotations in torsion tests and the critical diameter reduction in cone-type piercing tests follow similar mathematical laws.

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3.3.2 Influence of deformation conditions

3.3.2.1 Modelling of temperature influence

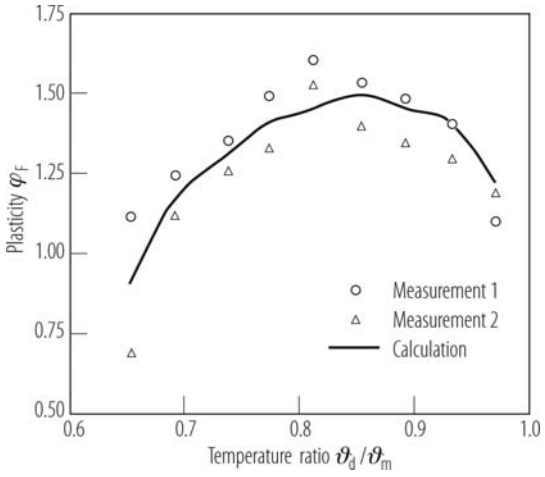
The dependence of hot plasticity on the temperature is mainly explained by the acceleration of the softening and the movement of the displacement, by the dissolution of precipitations, by phase transformations and by the grain growth and incipient grain boundary fusion at high temperatures. For example, a relationship between hot plasticity and the rate of softening exists in terms of a law of powers [3.5]. On account of the great number of processes that occur simultaneously during hot deformation, it is not possible to mathematically model their influence on hot plasticity except for limited temperature and rate ranges. For the single-phase space, the term

$$\varphi_{\mathrm{Fr}} = A + B \cdot (\vartheta_{\mathrm{d}}/\vartheta_{\mathrm{m}}) + C \cdot \ln(\vartheta_{\mathrm{d}}/\vartheta_{\mathrm{m}}) + D \cdot \ln(1 - \vartheta_{\mathrm{d}}/\vartheta_{\mathrm{m}}), \tag{3.4}$$

with $\vartheta_{\mathrm{d(m)}}$ the deformation (solidus) temperature (in °C) and A, B, C, D constants, can be used to define the influence of temperature on hot plasticity.

The above equation yields multiple determinations of > 0.9800 even for ledeburitic steels where plasticity drops from approx. 1.50 to almost 0 between 1200°C and the liquidus temperature of 1230…1240°C. Fig. 3.11 shows a comparison between measured and calculated values of hot plasticity according to equation (3.3) in a torsion test for steel X165CrMoV12. Agreement between measured and calculated results is excellent over the entire considered temperature range.

Fig. 3.11.
Hot plasticity of X165CrMoV12 in the torsion test. $\vartheta_{\mathrm{d(m)}}$ denotes the deformation (solidus) temperature (in °C).



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3.3.2.2 Modelling of strain rate influence

The influence of the strain rate on hot plasticity is relatively low (30% at most when the rate changes by three powers of ten). A correction in equation (3.3) due to the rate can be introduced by means of a product of a power and an exponential function,

$$\varphi_{\mathrm{Fr}}(\dot{\varphi}) = A \cdot \dot{\varphi}^{B} \cdot \exp(C/\dot{\varphi}), \quad \vartheta = \text{const.} \tag{3.5}$$

In the case of steel C 15 with ϑ = 1100°C and $\dot{\varphi}$ = 0.003…200 s^{-1} the constants are A = 3.959, B = 0.00612 and C = − 2.494·10^{-4}. Accordingly, the plasticity is improved by about 10% when the strain rate rises from 0.01 to 1000 s^{-1}. Modelling the influence of both strain rate and temperature on the hot plasticity based on the Zener-Hollomon parameter yielded excellent results [3.6]. However, a universal application of this method requires the knowledge of the activation energy as a material dependent physical quantity.

3.3.2.3 Modelling the influence of temperature, strain rate and stress

In general, it is possible to define the correlation between strain limits, deformation conditions and the related mean stress value by [3.7]

$$\varphi_{\mathrm{Fr}} = A_0 \cdot Z^{-a_1} \cdot \exp\left[-\frac{\sigma_{\mathrm{m}}}{\sigma_{\mathrm{F}}}(a_2 + a_3 \cdot \ln Z)\right] = \exp\left[a_0 - a_1 \ln Z - a_2 \frac{\sigma_{\mathrm{m}}}{\sigma_{\mathrm{F}}} - a_3 \cdot \ln Z \frac{\sigma_{\mathrm{m}}}{\sigma_{\mathrm{F}}}\right], \tag{3.6}$$

with a_0 to a_3 constants, Z the Zener-Hollomon parameter from equation (2.14), σ_{m} the mean stress value (in MPa) and σ_{F} the flow stress (in MPa). However, this general correlation is presently still under investigation, and in most cases a linear multiple regression is used instead. After rearrangement (3.6) reads

$$\varphi_{\mathrm{Fr}} = \exp\left(b_0 - b_1 \cdot \ln\dot{\varphi} - b_2 \cdot T^{-1} + b_3 \cdot \ln Z \cdot \frac{\sigma_{\mathrm{m}}}{\sigma_{\mathrm{F}}} + b_4 \cdot \ln\dot{\varphi} \cdot \frac{\sigma_{\mathrm{m}}}{\sigma_{\mathrm{F}}}\right), \tag{3.7}$$

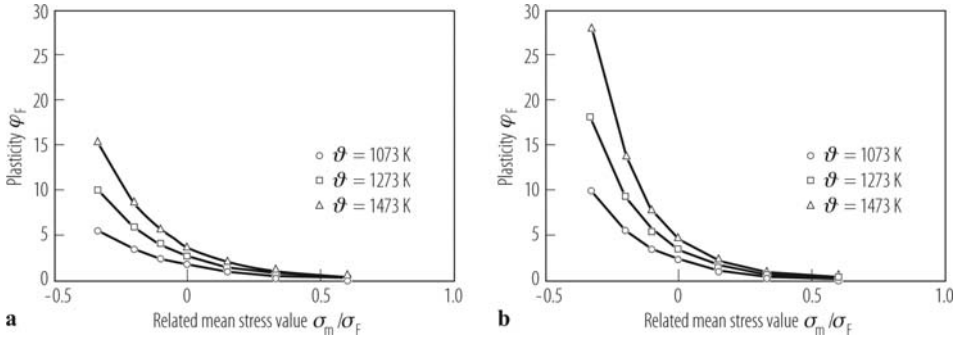
with b_0 to b_5 constants, T the temperature (in K) and $\dot{\varphi}$ the strain rate (in s^{-1}). This simple dependence is in agreement with the phenomenologic ideas of Kolmogorov [3.8]. Table 3.5 contains the constants b_0 to b_4 for one steel. They are used for calculating the strain limits and are very close to the torsion and tensile test results. Fig. 3.12 is a graphic representation of equation (3.7) for steel 14MoV6-3 at three different temperatures.

Table 3.5.
Calculation constants for the plasticity until rupture for different steels.

Material	b_0	b_1	b_2	b_3	b_4
14MoV6-3	3.2839	0.0359	−2826	−7.392	−0.1534

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Fig. 3.12.
Relationship between strain at fracture, temperature and related mean stress value for steel 14MoV6-3 at a strain rate (a) $\dot{\varphi} = 0.1\ s^{-1}$ and (b) $\dot{\varphi} = 100\ s^{-1}$.



3.4 Considerations on metal physics

Elfmark [3.9] starts from the following conditions:

- hot deformation in the single-phase space (γ-area);
- complete cycle of dynamic recrystallization during hot deformation;
- exhaustion of the material's plasticity fracture when exceeding a given critical crack number;
- formation of crack nuclei on the grain boundaries of the recrystallizing structure in the course of which crack nuclei may get into the interior of grains;
- constant relationship between the mean strain rate and the rate of grain boundary sliding;
- correlation between the grain size in the steady state range after dynamic recrystallization and the occurring flow stress.

Relying on [3.10, 3.11, 3.12] he derived the plasticity equation

$$\varphi_{Fr} = \frac{\gamma}{\sqrt{3}} = \frac{12 \cdot \Gamma \cdot E \cdot B \cdot K \cdot T}{C \cdot \Omega \cdot D_{ov}} \cdot \exp\left(\frac{Q_V}{R \cdot T}\right) \cdot \dot{\varphi} \cdot \sigma_{F-ss}^{-(3+j)}. \tag{3.8}$$

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φ_{Fr}	Strain before rupture
γ	Shear strain
$\Gamma \approx 1.3{\cdot}10^{-4}$ J mm^{-2}	Energy necessary for crack formation
$E \approx 2.4\ldots1.1{\cdot}10^{5}$ MPa	Young's modulus
$B \approx 21$ MPa	Coefficient
$K = 1.3803{\cdot}10^{-23}$ J K^{-1}	Stefan-Boltzmann constant
T	Temperature (in K)
$C = 40$	Coefficient [3.9]
$\Omega = 2{\cdot}10^{-20}$ mm^3	Atomic volume
$D_{ov} = 18$ mm^2 s^{-1}	Diffusion coefficient (volume self-diffusion) [3.9]
$Q_V = 2.69{\cdot}10^{5}$ J mol^{-1}	Activation energy of self-diffusion
$R = 8.317$ J mol^{-1} K^{-1}	Gas constant
$\dot{\varphi}$	Strain rate (in s^{-1})
$\sigma_{F\text{-}ss}$	Yield stress in steady state range (in MPa)
$j = 1.333$	Exponent [3.9]

Using the Zener-Hollomon parameter from equation (2.14)

$$Z = \dot{\varphi} \cdot exp\left(\frac{Q}{R \cdot T}\right), \tag{3.9}$$

we obtain for the above assumptions a correlation between the strain before rupture and the yield stress in the steady state range:

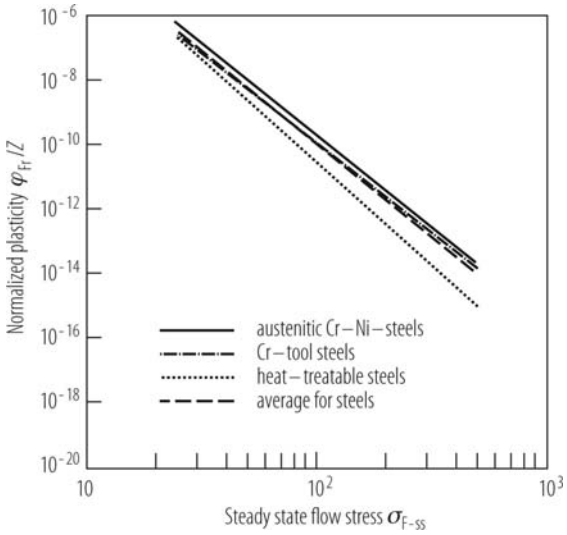
$$\frac{\varphi_{Fr}}{Z} = \frac{\gamma}{\sqrt{3} \cdot Z} = 0.42 \cdot \sigma_{F-ss}^{-4.33}. \tag{3.10}$$

However, setting the entire first fraction in equation (3.8) is not quite correct, because the temperature T is a variable and the Young's modulus is a function of the temperature.

When evaluating the scattering band of the measurement results of the plasticity as a function of the steady state range yield stress for 15 plain carbon, alloyed and highly alloyed steels (see Fig. 3.13), we obtain a mean value curve that differs in its coefficients and exponents from equation (3.10). It is steeper, i.e. the plasticity is lower than theoretically expected, when the steady state range yield stress is higher. A calculation of the mean value curve for a given group of steel grades shows that the difference is not caused by the exponents $(3 + j)$ but by the coefficient A. Both factors are material dependent but also dependent on the strain rate.

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Fig. 3.13.
Hot plasticity φ_F as a function of steady state flow stress $\sigma_{F\text{-}ss}$. Z denotes the Zener-Hollomon parameter from equation (2.14).



Summing up, there is a correlation between yield stress and plasticity, and this correlation can be represented in a highly accurate mathematical model that is in accordance with equation (3.8) and the existing test results. But a further calculation of the plasticity dependence from the steady state range yield stress is impossible, as the variables in equation (3.8) and their dependence on the conditions of deformation are not precisely known.

3.5 Calculation of boundary deformation degrees at rolling

The octahedron slip in torsion tests is the same as the octahedron slip in the roll gap at rolling. The maximum possible deformation degree over the height φ_H at rolling is

$$\varphi_H = \frac{\varphi_{Fr}\left(1+\frac{\mu}{2}\cdot\frac{l_d}{h_m}\right)}{\sqrt{1+\frac{h_0\cdot\Delta b}{b_0\cdot\Delta h}+\left(\frac{h_0\cdot\Delta b}{b_0\cdot\Delta h}\right)^2}}, \tag{3.11}$$

with φ_{Fr} the equivalent strain at rupture in torsion tests, μ the friction value in the roll gap, l_d the contact length roll (in mm), h_m the mean height of the rolled material in the roll gap (in mm), h_0 and b_0 the height and width before rolling, respectively (in mm). Last, Δh and Δb are the variation of height and width during the pass.

Zajkov et al. [3.13] suggest an equation for calculations of the maximum deformation $\varepsilon_{H,Fr}$ at rolling that also includes structure and the microstructure conditions (as-cast or as-rolled)

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beside the plasticity in the torsion test. Correction factors reflect the effect of the material surface quality and the proportions of the rolled samples [3.14]:

$$\varepsilon_{H,Fr} = \left(1 - \sqrt[\beta n]{(1 - \varphi_{Fr} \cdot K_{cs})}\right) \cdot K_{size} \cdot K_{surf.}, \tag{3.12}$$

where $\beta = 1.155$ is the Lode coefficient, n a factor for the stress state, K_{cs} a casting state coefficient (as-cast and as-rolled condition), $K_{surf.}$ a factor for the surface quality and K_{size} a size related correction factor.

As conclusion of the possible calculation variants for the boundary deformation degree equation (3.12) we have

$$\varphi_{H,tot} = \left[\frac{\varphi_{Fr}\left(1 + \frac{\mu}{2} \cdot \frac{l_d}{h_m}\right)}{\sqrt{1 + \frac{h_0 \cdot \Delta b}{b_0 \cdot \Delta h} + \left(\frac{h_0 \cdot \Delta b}{b_0 \cdot \Delta h}\right)^2}}\right] \cdot K_{cs} \cdot K_{size} \cdot K_{surf.}. \tag{3.13}$$

3.5.1 Calculation of boundary deformation in first passes of a rod rolling mill

Plasticity calculations are based on the highest deformation degree φ_g. When rolling ingots, slabs, sheets and strips, this is the deformation degree over the height φ_h. When rolling in grooves, different deformation degrees over height and width of the section exist. These are caused by the contour of the grooves and the pass situation. The calculation is performed by transforming the profile cross section into rectangles with the same cross section area. For the calculation of the deformation degree over the height φ_h, Siebel recommends [3.15]

$$\varphi_h = \ln \frac{h_{1m}}{h_{0m}}. \tag{3.14}$$

The mean heights h_{0m} and h_{1m} before and after the stand are given by

$$h_{0m,1m} = \frac{A_{0,1}}{b_{0,1}}. \tag{3.15}$$

with $A_{0,1}$ the cross section (in mm^2) of the rolled material and $b_{0,1}$ the maximum width of the rolled material (in mm) before and after the stand. This simple method is only useful for small cross sections < 15 mm. For higher thicknesses the results do not fulfil the law of volume constancy

$$\varphi_h + \varphi_w + \varphi_l = 0 \tag{3.16}$$

anymore (see Equation 3.13), with φ_h, φ_w and φ_l the deformation degree over height, width and length.

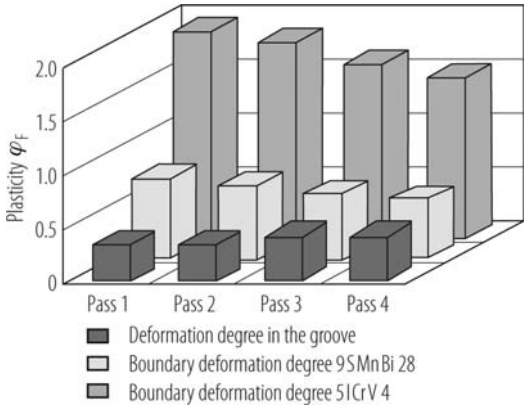
If these considerations are applied to the first four passes of a rod rolling mill, the boundary deformation degrees summarized in Table 3.6 can be obtained. However, it has to be kept in mind that continuous casted strands with a cross section of 160×160 mm are rolled in grooves (Swedish ovals). The calculated boundary deformation degrees differ considerably from the maximum deformation degree in each pass, which is shown in Fig. 3.14 for the steels 9SMnBi28 and 51CrV4.

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Table 3.6.
Geometrical parameters for the calculation of the boundary deformation degree at an initial section of 160 × 160 mm.

Pass	Height h_0 [mm]	Width b_0 [mm]	Section A_0 [mm^2]	Height h_1 [mm]	Width b_1 [mm]	Section A_1 [mm^2]	φ_h	φ_b	φ_l	$\Sigma\,\varphi$
1	160	160.0	25344	130.0	186	18465	−0.337	0.021	0.317	$8{\cdot}10^{-5}$
2	186	130.0	18465	156.0	156	14110	−0.313	0.045	0.269	0.001
3	120	120.0	14110	85.0	148.5	10710	−0.417	0.141	0.276	$1{\cdot}10^{-5}$
4	148.5	85.0	10710	105.3	105.3	8700	−0.383	0.175	0.208	$4{\cdot}10^{-5}$

Fig. 3.14.
Boundary deformation degree of steels 9SMnBi28 and 51CrV4.



3.5.2 Boundary deformation degrees at cold rolling

The equations (3.11) and (3.13) can also be used for cold rolling processes if reliable parameters about the material deformation behavior are available both from plastometer tests (tensile or flat torsion test) and from rolling trials. Considering the material's dimensions before and after rolling, the denominator in the equations becomes less significant. Hence for rolling processes the deformation degree up to the appearance of cracks is determined by the product of the plasticity and the stress state parameters.

For plasticity evaluations at cold rolling, mainly the results of tensile tests at room temperature are used. Table 3.7 summarizes the most important criteria. High plasticity at cold rolling is characterized by low strength and high toughness. For instance, the reduction of area Z should be more than 50% for highly formable steels, or the yield/tensile strength ratio should be 0.50…0.65. Values of 0.75…0.90 are typical for a low plasticity at cold rolling. It is also possible to combine these two criteria in order to obtain a maximum degree of cold rolling.

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Table 3.7.
Criteria for the evaluation of the deformation behavior at cold rolling.

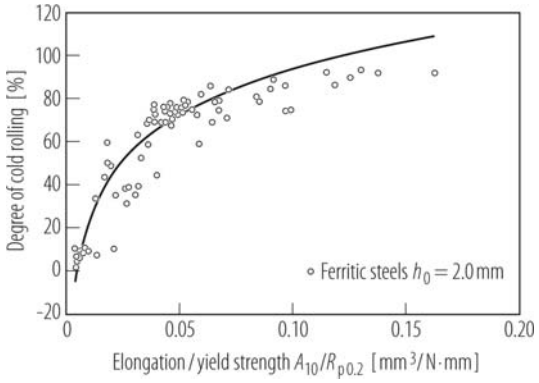
Parameter	Criteria	High degree of cold rolling
Yield/tensile strength R_e, R_m	R_e/R_m	0.5…0.65
Reduction of area Z	$\frac{Z}{1-Z}$	
Yield/tensile strength R_e/R_m, Reduction of Area Z	$\frac{R_e/R_m}{Z/100}$	1.0…1.35
Elongation A_{10}, yield strength R_e	A_{10}/R_e	> 0.05 mm^3/(N mm)
Area reduction after fracture Z_{Fr}, area reduction at the end of uniform elongation Z_G	$\frac{Z_{Fr}-Z_G}{1-Z_G}$	
Uniform elongation A_G, yield/tensile strength R_e, R_m, factor k = 0.666…0.75	$k\frac{A_G}{100}(R_m-R_e)$	> 25 N mm/mm^3

It was verified for the evaluation of the maximum degree of cold rolling for suitable values of the ratio $A_{10}/R_{p0,2}$ [3.18]. This ratio expresses the volume that can be deformed by the energy of 1.00 N mm: the higher the value, the higher the maximum degree of cold rolling. For carbon steels and low alloyed steels with ferritic, ferritic-perlitic or perlitic structures, the ratio $A_{10}/R_{p0,2}$ has values 0.01…0.15, for austenitic steels up to 0.30. The advantage of this relation is its simplicity and physical substantiation, as it includes both the effect of the initial structure as its interaction with dislocations and effects on plasticity at cold rolling up to fracture.

Fig. 3.15 shows the correlation between the ratio $A_{10}/R_{p0,2}$ and the maximum possible reduction at cold rolling without formation of cracks. It summarizes the results of rolled strips with different carbon contents, low alloyed Mn-, Si-, Cr- and Ni-steels with different portions of perlite and ferritic Cr- and Cr-Al-steels with different heat treatment conditions in a thickness range 1.80…3.0 mm [3.18]. All measured values lie within a scattering band (independent from their chemical composition and heat treatment condition) and can be described by a power function. However, compared to unalloyed and alloyed steels, some lower maximum degrees up to the formation of cracks exist at relations $A_{10}/R_{p0,2} \leq 0.03$ for ferritic steels. Possibly this is due to coarse grain at highly alloyed Cr steels.

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Fig. 3.15.
Correlation between maximum degree of cold rolling and the elongation/yield strength ratio for both unalloyed and alloyed strip steels and for ferritic steels (according to [3.17, 3.18] and own investigations).



The correlation between the maximum degree of cold rolling and the ratio $A_{10}/R_{p0,2}$ presented in Fig. 3.15 depends on the geometry of the deformation range. Hence higher $A_{10}/R_{p0,2}$ values are required to guarantee a high maximum degree of cold rolling if the initial thickness rises. The typical improvement of the maximum cold rolling degree at higher $A_{10}/R_{p0,2}$ values still holds, but the curve ascent decreases with higher initial thickness or a smaller roll gap ratio l_d/h_m. This proves that this ratio can be used as a parameter for the stress state when calculating the boundary deformation degree in equations (3.11) and (3.13).

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4.1 Mechanical properties of steel after cold deformation

Introduction and Definitions

4.1 Mechanical properties after cold deformation

Cold deformation leads to higher yield strength, tensile strength and hardness. Yet the elongation and the area reduction 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 point, 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 on the yield strength, the tensile strength and also the elongation of a material can be expressed by the Ludwik equation with a high degree of agreement between measured and calculated results.

The change in the mechanical properties caused by cold deformation can be calculated by

$$R_{\mathrm{p}} = R_{\mathrm{p,ex}} + A \cdot \varepsilon^{n_1}, \tag{4.1}$$

$$R_{\mathrm{m}} = R_{\mathrm{m,ex}} + B \cdot \varepsilon^{n_2}, \tag{4.2}$$

with

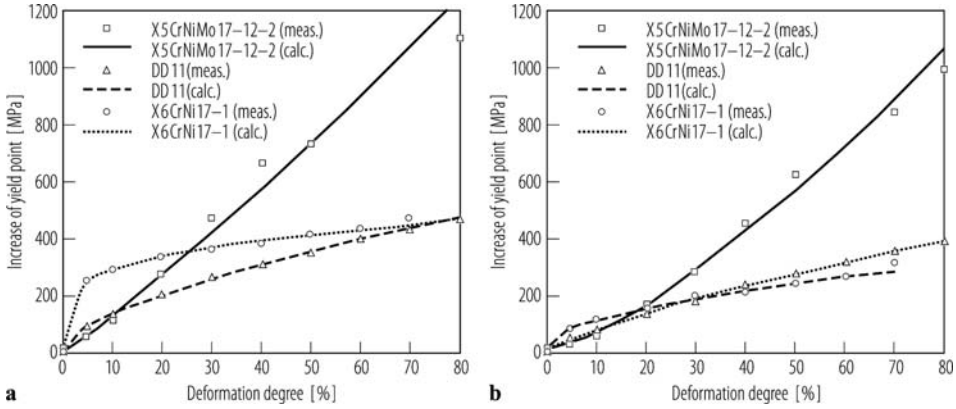
R_{p}	the yield strength (in MPa),
R_{m}	the tensile strength (in MPa),
ε	the related strain,
$R_{\mathrm{p,ex}}$	the yield strength at initial state at $\varepsilon = 0\%$,
$R_{\mathrm{m,ex}}$	the tensile strength at initial state at $\varepsilon = 0\%$

and A, B, $n_{1,2}$ constants.

Fig. 4.1 presents the correlation between yield point, tensile strength and related strain for an unalloyed, a ferritic and an austinitic steel. Obvisously the calculated and measured values are in good accordance. The influence of cold deformation (expressed by the deformation degree or the related strain) on yield point and tensile strength after cold deformation can be modelled by power and exponential functions.

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Fig. 4.1.
(a) Increase of the yield point and (b) the tensile strength as a function of the deformation degree. The shown measurement results were obtained from cold drawn and rolled samples, but are also applicable to the cold rolling of flat products.



4.1.2 Elongation

The decline of elongation at higher strain can be described by

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

The elongation is hence given by

$$A_5 = A_{5,0} - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon}, \tag{4.4}$$

where A_5 is the elongation, ε the related strain, $A_{5,0}$ the elongation at initial state at $\varepsilon = 0\%$. C and $n_{3,4}$ are constants. The correlation between the logarithm of the elongation and the strain can be mathematically described by a polynomial or by a power function approximation. For steel X5CrNi18-10 the following equations hold:

$$\Delta A_5 = 6.32102 \cdot \varepsilon^{0.47919} \cdot e^{-4.29659/\varepsilon} \tag{4.5}$$

or

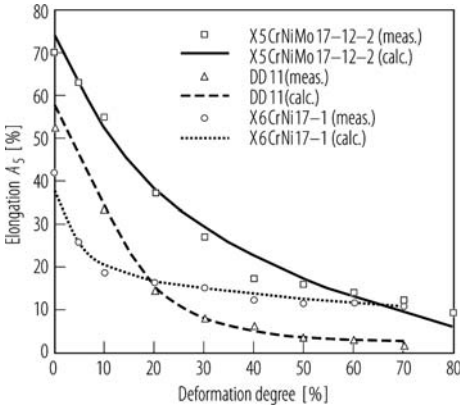
$$\ln \Delta A_5 = -0.41209 + 1.56947 \cdot \ln \varepsilon - 0.13851 \cdot (\ln \varepsilon)^2 \tag{4.6}$$

It was found that coefficients of the power functions for a special steel and treatment condition are nearly independent of the melt. The correlation coefficient of the polynomial is higher than the coefficient of the combination of power and exponential function. However, the latter should be preferred because it yields smaller divergencies for extrapolations in ranges that are not confirmed by measured values.

The decrease in elongation with higher related strain, which is reflected in equation (4.4) for the above named steels, can be seen in Fig. 4.2. The correlation between measured and calculated values is good.

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Fig. 4.2.
Elongation as a function of deformation degree. The shown measurement results were obtained from cold drawn and rolled samples, but are also applicable to the cold rolling of flat products.



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4.2 Young's modulus of steel

Introduction and Definitions

4.2.1 Definition and functional relationships

The three elastic moduli – namely the 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 through

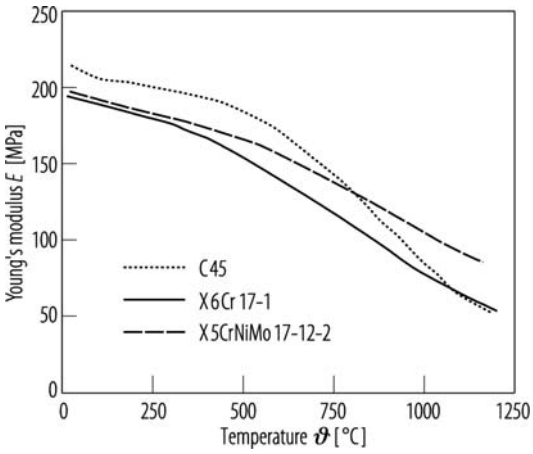
$$E = 2G \cdot (v + 1) = 3D \cdot (1 - 2v), \tag{4.7}$$

and hence

$G = E/(2(v + 1))$
$D = E/(3(v - 1))$
$v = E/(2G) - 1$

with v the Poisson ratio, i.e. a transverse contraction to the linear expansion ratio. The Poisson ratio lies between 0.25 and 0.35 for most metals. As can be seen in Table 4.1, the transverse contraction rate depends on the steel grade and temperature. At room temperature, the Young's modulus has values of 210…215 MPa for unalloyed and low alloyed steels, of 190…195 MPa for ferritic steels and of 195…200 MPa for austenitic steels. Fig. 4.3 shows the correlation between Young's modulus and temperature for the steels C45, X6CrNi17-1 and X5CrNiMo17-12-2.

Fig. 4.3.
Young's modulus as a function of temperature in C45, X6CrNi17-1 and X5CrNiMo17-12-2.



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Table 4.1.
Poisson's ratio of steels.

Temperature T [°C]	Poisson's ratio ν	
	Mild steel	Stainless steel
17	0.296	0.294
200	0.301	0.301
400	0.312	0.311
600	0.319	0.325
800	0.338	0.346
1000	0.354	0.350

The temperature coefficient α_E of the three elastic moduli changes with temperature exactly in the same manner as the coefficient of the specific heat capacity, namely

$$\alpha_E = \frac{12}{5}\pi^4 R \cdot \left(\frac{T}{\Theta}\right)^3, \quad \frac{\Theta}{T} \gg 1, \tag{4.8}$$

$$\alpha_E = 3R, \ \frac{\Theta}{T} \ll 1 \tag{4.9}$$

with R the universal gas constant, T the temperature (in K), Θ the Debye temperature (in K). This means that the Young's modulus is proportional to T^4 at low temperatures and decreases linearly for high temperatures $\Theta < T < 0.5T_s$ (with T_s the melting temperature). The Debye temperature for iron is 407 K or 420 K, depending on the calculation basis (either absolute melting temperature or specific heat capacity).

4.2.2 Temperature dependent modelling of the Young's modulus

Within the range 20…1200°C, the Young's modulus E of steels cannot be defined appropriately, neither by a temperature coefficient as in equation (4.8) nor as a linear dependence as in equation (4.9). Hence, a function containing the temperature with an exponent > 1.0 must be used, and a fourth order polynomial was chosen to define the temperature dependence of the Young's modulus of steels:

$$E(\vartheta) = E_{20°C} \cdot \left(A_1 + A_2 \cdot \vartheta + A_3 \cdot \vartheta^2 + A_4 \cdot \vartheta^3 + A_5 \cdot \vartheta^4\right), \tag{4.10}$$

with ϑ the temperature (in °C) and $A_{1,\ldots,5}$ constants. Table 4.2 lists these constants for different steels. They are valid in the temperature range 20…1000°C.

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Table 4.2.
Constants for calculation of Young's modulus for different steels.

Steel	A_1	A_2	A_3	A_4	A_5
C45	1.01248	−0.000667	0.00000226	$-3.93568\cdot10^{-9}$	$1.72698\cdot10^{-12}$
X6CrNi17-1	1.00471	−0.00235	$-6.29647\cdot10^{-8}$	$-7.89268\cdot10^{-10}$	0
X5CrNiMo17-12-2	1.00639	−0.000327	$3.75352\cdot10^{-7}$	$-9.73920\cdot10^{-10}$	0

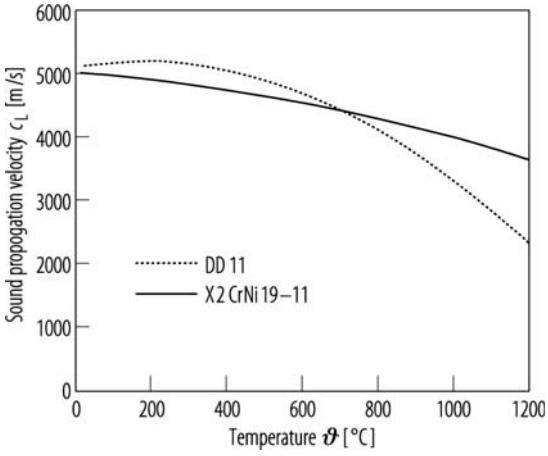
The knowledge of the Young's modulus allows the determination of the sound velocity c_L according to

$$c_L = \sqrt{\frac{E}{\rho}} \text{ in thin rods,} \tag{4.11}$$

$$c_L = \sqrt{\frac{E \cdot (1-\nu)}{\rho \cdot (1+\nu) \cdot (1-2\nu)}} \text{ in indefinite matters,} \tag{4.12}$$

with ρ the material density (in g mm^{-3}) and ν the Poisson ratio. Fig. 4.4 shows the correlation between sound propagation velocity and the temperature according to equations (4.11) and (4.12).

Fig. 4.4.
Sound propagation velocity c_L versus temperature ϑ for different steels.



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4.3 Thermal conductivity of steel

Introduction and Definitions

4.3.1 Definition of the thermal conductivity

The thermal conductivity λ characterizes the ability of a body to transfer thermal energy from one point to another if there is a temperature difference between those points. It depends on the temperature and the material. The thermal conductivity of pure iron at $T = 0°C$ is approx. 75 W/mK. According to a number of author's [4.3, …, 4.11] this is a mean value, and the measured results deviate remarkably from this value. The thermal conductivity decreases with rising temperature, and the conductivity is smallest within a narrow temperature band around the Curie temperature. Any further temperature rise leads to a new increase, which is only interrupted by the unsteadiness in the α-γ structure transformation (see Fig. 4.5) [4.3, …, 4.9, 4.12].

Fig. 4.5.
Thermal conductivity λ of pure iron in dependence of the temperature ϑ.

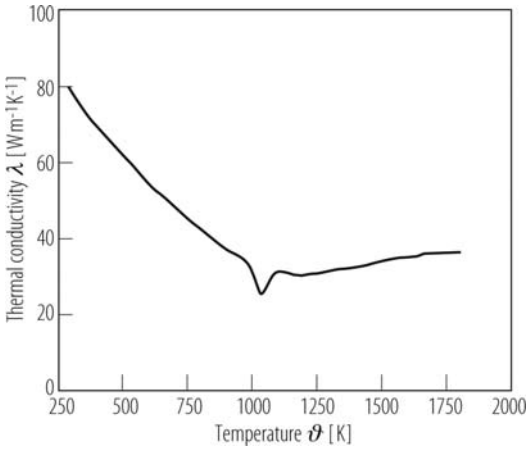


Fig. 4.6 shows how alloyants, mainly silicon, aluminium and carbon, reduce the thermal conductivity of iron alloys [4.10]. The thermal conductivity of iron alloys is further diminished by the structure of the alloy, which has a higher dislocation density.

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Fig. 4.6.
(a) Decrease and (b) complete graph of the iron thermal conductivity λ_{Fe} by various alloying elements [4.10].

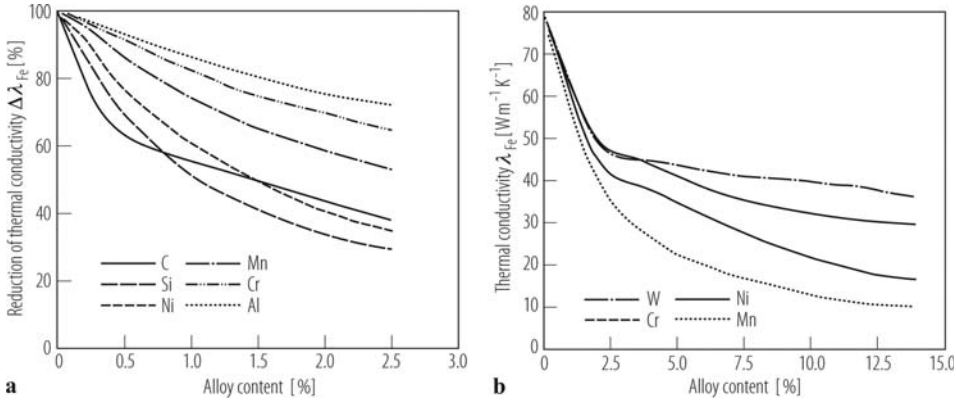
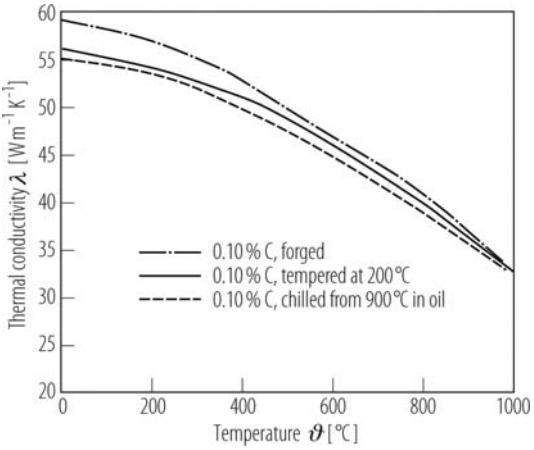


Fig. 4.7 shows the temperature dependence of the thermal conductivity for steels with different carbon content. At the same temperature the hot deformed (forged) steel has the highest, the hardened steel the lowest thermal conductivity. The dispersion results from the different structures, whose thermal conductivities $\lambda_{0°C}$ are listed in Table 4.3. Meanwhile, the grain size is of much lower significance, as can be seen in Table 4.4.

Fig. 4.7.
Influence of the microstructure condition on the thermal conductivity of steels.



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Table 4.3.
Thermal conductivities at 0°C for different carbon containing structures.

Structure	Thermal conductivity $\lambda_{0°C}$ [W/mK]
Austenite	41.9
Ferrite	76.8
Cementite	7.1
Perlite	51.9
Graphite	155.0

Table 4.4.
Dependence of the thermal conductivity at 0°C on the grain size.

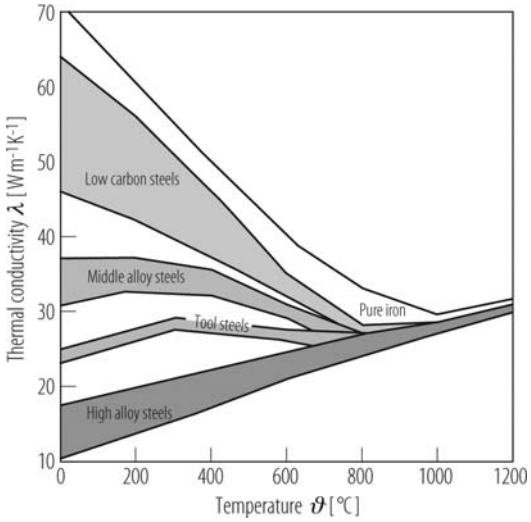
Mean number of grains/cm	Thermal conductivity $\lambda_{0°C}$ [W/mK]
11	93.0
175	90.0
644	54.0

There are three groups of steels regarding to temperature influence on the thermal conductivity (see Fig. 4.8):

- significant decrease up to ca. 800°C, followed by a slight increase (pure iron, low-carbon and low-alloy steels);
- moderate increase up to ca. 300°C, followed by a decrease up to ca. 800°C and another increase up to 1200°C (medium-alloyed steels and tool steels);
- continuous increase within the temperature range 0…1200°C (austenitic chrome nickel steels and nickel alloys).

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Fig. 4.8.
Thermal conductivity λ for selected steel grade groups.



In the temperature range 900…1200°C, the thermal conductivity assumes an almost identical value of 27…33 W/mK for all steels [4.11].

4.3.2 Thermal conductivity calculation

The calculation of the thermal conductivity follows two different paths. First, it's dependence on temperature can be alloy-specifically modelled. Second, a combined calculation from the chemical composition and the temperature influence, while the composition represents the influence of each alloyant, the total content of all alloyants and accompanying elements or the atomic ratio.

If no phase transition takes place within the temperature range under consideration, the thermal conductivity change due to temperature increase can be expressed by [4.2]

$$\lambda(T) = \lambda_{0°C} \cdot (1 + \alpha \cdot T), \tag{4.13}$$

where α is the temperature coefficient of the thermal conductivity. It is positive if the conductivity increases with rising temperature, which applies to a great number of alloys. A negative temperature coefficient is typical for numerous pure metals (Al, Cu, Mo, Ni and Fe). In the case of plain carbon and low-alloyed steels the temperature coefficient is negative between room temperature and the Curie temperature but positive in the austenitic range.

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

$$\lambda(T) = \lambda_{0°C} + B \cdot T, \tag{4.14}$$

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where B (in 1/°C) is the temperature coefficient. The results of this calculation is shown in Table 4.5 for a number of steels. Tab. 4.6 reflects the correlation between measured and calculated values of the thermal conductivity at different temperatures for the steel X5CrNi18-10. The influence of the heat treatment condition decreases with lower carbon content and rising temperature.

Table 4.5.
Constants for thermal conductivity calculation.

Material	T [°C]	$\lambda_{0°C}$ [W/mK]	B [1/°C]
C10	100…750	61.8	−0.04240
C10	900…1200	17.6	0.01010
30Mn5	0…750	48.1	−0.02230
30Mn5	900…1100	12.1	0.01500
X20CrNiSi25-4	20…1000	17.1	0.01150
X5CrNi18-10	20…750	14.3	0.01519

Table 4.6.
Measured and calculated values of the thermal conductivity for the steel X5CrNi18-10.

Temperature T [°C]	Conductivity λ [W/mK]	
	measured [4.13]	calculated by Table 4.3
0	14.0	14.5
20	14.5	14.8
100	16.0	16.0
200	17.6	17.5
300	19.1	19.1
400	20.4	20.6
500	21.9	22.1
600	23.3	23.6
700	24.7	25.1
800	26.1	26.6

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

$$\lambda(T,\psi) = \lambda_{0°C}(\psi) \cdot K_{T-\lambda}(T,\psi), \tag{4.15}$$

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where $\lambda_{0°C}$ is the thermal conductivity at 0°C for a given chemical composition, $K_{T-\lambda}$ is a temperature influence correction function (dependent on the chemical composition) and ψ is the atomic ratio

$$\psi = \sum c_i \frac{A_{\mathrm{Fe}}}{A_i} = 4.649c_{\mathrm{C}} + 1.988c_{\mathrm{Si}} + 1.016c_{\mathrm{Mn}} + 1.803c_{\mathrm{P}} + 1.742c_{\mathrm{S}} + 1.074c_{\mathrm{Cr}} + 0.951c_{\mathrm{Ni}} + 0.582c_{\mathrm{Mo}} + 1.096c_{\mathrm{V}} + 1.166c_{\mathrm{Ti}} + 0.601c_{\mathrm{Nb}} + 0.303c_{\mathrm{W}} + 2.069c_{\mathrm{Al}} + 0.879c_{\mathrm{Cu}} + \cdots \tag{4.16}$$

A_i and c_i denote the atomic mass and the mass percent of the i-th element, respectively. A_{Fe} is the atomic mass of iron. According to the differences in the temperature dependence of each steel group (plain carbon, austenitic or ferritic), the functions $\lambda_{0°C}(\psi)$ and $K_T(T, \psi)$ are structured differently. In the case of steel C75 at 0°C, the measured (calculated) thermal conductivity [4.10] is λ = 49.8 (47.2) W/mK, in the case of 1100°C the measured (calculated) conductivity was 28.6 (27.9) W/mK. Differences between measured and calculated results are somewhat bigger within the Curie temperature and the α-γ-transition range 720…850°C, but they never exceed 1.0…2.0 W/mK [4.10].

Fig. 4.9a shows a comparison of measured and calculated values for the thermal conductivity of unalloyed steels at temperatures between 20 und 1200°C. The correlation of both values is good. The same can be said for alloyed steels (see Fig. 4.9b) as well as for ferritic Cr- and austenitic Cr-Ni-steels (see Fig. 4.9c). For the latter, this holds for the temperature range 20…1200°C and the atomic ratio between 20 and 60, a range among which the classic type 18-10 Cr-Ni-steels and the modern corrosion resistant steels with increased Ni and Mo contents are classified.

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Fig. 4.9.
Comparison of measured and calculated thermal conductivities in (a) carbon steels, (b) alloyed steels and (c) high alloyed steels [4.10; 4.13].

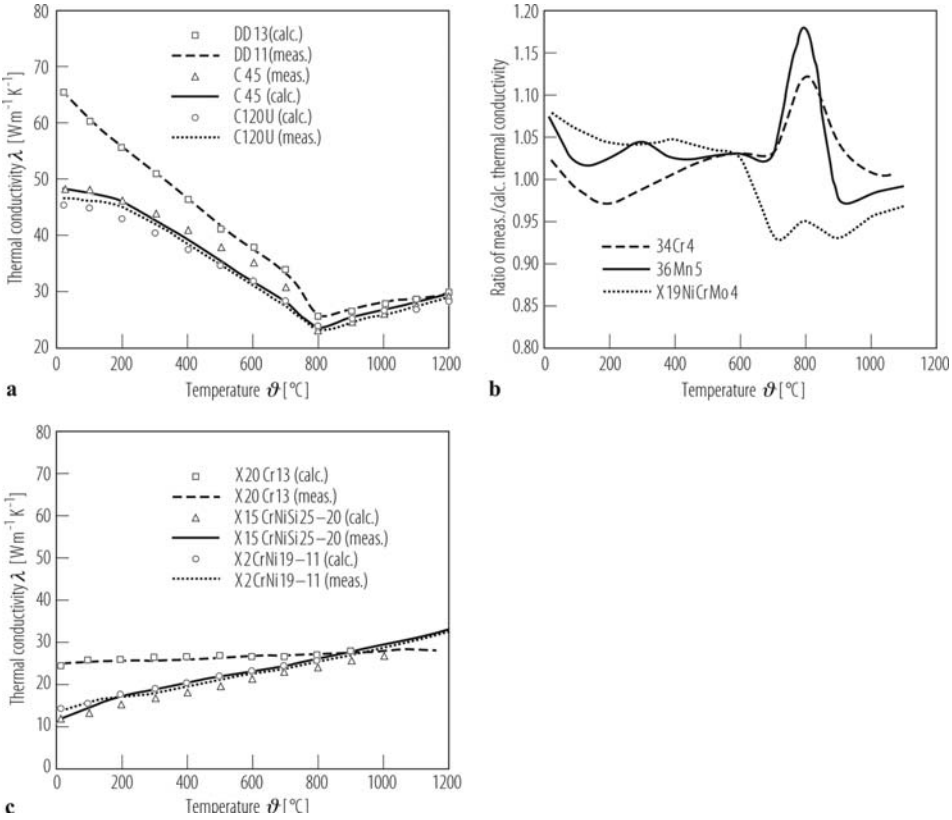
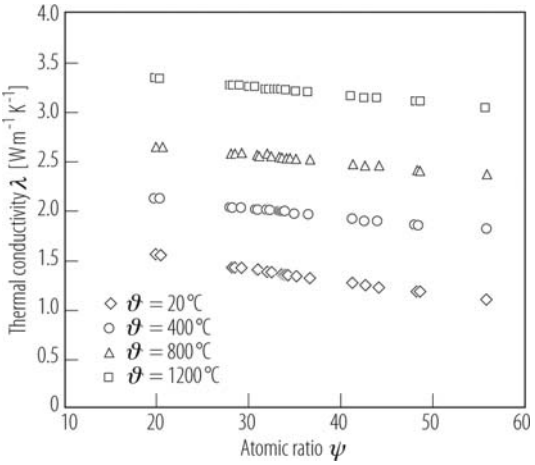


Fig. 4.10 shows the variation of thermal conductivity with rising atomic ratio (content of alloying elements) in a temperature range 20…1200°C – the lower the absolute value, the higher the temperature dependence.

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Fig. 4.10.
Thermal conductivity λ as a function of atomic ratio ψ of the austenitic Cr-Ni-(Mo)-steels.



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4.4 Specific heat capacity of steel

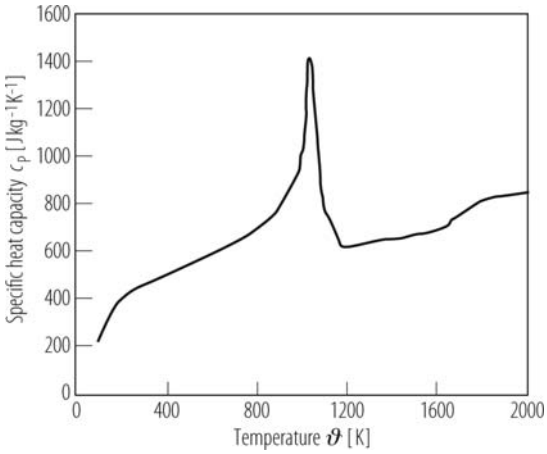
Introduction and Definitions

4.4.1 Definition and dependences

The specific heat capacity C expresses the heat quantity which is necessary to heat up 1 kg of a material by 1 K. The heat capacity related to the mass of a material is referred to as specific heat capacity c and depends on both material and temperature.

Fig. 4.11 shows the heat capacity of iron between absolute zero and melting temperature. Livschitz [4.2] concluded from the electron theory of the specific heat that the increase in heat capacity as a function of the temperature is linear at small temperature alterations but is in accordance with power and exponential functions in other ranges. The anomalous increase of the specific heat capacity which occurs when heating up to the Curie temperature $T_c = 1042$ K is necessary for overcoming the exchange forces causing the magnetic properties.

Fig. 4.11.
Specific heat c_p (at constant pressure) of iron as a function of the temperature ϑ.



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4.4.2 Specific heat capacity calculation

For a temperature range that starts at a sufficient distance from the absolute zero point and ends at about 90% of the absolute melting temperature, the linear relation

$$c_p = a + B \cdot T \tag{4.17}$$

holds, with

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

Moreover, no structure deformation must occur within the said temperature range, which is the case with iron materials. Also, alloyants and accompanying elements influence the specific heat capacity. A definition of the temperature dependence of the specific heat capacity as in equation (4.17) is only possible for nonferrous metals and transition-free austenitic steels. For steel X5CrNi 18-10 the relation

$$c_{p,m}(T) = 491.96 + 0.09044 \cdot T \tag{4.18}$$

is valid between 20 and 1300°C. As can be seen in Table 4.8, the measured values are within the range of calculated values from different authors.

Table 4.8.
Measured and calculated values of the mean specific heat capacity of X5CrNi18-10.

Temperature T [°C]	Mean specific heat capacity $c_{p,m}$ [J kg^{-1} K^{-1}]				
	calc. with eq. (4.18)	measured [4.14]	measured [4.13]	measured [4.10]	measured [4.15]
100	501	472	487	511	512
200	510	489	503	523	522
300	519	503	512	532	532
400	528	516	520	540	542
500	537	528	530	553	552
600	546	538	541	569	–
700	555	547	551	578	–
800	564	554	559	586	–

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Table 4.8. (continued)

Temperature T [°C]	Mean specific heat capacity $c_{p,m}$ [J kg^{-1} K^{-1}]				
	calc. with eq. (4.18)	measured [4.14]	measured [4.13]	measured [4.10]	measured [4.15]
900	573	562	565	595	–
1000	582	568	571	599	–
1100	591	574	–	603	–
1200	601	579	–	607	–
1300	610	–	–	615	–

The mean specific heat capacity $c_{p,\mathrm{m}}$ within a temperature range $T_1 < T < T_2$ is defined by

$$c_{p,\mathrm{m}} = \int_{T_1}^{T_2} c_p(\vartheta) d\vartheta. \tag{4.19}$$

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

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

This entity can be used to calculate the heat quantity Q that is required to heat a material from T_0 to T.

Chapter 4.5, which is based on work published by Livschitz [4.2], shows that there is a qualitative relationship between the linear expansion coefficient and the specific heat capacity. Therefore the term

$$c_{p,m}(T) = A \cdot e^{B \cdot T} \cdot e^{C/T} \cdot \psi^{D} \cdot T^{E \cdot \psi}, \tag{4.20}$$

with A, …, E constants and ψ the atomic ratio, was considered for the temperature range 20…1300°C in Table 4.9. In this equation, also the chemical composition of steel is reflected via the atomic ratio. Compared to the temperature, however, the impact of the chemical composition on the mean specific heat capacity is fairly low, which can be seen in Fig. 4.12 for corrosion resistant chromium steels. The same holds for unalloyed and low alloyed steels and for austenitic and two phase steels.

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Table 4.9.

Constants for the relation (4.20) for the mean specific heat capacity $c_{p,m}$ of various steels.

Steels	Plain carbon steels	Cr-Ni-steels	Cr-Al-steels
Temperature T [°C]	100…750	20…1300	20…1200
A	427.8	493.6	391.3
B	$5.21 \cdot 10^{-4}$	$1.66 \cdot 10^{-4}$	$3.80 \cdot 10^{-4}$
C	7.824	–	−1.588
D	$8.49 \cdot 10^{-3}$	–	0.657
E	$1.40 \cdot 10^{-4}$	–	–

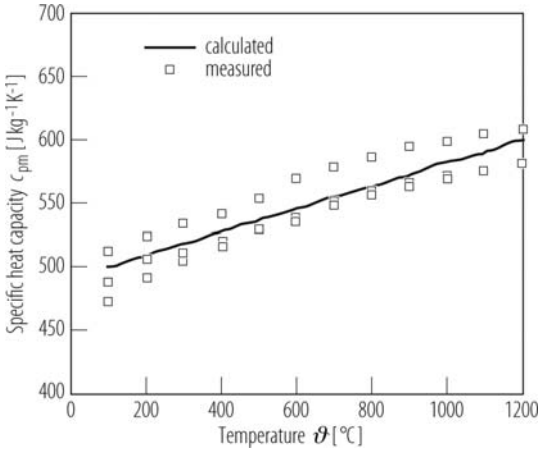
Tab. 4.10.

Comparison between measured and calculated heat capacity for the steel C22.

Temperature T [°C]	Mean specific heat capacity c_p [kJ kg^{-1} K^{-1}] with T_0 = 20°C (see eq. 19)	
	calculated	measured
100	490.6	486
200	497.1	502
300	516.9	519
400	541.1	540
700	627.4	628
900	689.1	703
1000	689.6	695
1200	681.7	687

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Fig. 4.12.
Mean specific heat capacity $c_{p,m}$ of chromium steel X10Cr13 as a function of temperature (measured values according to [4.10, 4.14]).



The Curie-Temperature and the α-γ-transformation of steels are connected by a pronounced unsteadiness of the temperature dependence of the specific heat capacity. It is therefore necessary to use separate modelling for the α- and the γ-region. Calculations for steel C22 as presented in Table 4.9 show that this method leads to a good correlation between measured and calculated values.

A calculation of the mean specific heat capacities with a high multiple determination is possible. Regarding the austenitic steel group, this means for example that the results that were calculated in accordance with (4.20) differ by a maximum of 20 J kg^{-1} K^{-1} from the measured results reported by a number of authors [4.10, 4.13, 4.14, 4.15].

It is pointed out regarding an appreciation of the measurement results that even information of a producer of austenitic steel about specific heat capacities vary between 450 and 500 J kg^{-1} K^{-1} at 20°C.

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4.5 Thermal expansion of steel

Introduction and Definitions

4.5.1 Definition and factors of influence

Most solids expand when being heated, which means that the interatomic distance in a space lattice becomes larger. The mean linear coefficient of expansion α_m is defined by

$$\alpha_m = \frac{1}{L_1}\frac{L_2 - L_1}{T_2 - T_1}, \tag{4.21}$$

where 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 the thermal expansion $\alpha(T)$ is hence given by

$$\alpha(T) = \frac{1}{L(T)}\frac{\mathrm{d}L(T)}{\mathrm{d}T}. \tag{4.22}$$

The thermal expansion of crystals is isotropic and the volume expansion coefficient β_V is given by

$$\beta_V = \alpha_1 + \alpha_2 + \alpha_3, \tag{4.23}$$

with $\alpha_{1,2,3}$ the coefficients of linear expansion along the main axes. As the following paragraphs refer to cubic metals such as aluminium, iron and copper (including their alloys), the volume expansion coefficient is $\beta_V = 3\alpha$.

The linear coefficient of expansion depends on the chemical composition of steel and its structure portions. Fig. 4.13 shows how alloying elements affect the coefficient of expansion in a temperature range 0…400°C.

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Fig. 4.13.
Effect of alloying elements in iron alloys on the variation of the linear coefficient of expansion α.

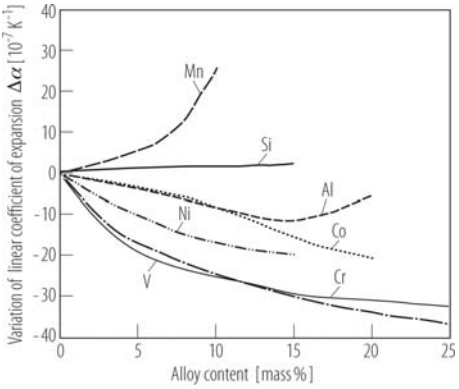
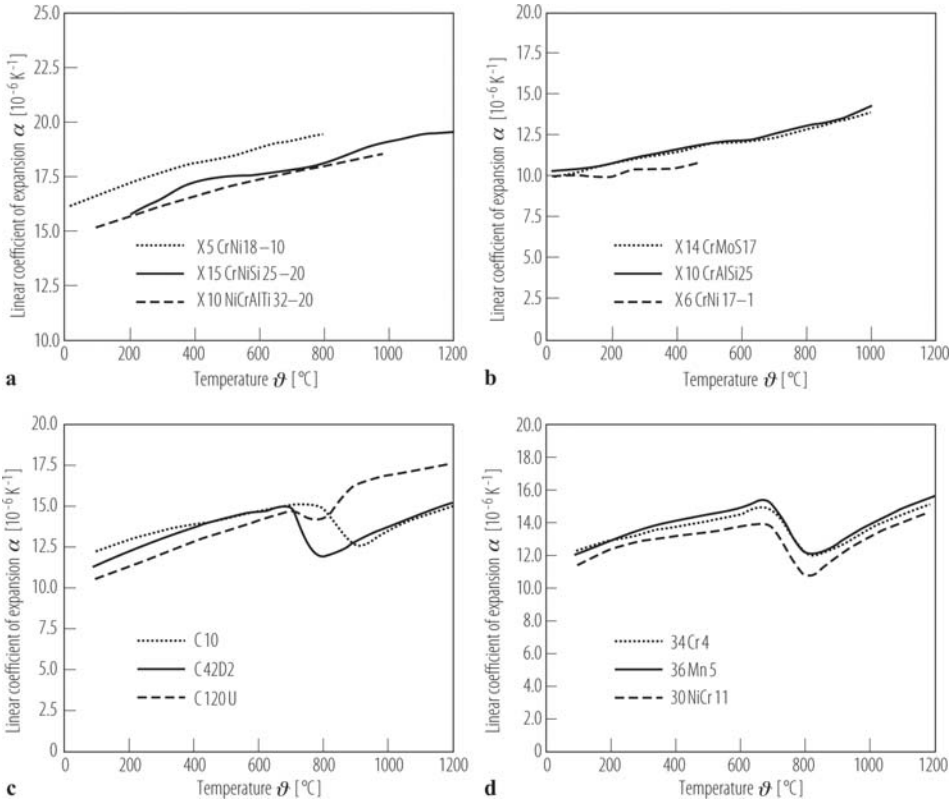


Fig. 4.14 reflects the correlation between the linear coefficient of expansion and the temperature for austenitic, ferritic, alloyed and unalloyed steels. The coefficient of expansion rises continuously with the temperature for highly alloyed steels, while the absolute values are significantly higher for austenitic steels than for ferritic steels. At steels with a α-γ-transition the slope of the linear coefficient of expansion is generally different in the two phase regimes.

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Fig. 4.14.
Linear coefficient of longitudinal expansion as a function of the temperature for (a) austenitic steels [4.10, 4.13, 4.16], (b) ferritic steels [4.10, 4.13] (c) carbon steels [4.10] (d) alloyed steels [4.10].



The highest mean linear coefficient of expansion was found for austenitic structures, no matter if the austenite was created at higher temperatures (for instance after α-γ-transformation) or exists even at lower temperatures (as in austenitic steels). The extension of ferrite, cementite and martensite at heating is less pronounced (Tab. 4.11) [4.2].

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Table 4.11.
Mean coefficient of expansion for different structures.

Structure	Mean coefficient of expansion α_m [10^{-6} K^{-1}]	
	linear	volume
ferrite	14.50	43.50
austenite	23.00	70.00
martensite	11.50	35.00
cementite	12.50	37.50

4.5.2 Influence of temperature on the coefficient of expansion

Regarding the impact of temperature on the linear coefficient of expansion, different temperature ranges must be distinguished. At intermediate temperatures, the linear thermal expansion coefficient and the specific heat capacity are proportional to T^3. If T is much smaller than the Debye temperature Θ, the thermal expansion is proportional to the temperature. In the range about −50…+400°C, the temperature dependence of the thermal expansion can be expressed by

$$\alpha_m = \alpha_0 + \beta \cdot T. \tag{4.24}$$

The constants α_0 and β are listed in Table 4.12 for austentic steels, whereas the measured values of steel X5CrNi18-10 were found in different publications. Though α_0 and β are different for the single steels and for X5CrNi18-10 according to the several authors, the results are quite close. It is hence acceptable for engineering calculations to assume that the mean linear coefficient of thermal expansion is nearly the same for all austenitic steels.

Table 4.12.
Calculation constants for the linear thermal expansion coefficient of austenitic Cr-Ni-steels.

Material	α_0 [10^{-6} K^{-1}]	β	Reference
X5CrNi18-10	16.54	0.00358	[4.13]
X5CrNi18-10	16.13	0.00437	[4.16]
X5CrNi18-10	16.83	0.00309	[4.10]
X5CrNi18-10	16.46	0.00381	[4.17]
X5CrNi18-10	16.48	0.00368	–
X5CrNiMo17-13-3	16.18	0.00338	[4.18]
X15CrNiSi20-12	16.22	0.00307	[4.18]
X15CrNiSi25-20	15.14	0.00379	[4.18]
X10NiCrAlTi32-20	16.46	0.00381	[4.17]

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The temperature dependence of the intermediate linear coefficient of thermal expansion of steels is best expressed by a product of exponential and power functions

$$\alpha_m(T,\psi) = A \cdot e^{B \cdot T} \cdot e^{C/T} \cdot e^{D \cdot \psi} \cdot \psi^{E/T}, \quad (4.25)$$

with ψ the atomic ratio. Equation (4.25) applies to atomic ratios 0.15…5.0 in the case of alloyed and plain carbon steels and 10…30 in the case of corrosion resistant chrome steels. The constants *A*, *B*, *C*, *D* and *E* are listed in Table 4.13. Table 4.14 presents a comparison between measured and calculated mean linear coefficients of thermal expansion for the example steel C15.

Table 4.13.
Calculation constants according to equation (4.25) for the thermal expansion of steel.

Steels	Plain carbon and low-alloy steels	Cr-Ni-steels	Cr-steels
Temperature *T* [°C]	50…750	50…1250	50…1250
A	11.997	16.44	10.115
B	$3.63 \cdot 10^{-4}$	$1.72 \cdot 10^{-4}$	$3.11 \cdot 10^{-4}$
C	0.595	–	–
D	−0.0098	–	–
E	−3.9614	–	–

Table 4.14.
Comparison of measured [4.10] and calculated mean linear coefficients of thermal expansion.

Temperature *T* [°C]	Mean linear expansion coefficient α_m $[10^{-6}\ K^{-1}]$	
	calculated	measured
50	11.79	11.93
400	13.55	13.47
700	15.14	14.88
900	12.85	12.41
1000	13.54	13.37
1200	14.75	14.81

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4.6 Density of steel

Introduction and Definitions

4.6.1 Definition and factors of influence

The density ρ of a metal is defined as its mass m per unit of volume V,

$$\rho = m/V. \tag{4.26}$$

The density of pure iron at $T = 0°C$ is 7880 kg/m^3. Alloyants and accompanying elements change its density, which is summarized in Table 4.15. Therefore, the density of a steel grade results is

$$\rho = \rho_{Fe} + \sum \Delta\rho_i \cdot c_i, \tag{4.27}$$

where ρ_{Fe} is the density of iron (in g/cm^3), $\Delta\rho_i$ the change in density for 1% of the respective alloying element (in g/cm^3) and c_i the respective element content (in mass-%).

Equation (4.27) refers to normalized conditions. Accordingly, the density of plain carbon and low alloyed steels ranges between 7800 and 7850 kg/m^3, but is higher in the case of austenitic Cr-Ni-steels and high-speed steels. The density of steels is influenced by their chemical composition but also by their structural condition. It may be lower by up to 10% than calculated from equation (4.27) in the case of teemed ingots.

The density of steel also depends on the structure that is produced during heat treatment. Densities increase from left to right in the following list: martensite, α-Fe + Fe_3C (perlite, sorbite and bainite), austenite. Accordingly, volume changes occur in hardened steel during quenching, depending on internal transformations. Martensite quenching causes the steel to contract, and transforming austenite to martensite means steel expansion.

Equation (4.27) yields calculated density values for unalloyed plain carbon steels, low-alloy and austenitic Cr-Ni-steels that are in a relatively high agreement with the measured results (see Table 4.16). However, the calculated density of ferritic steels is too high by 50…60 kg/m^3 on average. Also, phase transitions suddenly change the volume and therefore the density.

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Table 4.15.

Changes in iron density caused by alloy elements.

Element	$\Delta\rho_i$ [g cm^{-3} %]	Range of validity [%]
Carbon	−0.040	< 1.55
Phosphorus	−0.117	< 1.10
Sulfur	−0.164	< 0.20
Copper	+0.011	< 1.00
Manganese	−0.016	< 1.50
Nickel	+0.004	< 5.00
Chromium	−0.001	< 1.20
Tungsten	+0.095	< 1.50
Silicon	−0.073	< 4.00
Aluminium	+0.120	< 2.00
Arsenic	+0.100	< 0.15

Table 4.16.

Measured and calculated steel densities at room temperature.

Steel	Density ρ [g/cm^3]	
	measured (pycnometer)	calculated
S235JRG2	7869.7	7851.2
S355J2G3	7846.4	7819.8
DD11	7856.7	7856.9
DC06	7856.0	7855.6
S420MC	7842.3	7816.7
C35	7838.5	7825.7
S690QL1	7844.1	7837.0
10CrMo9-10	7844.1	7842.3
15NiCuMoNb5	7894.0	7856.6
X8Ni9	7919.9	7946.5
X5CrNi18-10	7845.9	7766.2
X2CrNiMoN22-5-3	7793.9	7785.8
X10CrAl7	7689.3	7691.7
X10CrAlSi18	7552.6	7578.9

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4.6.2 Modelling the dependence on temperature

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

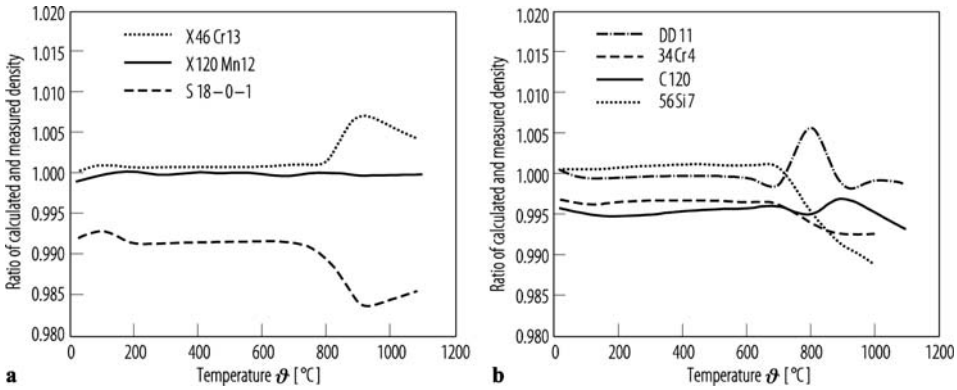
$$\rho(T) = \rho_{0^\circ C}(1 - \beta_V \cdot T), \tag{4.28}$$

with $\rho_{0^\circ C}$ the density at 0°C and β_V the volume expansion coefficient from equation (4.23; see chapter 4.5). If the mean linear expansion coefficient changes linearly with temperature, (4.23) and (4.28) yields

$$\rho(T) = \rho_{0^\circ C} \cdot (1 - 3 \cdot \alpha_m(T) \cdot T) = \rho_{0^\circ C}\left[1 - 3 \cdot 10^{-6} \cdot T \cdot (\alpha_0 + \beta \cdot T)\right], \tag{4.29}$$

with α_m the mean linear expansion coefficient. According to equation (4.29), the reduction in density with rising temperature is proportional to T^2. The comparison of measured and calculated densities for different steels is shown in Table 4.16. However, the mean linear expansion coefficient of steels does not change linearly with the temperature. The change is unsteady in the α-γ-transition region. Fig. 4.15 illustrates that the density of steels indeed decreases almost proportional to T^2, but the decrease depends on the structural condition, and one notes a faster decrease in the austenitic range than in the ferritic + perlitic range.

Fig 4.15.
Ratio of calculated and measured density for the steels (a) X46Cr13, X120Mn12 and S18-0-1 and (b) DD11, C120, 34Cr4, 56Si7 as a function of temperature [4.10].



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5 Deformation parameters

Origin, preparation and selection of the data - References

5.1 Introduction

5.1.1 Base of the data bank

Basing on measured values for the following often used steel grades material related parameters were compiled dependent on the deformation conditions. These data, which are required for calculations of deformation processes, are based on measured values and characterised by half empirical mathematical equations res. physical laws:

- Flow stress at hot and cold deformation,
- Plasticity,
- Mechanical and physical properties

The chemical composition is based on the book "Stahlschlüssel", which was used by courtesy of Verlag Stahlschlüssel Wegst GmbH Marbach [5.1] in combination with [5.3]. For the international steel grade comparison [5.1, 5.2, 5.4, 5.5 and 5.161] were used.

Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds DIN or EN.

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:

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

Cold forming:

$$\sigma_F = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot \dot{\varphi}^{m_3} \tag{2.7}$$

where:

σ_F	flow stress [MPa]
A	constant [–]
$m_1 \ldots m_8$	exponents which contain the influence exerted by the conditions of deformation on flow stress [–]

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ϑ	deformation temperature [°C]
φ	strain [–]
$\dot{\varphi}$	strain rate [s^{-1}]

Additionally the data sheets include the stress σ_{F0}. This value was found at the fundamental conditions for flow stress evaluation at hot ($\vartheta = 1000°C$) or cold deformation ($\vartheta = 20°C$), $\varphi = 0{,}10$ and $\dot{\varphi} = 10$ [s^{-1}]. It allows for these conditions and different steels a rough comparison of required forces and deformation energy. At steels with $\alpha - \gamma -$ transformation in brackets for the ferrite range also a σ_{F0}–value can be seen. This is the result of mere calculations and reflects the flow stress at $\vartheta = 1000°C$, in the case the structure would be still ferritic.

5.1.2.1 Remarks to the flow stress constants

The constants for the calculation of hot and cold flow curves base on own compression and/or torsion tests with several heats, different microstructures and were realised partly with material from different steel manufacturers. Furthermore included were flow curves found in international publications, which precisely informed about the chemical compositions, the test procedures and the material conditions. Hot and cold flow curves of steels discussed in 5.1 res. identical foreign steel grades found in [5.6, 5.7…5.26, 5.28…5.33, 5.43…5.45, 5.77…5.79] were also included in the regression calculations. The decision to accept any flow curves from the literature for the data files of the regression calculations bases on the following criteria:

- For hot flow curves data of the relevant microstructure condition up to a deformation degree of min. 1.00 at least four temperatures and three deformation rates have to be available.
- For cold flow curves a data matrix of three temperatures and three deformation rates is required. If a temperature addicted blue-brittle range exists, only measured data are used, which clearly quantify this phenomenon. If two hardening zones appear in a cold flow curves 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 ±3.0 [%].
- For the same homolog temperature exists a dependency between flow stress and activation energy at hot deformation.
- Classification of flow stress at cold deformation in its dependency to the carbon content for each steel group and heat treatment condition.

In one case values for constant A and the exponents $m_1 \ldots m_8$ respectively $m_1 \ldots m_4$ were found, which have to be seen as statistical firmed parameters within the tolerable analyse limits of the mentioned materials.

Beside own research results, the absolute flow stress value, its dependency on material, condition, temperature, deformation degree and deformation rate, was assured by literature, cited above, and [5.27, 5.34…5.42, 5.46…5.76 as 5.80…5.108]. These publications also delivered information for mathematical modelling.

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5.1.2.2 Extrapolation

Modern forming processes require stress-strain curves for conditions that can be simulated only with limits by the standard testing processes, that is, the measured values obtained and the calculation constants from them must be extrapolated.
In the extrapolation to other forming conditions the following applies:

- *For the deformation temperature is valid: The calculated flow stresses should not be extrapolated beyond the range of measured values.*
- *If phase composition, precipitation condition as when as the character of the forming do not change and if the grain size remains approximately constant*, then the constants can be extrapolated up to the lowest possible deformation temperature. It must be kept in mind that the thermally activated process as, for example, the $\alpha-\gamma-$transformation of steels are incluenced by the forming.
- On the other hand the influence of deformation rate can be extrapolated by a power function, if the speed exponent must be expressed as a function of temperature; room temperature is to be viewed as the lower threshold value.
- 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 (forging processes).

5.1.3 Plasticity curves

Mainly the plasticity curves related to the deformation conditions covered by the data sheets were recorded in torsion tests. In certain cases these base on the results of tensile tests res. rolling trials with wedges [5.8 and 5.23].

Own torsion tests and of [5.13, 5.117 and 5.121] was 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 inhomogeneities 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 possible deformation concentrations in the centre of the test length, which would cause significant local temperature rises.

Results found in the literature [5.111, 5.113, 5.114, 5.115 and 5.123], which base 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 [5.122].

Beside own investigations about the correlation between plasticity and

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

The following publications were used: [5.30, 5.43, 5.110, 5.112, 5.116-5.121 and 5.123-5.153].

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

- For the relevant deformation conditions the experimental acquired plasticity integrates into the relation $\varphi_V = f(\sigma_{F\text{-}SS})$ in the single phase field, see Fig 3.11.
- At the same deformation conditions and near the flow stress maximum, i.e. at the beginning of dynamic recrystallisation, exists a qualitative correlation between plasticity and deformation degree, the higher the deformation, the lower is the plasticity.
- In the single phase field plasticity follows rising temperatures by a power function up to its maximum.

Because of numerous material and process related parameters at the same deformation conditions the scatter band of absolute plasticity values can be remarkable. Examples are austenitic steels as 1.4301, 1.4401, 1.4541 and 1.4571. More than 20 melts of these steels were tested 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 the same deformation and material conditions exists in the single phase range a linear correlation between plasticity and temperature. 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 local inhomogeneous.
- In case of transferring plasticity to other structure conditions (e.g. as-cast, as-rolled) has to be seen, that remarkable differences can appear [5.112], 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.

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5.1.4 Mechanical and physical properties

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

$$R_p = R_{p-exit} + A \cdot \varepsilon^{n_1} \tag{4.1}$$

$$R_m = R_{m-exit} + B \cdot \varepsilon^{n_2} \tag{4.2}$$

$$A_5 = A_{5-0} - C \cdot \varepsilon^{n_3} \cdot e^{n_4/\varepsilon} \tag{4.4}$$

where:

R_p	yield strength [MPa]
R_{p-exit}	yield strength at initial state at ε = 0 [MPa]
R_m	tensile strength [MPa]
R_{m-exit}	tensile strength of initial state at ε = 0 [MPa]
ε	related strain [–]
A, B, and n_i	constants [–]
A_5	elongation [%]
ΔA_5	decline of elongation [%]
A_{5-0}	elongation of the initial state at ε = 0 [%]
C and n_i	constants [–]

were found after regression analyses of own investigations res. in literature [5.9, 5.17, 5.23, 5.26, 5.29, 5.109, 5.116 and 5.158]. Partial these are for different material conditions. The stated stray area for the initial values of yield strength, tensile strength and elongation in non-deformed condition result from several tested heats.

The numerical values for temperature-dependent physical properties as thermal conductivity, mean specific heat capacity, average coefficient of linear expansion, density and Young's modulus were calculated according to the correlations discussed in chapter 4, [4.16, 4.21, 4.25res. 4.26, 4.30 and 4.12]. These calculations are based on measured data [5.8, 5.154…5.179, 5.186 and 5.187]. More detailed information about the importance of the boundary values as the limits of its application can be found in [5.180…5.185]. Information from literature about Young's modulus of unalloyed, alloyed and high alloyed steels [5.4, 5.8, 5.155, 5.157 and 5.158] could be combined with own investigations. At an interpolation of interim values for physical properties should be noticed, that here a temperature related unsteadiness at Curie-temperature appears.

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Steel symbol/number: S235JRG2/1.0038

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Mn	P	S	N
0.00…0.17	0.00…1.40	0.000…0.045	0.000…0.045	0.000…0.009

International comparison of standards

ISO		Euronorm		
		S235JRG2	10025 (08/1993)	
		S235JRG2	10025–2 (10/1999)	
United Kingdom		Russia		
37/23 HR	1449 Part 1 (1991)	St3ps	380 (1994)	
S235JRG2	EN 10025–2 (10/1999)	St3sp	380 (1994)	
Japan		China		
		Q235A–b	T 701 (1997)	
		U12355	T 3091 (2000)	
USA				
ASTM		AISI	SAE	UNS
A252 (1)(2)(3)	A252–02			K02502
A501	A501–98			K0300

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

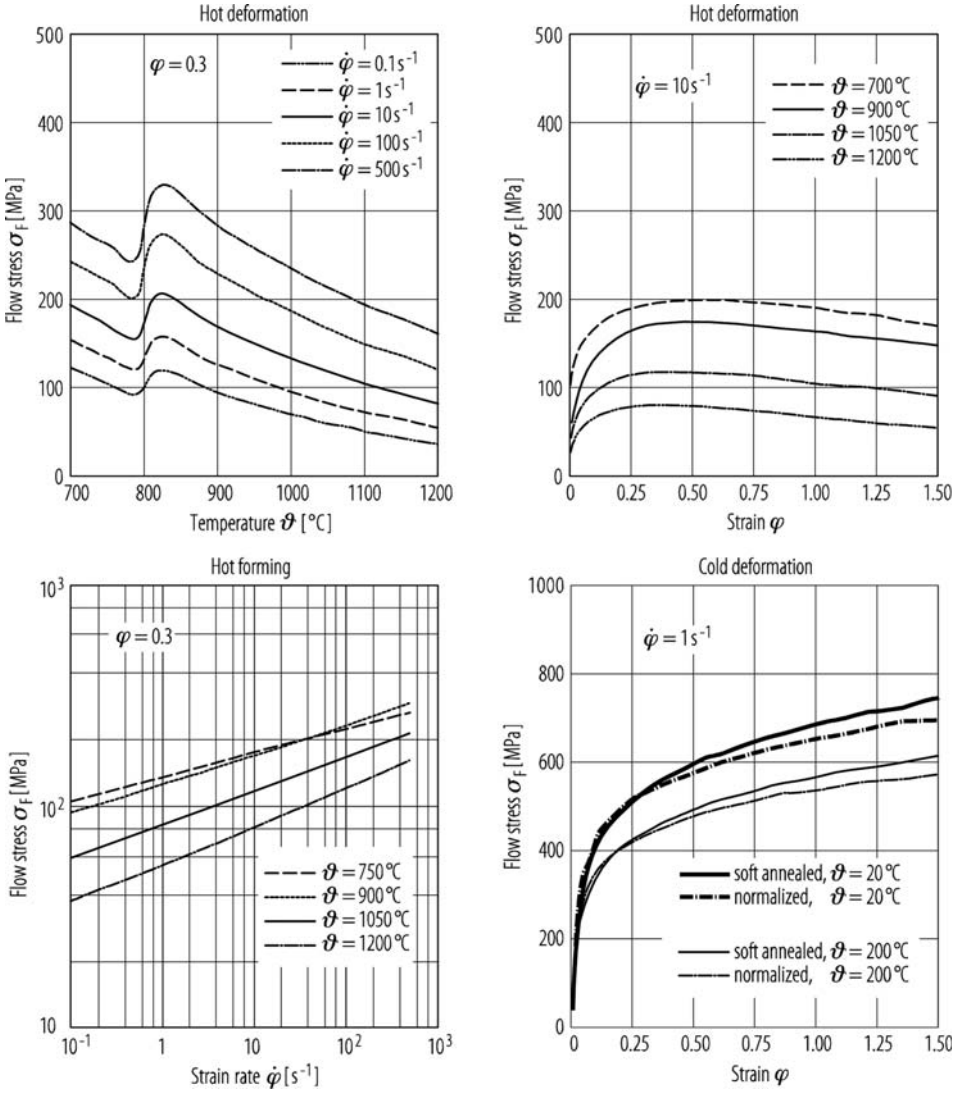
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Flow curves

	Hot deformation			Cold deformation	
	deformed state		casting state	soft annealed	normalized
State of material	austenite	ferrite+Fe_3C	austenite		
σ_{F0} [MPa]	108.10	(82.33)	87.8	415.6	437.5
A	2513.90	1359.38	2090.04	706.469	672.609
Effect of temperature K_ϑ					
m_1	−0.00250	−0.00276	−0.00237	−0.00106	−0.00110
Effect of strain K_φ					
m_2	0.37825	0.16057	0.46642	0.18666	0.15529
m_4	0.00101	−0.00025	0.00713	−0.01008	−0.00981
m_5	−0.00119	0.00050	−0.00121		
m_7	−0.03840	−0.51028	−0.03793		
Effect of strain rate $K_{\dot\varphi}$					
m_3				0.00922	0.01121
m_8	0.000144	0.000144	0.00014		
Range of validity					
ϑ [°C]	820…1200	700…790	900 … 1200	20…320	20…320
φ	0.04…1.50	0.04…1.50	0.04…1.50	0.04…1.60	0.04…1.60
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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Fig. 5.1.
S235JRG. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
normalized	230…270	54.4656	0.46286	370…450	15.8981	0.68423
hot rolled	230…270	43.4065	0.54398	380…440	34.3791	0.55753

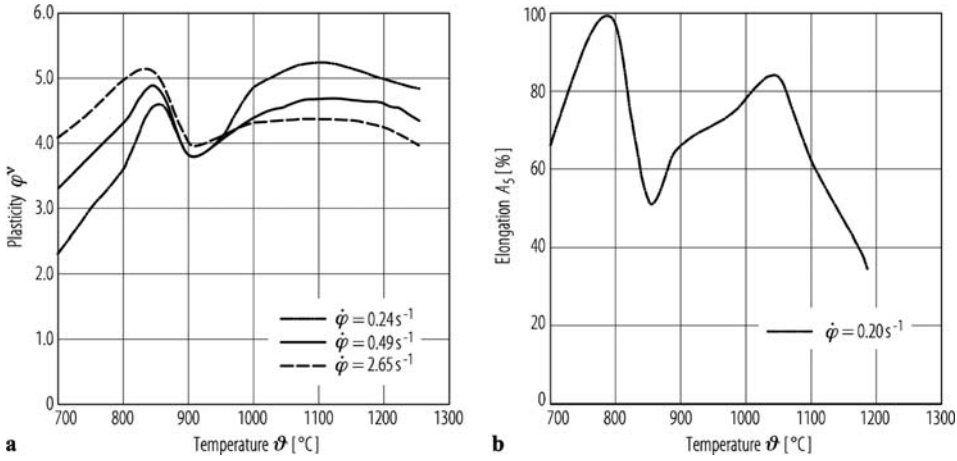
DOI: 10.1007/978-3-540-44760-3_12
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
normalized	35….50	125.73418	−0.20532	−13.5638	<70
hot rolled					<85

Fig. 5.2.
S235JRG. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1150°C. (b) Deformed state. Direct heating on deformation temperatures.

Plasticity by torsion (left) and by tensile test (right)



DOI: 10.1007/978-3-540-44760-3_12
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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	55.48	470.62	11.74	7851.2	212.9
100	53.35	483.47	12.06	7822.8	206.5
200	50.63	496.50	12.60	7791.9	200.8
300	46.87	516.33	13.09	7758.7	195.6
400	42.7	540.44	13.60	7723.1	189.1
500	38.53	567.2	14.10	7685.1	180.0
600	34.53	595.96	14.64	7644.4	167.5
700	30.80	626.68	15.18	7600.9	150.9
800	24.58	690.87	12.08	7623.6	130.2
900	26.11	688.39	12.83	7579.3	106.7
1000	27.27	685.91	13.50	7533.2	80.6
1100	28.40	683.45	14.11	7485.6	64.1
1200	29.69	680.99	14.68	7436.3	53.9

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Steel symbol/number: S275JRC/1.0128

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Mn	P	S	N
0.00…0.21	0.00…1.50	0.000…0.045	0.000…0.045	0.000…0.009

International comparison of standards

ISO		Euronorm		
		S275JRC	10249–1 (06/1995)	
United Kingdom		Russia		
S275JRC	EN 10249–1 (06/1995)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

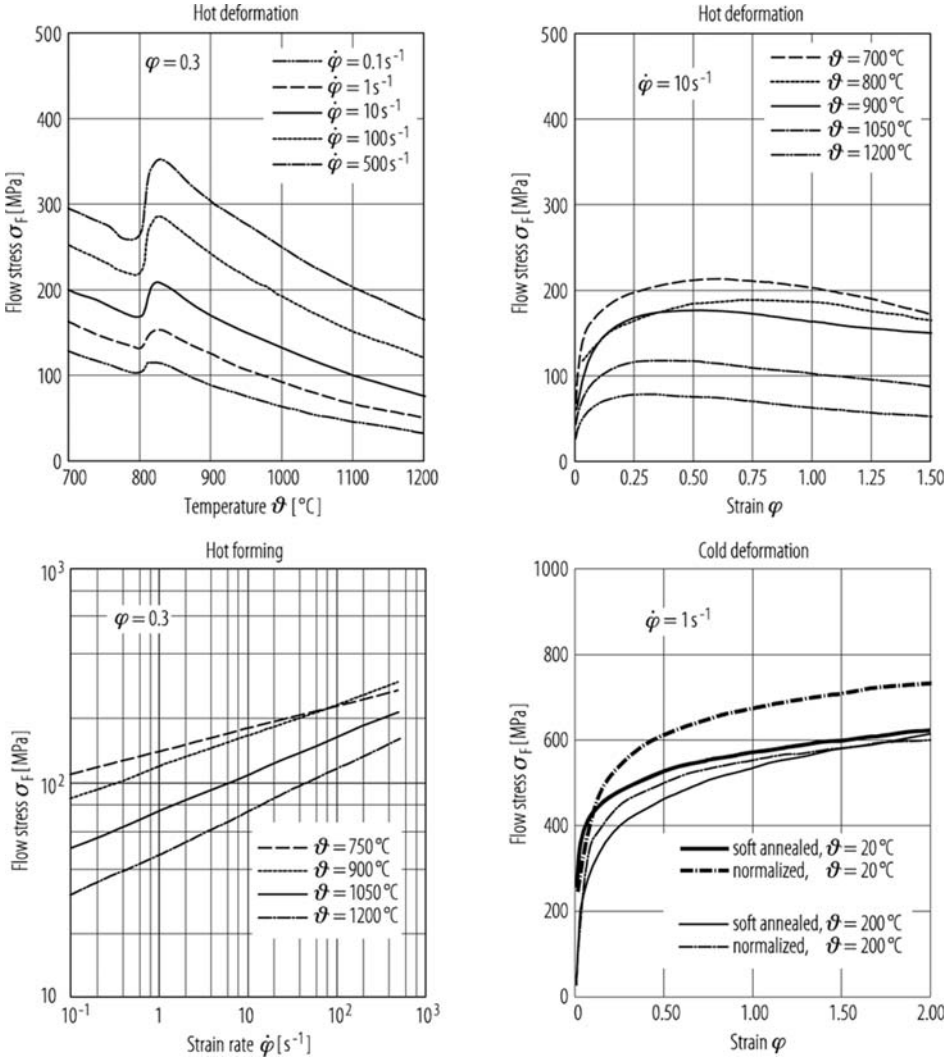
DOI: 10.1007/978-3-540-44760-3_13
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Flow curves

	Hot deformation			Cold deformation	
	deformed state		casting state	soft annaeled	normalized
State of material	austenite	ferrite+Fe_3C	austenite		
σ_{F0} [MPa]	109.61	(93.20)	88.3	421.1	441.4
A	2852.50	1033.03	2371.55	580.458	698.480
Effect of temperature K_ϑ					
m_1	−0.00268	−0.00255	−0.00257	−0.00082	−0.00113
Effect of strain K_φ					
m_2	0.36285	0.09433	0.45097	0.11751	0.1144
m_4	0.00086	−0.00391	0.00699	−0.0017	−0.01779
m_5	−0.00135	0.00193	−0.00135		
m_7	0.05778	−1.00864	0.05821		
Efect of strain rate $K_{\dot\varphi}$					
m_3				−0.00737	0.00213
m_8	0.000161	0.000138	0.000161		
Range of validity					
ϑ [°C]	825…1200	700…800	900…1200	20…320	20…200
φ	0.04…1.50	0.04…1.50	0.04…1.50	0.04…2.00	0.04…2.00
$\dot\varphi$[s^{-1}]	<500	<500	<500	<500	<500

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Fig. 5.3.
S275JRC. Flow stress curves by hot and cold forming.



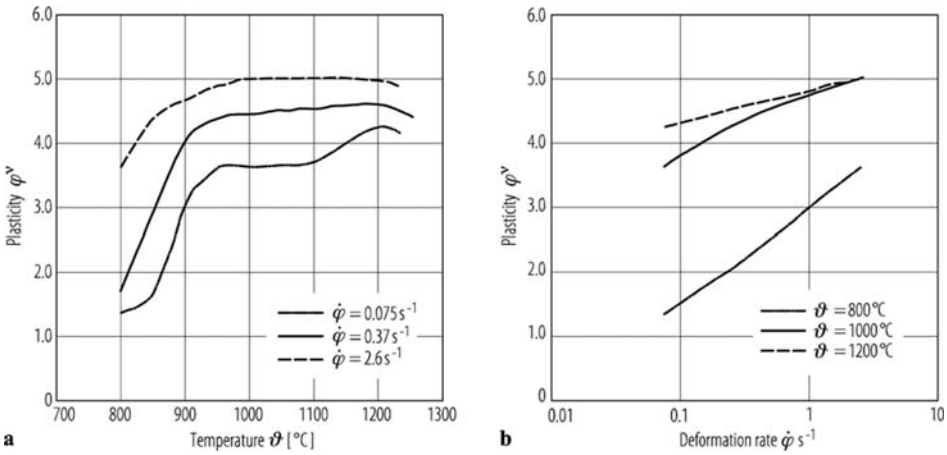
Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
hot rolled	250…280	70.7753	0.4836	430…500	33.8118	0.57723	<85

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Fig. 5.4.
S275JRC. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1150 °C. (b) Deformed state. Austenitised at 1150 °C.

Plasticity by torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	54.20	471.14	11.63	7849.1	214.8
100	52.35	484.09	11.97	7820.9	205.6
200	49.86	497.15	12.53	7790.0	199.0
300	46.21	517.01	13.04	7756.9	194.7
400	42.1	541.16	13.55	7721.5	190.1
500	38.03	567.9	14.1	7683.5	183.0
600	34.09	596.76	14.59	7642.9	172.4
700	30.41	627.53	15.14	7599.6	157.8
800	24.40	691.67	12.08	7621.5	139.3
900	25.97	689.19	12.86	7576.6	118.2
1000	27.16	686.71	13.55	7530.0	94.4
1100	28.31	684.24	14.18	7481.7	78.1
1200	29.63	681.78	14.77	7431.8	64.7

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Steel symbol/number: C4D/1.0300

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.06	0.00…0.10	0.20…0.45	0.000…0.025	0.000…0.025	0.00…0.15
Mo	Ni	Al	Cu		
0.00…0.03	0.00…0.15	0.000…0.050	0.00…0.15		

International comparison of standards

ISO		Euronorm		
~ C4D	16120–3 (2001)	C4D	10016–3 (12/1994)	
United Kingdom		Russia		
C4D1	EN 10016–3 (12/1994)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

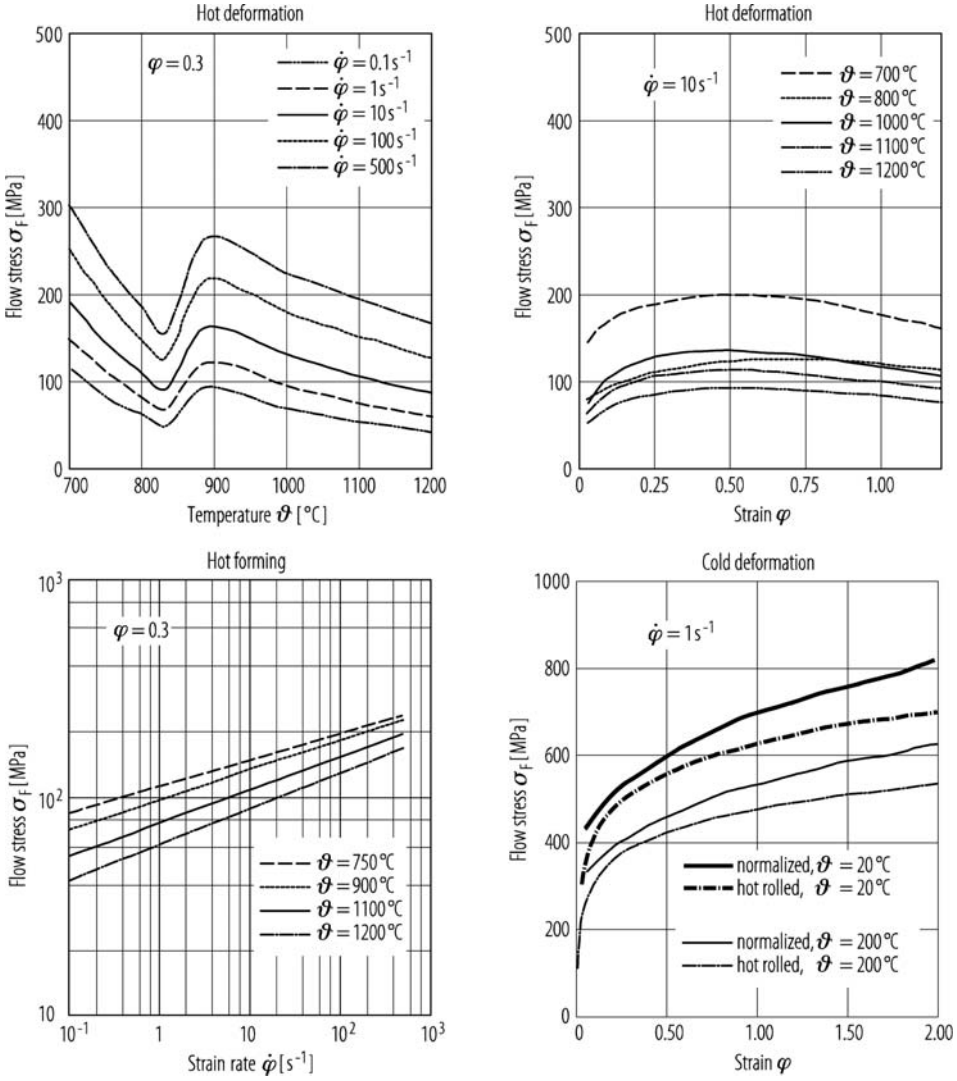
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Flow curves

State of material	Hot deformation		Cold deformation	
	deformed state		normalized	hot rolled
	austenite	ferrite+Fe_3C		
σ_{F0} [MPa]	104.60	(35.31)	405.6	462.4
A	1939.81	14912.8	654.104	703.200
Effect of temperature K_ϑ				
m_1	−0.00246	−0.00666	−0.00159	−0.00146
Effect of strain K_φ				
m_2	0.31076	0.04969	0.15963	0.23909
m_4	−0.00056	−0.00306	−0.00889	0.01314
m_5	0.00046	0.00341		
m_7	−0.98375	−1.69219		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.00475	0.00573
m_8	0.000137	0.000162		
Range of validity				
ϑ [°C]	890…1200	700…835	20…300	20…300
φ	0.04…1.00	0.04…1.00	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<100	<500	<500

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Fig. 5.5.
C4D. Flow stress curve by hot and cold forming.



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Mechanical properties after cold deformation

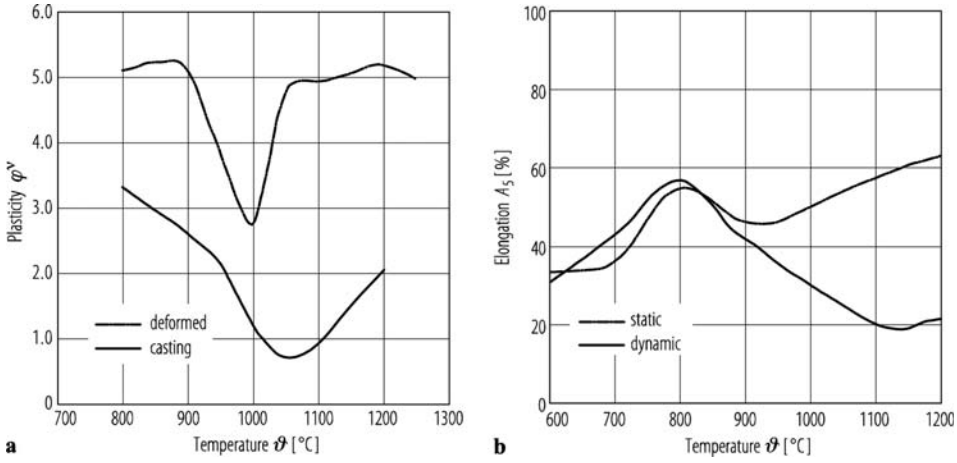
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
hot rolled	320…350	30.5025	0.58169	390…430	9.75441	0.80955

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
hot rolled	20…33	24.9546	0.02199	−4.02436	< 85

Fig. 5.6.
C4D. Hot plasticity as a function of the temperature. (a) Deformation rate: 0.2 s^{-1}. Direct heating on deformation temperature. (b) Deformation rate: 0.2 s^{-1}. Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	59.48	470.58	11.74	7857.1	
100	56.30	483.53	12.32	7828.1	
200	52.85	494.59	12.77	7796.9	
300	48.75	514.32	13.24	7763.5	
400	44.3	538.33	13.73	7727.7	
500	39.97	564.9	14.2	7689.4	
600	35.79	593.61	14.76	7648.4	
700	31.91	624.20	15.30	7604.6	
800	25.12	688.43	12.23	7626.4	
900	26.55	685.95	12.91	7583.2	
1000	27.62	683.49	13.52	7538.3	
1100	28.66	681.03	14.08	7492.0	
1200	29.87	678.59	14.59	7444.3	

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Steel symbol/number: C10/1.0301

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S
0.07…0.13	0.00…0.40	0.30…0.60	0.000…0.045	0.000…0.045

International comparison of standards

ISO		Euronorm		
∼C10	683–18(1996)	C10	10277–2 (07/1999)	
∼CE 10	4954 (1993)			
United Kingdom		Russia		
∼040 A 10	970 Part 1 (1996)	∼10	1050 (1988)	
∼045 M 10	970 Part 1 (1996)			
Japan		China		
∼S 10 C	G 4051 (1979)	∼DX 1	T 15675 (1995)	
		∼ U59110	T 15675 (1995)	
USA				
ASTM		AISI	SAE	UNS
∼A 331 (1010)	A 331–00	∼ 1010	∼1010	∼G10100
∼A 635 (1010)	A 635–02			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

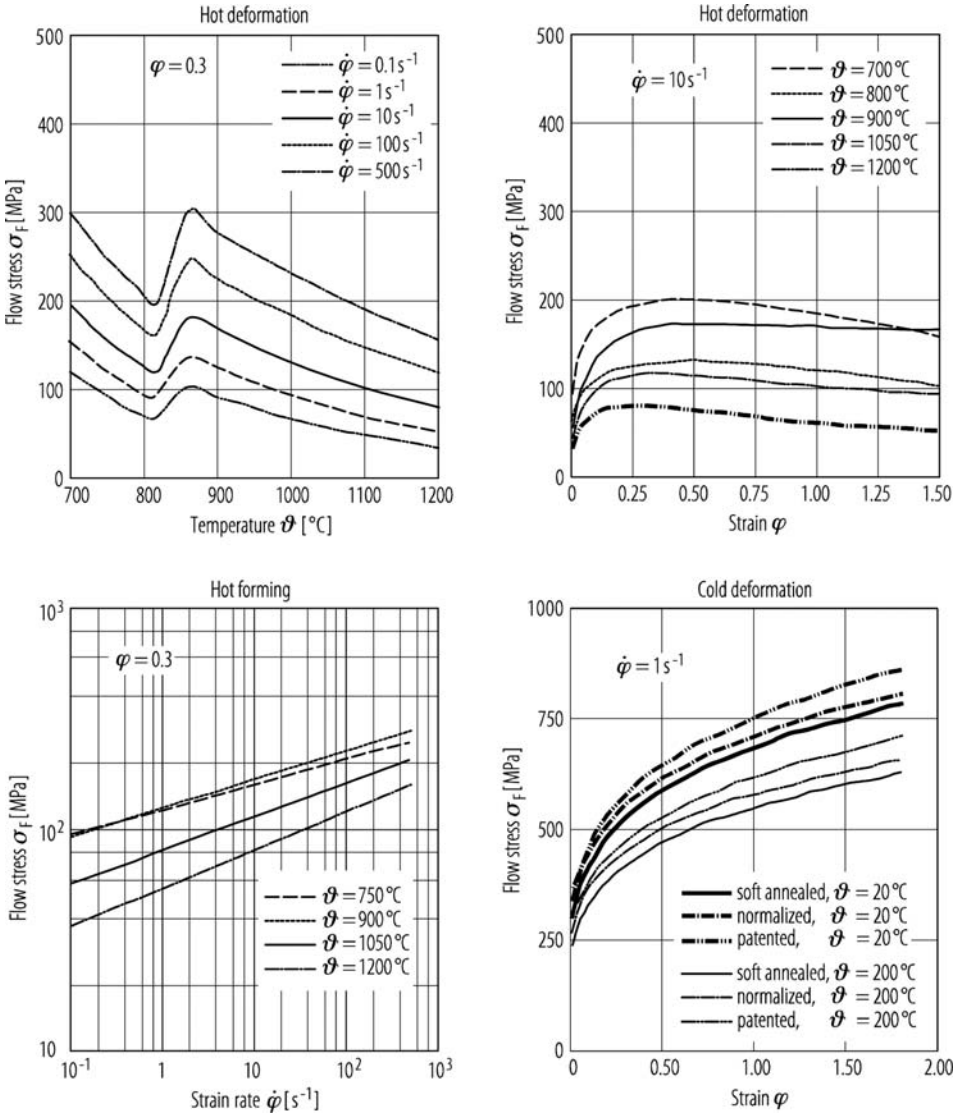
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Flow curves

	Hot deformation	Cold deformation			
	deformed state		soft annealed	normalized	patented
State of material	austenite	ferrite+Fe_3C			
σ_{F0} [MPa]	108.00	(46.71)	423.8	457.5	571.7
A	2171.12	5921.00	701.729	724.324	768.251
Effect of temperature K_ϑ					
m_1	−0.00222	−0.00463	−0.00124	−0.00117	−0.00112
Effect of strain K_φ					
m_2	0.42056	0.22439	0.22701	0.21782	0.23079
m_4	0.00117	0.00007	0.00196	0.00426	0.00205
m_5	−0.00220	0.00003			
m_7	0.51586	−0.49041			
Effect of strain rate $K_{\dot\varphi}$					
m_3			0.01026	0.00994	0.10328
m_8	0.000145	0.000152			
Range of validity					
ϑ [°C]	860…1200	700…820	20…300	20…300	20…300
φ	0.04…1.50	0.04…1.50	0.04…1.80	0.04…1.80	0.04…1.80
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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Fig. 5.7.
C10. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

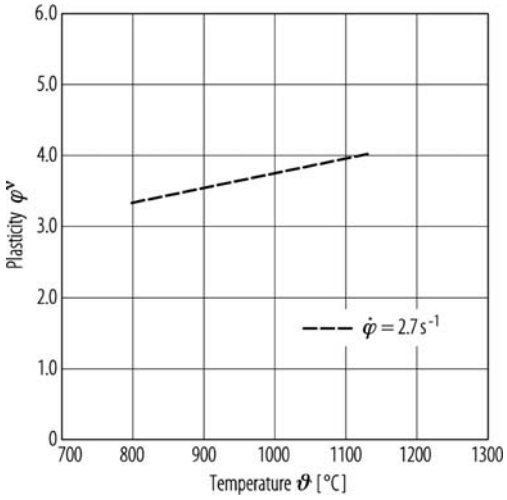
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
soft annealed	260…300	61.9118	0.50926	380…420	37.8912	0.55545
normalized	250…300	28.4540	0.64398	350…390	26.8284	0.62386
hot rolled	260…300	74.5843	0.48298	380…420	50.2887	0.54336
patented				460…500	21.4439	0.72663

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
soft annealed					<80
normalized	30…35	35.76894	−0.01266	−7.77631	<70
hot rolled	30…35	23.65726	0.13364	−5.83619	<70
patented					<80

Fig. 5.8.
C10. Hot plasticity as a fuction of the temperature (and deformation rate); deformed state and austenitized at 1150 C. Note: At hot deformation the relation of plasticity between as–cast and as-deformed state is: 0.60…0.95.

Plasticity by torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	55.64	470.52	11.75	7834.3	
100	53.47	483.47	12.07	7805.9	
200	50.72	496.42	12.60	7775.0	
300	46.94	516.25	13.10	7741.9	
400	42.8	540.36	13.60	7706.4	
500	38.59	567.1	14.1	7668.4	
600	34.59	595.86	14.64	7627.8	
700	30.85	626.58	15.19	7584.4	
800	24.60	690.77	12.08	7607.1	
900	26.13	688.29	12.83	7562.9	
1000	27.29	685.82	13.50	7517.0	
1100	28.41	683.35	14.11	7469.5	
1200	29.69	680.90	14.67	7420.5	

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Steel symbol/number: DD11/1.0332

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Mn	P	S
0.00…0.12	0.00…0.60	0.000…0.045	0.000…0.045

International comparison of standards

ISO		Euronorm		
~HR 2	6317 (2000)	DD11	10111 (02/1998)	
~HR 2	3573 (1999)			
United Kingdom		Russia		
~14HR	1449 Part 1 (1991)	15kp	1050 (1988)	
~4 CR	1449 Part 1 (1991)			
Japan		China		
~SPHD	G 3131 (1996)-	-	-	
~HR 1	G 3131 (1996)-			
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

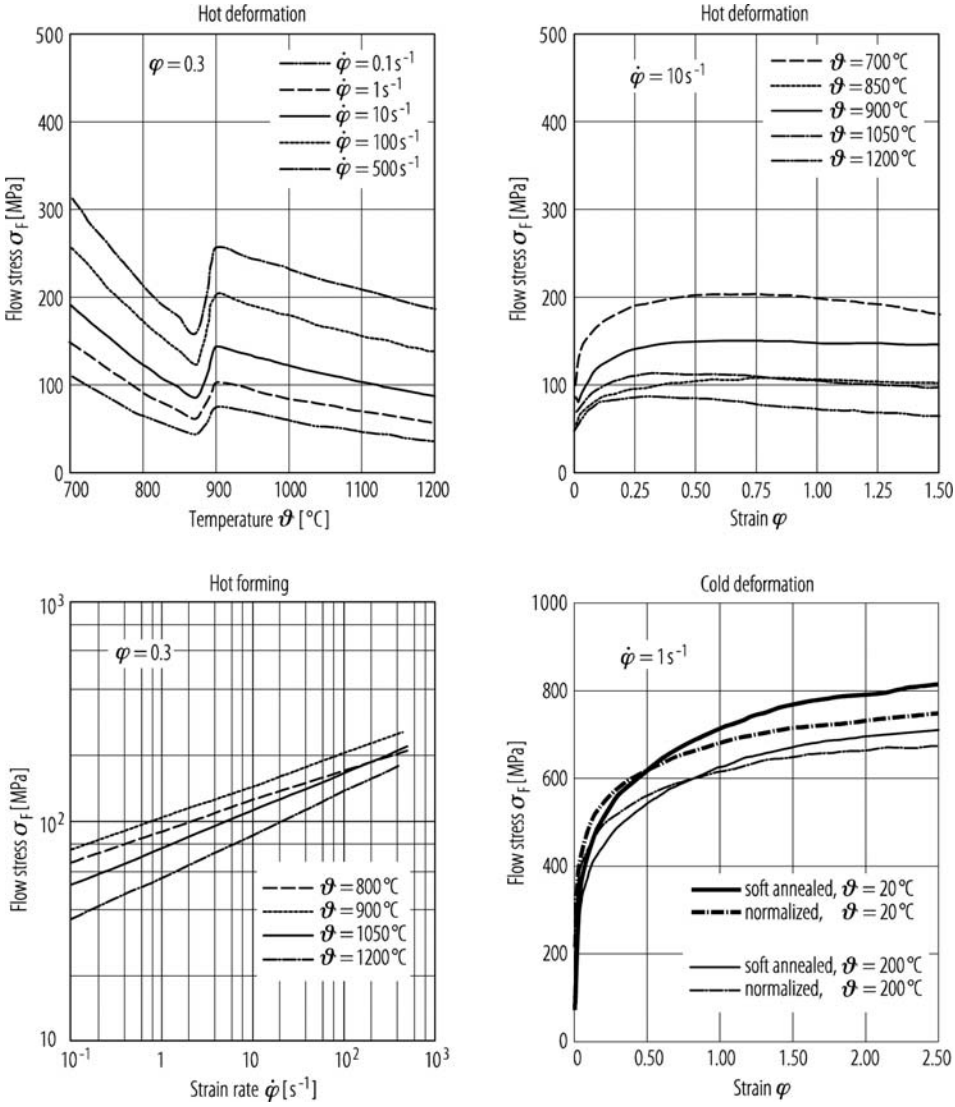
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Flow curves

State of material	Hot deformation		Cold deformation	
	deformed state		soft annealed	normalized
	austenite	ferrite+Fe_3C		
σ_{F0} [MPa]	103.00	(40.99)	449.9	486.7
A	948.09	6451.74	732.017	695.038
Effect of temperature K_ϑ				
m_1	−0.00168	−0.00514	−0.00074	−0.00057
Eeffect of strain K_φ				
m_2	0.36013	0.14477	0.18439	0.20685
m_4	0.00367	−0.00075	−0.00824	−0.0058
m_5	−0.00160	0.00081		
m_7	0.32298	−0.55679		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.01519	0.00222
m_8	0.000162	0.000174		
Range of validity				
ϑ [°C]	900…1200	700…875	20…240	20..320
φ	0.04…1.50	0.04…1.50	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.9.
DD11. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

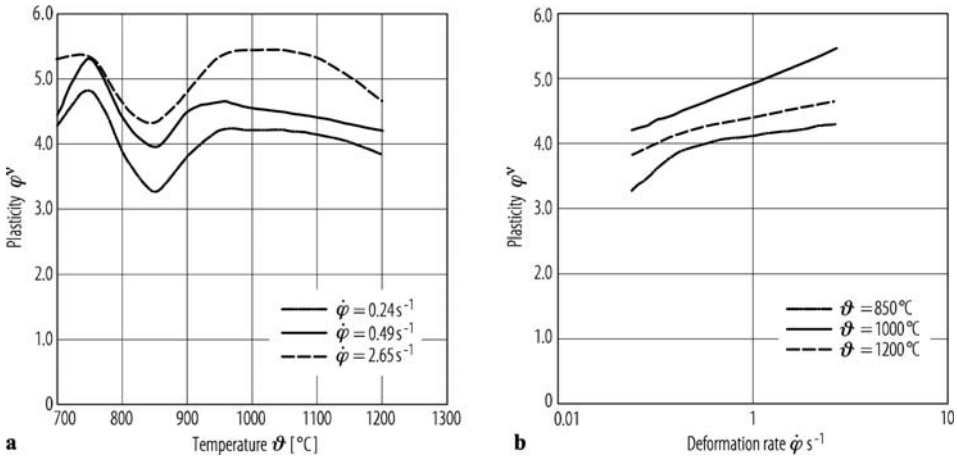
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
hot rolled	240…270	20.0861	0.71282	320…350	8.5196	0.89231
normalized	200…230	33.4085	0.60373	300…330	14.2337	0.75466

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
hot rolled					<85
normalized	45…55	180.90282	−0.24525	−16.8439	<70

Fig. 5.10.
DD11. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity by torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	61.45	468.04	12.21	7856.9	
100	57.66	480.26	12.45	7827.5	206.9
200	53.86	493.67	12.85	7796.3	201.7
300	49.60	513.36	13.30	7762.8	198.0
400	45.1	537.32	13.78	7726.9	192.8
500	40.61	563.9	14.3	7688.5	183.9
600	36.35	592.48	14.81	7647.4	170.3
700	32.40	623.02	15.35	7603.6	151.6
800	25.38	687.22	12.38	7623.4	128.6
900	26.76	684.75	13.03	7580.5	102.9
1000	27.78	682.29	13.61	7536.0	76.8
1100	28.78	679.84	14.14	7490.2	60.2
1200	29.96	677.39	14.63	7442.9	47.1

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: DD13/1.0335

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Mn	P	S
0.00…0.08	0.00…0.40	0.000…0.030	0.000…0.030

International comparison of standards

ISO		Euronorm			
~HR4	6317 (2000)	DD13	10111 (02/1998)		
~CR23	6932 (2001)				
United Kingdom		Russia			
~2 CS	1449 Part 1 (1991)				
~2 HS	1449 Part 1 (1991)				
Japan		China			
~SPHE	G 3131 (1996)-	-	-		
USA					
ASTM		AISI	SAE	UNS	

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

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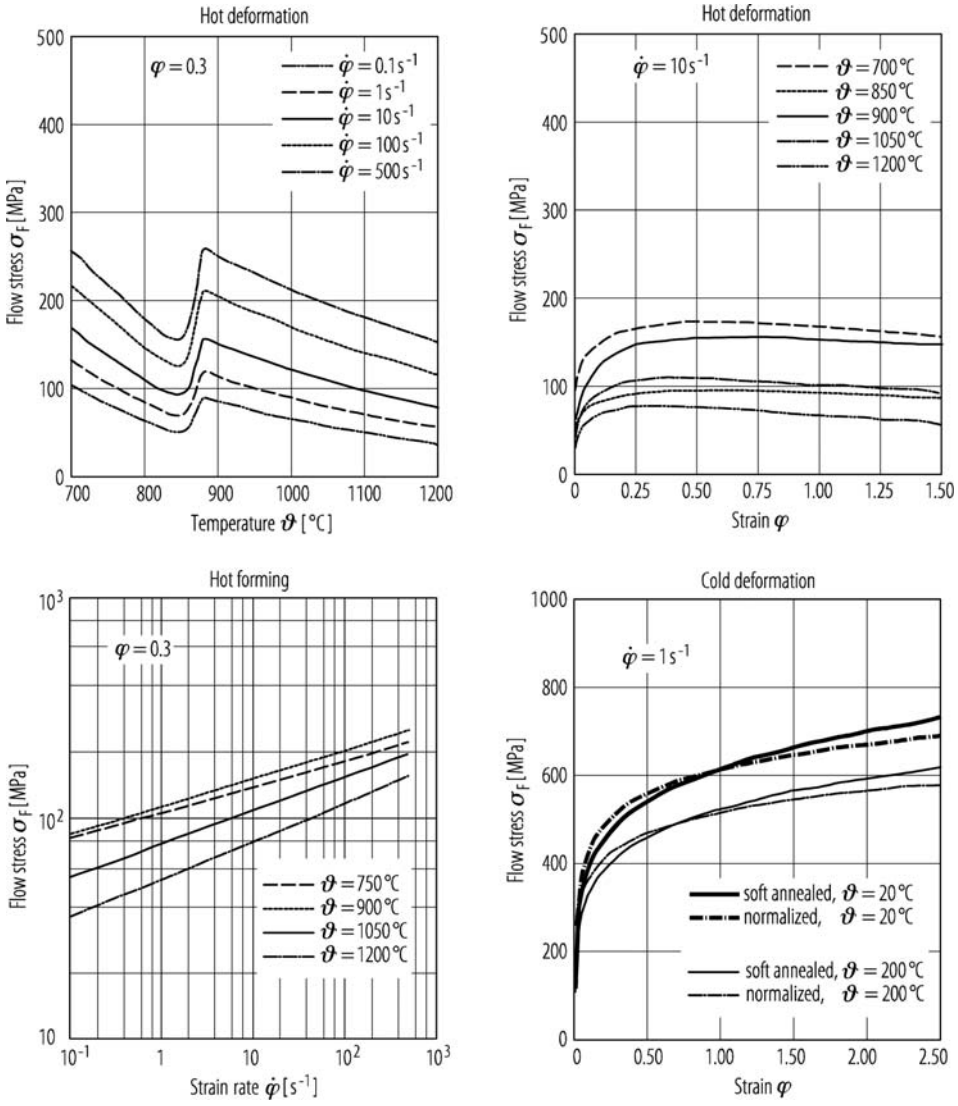
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Flow curves

State of material	Hot deformation		Cold deformation	
	deformed state		soft annaeled	normalized
	austenite	ferrite+Fe_3C		
σ_{F0} [MPa]	100.22	(44.58)	420.4	438.6
A	1546.89	3611.65	631.472	630.417
Effect of temperature K_ϑ				
m_1	−0.00219	−0.00433	−0.00091	−0.00097
Effect of strain K_φ				
m_2	0.33436	0.16920	0.17923	0.12506
m_4	0.00027	0.00009	−0.00398	−0.00675
m_5	−0.00129	−0.00003		
m_7	0.16538	−0.27400		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.01777	0.0052
m_8	0.000142	0.000154		
Range of validity				
ϑ [°C]	880…1200	700…850	20…320	20…320
φ	0.04…1.50	0.04…1.50	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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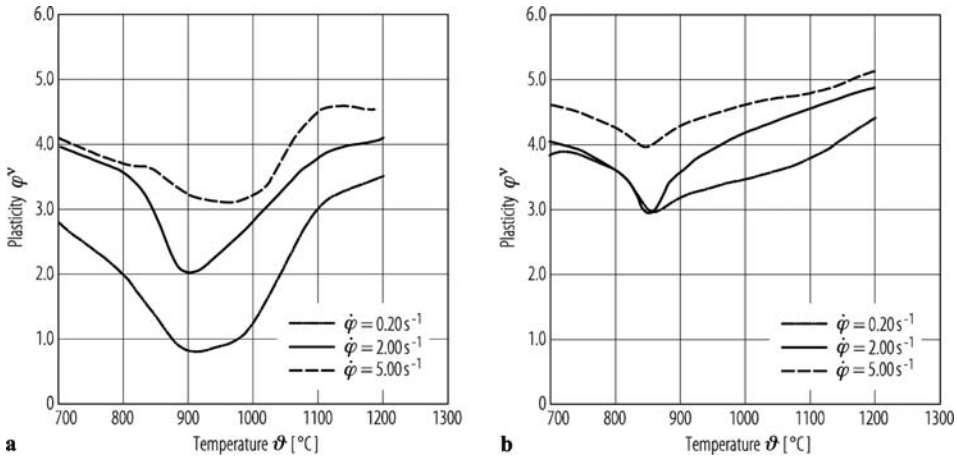
Fig. 5.11.
DD13. Flow stress curves by hot and cold forming.



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Fig. 5.12.
DD13. Hot plasticity as a function of the temperature. (a) Casting state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	65.08	466.37	12.49	7861.2	214.1
100	60.03	479.26	12.68	7831.3	207.5
200	55.58	491.93	12.98	7800.0	202.3
300	51.3	511.55	13.41	7766.4	198.0
400	46.3	535.42	13.87	7730.4	192.2
500	41.68	561.9	14.4	7691.8	183.3
600	37.29	590.38	14.89	7650.6	170.1
700	33.22	620.80	15.43	7606.5	152.2
800	25.86	684.90	12.76	7620.4	125.9
900	27.14	682.44	13.35	7577.8	99.0
1000	28.08	679.98	13.88	7533.8	77.8
1100	29.01	677.54	14.37	7488.4	61.2
1200	30.13	675.10	14.82	7441.7	48.1

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Steel symbol/number: DC04/1.0338

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Mn	P	S
0.00…0.08	0.00…0.40	0.000…0.030	0.000…0.030

International comparison of standards

ISO		Euronorm		
~CR24	6932 (2001)	DC04	10130 (05/1998)	
		DC04–ZE	10152 (10/1993)	
United Kingdom		Russia		
DC04	EN 10130 (05/1998)	~08JuA	4041 (1971)	
DC04-ZE	EN 10152 (10/1993)			
Japan		China		
~SPCE	G3141 (1996)	-	-	
~CR4	G3141 (1996)-			
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

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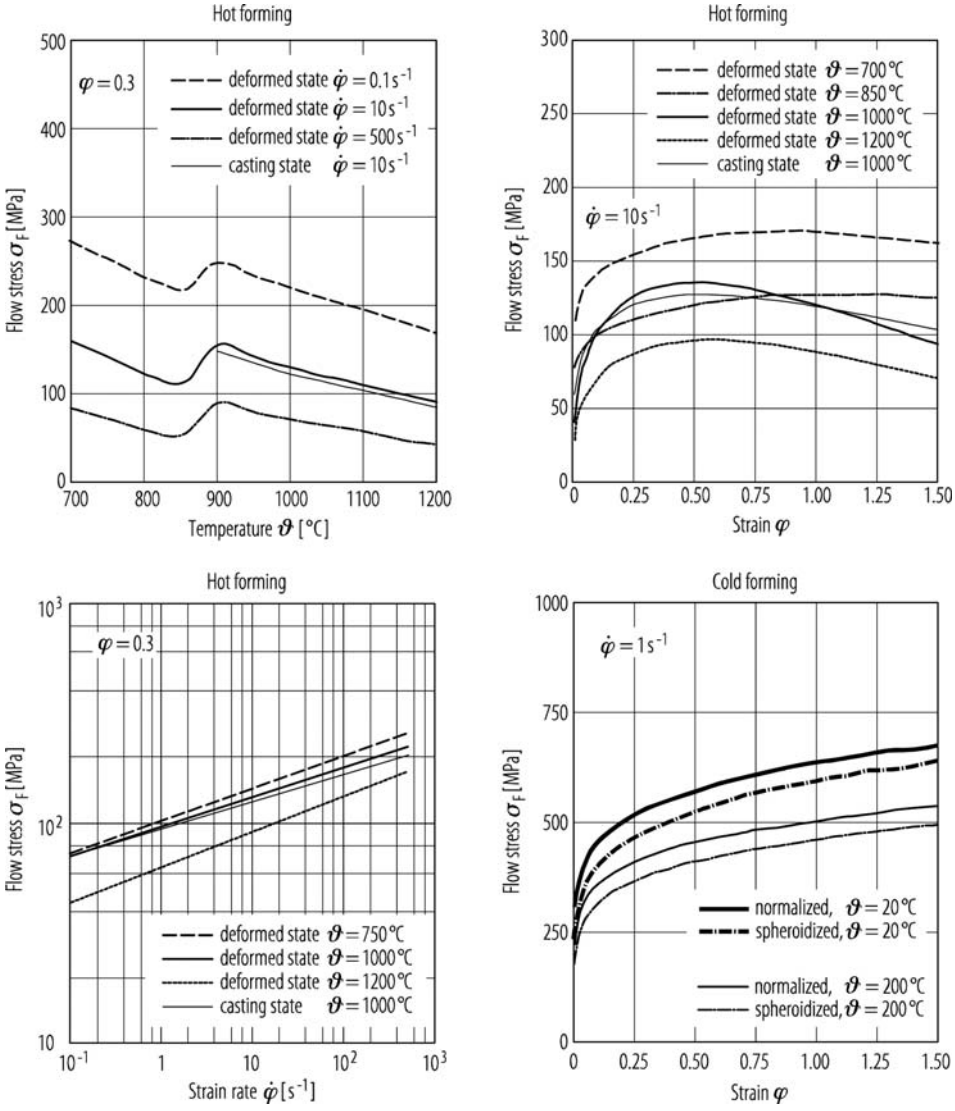
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Flow curves

	Hot deformation			Cold deformation	
	deformed – state		casting state	normalized	spheroidized
State of material	austenite	ferrite+Fe_3C	austenite		
σ_{F0} [MPa]	101.59	(51.26)	103.82	477.2	422.5
A	1561.21	956.12	1167.38	655.42	614.31
Effect of temperature K_ϑ					
m_1	−0.00226	−0.00291	−0.002182	−0.00132	−0.00143
Effect of strain K_φ					
m_2	0.31681	0.09166	0.21723	0.14496	0.16477
m_4	−0.00048	0.00010	0.00011	0.00013	−0.0006
m_5	0.00057	0.00086	0.00033		
m_7	−1.00839	−0.43700	−0.62386		
Effect of strain rate $K_{\dot\varphi}$					
m_3				0.01803	0.00854
m_8	0.000134	0.000198	0.000126		
Range of validity					
ϑ [°C]	900 … 1200	700…850	900…1200	20…180	20…180
φ	0.04…1.50	0.04…1.50	0.03…1.50	0.03…1.50	0.03…1.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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Fig. 5.13.
DC04. Flow stress curves by hot forming in deformed state.



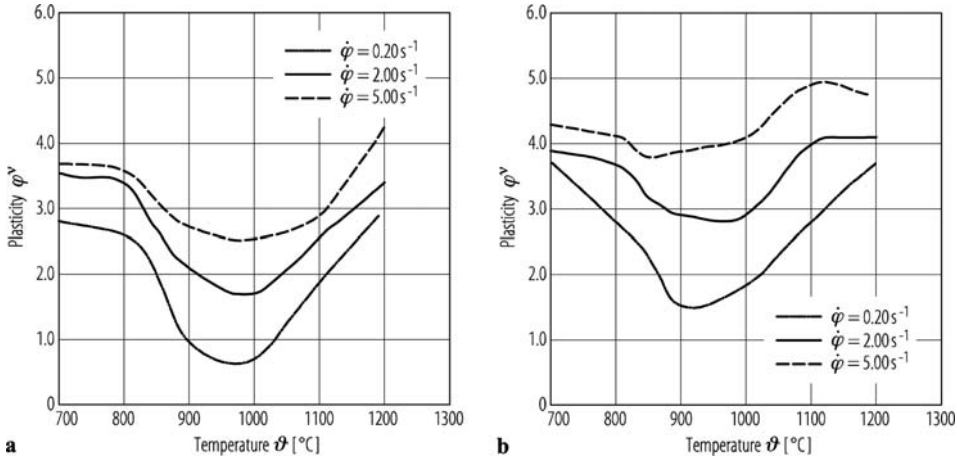
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Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
soft annealed	200…230	12.8428	0.8652	300…330	8.1955	0.92909	<80
hot rolled	230…260	20.8499	0.71253	310…340	8.2829	0.90032	<85

Fig. 5.14.
DC04. Hot plasticity as a function of the temperature. (a) Casting state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m* K]	c_{pm} [kJ/kg* K]	$\alpha_{m} * 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E * 10^5$ [MPa]
20	65.08	466.43	12.49	7861.2	214.2
100	60.03	479.22	12.68	7831.3	206.3
200	55.58	491.93	12.98	7800.0	200.6
300	51.03	511.55	13.41	7766.4	196.6
400	46.3	535.42	13.87	7730.4	191.4
500	41.68	561.9	14.4	7691.8	183.2
600	37.29	590.38	14.89	7650.6	170.5
700	33.22	620.80	15.43	7606.5	152.8
800	25.86	684.90	12.76	7620.4	130.3
900	27.14	682.44	13.35	7577.8	98.6
1000	28.08	679.98	13.88	7533.8	77.0
1100	29.01	677.54	14.37	7488.4	60.2
1200	30.13	675.10	14.82	7441.7	47.0

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Steel symbol/number: C15/1.0401

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S
0.12…0.18	0.00…0.40	0.30…0.60	0.000…0.045	0.000…0.045

International comparison of standards

ISO		Euronorm		
~C15E4	683–18(1996)	C15	10277 (07/1999)	
United Kingdom		Russia		
~080 A 15	PD 970 (2001)	~15K	5520-(1979)	
~17 CS	1449 Part 1 (1991)			
Japan		China		
~S15C	G4051 (1979)			
USA				
ASTM		AISI	SAE	UNS
~A 29 (M 1015)	A 29–99	~1015	~1015	~10150
~A 510 (1017)	A 510–02	~1017	~1017	~10170

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

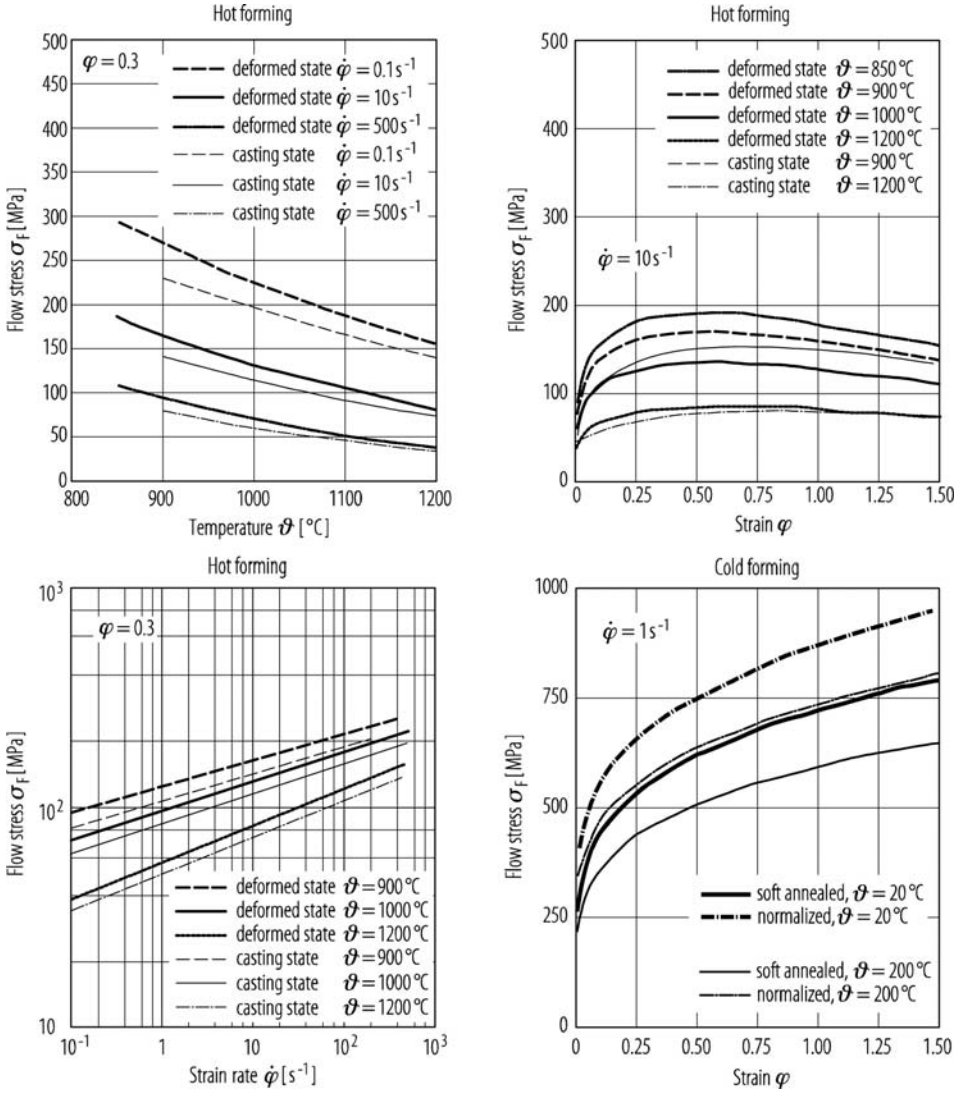
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Flow curves

State of material	Hot deformation		Cold deformation		
	deformed state	casting state	hot rolled	normalized	soft annealed
	austenite	austenite			
σ_{F0} [MPa]	109.9	90.3		552.9	451.1
A	2098.29	1744.51		888.34	738.29
Effect of temperature K_ϑ					
m_1	−0.00272	−0.00259		−0.00096	−0.0011
Effect of strain K_φ					
m_2	0.22312	0.31124		0.20978	0.22065
m_4	0.00003	0.00616		0.00198	0.00065
m_5	0.00028	0.00028			
m_7	−0.58508	−0.58508			
Effect of strain rate $K_{\dot\varphi}$					
m_3				0.00359	0.01342
m_8	0.000137	0.000137			
Range of validity					
ϑ [°C]	850…1200	900 … 1200		20…300	20…300
φ	0.04…1.50	0.04…1.50		0.04…1.8	0.04…1.8
$\dot\varphi$ [s^{-1}]	<500	<500		<500	<500

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Fig. 5.15.
C15. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

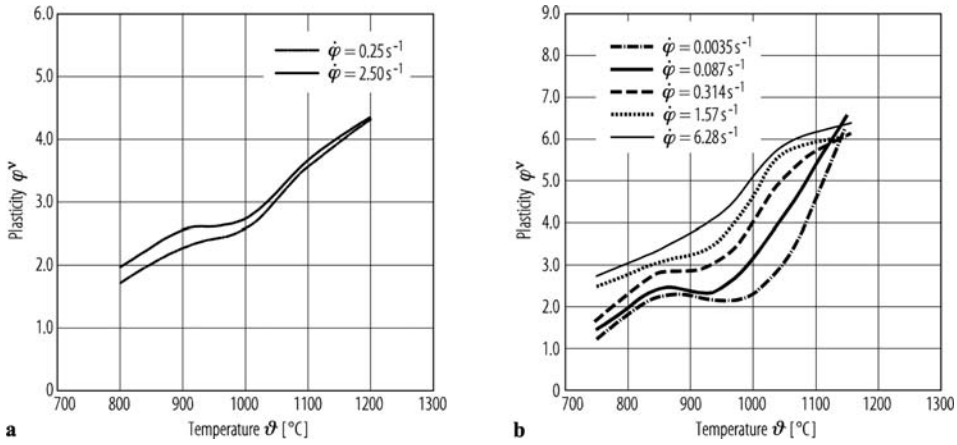
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
normalized	280…320	14.2703	0.82017	390…440	12.2670	0.82036
soft annealed	270…310	29.5304	0.62386	380…430	17.9073	0.71442

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
normalized					<80
soft annealed	32…36	48.07297	−0.07626	−7.5465	<70

Fig. 5.16.
C15. Hot plasticity of as a function of the temperature. (a) Casting state. Austenitised at 1200 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	54.36	472.11	11.64	7832.1	208.2
100	52.48	484.14	11.98	7803.9	199.3
200	49.96	497.07	12.54	7773.1	193.6
300	46.30	516.92	13.05	7740.1	189.9
400	42.2	541.07	13.55	7704.7	184.8
500	38.10	567.8	14.1	7666.8	176.0
600	34.15	596.65	14.60	7626.3	162.1
700	30.46	627.42	15.14	7583.0	142.9
800	24.42	691.57	12.08	7605.1	119.1
900	25.98	689.08	12.85	7560.3	106.6
1000	27.18	686.60	13.54	7513.9	82.7
1100	28.32	684.14	14.17	7465.8	63.2
1200	29.63	681.68	14.75	7416.1	53.3

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Steel symbol/number: C22/1.0402

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.17…0.24	0.00…0.40	0.40…0.70	0.00…0.045	0.00…0.045	0.00…0.40
Mo	Ni				
0.00…0.10	0.00…0.40				

International comparison of standards

ISO		Euronorm		
~ C20	683–18 (1996)	C22	10083–2 (08/1996)	
		C22	10250–2 (10/1999)	
United Kingdom		Russia		
~ 055 M 15	970 Part 1 (1996)			
~ 22 CS	1449 Part 1 (1991)			
Japan		China		
~ S 20 C	G 4051 (1979)			
~ S 22 C	G 4051 (1979)			
USA				
ASTM		AISI	SAE	UNS
~ A 29 (M1020)	A 29–99	~ 1020	~ 1020	~ G10200
~ A 331 (1023)	A 331–00	+ 1023	~ 1023	~ G10230

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

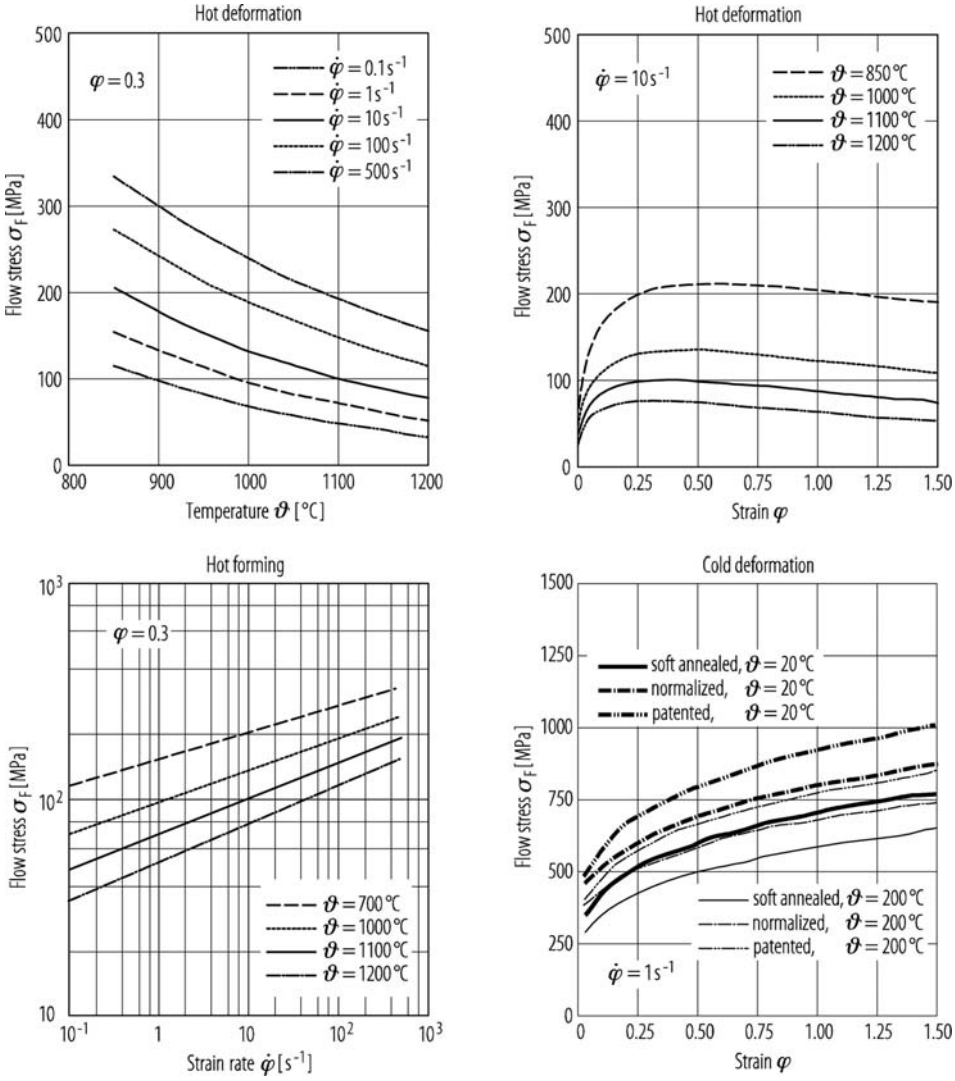
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Flow curves

State of material	Hot deformation	Cold deformation		
	deformed state	normalized	soft annealed	patented
	austenite			
σ_{F0} [MPa]	111.86	521.5	438.4	655.3
A	3304.39	811.79	718.40	941.888
Effect of temperature K_ϑ				
m_1	−0.00281	−0.0009	−0.00103	−0.00103
Effect of strain K_φ				
m_2	0.34766	0.21672	0.22701	0.22040
m_4	0.00002	0.00578	0.00196	0.00208
m_5	−0.00130			
m_7	0.07632			
Effect of strain rate $K_{\dot\varphi}$				
m_3		0.00726	0.01294	0.00726
m_8	0.000148			
Range of validity				
ϑ [°C]	850…1200	20…300	20…300	20…300
φ	0.04…1.50	0.04…2.0	0.04…1.80	0.04…1.80
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.17.
C22. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

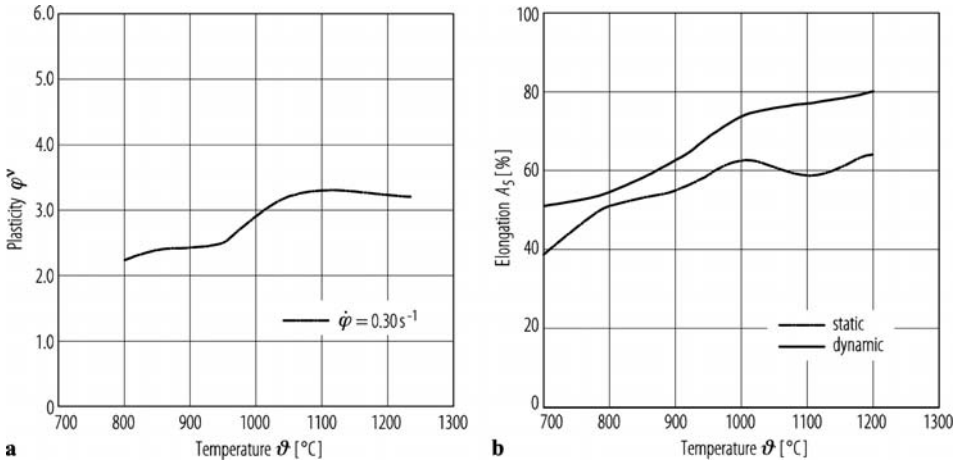
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
soft annealed	340…380	30.4794	0.64398		5.5442	0.98609
normalized	360…400	62.4434	0.50311	480…520	11.2286	0.83516
patented				560…600	22.3955	0.71459

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
soft annealed	35…40	47.44068	−0.06513	−11.4471	<70
normalized	30…35	151.94217	−0.3253	−18.7084	<70
patented					<80

Fig. 5.18.
C22. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformation rate: 0.2 [s^{-1}]. Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m * K]	c_{pm} [kJ/kg * K]	$\alpha_m * 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E * 10^5$ [MPa]
20	55.05	472.3	11.36	7842.4	
100	50.07	485.5	11.74	7814.8	
200	48.09	498.7	12.37	7787.1	
300	44.69	518.6	12.90	7751.3	
400	40.81	542.9	13.41	7716.2	
500	36.86	569.7	13.93	7678.5	
600	33.06	598.7	14.46	7638.2	
700	29.50	629.6	15.01	7595.2	
800	24.00	693.5	12.21	7612.6	
900	25.64	691.0	13.05	7566.0	
1000	26.91	688.6	13.81	7517.4	
1100	28.13	686.1	14.50	7467.1	
1200	29.50	683.6	15.14	7415.1	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

DOI: 10.1007/978-3-540-44760-3_20
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Steel symbol/number: L290MB/1.0429

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.16	0.00…0.45	0.00…1.50	0.000…0.025	0.000…0.020	0.00…0.30
Mo	Ni	V	Al	Cu	N
0.00…0.10	0.00…0.30	0.000…0.040	0.015…0.06	0.000…0.250	0.000…0.012
Nb					
0.00 0.04					

International comparison of standards

ISO		Euronorm		
		L290MB	10208–2 (8/1996)	
United Kingdom		Russia		
L290MB	EN 10208 (8/1996)			
Japan		China		
USA				
ASTM		API	SAE	UNS
		API 5LX42∼1015		

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

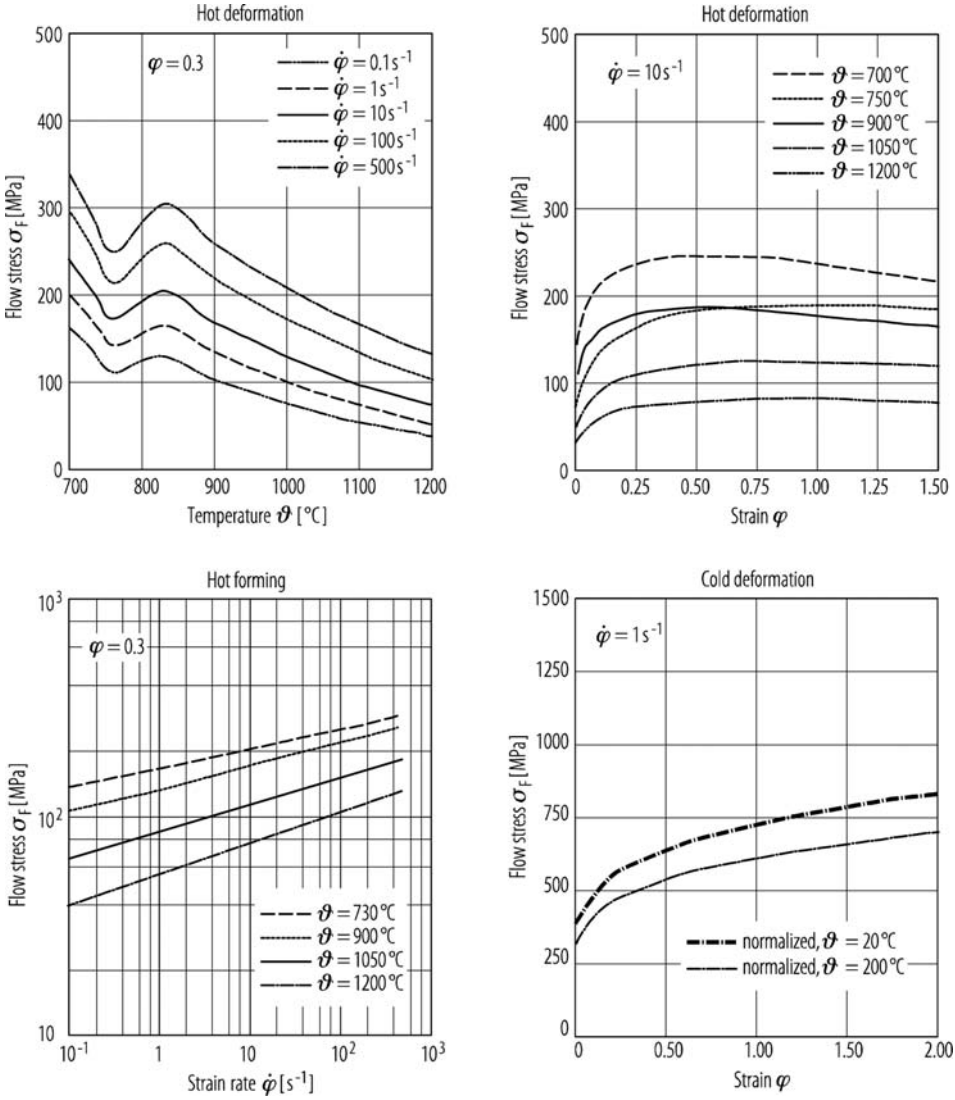
DOI: 10.1007/978-3-540-44760-3_21
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Flow curves

State of material	Hot deformation		Cold deformation
	deformed state		normalized
	austenite	ferrite+Fe_3C	
σ_{F0} [MPa]	103.40	(41.17)	488.7
A	2941.44	15111.10	739.011
Effect of temperature K_ϑ			
m_1	−0.00296	−0.00574	−0.00102
Effect of strain K_φ			
m_2	0.27379	0.17932	0.19023
m_4	0.00077	0.00056	0.00212
m_5	−0.00020	−0.00011	
m_7	−0.20252	−0.28587	
Effect of strain rate $K_{\dot\varphi}$			
m_3			0.01026
m_8	0.000119	0.000122	
Range of validity			
ϑ [°C]	830…1200	700…760	20…300
φ	0.04…1.50	0.04…1.50	0.04…2.20
$\dot\varphi$ [s^{-1}]	<500	<500	<500

DOI: 10.1007/978-3-540-44760-3_21
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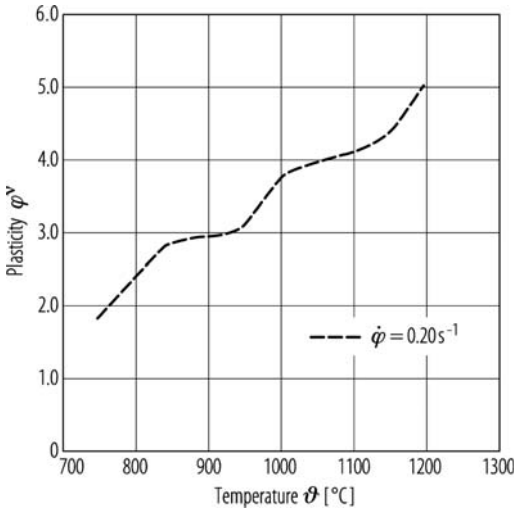
Fig. 5.19.
L290MB. Flow stress curves by hot and cold forming.



DOI: 10.1007/978-3-540-44760-3_21
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Fig. 5.20.
L290MB. Hot plasticity as a function of temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.60…0.90.

Plasticity in torsion



DOI: 10.1007/978-3-540-44760-3_21
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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	50.34	473.05	11.25	7831.4	
100	49.20	486.27	11.65	7804.0	
200	47.40	499.36	12.30	7773.6	
300	44.10	519.33	12.84	7740.9	
400	40.3	543.62	13.35	7705.9	
500	36.41	570.5	13.9	7668.4	
600	32.66	599.50	14.40	7628.4	
700	29.15	630.43	14.95	7585.5	
800	23.85	694.27	12.32	7599.8	
900	25.52	691.78	13.20	7552.2	
1000	26.82	689.29	13.99	7502.7	
1100	28.06	686.82	14.70	7451.4	
1200	29.45	684.35	15.36	7398.2	

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

DOI: 10.1007/978-3-540-44760-3_21
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Steel symbol/number: H300BD/1.0445

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.00…0.10	0.00…0.50	0.00…0.70	0.000…0.120	0.000…0.025	>0.020

International comparison of standards

ISO		Euronorm		
		H300BD	10292 (08/2002)	
United Kingdom		Russia		
H300BD	EN 10292 (08/2002)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS
A 414 (F)	A 414–01			K03101
A 515 (70) (485)	A 515–01			K03102

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

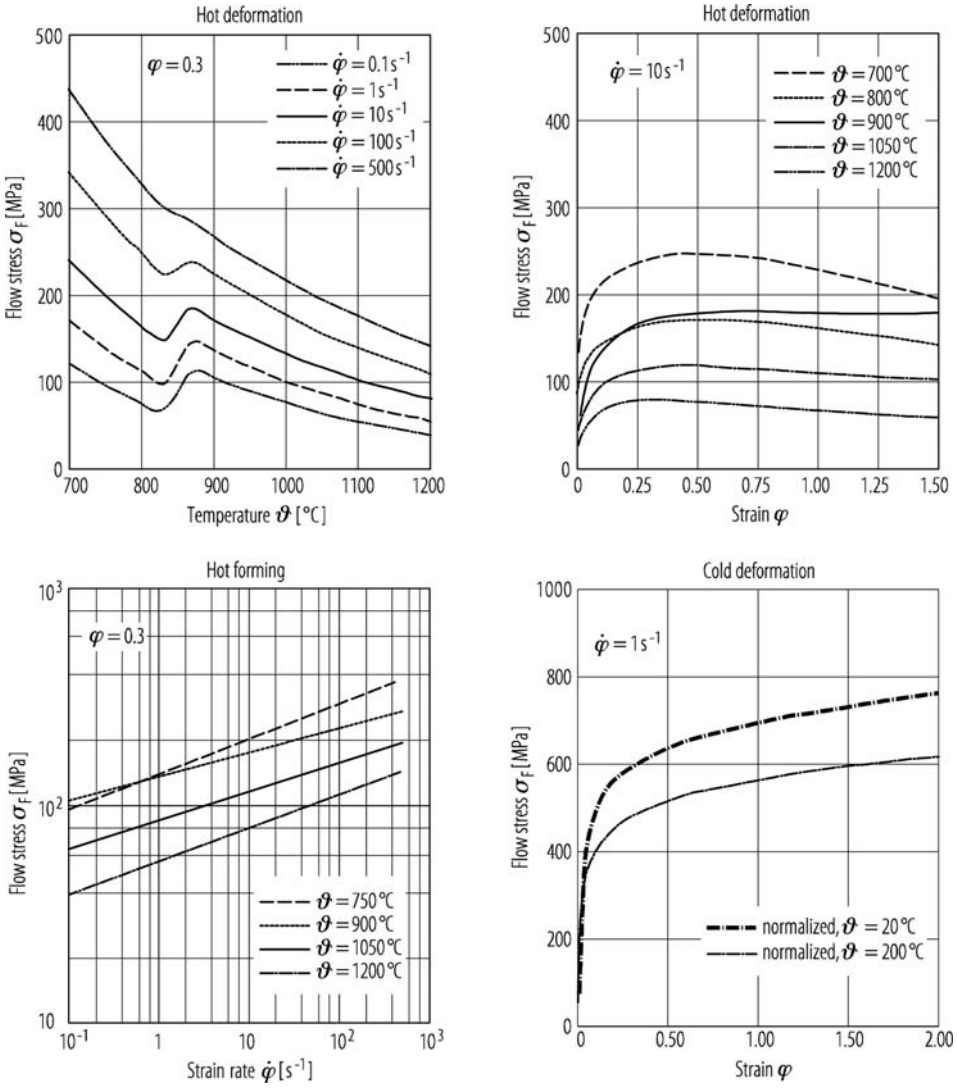
DOI: 10.1007/978-3-540-44760-3_22
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Flow curves

State of material	Hot deformation		Cold deformation
	deformed state		normalized
	austenite	ferrite+Fe_3C	
σ_{F0} [MPa]	107.99	(66.57)	502.4
A	2633.03	4863.24	723.460
Effect of temperature K_ϑ			
m_1	−0.00250	−0.00441	−0.00120
Effect of strain K_φ			
m_2	0.37677	0.16332	0.11291
m_4	0.00099	−0.00018	−0.0106
m_5	−0.00160	0.00072	
m_7	0.30801	−0.67087	
Effect of strain rate $K_{\dot\varphi}$			
m_3			0.01860
m_8	0.000124	0.000215	
Range of validity			
ϑ [°C]	870…1250	700…830	20…300
φ	0.04…1.50	0.04…1.50	0.04…2.10
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.21.
H300BD. Flow stress curves by hot and cold forming.



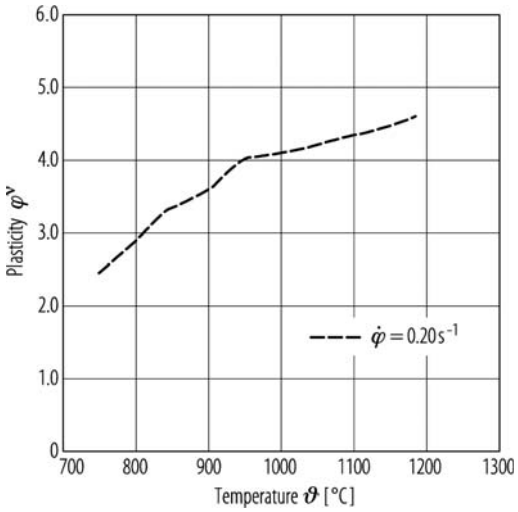
Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
hot rolled	300…340	33.2518	0.60008	380…430	19.0343	0.69329	<80

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Fig. 5.22.
H300BD. Hot plasticity as a function of temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.60…0.90.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	55.53	470.04	11.74	7838.5	
100	53.38	483.51	12.06	7810.1	
200	50.65	496.48	12.60	7781.8	
300	46.89	516.31	13.10	7746.1	
400	42.73	540.42	13.60	7710.6	
500	38.55	567.13	14.11	7672.6	
600	34.55	595.93	14.64	7631.9	
700	30.81	626.65	15.19	7588.5	
800	24.58	690.84	12.08	7611.3	
900	26.11	688.36	12.83	7567.0	
1000	27.28	685.89	13.50	7521.0	
1100	28.40	683.42	14.11	7473.4	
1200	29.69	680.97	14.68	7424.3	

DOI: 10.1007/978-3-540-44760-3_22
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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: P295GH/1.0481

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.08…0.20	0.00…0.40	0.90…1.50	0.000…0.025	0.000…0.015	0.00…0.30
Mo	Ni	V	Al	Cu	Nb
0.00…0.08	0.00…0.30	0.00…0.02	>0.0200	0.00…0.30	0.000…0.020
Ti	N				
0.00…0.03	0.000…0.012				

International comparison of standards

ISO		Euronorm		
		P295GH	10028–2 (06/2003)	
		P295GH	10273 (01/2000)	
United Kingdom		Russia		
P295GH	EN 10028–2 (06/2003)	14G2	19281 (1989)	
Japan		China		
~SG 365	G 3116 (2000)	–	–	
~SGV 410	G 3118 (2000)			
USA				
ASTM		AISI	SAE	UNS
~A 210 (C)	A 210–02			K02704
~A 414 (E)	A 414–01			K03101

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

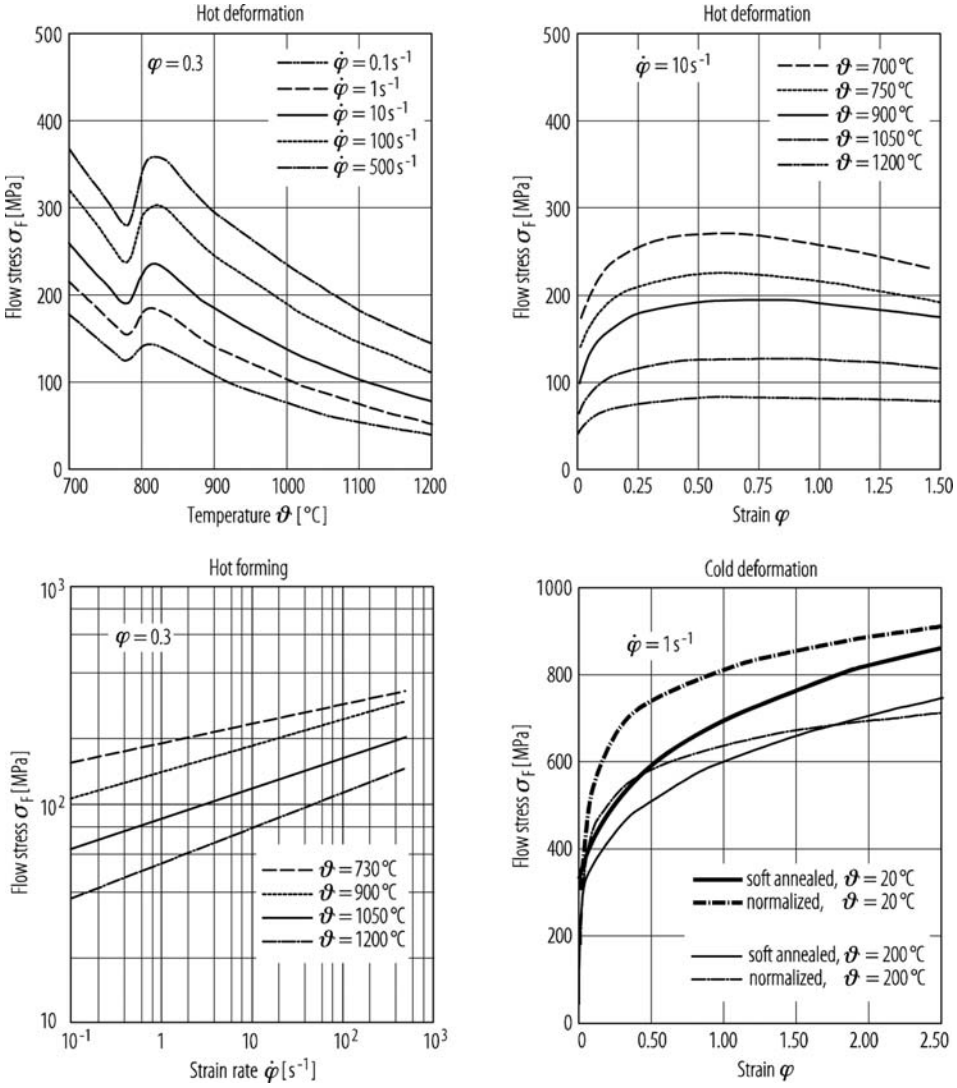
DOI: 10.1007/978-3-540-44760-3_23
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Flow curves

State of material	Hot deformation			Cold deformation	
	deformed state		casting state	soft annealed	normalized
	austenite	ferrite+Fe_3C	austenite		
σ_{F0} [MPa]	114.76	(66.67)	93.8	490.3	549.9
A	3659.66	6024.57	3042.64	704.734	848.855
Effect of temperature K_ϑ					
m_1	−0.00326	−0.00436	−0.00313	−0.00081	−0.00139
Effect of strain K_φ					
m_2	0.21374	0.19415	0.30182	0.23473	0.11555
m_4	0.00078	0.00184	0.00691	0.00437	−0.01444
m_5	0.00018	0.00063	0.00017		
m_7	−0.41323	−0.60697	−0.41298		
Effect of strain rate $K_{\dot\varphi}$					
m_3				0.00432	0.00186
m_8	0.000133	0.000124	0.000131		
Range of validity					
ϑ [°C]	815…1200	700…780	900…1200	20…250	20…250
φ	0.04…1.50	0.04…1.50	0.04…1.50	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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Fig. 5.23.
P295GH. Flow stress curves by hot and cold forming.



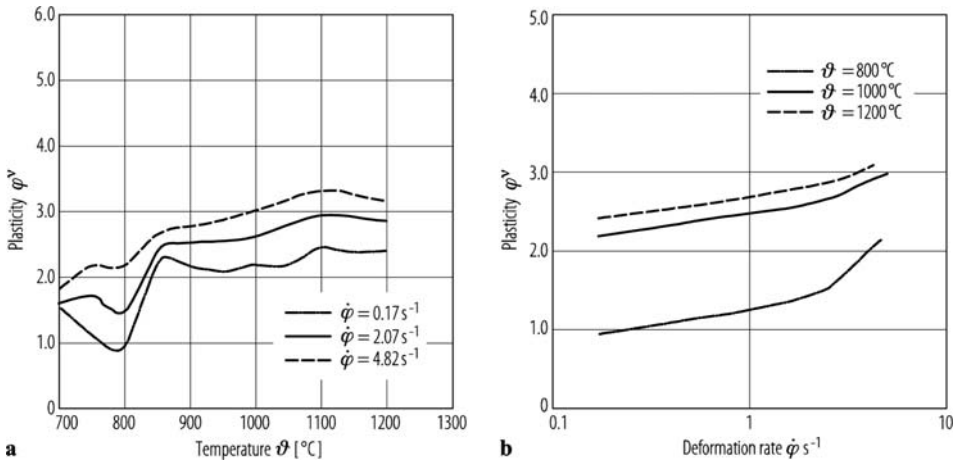
Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
hot rolled	300…350	68.2529	0.50288	460…520	27.2695	0.66542	<80

DOI: 10.1007/978-3-540-44760-3_23
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Fig. 5.24.
P295GH. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	49.29	473.65	11.13	7831.9	211.8
100	48.31	486.93	11.54	7804.8	202.4
200	46.70	500.10	12.22	7774.5	194.4
300	43.50	520.12	12.76	7742.0	187.9
400	39.8	544.45	13.28	7707.1	180.8
500	35.94	571.4	13.8	7669.8	171.3
600	32.25	600.43	14.33	7629.9	158.5
700	28.79	631.41	14.87	7587.3	142.0
800	23.70	695.10	12.50	7597.0	122.3
900	25.40	692.60	13.42	7548.2	100.3
1000	26.72	690.12	14.24	7497.3	79.2
1100	27.99	687.64	14.99	7444.5	62.4
1200	29.40	685.16	15.68	7389.8	49.1

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Steel symbol/number: H280LA/1.0489

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.00…0.10	0.00…0.50	0.00…0.80	0.000…0.025	0.000…0.025	>0.0150
Nb	Ti				
0.000…0.090	0.00…0.15				

International comparison of standards

ISO		Euronorm		
		H280LA	10268 (11/1998)	
United Kingdom		Russia		
H280LA	EN 10268 (11/1998)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

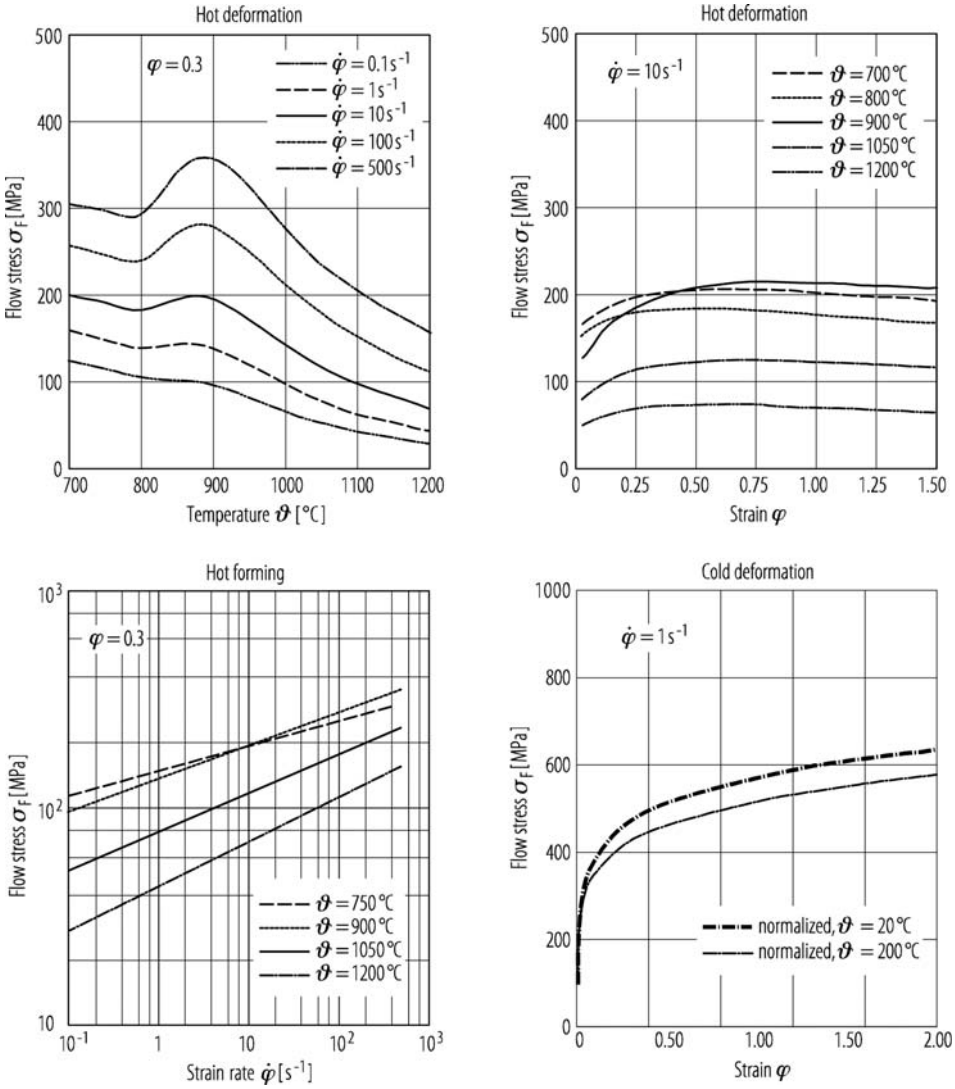
DOI: 10.1007/978-3-540-44760-3_24
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Flow curves

State of material	Hot deformation		Cold deformation
	deformed state		normalized
	austenite	ferrite+Fe_3C	
σ_{F0} [MPa]	109.49	(138.04)	363.2
A	6686.99	515.22	561.318
Effect of temperature K_ϑ			
m_1	−0.00361	−0.00115	−0.00059
Effect of strain K_φ			
m_2	0.39719	0.21599	0.15198
m_4	0.01035	0.00558	−0.00641
m_5	−0.00081	−0.00074	
m_7	−0.05298	−0.03061	
Effect of strain rate $K_{\dot\varphi}$			
m_3			−0.00325
m_8	0.000170	0.000151	
Range of validity			
ϑ [°C]	895 … 1200	700 …810	20…320
φ	0.04…2.00	0.04…2.00	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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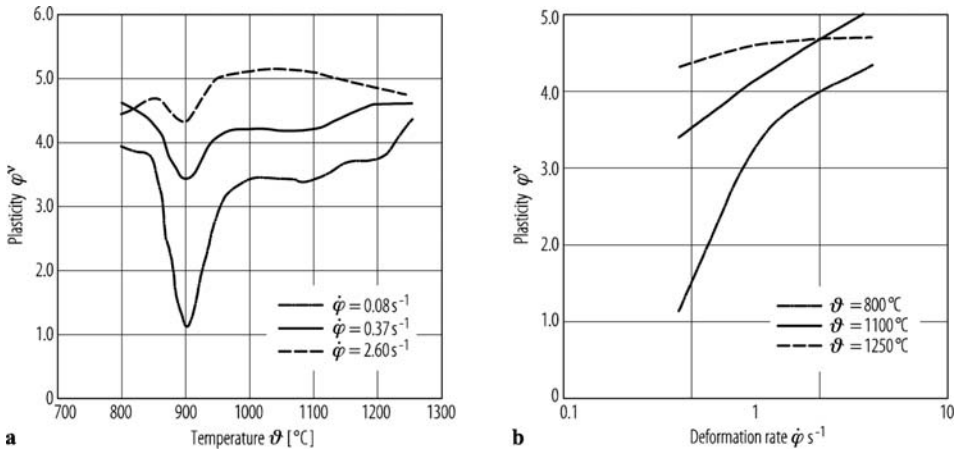
Fig. 5.25.
H280LA. Flow stress curves by hot and cold forming.



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Fig. 5.26.
H280LA. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	55.16	470.73	11.71	7824.0	215.2
100	53.10	483.76	12.04	7795.8	206.2
200	50.44	496.66	12.58	7765.0	200.5
300	46.71	516.50	13.08	7731.9	197.0
400	42.6	540.62	13.58	7696.5	192.4
500	38.41	567.3	14.1	7658.6	184.2
600	34.43	596.15	14.63	7618.0	171.2
700	30.70	626.89	15.17	7574.7	153.2
800	24.53	691.07	12.08	7597.3	131.1
900	26.07	688.58	12.83	7552.9	99.3
1000	27.25	686.11	13.51	7506.9	76.6
1100	28.38	683.64	14.13	7459.3	58.7
1200	29.67	681.19	14.70	7410.1	46.4

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DOI: 10.1007/978-3-540-44760-3_24
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Steel symbol/number: C35/1.0501

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.32…0.39	0.00…0.40	0.50…0.80	0.000…0.045	0.000…0.045	0.00…0.40
Mo	Ni				
0.00…0.10	0.00…0.40				

International comparison of standards

ISO		Euronorm		
~C35	683–1 (1987)	C35	10083–2 (08/1996)	
~CS 35	4960 (1999)	C35	10250–2 (10/1999)	
United Kingdom		Russia		
C35	EN 10277–2 (07/1999)			
~40 HS	1449 Part 1 (1991)			
Japan		China		
~S 35 CM	G 3311 (1998)	–	–	
~S 35 C	G 4051 (1979)			
USA				
ASTM		AISI	SAE	UNS
~A 29 (1035)	A 29–99	~1035	~1035	~G10350
~A 510 (1035)	A 510–02			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

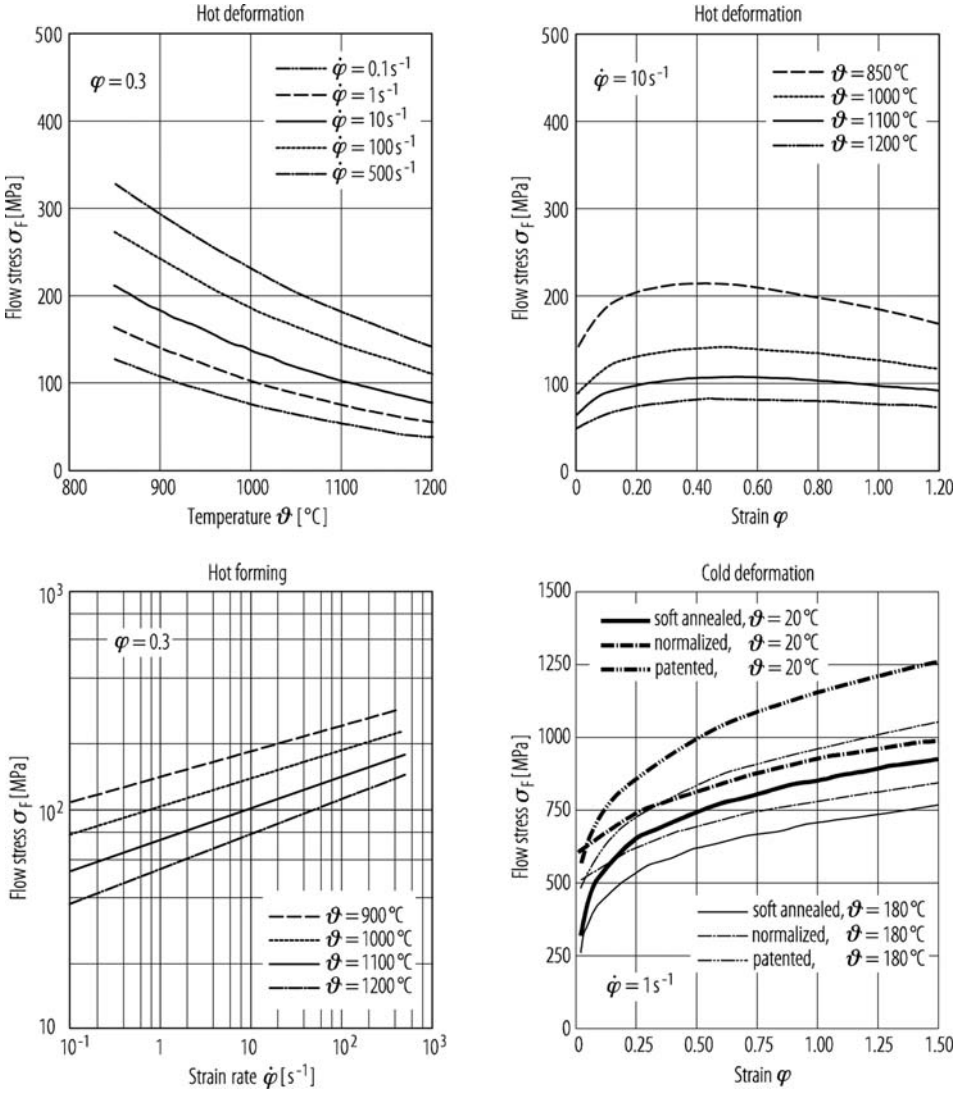
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Flow curves

State of material	Hot deformation	Cold deformation		
	deformed state	soft annealed	normalized	patented
	austenite			
σ_{F0} [MPa]	117.07	545.3	667.9	738.4
A	4204.27	882.793	939.615	1178.940
Effect of temperature K_ϑ				
m_1	−0.00342	−0.00120	−0.00107	−0.00114
Effect of strain K_φ				
m_2	0.20033	0.1845	0.17735	0.21229
m_4	0.00167	−0.00613	0.00611	0.00211
m_5	0.00082			
m_7	−0.96960			
Effect of strain rate $K_{\dot\varphi}$				
m_3		0.01237	0.01187	0.01201
m_8	0.000131			
Range of validity				
ϑ [°C]	850…1200	20…300	20…180	20…180
φ	0.04…1.2	0.04..2.00	0.04…1.80	0.04…1.80
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.27.
C35. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

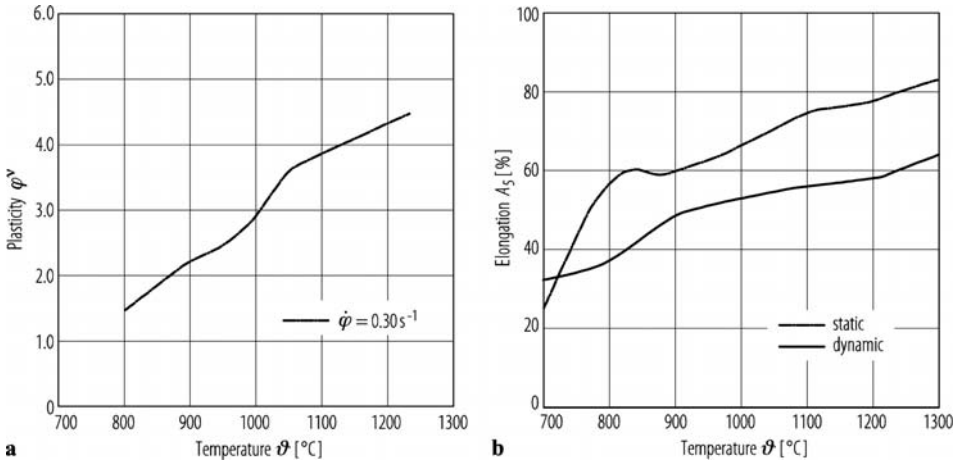
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
hot rolled	700…750	16.8684	0.81793			
normalized	410…450	37.5386	0.6336	500…600	32.6358	0.60373
patented				700…750	22.6419	0.70603

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
hot rolled					<60
normalized	25…32	33.06747	−0.00782	−7.72004	<70
patented					<80

Fig. 5.28.
C35. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on temperature. (b) Deformation rate: 0.2 [s^{-1}]. Deformed state. Direct heatin on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	48.82	474.03	11.06	7825.7	214.3
100	47.90	487.31	11.48	7798.8	205.8
200	46.37	500.48	12.17	7768.6	200.2
300	43.21	520.52	12.72	7736.1	196.4
400	39.5	544.87	13.24	7701.4	191.3
500	35.72	571.8	13.8	7664.2	182.9
600	32.05	600.91	14.29	7624.4	169.7
700	28.61	631.91	14.83	7581.9	151.1
800	23.63	695.52	12.61	7588.9	127.6
900	25.35	693.02	13.55	7539.4	100.1
1000	26.68	690.53	14.40	7487.7	73.5
1100	27.95	688.05	15.16	7434.1	55.0
1200	29.38	685.57	15.87	7378.6	46.8

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Steel symbol/number: C45/1.0503

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.42…0.50	0.00…0.40	0.50…0.80	0.000…0.045	0.000…0.045	0.00…0.40
Mo	Ni				
0.00…0.10	0.00…0.40				

International comparison of standards

ISO		Euronorm		
~C45	683–1 (1987)	C45	10083–2 (08/1996)	
~CS 45	4960 (1999)	C45	10250–2 (10/1999)	
United Kingdom		Russia		
C45	EN 10083–2 (08/1996)			
~50 HS	1449 Part 1 (1991)			
Japan		China		
~S 45 CM	G 3311 (1998)		–	
~S 45 C	G 4051 (1979)			
USA				
ASTM		AISI	SAE	UNS
~A 29 (1045)	A 29–99	~1043	~1043	~G10430
~A 510 (1045)	A 510–02	~1045	~1045	~G10450

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

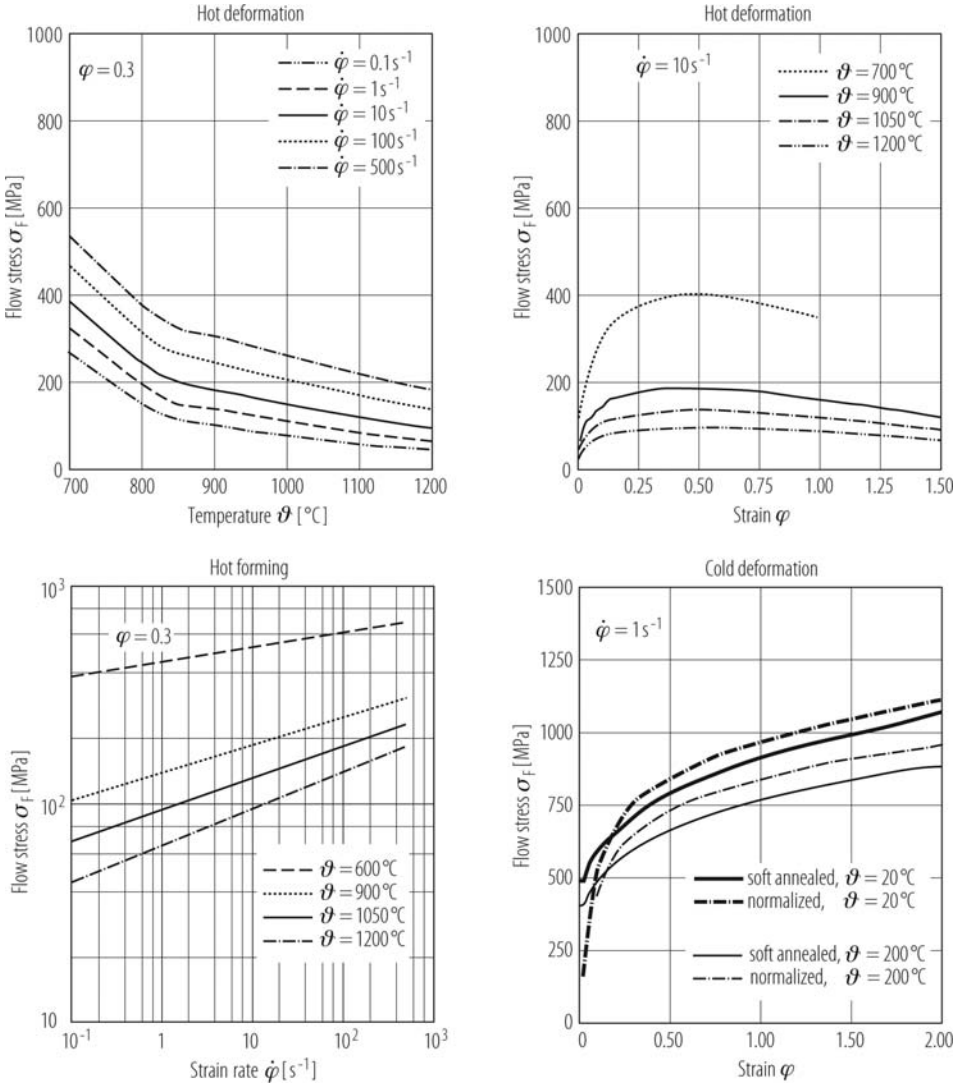
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Flow curves

State of material	Hot deformation		Cold deformation	
	deformed state		soft annealed	normalized
	austenite	ferrite+Fe_3C		
σ_{F0} [MPa]	118.74	(121.55)	594.6	735.6
A	2731.39	6532.26	928.64	1023.741
Effect of temperature K_ϑ				
m_1	−0.00268	−0.00331	−0.0010	−0.00082
Effect of strain K_φ				
m_2	0.31076	0.37825	0.21903	0.1674
m_4	−0.00056	0.00018	0.00457	−0.0239
m_5	0.00046	0.00029		
m_7	−0.98375	−0.95149		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.014	0.01742
m_8	0.000139	0.000114		
Range of validity				
ϑ [°C]	820…1200	500..770	20…300	20…300
φ	0.04…1.50	0.04…1.00	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.29.
C45. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

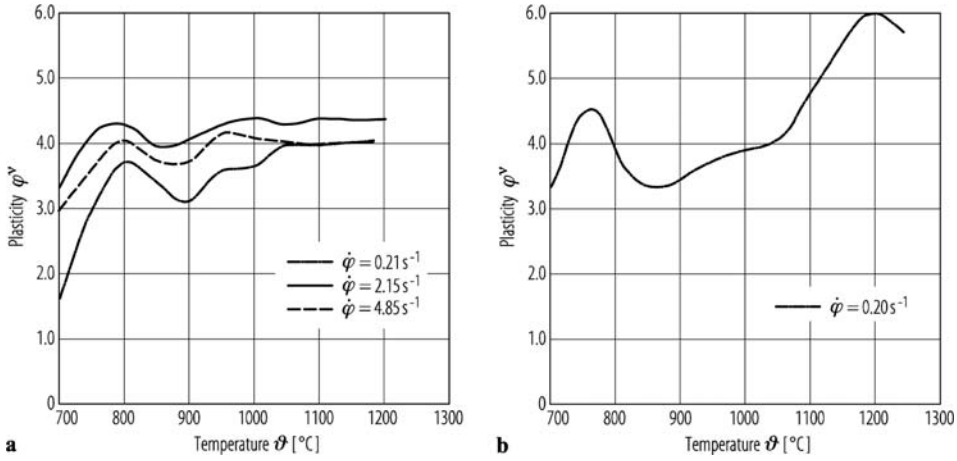
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
soft annealed	290…330	21.4218	0.78096	450…500	12.2551	0.8453
normalized	320…350	83.8836	0.48298	570…630	13.8198	0.83516
patented				800…850	12.4034	0.85108

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
soft annealed					<80
normalized	28….33	31.98509	−0.00317	−8.94799	<70
patented					<80

Fig. 5.30.
C45. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	48.03	474.62	10.93	7820.9	213.9
100	47.21	487.94	11.36	7794.3	206.4
200	45.82	501.20	12.08	7764.2	201.2
300	42.74	521.29	12.64	7732.0	197.5
400	39.1	545.69	13.16	7697.4	192.3
500	35.35	572.7	13.7	7660.4	183.8
600	31.73	601.83	14.21	7620.9	170.8
700	28.33	632.89	14.75	7578.7	153.2
800	23.52	696.29	12.87	7579.4	131.7
900	25.25	693.79	13.86	7528.3	107.9
1000	26.61	691.30	14.74	7475.0	84.2
1100	27.90	688.81	15.55	7419.7	64.2
1200	29.34	686.34	16.29	7362.3	51.9

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Steel symbol/number: C56D/1.0518

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.53…0.58	0.10…0.30	0.50…0.80	0.000…0.035	0.000…0.035	0.00…0.010
Cr	Cu	Mo	Ni		
0.00…0.15	0.00…0.25	0.00…0.05	0.00…0.20		

International comparison of standards

ISO		Euronorm		
~2CD55A	8457–2(1989)	C56D	10016–2 (12/1994)	
~C56D	16120–2 (2001)			
United Kingdom		Russia		
C56D	EN 10016–2 (12/1994)			
Japan		China		
		–	–	
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

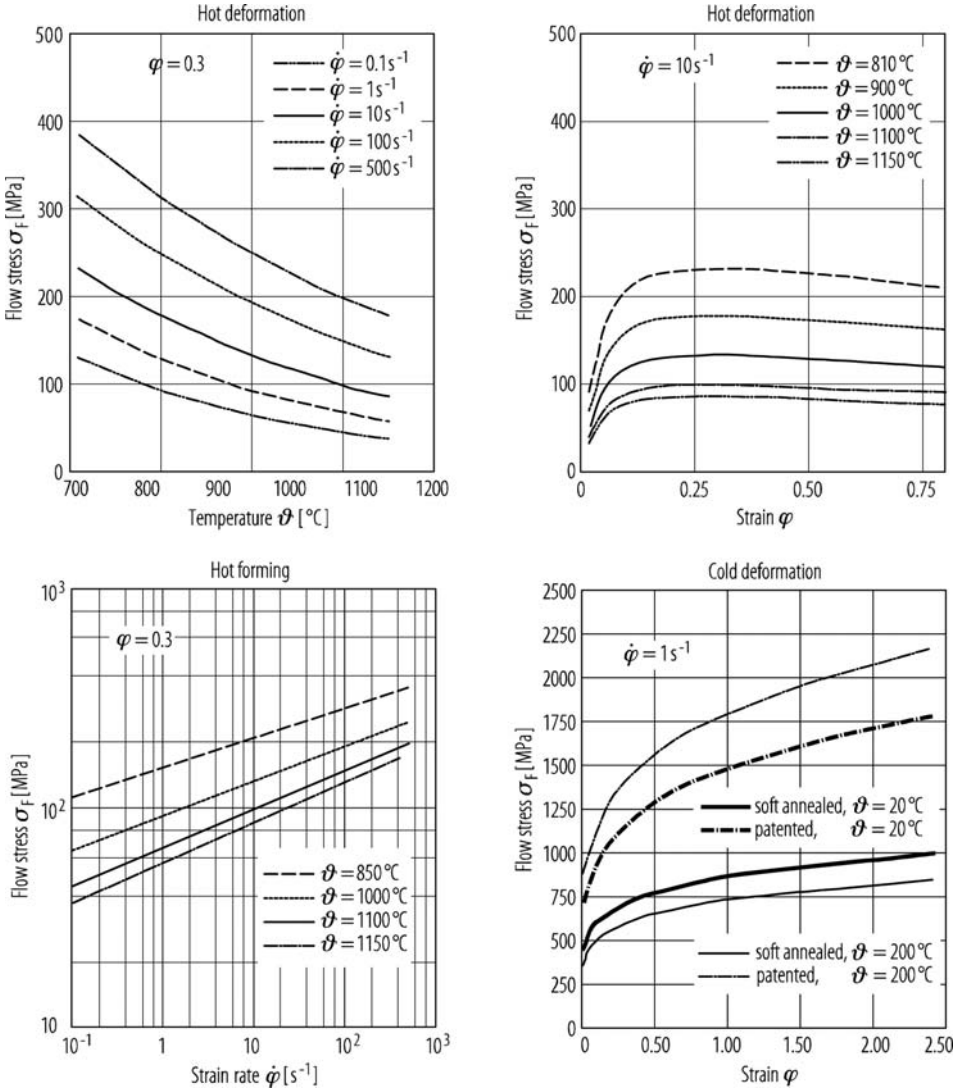
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annaeled	patented
	austenite		
σ_{F0} [MPa]	119.20	614.8	916.5
A	3006.43	881.519	1450.571
Effect of temperature K_ϑ			
m_1	−0.00324	−0.00096	−0.00106
Effect of strain K_φ			
m_2	0.03674	0.15922	0.20897
m_4	−0.02247	0.00080	0.00235
m_5	−0.00021		
m_7	−0.24543		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.00771	0.00952
m_8	0.000159		
Range of validity			
ϑ [°C]	810 … 1150	20…200	20…200
φ	0.04…0.80	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.31.
C56D. Flow stress curves by hot and cold forming.



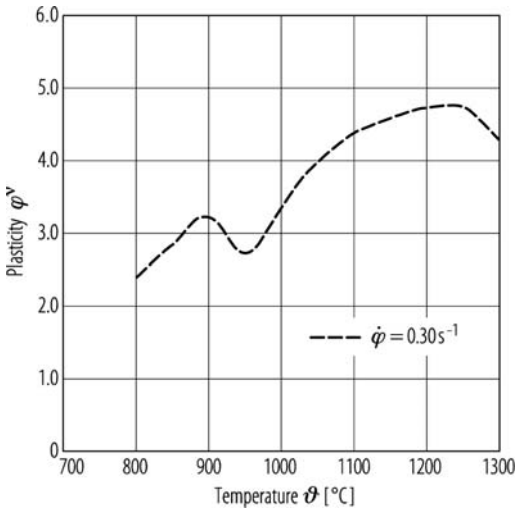
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Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
soft annealed	400…450	36.6979	0.63162	600…650	15.0891	0.76408	<80
hot rolled	600…660	37.2637	0.68717				<70
patented				900…930	11.6546	0.86349	<80

Fig. 5.32.
C56D. Hot plasticity as a function of temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.95.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	47.82	474.74	10.89	7824.8	
100	47.03	488.16	11.33	7798.2	
200	45.68	501.43	12.05	7768.2	
300	42.61	521.53	12.61	7736.0	
400	39.0	545.95	13.13	7701.5	
500	35.25	573.0	13.7	7664.5	
600	31.64	602.11	14.18	7625.0	
700	28.25	633.19	14.72	7582.8	
800	23.48	696.53	12.96	7581.4	
900	25.23	694.03	13.96	7529.8	
1000	26.59	691.53	14.86	7475.9	
1100	27.88	689.05	15.68	7419.9	
1200	29.33	686.57	16.44	7361.8	

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Steel symbol/number: C30/1.0528

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.27…0.34	0.00…0.40	0.50…0.80	0.000…0.045	0.000…0.045	0.00…0.40
Mo	Ni				
0.00…0.10	0.00…0.40				

International comparison of standards

ISO		Euronorm		
∼C30	683–1 (1987)	C30	10083–2 (08/1996)	
∼CS 30	4960 (1999)	C30	10250–2 (10/1999)	
United Kingdom		Russia		
C30	EN 10083–2 (08/1996)	–	–	
C30	EN 10250–2 (10/1999)			
Japan		China		
		–	–	
USA				
ASTM		AISI	SAE	UNS
∼A 29 (1030)	A 29–99	∼1030	∼1030	∼G10300
∼A 510 (1030)	A 510–02			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

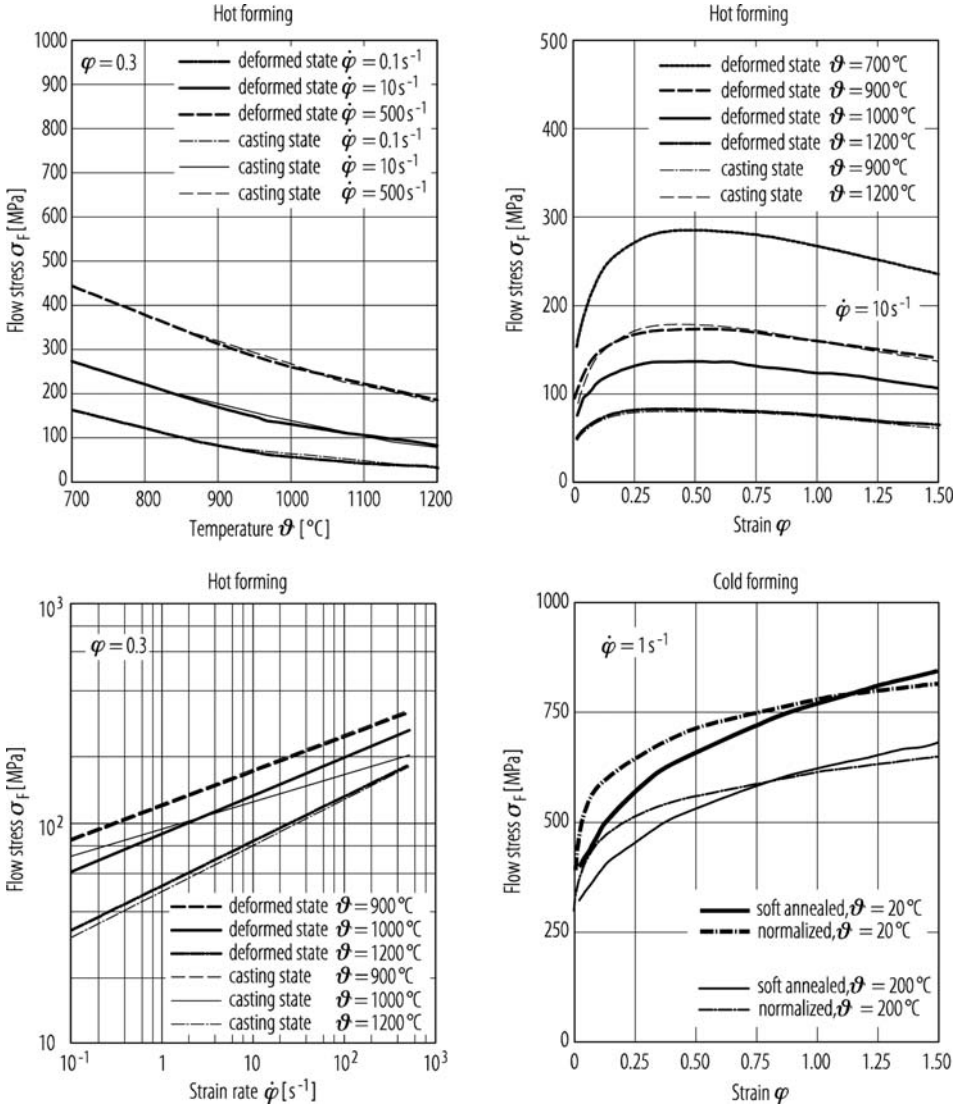
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Flow curves

	Hot deformation		Cold deformation	
	deformed state	casting state	soft annaeled	normalized
State of material	austenite	austenite		
σ_{F0} [MPa]	112.58	111.02	490.2	592.9
A	2322.37	2852.82	787.21	803.452
Effect of temperature K_ϑ				
m_1	−0.00274	−0.00286	−0.00120	−0.00134
Effect of strain K_φ				
m_2	0.27244	0.31270	0.22973	0.13145
m_4	0.00111	0.00127	0.00486	−0.00029
m_5	−0.00030	−0.00039		
m_7	−0.37926	−0.42514		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.01317	0.01237
m_8	0.000172	0.000174		
Range of validity				
ϑ [°C]	700…1200	700…1200	20…300	20…300
φ	0.04…1.50	0.04…1.50	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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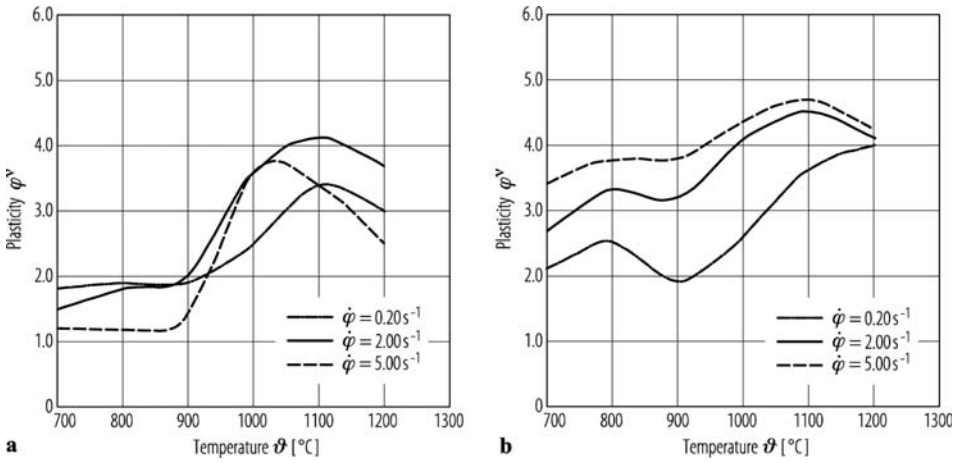
Fig. 5.33.
C30. Flow stress curves by hot and cold forming.



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Fig. 5.34.
C30. Hot plasticity as a function of the temperature. (a) Casting state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	49.28	474.11	11.12	7827.9	
100	48.30	486.93	11.53	7800.8	
200	46.69	500.11	12.22	7770.5	
300	43.49	520.13	12.76	7738.0	
400	39.7	544.46	13.28	7703.2	
500	35.93	571.4	13.8	7665.9	
600	32.24	600.44	14.33	7626.0	
700	28.78	631.43	14.87	7583.4	
800	23.70	695.12	12.50	7593.0	
900	25.40	692.62	13.42	7544.2	
1000	26.72	690.13	14.25	7493.3	
1100	27.98	687.65	15.00	7440.5	
1200	29.40	685.18	15.69	7385.8	

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Steel symbol/number: C55/1.0535

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.52…0.60	0.00…0.40	0.60…0.90	0.000…0.045	0.000…0.045	0.00…0.40
Mo	Ni				
0.00…0.10	0.00…0.40				

International comparison of standards

ISO		Euronorm		
~C55	683–18 (1996)	C55	10083–2 (08/1996)	
~CS 55	4960 (1999)	C55	10250–2 (10/1999)	
United Kingdom		Russia		
C55	EN 10250–2 (10/1999)	~55	1050 (1988)	
~070 M 55	PD 970 (2001)			
Japan		China		
~S 55 CM	G 3311 (1998)	–	–	
~S 55 C-CSP	G 4802 (1999)			
USA				
ASTM		AISI	SAE	UNS
~A 29 (1055)	A 29–99	~1055	~1055	~G10550
~A 682 (1055)	A 682–02			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

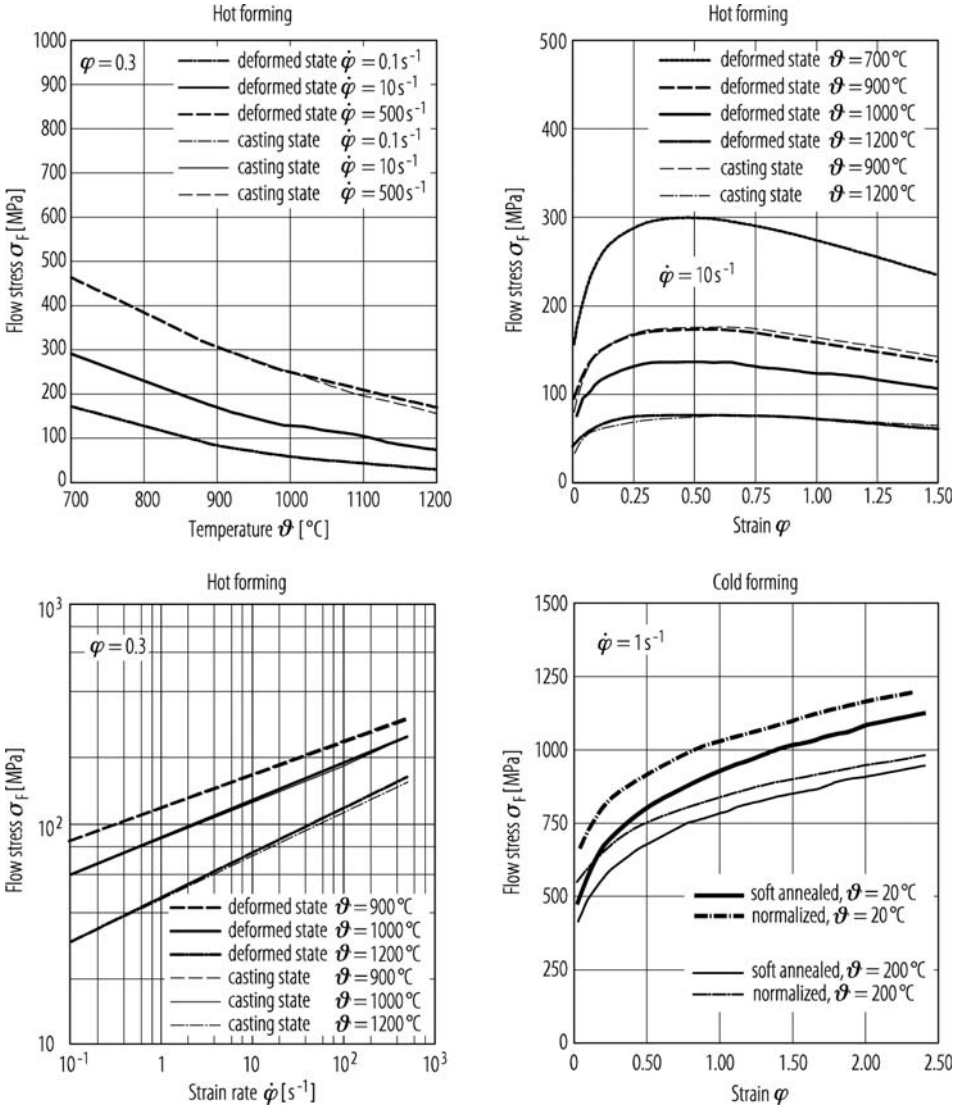
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Flow curves

	Hot deformation		Cold deformation	
	deformed state	casting state	soft annealed	normalized
State of material	austenite	austenite		
σ_{F0} [MPa]	109.20	107.01	602.8	741.2
A	3130.26	3431.07	949.56	1054.017
Effect of temperature K_ϑ				
m_1	−0.00316	−0.00330	−0.00097	−0.00117
Effect of strain K_φ				
m_2	0.23769	0.22312	0.21020	0.17346
m_4	0.00079	0.000026	0.00312	0.00560
m_5	0.00013	0.00028		
m_7	−0.55514	−0.58508		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.00772	0.00639
m_8	0.000168	0.000164		
Range of validity				
ϑ [°C]	700…1200	700…1200	20…300	20…120
φ	0.04…1.50	0.04…1.50	0.04…2.00	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.35.
C55. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_P [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
normalized	370…400	96.8884	0.47292	640…700	16.7122	0.80497

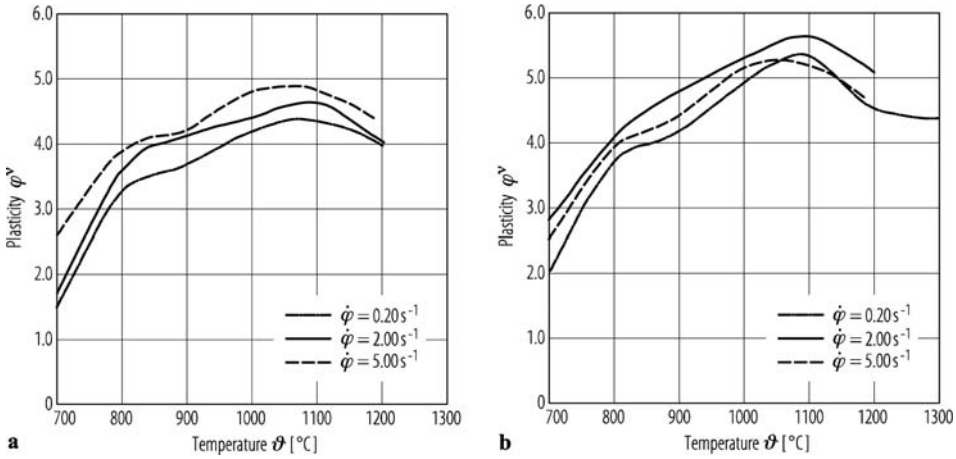
DOI: 10.1007/978-3-540-44760-3_29
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
normalized	25…30	34.08066	0.02884	−4.17911	<70

Fig. 5.36.
C55. Hot plasticity as a function of the temperature. (a) Casting state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	47.39	475.22	10.80	7816.1	
100	46.66	488.63	11.24	7789.8	
200	45.37	501.96	11.99	7759.9	
300	42.35	522.10	12.54	7727.9	
400	38.7	546.55	13.07	7693.6	
500	35.05	573.6	13.6	7656.8	
600	31.46	602.79	14.12	7617.5	
700	28.09	633.91	14.66	7575.5	
800	23.42	697.08	13.20	7568.5	
900	25.18	694.57	14.24	7515.6	
1000	26.55	692.07	15.18	7460.3	
1100	27.86	689.59	16.03	7402.8	
1200	29.31	687.11	16.81	7343.2	

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Steel symbol/number: S355J2G3/1.0570

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S
0.00…0.20	0.00…0.55	0.00…1.60	0.000…0.035	0.000…0.035

International comparison of standards

ISO		Euronorm		
~E 355-D	630 (1995)	S355J2G3	10025 (08/1993)	
~S355J2H–FF	10799 (2001)	S355J2G3	10250–2 (10/1999)	
United Kingdom		Russia		
~ERW 5	6323 Part 5 (1982)	~17G1S	19281 (1989)	
~SAW 5	6323 Part 7 (1982)	~17GS	19281 (1989)	
Japan		China		
~SM 490 YA	G 3106 (1999)	~L20166	6479 (2000)	
~SM 520 C	G 3106 (1999)	~16MnDR	T 3531 (1996)	
USA				
ASTM		AISI	SAE	UNS
~A 350 (LF2)	A 350–02		~1024	~K03011
~A 513 (1024)	A 513–00			~K03014

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

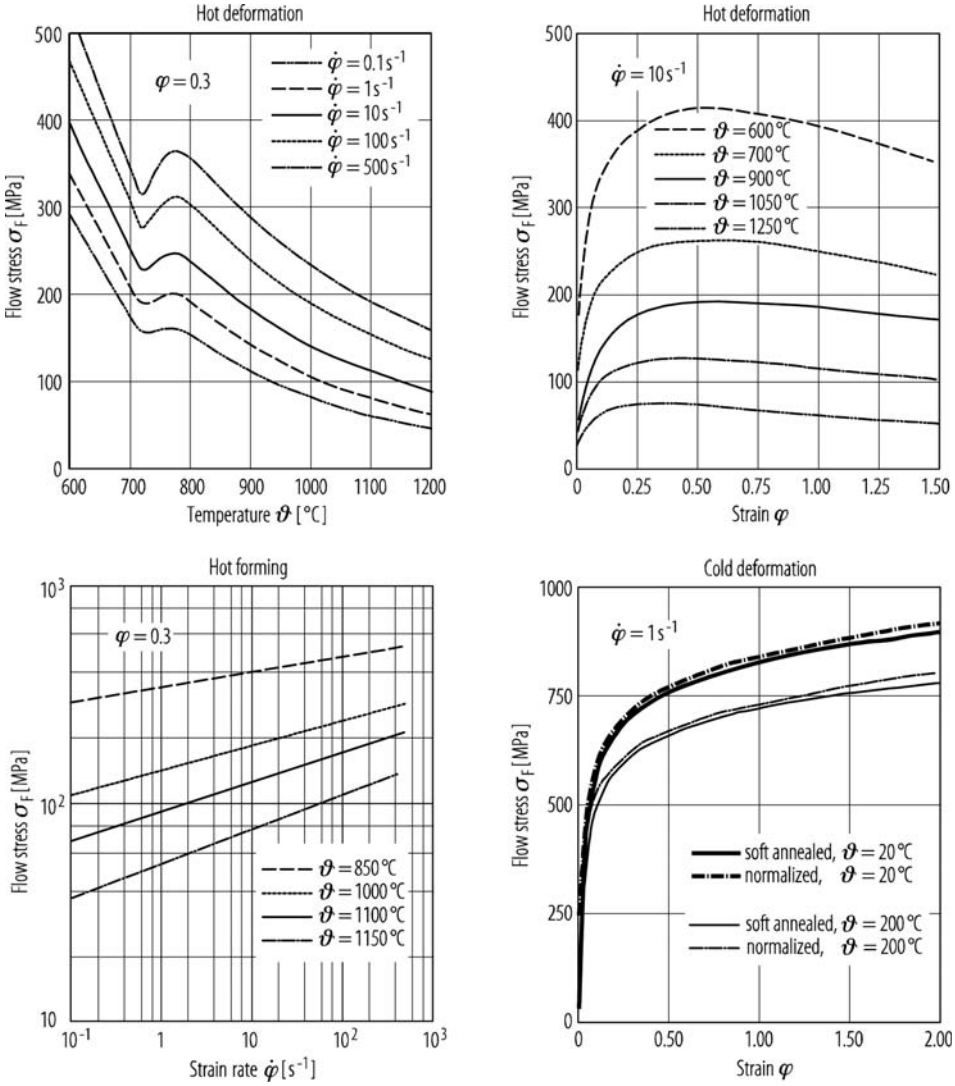
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Flow curves

State of material	Hot deformation			Cold deformation	
	deformed state		casting state	soft annealed	normalized
	austenite	ferrite+Fe_3C	austenite		
σ_{F0} [MPa]	112.37	(55.74)	93.3	554.7	587.6
A	2852.66	8831.08	2371.72	855.830	856.430
Effect of temperature K_ϑ					
m_1	−0.00244	−0.00472	−0.00231	−0.00077	−0.00077
Effect of strain K_φ					
m_2	0.41934	0.24359	0.50746	0.09887	0.12429
m_4	0.00088	−0.00002	0.00701	−0.01806	−0.00736
m_5	−0.00149	−0.00013	−0.00153		
m_7	0.12169	−0.38915	0.12172		
Effect of strain rate $K_{\dot\varphi}$					
m_3				−0.00429	−0.00061
m_8	0.000127	0.000116	0.000133		
Range of validity					
ϑ [°C]	780…1250	575…725	900 … 1200	20 … 300°C	20 … 300°C
φ	0.04…1.50	0.04…1.50	0.04…1.50	0.03 … 2.00	0.03 … 2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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Fig. 5.37.
S355J2G3. Flow stress curves by hot and cold forming.



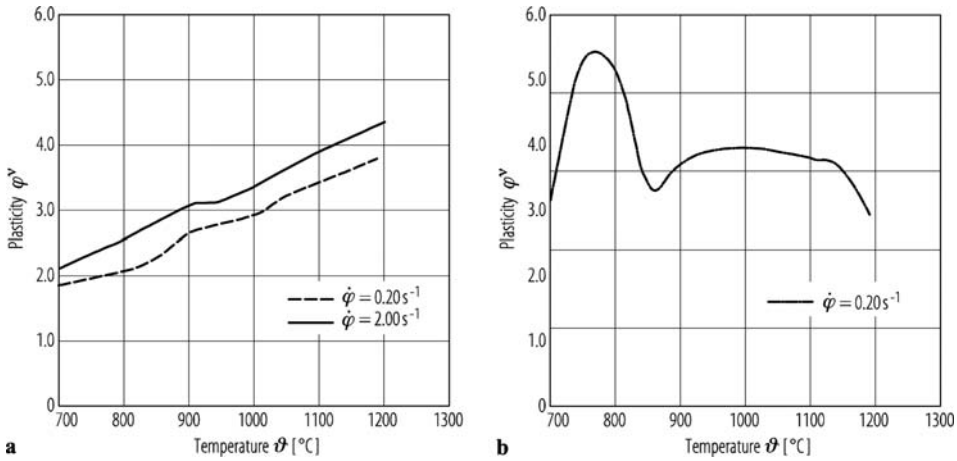
Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity
	A_0	A	n_1	B_0	B	n_2	ε [%]
hot rolled	400…450	68.9706	0.50061	580…620	25.4654	0.66589	<85

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Fig. 5.38.
S355J2G3. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	51.19	472.66	11.35	7819.8	216.0
100	49.91	485.69	11.73	7792.3	210.4
200	47.96	498.82	12.36	7761.8	204.9
300	44.59	518.77	12.89	7729.1	199.5
400	40.7	543.02	13.40	7694.0	192.9
500	36.78	569.9	13.9	7656.5	184.2
600	32.99	598.83	14.45	7616.3	172.9
700	29.44	629.71	15.00	7573.5	158.8
800	23.98	693.66	12.23	7590.3	142.2
900	25.62	691.16	13.08	7543.7	123.6
1000	26.90	688.68	13.84	7495.1	104.2
1100	28.11	686.21	14.53	7444.8	85.2
1200	29.49	683.74	15.17	7392.7	68.4

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

DOI: 10.1007/978-3-540-44760-3_30
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Steel symbol/number: C50D/1.0586

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.48…0.53	0.10…0.30	0.50…0.80	0.000…0.035	0.000…0.035	0.00…0.15
Mo	Ni	Al	Cu		
0.00…0.05	0.00…0.20	0.000…0.010	0.00…0.25		

International comparison of standards

ISO		Euronorm		
~2CD50A	8457–2 (1989)	C50D	10016–2 (12/1994)	
~C50D	16120–2 (2001)			
United Kingdom		Russia		
C50D	EN 10016–2 (12/1994)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

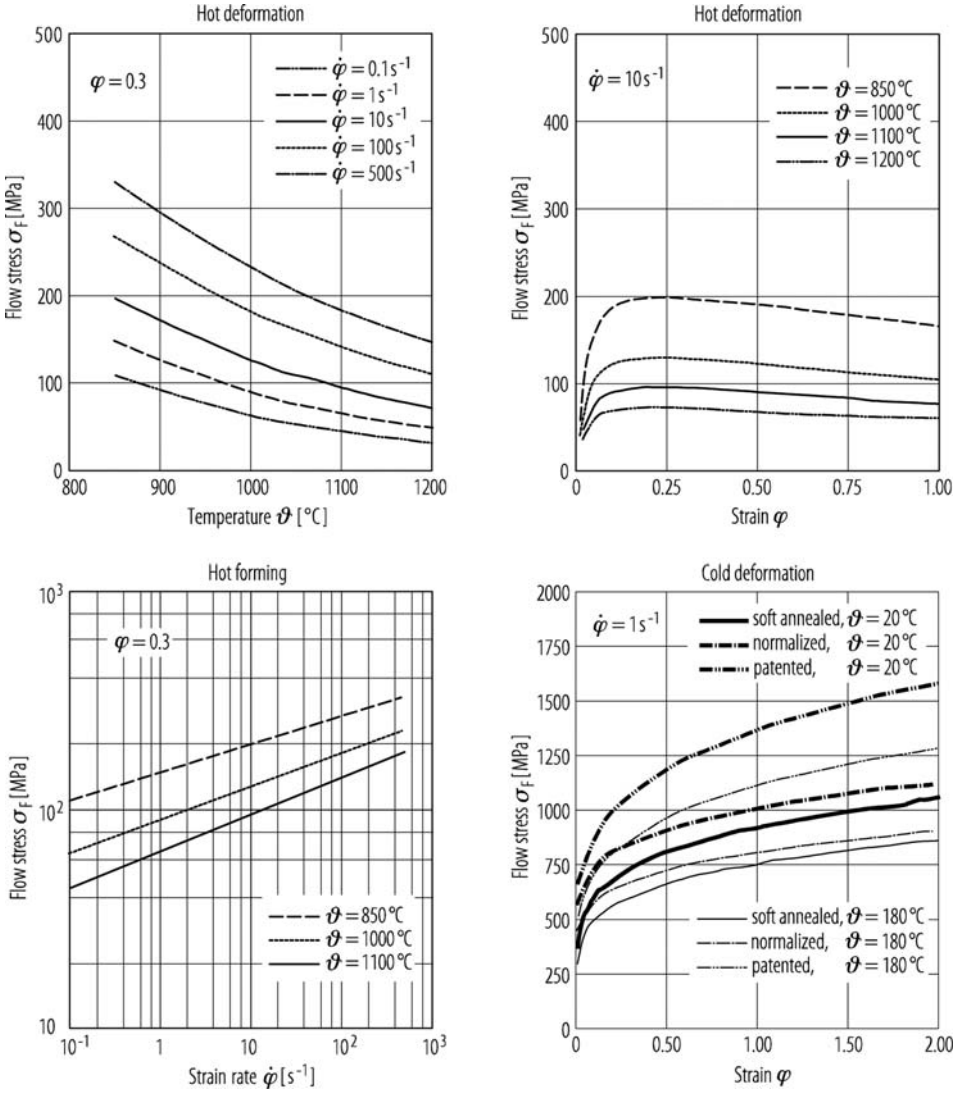
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Flow curves

State of material	Hot deformation	Cold deformation		
	deformed state	soft annealed	normalized	patented
	austenite			
σ_{F0} [MPa]	120.29	607.5	732.8	878.7
A	2719.43	937.628	1034.651	1394.740
Effect of temperature K_ϑ				
m_1	−0.00316	−0.00110	−0.00128	−0.00118
Effect of strain K_φ				
m_2	0.03416	0.18740	0.15221	0.21078
m_4	−0.01764	0.00002	0.00072	0.00233
m_5	−0.00044			
m_7	−0.14245			
Effect of strain rate $K_{\dot\varphi}$				
m_3		0.00846	0.01045	0.01145
m_8	0.000153			
Range of validity				
ϑ [°C]	850…1200	20…300	20…120	20…120
φ	0.04…0.80	0.04…2.20	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.39.
C50D. Flow stress curves by hot and cold forming.



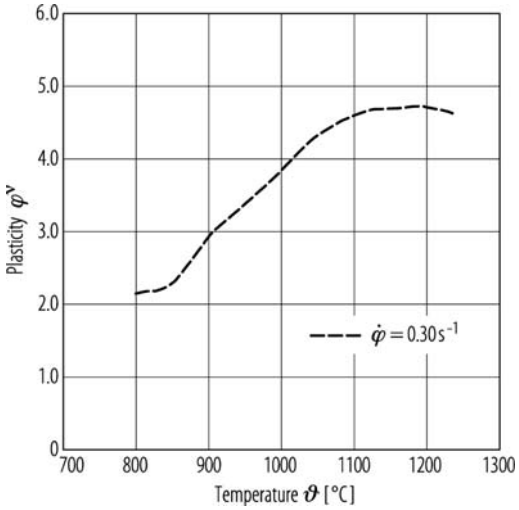
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Mechanical properties after cold deformation

State of material	Yield stress ΔR_P [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
normalized	350…400	46.8926	0.50891	640…700	17.8912	0.86624	<80
patented				850…900	12.0330	0.85877	<80

Fig. 5.40.
C50D. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.95.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	48.12	474.53	10.95	7827.0	
100	47.30	487.94	11.38	7800.2	
200	45.89	501.11	12.10	7770.2	
300	42.80	521.19	12.65	7737.9	
400	39.1	545.58	13.17	7703.3	
500	35.39	572.6	13.7	7666.2	
600	31.77	601.70	14.22	7626.6	
700	28.36	632.76	14.76	7584.3	
800	23.53	696.19	12.83	7585.9	
900	25.26	693.69	13.81	7535.1	
1000	26.62	691.20	14.69	7482.0	
1100	27.91	688.71	15.49	7426.8	
1200	29.34	686.24	16.23	7369.7	

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Steel symbol/number: C60/1.0601

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.57…0.65	0.00…0.40	0.60…0.90	0.000…0.045	0.000…0.045	0.00…0.40
Mo	Ni				
0.00…0.10	0.00…0.40				

International comparison of standards

ISO		Euronorm		
~C60	683–18 (1996)	C60	10083–2 (08/1996)	
~CS 60	4960 (1999)	C60	10250–2 (10/1999)	
United Kingdom		Russia		
C60	EN 10250–2 (10/1999)	~60	1050 (1988)	
~60 CS	1449 Part 1 (1991)	~60G	14959 (1979)	
Japan		China		
~S 65 CM	G 3311 (1998)			
~S 60 C-CSP	G 4802 (1999)			
USA				
ASTM		AISI	SAE	UNS
~A 29 (1060)	A 29–99	~1060	~1060	~G10600
~A 510 (1060)	A 510–02			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

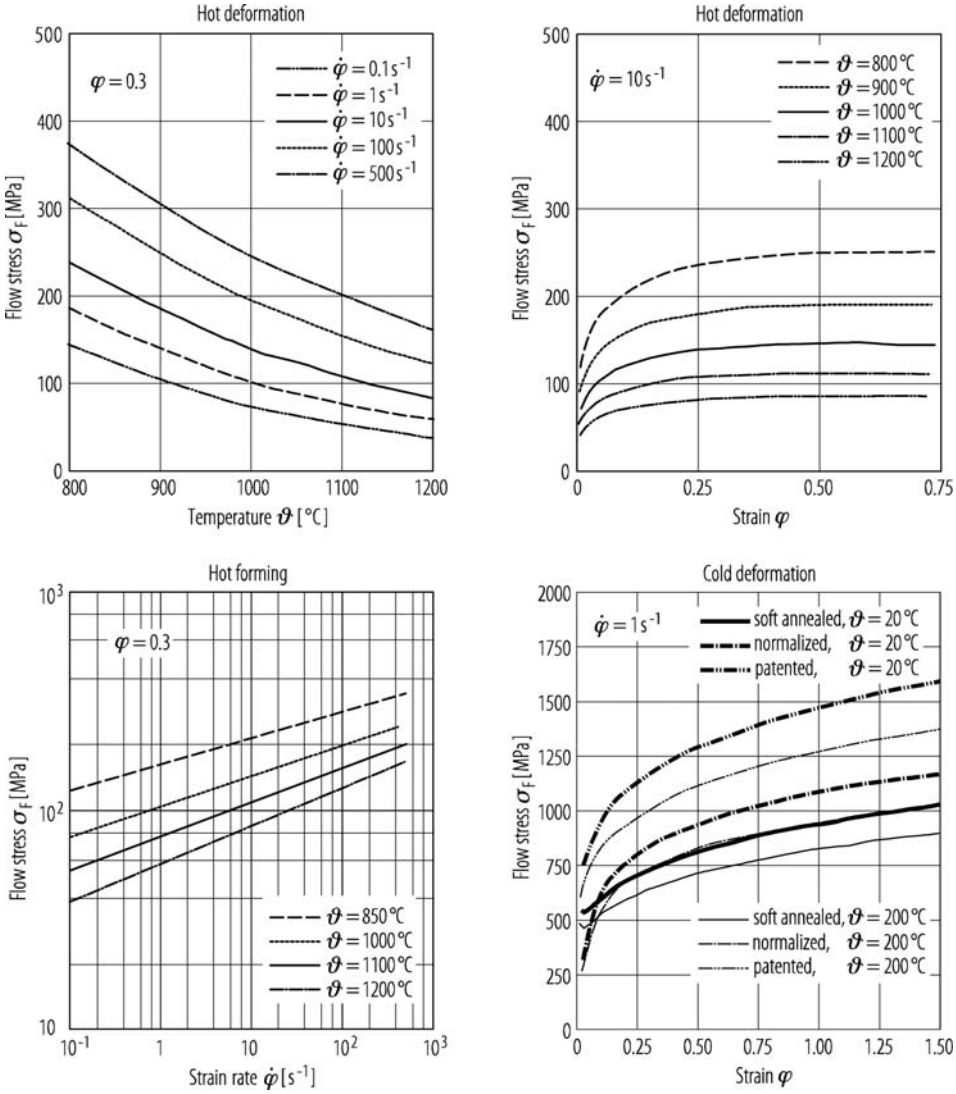
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Flow curves

	Hot deformation	Cold deformation		
	deformed state	soft annealed	normalized	patented
State of material	austenite			
σ_{F0} [MPa]	121.36	615.3	802.3	957.7
A	2811.77	946.491	1121.860	1503.100
Effect of temperature K_ϑ				
m_1	−0.00291	−0.00072	−0.00078	−0.00085
Effect of strain K_φ				
m_2	0.22291	0.21862	0.16673	0.20593
m_4	0.00030	0.00622	−0.02097	0.00234
m_5	−0.00021			
m_7	−0.27160			
Effect of strain rate $K_{\dot\varphi}$				
m_3		0.01074	0.01086	0.01082
m_8	0.000141			
Range of validity				
ϑ [°C]	900 1200	20…300	20…300	20…300
φ	0.04…0.70	0.04…2.00	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.41.
C60. Flow stress curves by hot and cold forming.



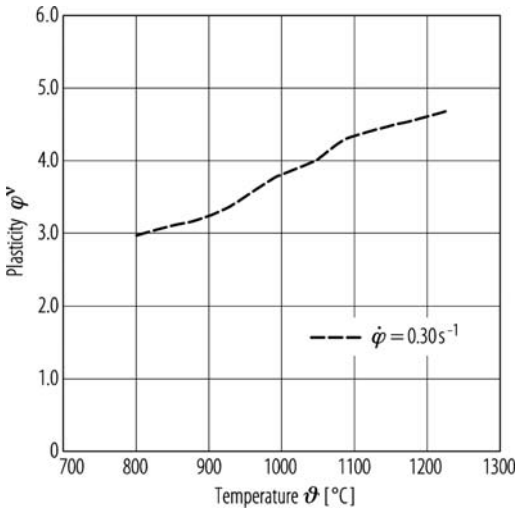
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Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
soft annealed	300…350	22.5413	0.79339	600…680	12.1547	0.85801	<80
patented				900…1000	11.9107	0.85615	<80

Fig. 5.42.
C60. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.95.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	47.20	475.46	10.75	7813.9	210.4
100	46.49	488.95	11.20	7787.7	201.5
200	45.24	502.26	11.95	7757.9	195.8
300	42.23	522.41	12.51	7726.0	192.1
400	38.6	546.88	13.03	7691.7	187.0
500	34.95	574.0	13.6	7655.1	178.2
600	31.38	603.16	14.08	7615.9	164.3
700	28.02	634.30	14.62	7574.0	145.1
800	23.39	697.37	13.35	7563.6	124.8
900	25.15	694.86	14.41	7509.9	100.6
1000	26.53	692.37	15.36	7453.8	79.3
1100	27.84	689.88	16.23	7395.4	58.9
1200	29.30	687.40	17.03	7334.8	47.2

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: C67/1.0603

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S
0.65…0.72	0.15…0.35	0.60…0.90	0.000…0.045	0.000…0.045

International comparison of standards

ISO		Euronorm		
~CS 70	4960 (1999)	~1 CS 67	132 (1979)	
United Kingdom		Russia		
~70 CS	1449 Part 1 (1991)			
~080 A 67	970 Part 1 (1996)			
Japan		China		
~S 70 CM	G 3311 (1998)-			
~S 70 C-CSP	G 4802 (1999)			
USA				
ASTM		AISI	SAE	UNS
~A 510 (1070)	A 510–02	~1070	~1070	~G10700
~A 682 (1070)	A 682–02			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

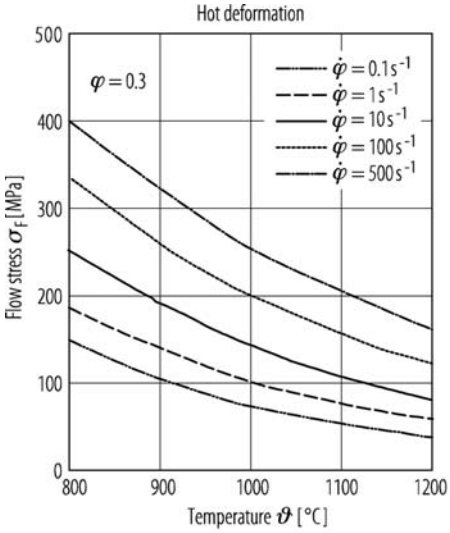
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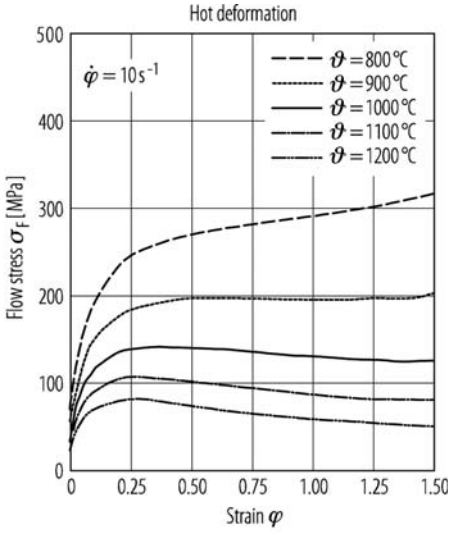
Flow curves

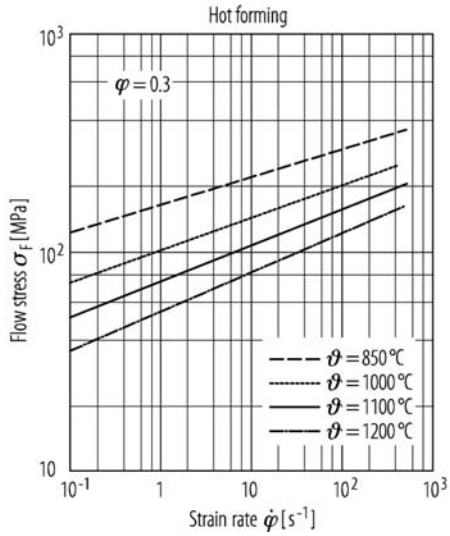
State of material	Hot deformation	Cold deformation		
	deformed state	soft annealed	normalized	patented
	austenite			
σ_{F0} [MPa]	118.0	626.7	823.9	1035.7
A	3394.71	968.615	1273.424	1600.780
Effect of temperature K_ϑ				
m_1	−0.00251	−0.00072	−0.00087	−0.00080
Effect of strain K_φ				
m_2	0.44545	0.21424	0.20145	0.19916
m_4	0.00075	0.00506	0.00061	0.00232
m_5	−0.00263			
m_7	0.73719			
Effect of strain rate $K_{\dot\varphi}$				
m_3		0.00942	0.01023	0.01137
m_8	0.000148			
Range of validity				
ϑ [°C]	800…1200	20…300	20…300	20…300
φ	0.04…1.50	0.04…2.00	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

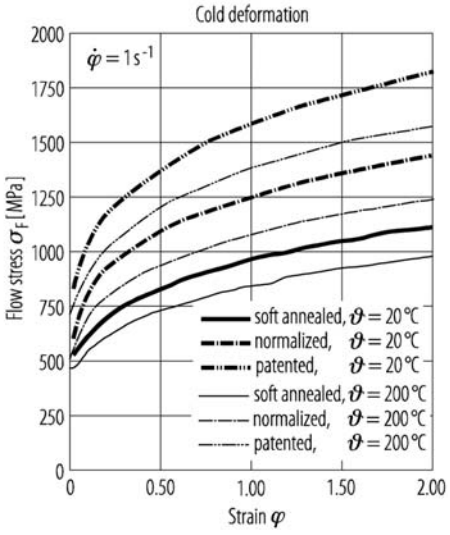
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Fig. 5.43.
C67. Flow stress curves by hot and cold forming.









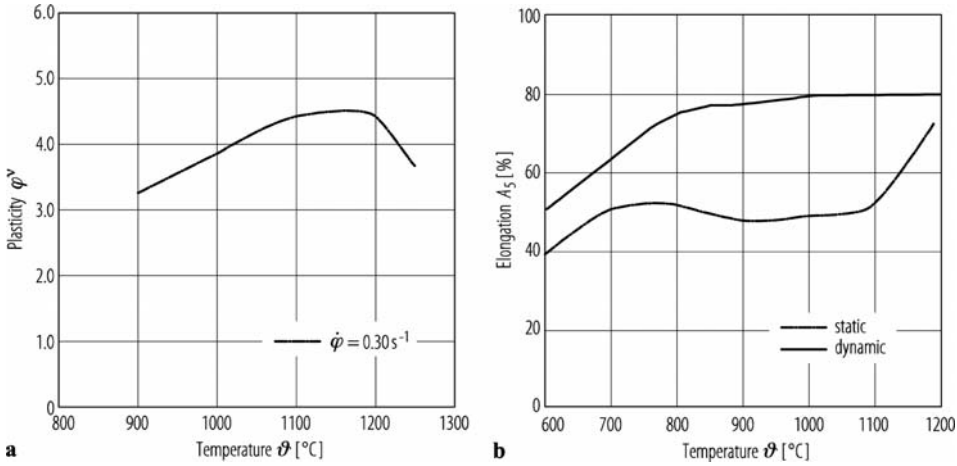
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Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
soft annealed	450…500	39.8718	0.60977	600…640	23.7309	0.67372	<75
sorbitic	630…680	17.9599	0.84292				<80

Fig. 5.44.
C67. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformation rate: 0.2 [s^{-1}]. Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



DOI: 10.1007/978-3-540-44760-3_33
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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	47.37	475.21	10.79	7810.0	
100	46.63	488.95	11.24	7783.7	
200	45.36	502.00	11.98	7753.9	
300	42.33	522.14	12.54	7721.9	
400	38.7	546.59	13.06	7687.6	
500	35.03	573.7	13.6	7650.9	
600	31.45	602.84	14.11	7611.6	
700	28.08	633.96	14.65	7569.7	
800	23.42	697.11	13.22	7562.2	
900	25.17	694.61	14.26	7509.3	
1000	26.55	692.11	15.20	7453.9	
1100	27.85	689.62	16.05	7396.4	
1200	29.31	687.14	16.84	7336.7	

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Steel symbol/number: C75/1.0605

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S
0.70…0.80	0.15…0.35	0.60…0.80	0.000…0.045	0.000…0.045

International comparison of standards

ISO		Euronorm		
~ CS 75	4960 (1999)	~ 1 CS 75	132 (1979)	
United Kingdom		Russia		
~ 80 CS	1449 Part 1 (1991)	~ 75	14959 (1979)	
~80 HS	1449 Part 1 (1991)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS
~ A 29 (1074)	A 29–99	~ 1074	~ 1074	~ G10740
~ A 29 (1075)	A 29–99	~ 1075	~ 1075	~ G10750

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

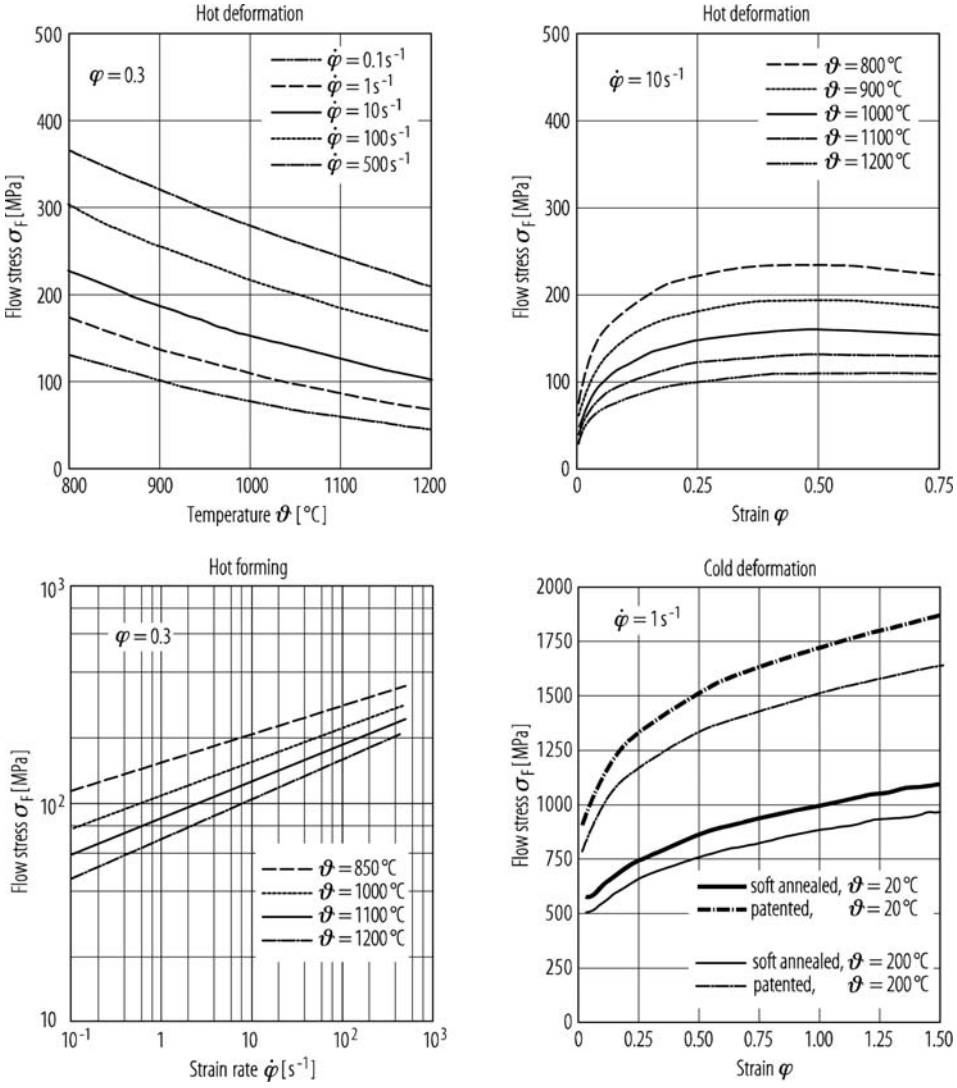
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	patented
	austenite		
σ_{F0} [MPa]	119.4	650.2	1159.0
A	2194.70	1011.777	1757.160
Effect of temperature K_ϑ			
m_1	−0.00248	−0.00069	−0.00075
Effect of strain K_φ			
m_2	0.31681	0.22724	0.19064
m_4	−0.00048	0.00747	0.00228
m_5	0.00057		
m_7	−1.00839		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.00875	0.00967
m_8	0.000152		
Range of validity			
ϑ [°C]	800…1200	20…250	20…250
φ	0.04…0.80	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.45.
C75. Flow stress curves by hot and cold forming.



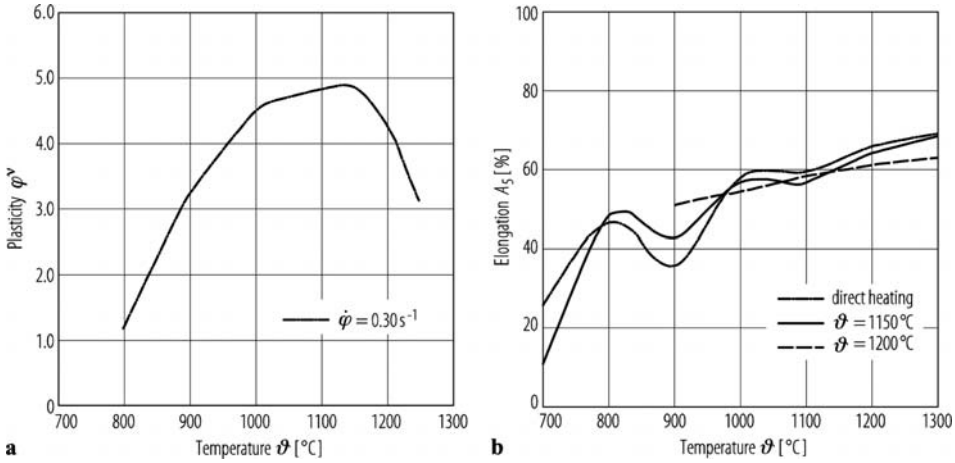
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Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
soft annealed	500…550	26.4723	0.73723				<80
patented				1200…1250	7.3954	0.96226	<80

Fig. 5.46.
C75. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformation rate: 0.2 [s^{-1}]. Deformed state. Direct heating on deformation temperature or austenitesed at 1150°C and 1200 °C.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m·K]	c_{pm} [kJ/kg·K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	47.16	475.57	10.73	7807.0	
100	46.45	488.96	11.19	7780.8	
200	45.21	502.32	11.94	7751.0	
300	42.21	522.48	12.50	7719.1	
400	38.6	546.95	13.02	7684.9	
500	34.94	574.0	13.5	7648.3	
600	31.36	603.25	14.07	7609.2	
700	28.00	634.39	14.61	7567.4	
800	23.39	697.43	13.38	7556.2	
900	25.15	694.93	14.45	7502.4	
1000	26.53	692.43	15.41	7446.1	
1100	27.84	689.94	16.28	7387.5	
1200	29.30	687.46	17.08	7326.8	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

DOI: 10.1007/978-3-540-44760-3_34
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Steel symbol/number: C70D/1.0615

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.68…0.73	0.10…0.30	0.50…0.80	0.000…0.035	0.000…0.035	0.00…0.15
Mo	Ni	Al	Cu		
0.00…0.05	0.00…0.20	0.000…0.010	0.00…0.25		

International comparison of standards

ISO		Euronorm		
~ 2CD70A	8457–2 (1989)	C70D	10016–2 (12/1994)	
~ C70D	16120–2 (2001)			
United Kingdom		Russia		
C70D	EN 10016–2 (12/1994)	~ 70	14959 (1979)	
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

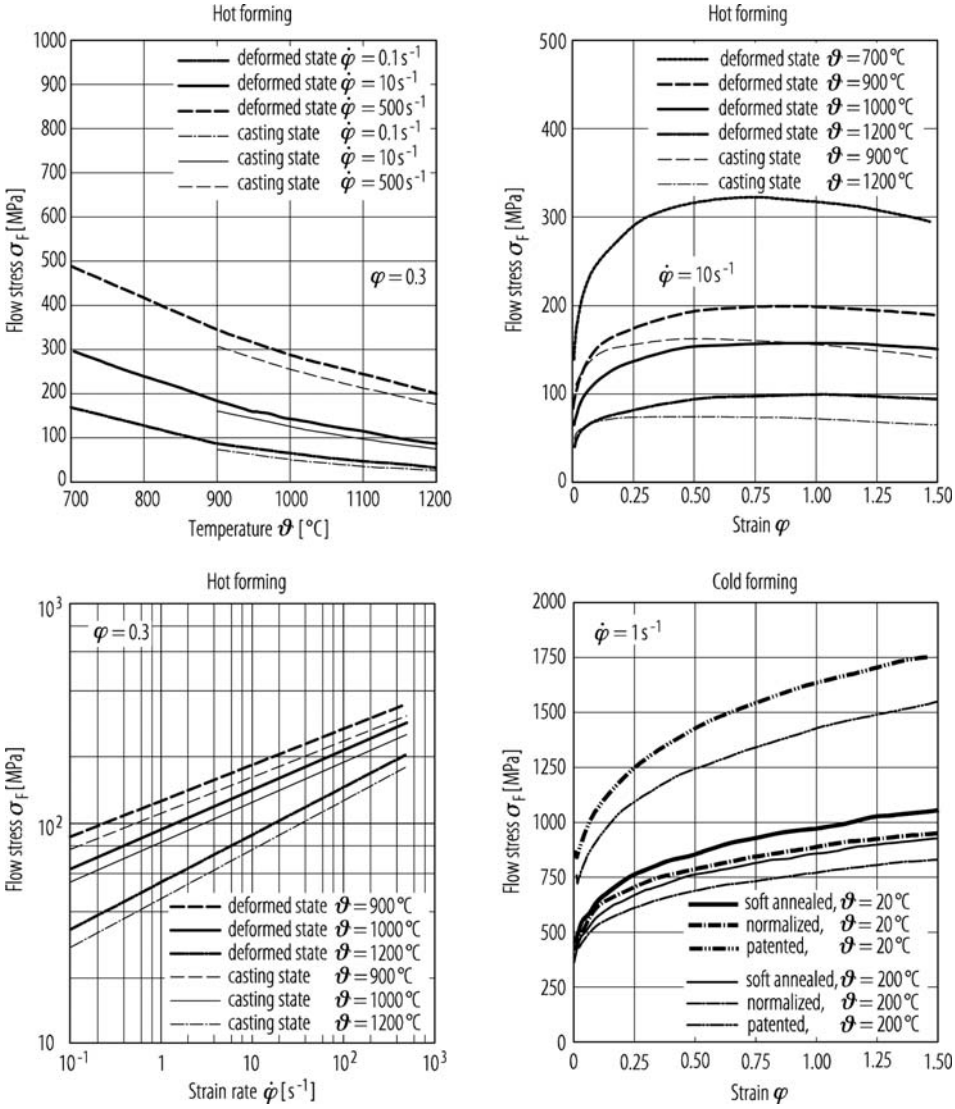
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Flow curves

State of material	Hot deformation		Cold deformation		
	deformed state	casting state	soft annealed	normalized	patented
	austenite	austenite			
σ_{F0} [MPa]	113.17	121.21	634.9	845.7	1076.6
A	2451.57	2094.91	987.977	895.771	1654.580
Effect of temperature K_ϑ					
m_1	−0.00296	−0.00292	−0.00070	−0.00077	−0.00079
Effect of strain K_φ					
m_2	0.21723	0.17614	0.18745	0.16611	0.19668
m_4	0.00011	0.00042	0.00086	0.00052	0.00231
m_5	0.00033	−0.000075			
m_7	−0.42386	−0.30104			
Effect of strain rate $K_{\dot\varphi}$					
m_3			0.00668	0.00534	0.00708
m_8	0.000180	0.000182			
Range of validity					
ϑ [°C]	700…1200	700…1200	20…250	20…250	20…250
φ	0.04…1.50	0.04…1.50	0.04…2.00	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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Fig. 5.47.
C70D. Flow stress curves by hot and cold forming.



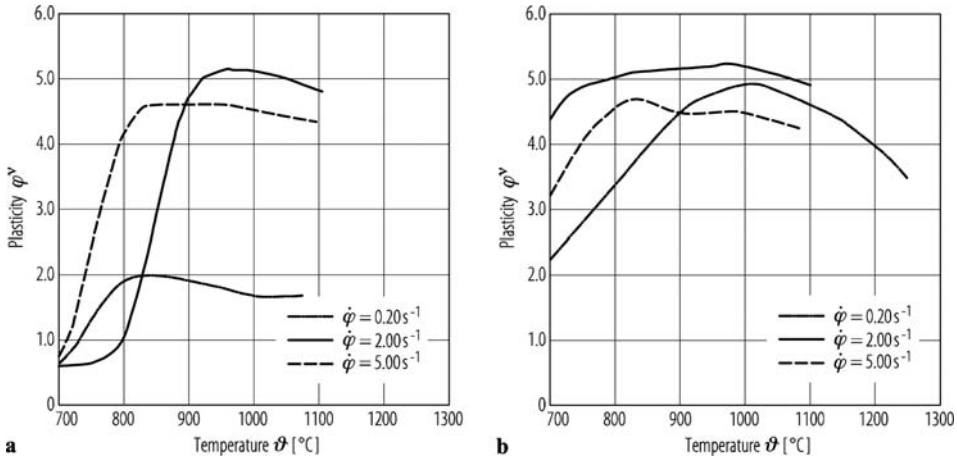
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Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
soft annealed	330…380	26.3121	0.75828	600…670	17.0020	0.79246	<80
patented				1100…1150	8.3946	0.93553	<80

Fig. 5.48.
C70D. Hot plasticity as a function of the temperature. (a) Casting state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	47.16	475.72	10.73	7818.2	
100	46.45	489.16	11.18	7792.0	
200	45.21	502.33	11.94	7762.2	
300	42.20	522.49	12.50	7730.3	
400	38.6	546.96	13.02	7696.1	
500	34.93	574.1	13.5	7659.4	
600	31.36	603.26	14.07	7620.2	
700	28.00	634.41	14.61	7578.3	
800	23.39	697.44	13.39	7567.0	
900	25.15	694.94	14.46	7513.1	
1000	26.53	692.44	15.42	7456.7	
1100	27.84	689.95	16.29	7398.0	
1200	29.30	687.47	17.09	7337.1	

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Steel symbol/number: C86D/1.0616

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.83…0.88	0.10…0.30	0.50…0.80	0.000…0.035	0.000…0.035	0.00…0.15
Mo	Ni	Al	Cu		
0.00…0.05	0.00…0.20	0.000…0.010	0.00…0.25		

International comparison of standards

ISO		Euronorm		
~ CS 85	4960 (1999)	C86D	10016–2 (12/1994)	
~ C86D	16120–2 (2001)			
United Kingdom		Russia		
C86D	EN 10016–2 (12/1994)	~85	14959 (1979)	
~ 80 CS	1449 Part 1 (1991)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS
~ A 29 (1086)	A 29–99	~ 1086	~ 1086	~ G10860
~ A 331 (1086)	A 331–00			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

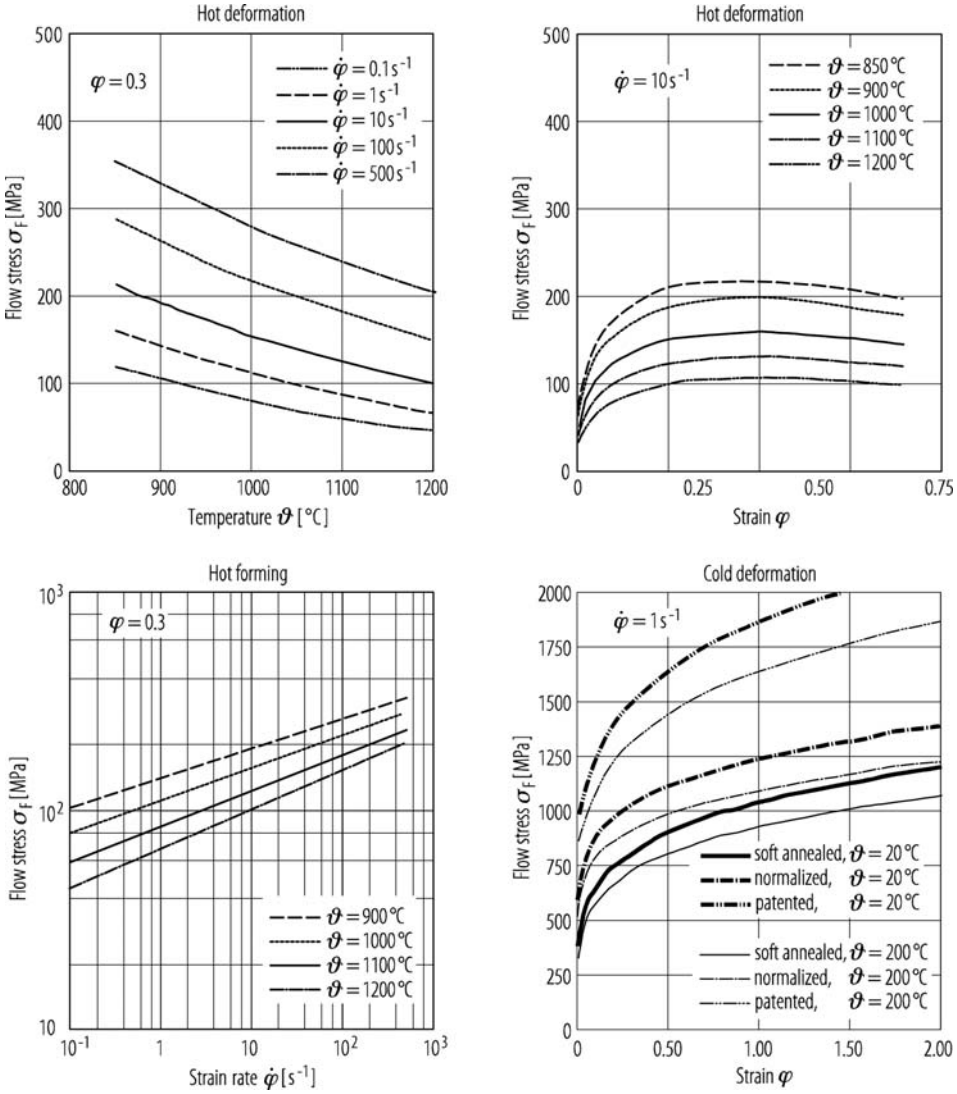
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Flow curves

State of material	Hot deformation	Cold deformation		
	deformed state	soft annealed	normalized	patented
	austenite			
σ_{F0} [MPa]	123.58	659.5	862.7	1252.9
A	2604.2	1053.165	1257.222	1887.580
Effect of temperature K_ϑ				
m_1	−0.00262	−0.00062	−0.00071	−0.00073
Effect of strain K_φ				
m_2	0.31076	0.20650	0.15724	0.18771
m_4	−0.00056	0.00013	0.00032	0.00224
m_5	0.00046			
m_7	−0.98375			
Effect of strain rate $K_{\dot\varphi}$				
m_3		0.00802	0.01006	0.01128
m_8	0.000151			
Range of validity :				
ϑ [°C]	850…1200	20…250	20…250	20…250
φ	0.04…0.90	0.04…2.00	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.49.
C86D. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

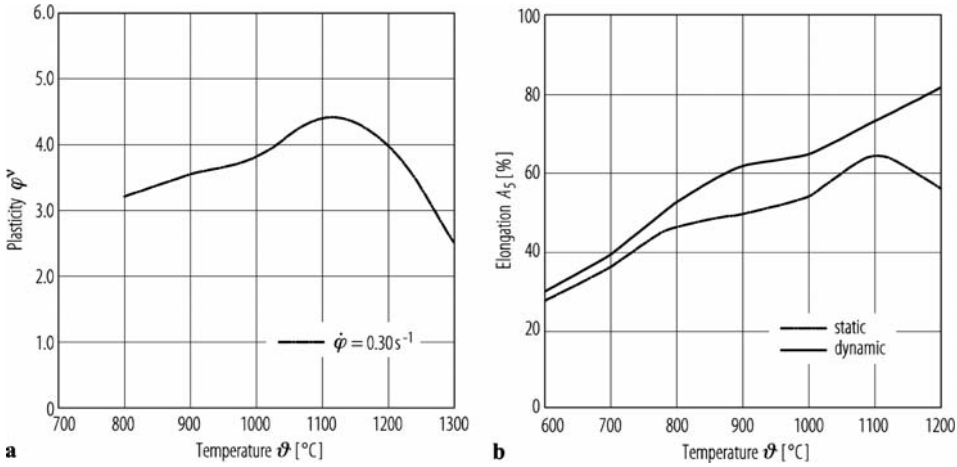
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
soft annealed	340…360	56.4604	0.56488	530…600	21.8725	0.73022
normalized	470…510	142.576	0.43267	920…970	20.1860	0.77479
hot rolled	570…610	129.362	0.41935	960…1000	28.6966	0.57428
patented				1300…1350	9.0784	0.92325

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
soft annealed	28…32	47.61034	−0.07612	−12.8827	<80
normalized	12…15	10.19666	−0.03069	−6.37091	<60
hot rolled					<75
patented					<80

Fig. 5.50.
C15. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformation rate: 0.2 [s^{-1}]. Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	46.81	476.11	10.59	7811.7	
100	46.14	489.63	11.05	7785.8	
200	44.96	503.15	11.83	7756.3	
300	41.98	523.36	12.39	7724.6	
400	38.4	547.89	12.92	7690.6	
500	34.76	575.0	13.4	7654.2	
600	31.21	604.31	13.96	7615.4	
700	27.87	635.52	14.50	7573.8	
800	23.33	698.24	13.87	7551.7	
900	25.11	695.73	15.00	7495.3	
1000	26.49	693.23	16.02	7436.2	
1100	27.82	690.74	16.95	7374.7	
1200	29.28	688.26	17.81	7310.8	

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Steel symbol/number: C78D/1.0620

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.75…0.80	0.10…0.30	0.50…0.80	0.000…0.035	0.000…0.035	0.000…0.010
Cr	Cu	Mo	Ni		
0.00…0.15	0.00…0.25	0.00…0.05	0.00…0.20		

International comparison of standards

ISO		Euronorm		
~2CD78A	8457–2 (1989)	C78D	10016–2 (12/1994)	
~C78D	16120–2 (2001)			
United Kingdom		Russia		
C78D	EN 10016–2 (12/1994)			
Japan		China		
~ SWRH 77 A	G 3506 (1996)			
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

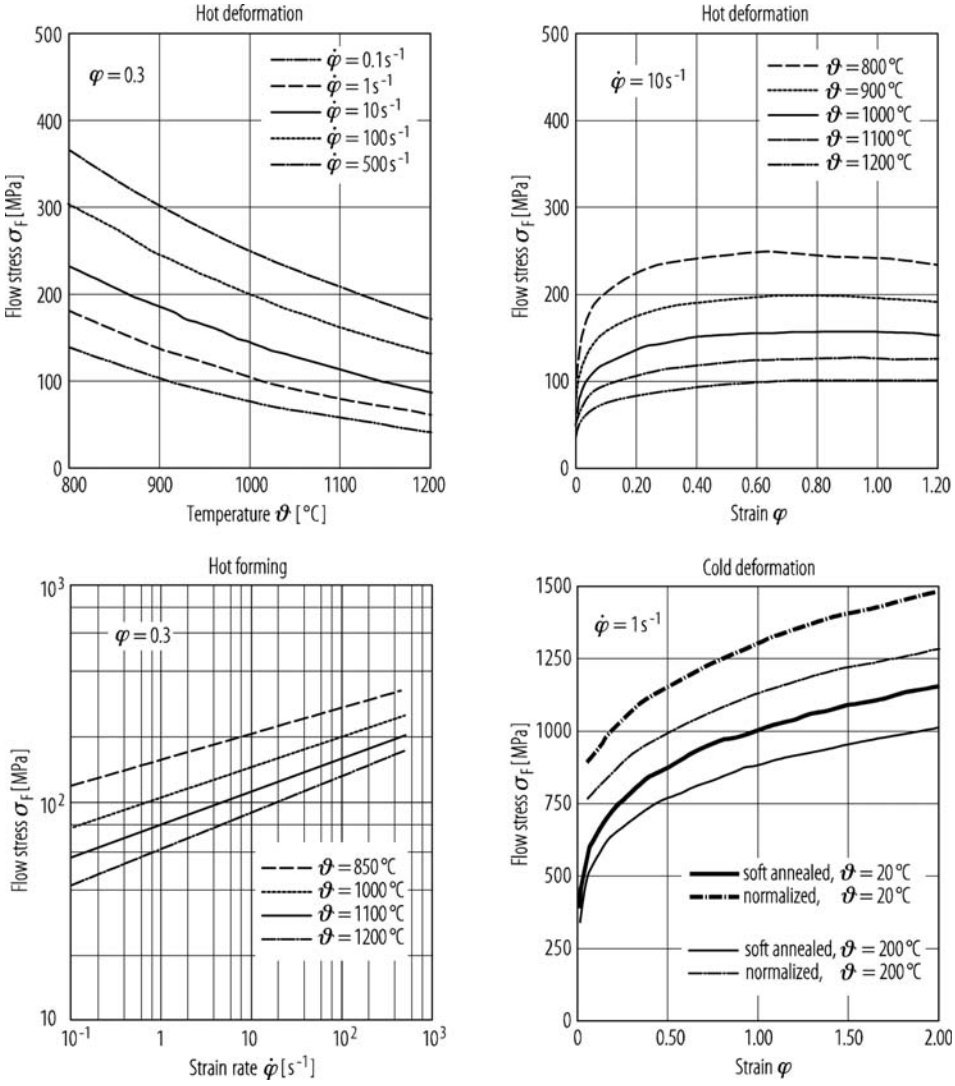
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	normalized
	austenite		
σ_{F0} [MPa]	121.98	718.9	831.8
A	2283.68	1020.060	1318.133
Effect of temperature K_ϑ			
m_1	−0.00290	−0.00072	−0.00083
Effect of strain K_φ			
m_2	0.14803	0.19629	0.18705
m_4	−0.00170	0.00036	0.00902
m_5	0.00055		
m_7	−0.48928		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.0104	0.00973
m_8	0.000141		
Range of validity			
ϑ [°C]	800…1200	20…250	20…250
φ	<1.20	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.51.
C78D. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

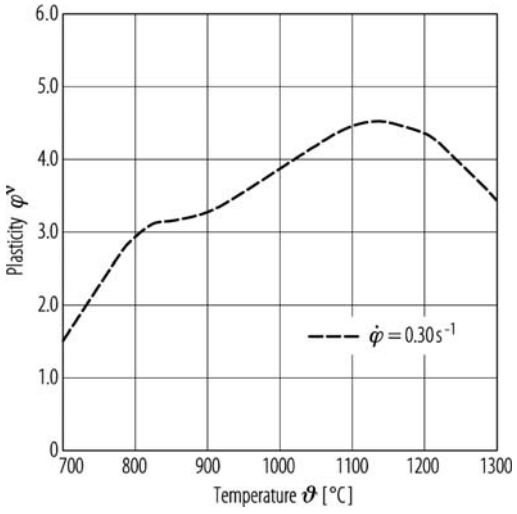
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
soft annealed	400…450	42.2879	0.61029	590…630	20.7364	0.68385
hot rolled	600…630	116.322	0.42367	950…1000	25.1036	0.64838
normalized	440…480	110.54	0.44274	630…680	21.1695	0.73454
patented				1250…1300	7.9088	0.95194

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
soft annealed					<75
hot rolled					<75
normalized	25…30	38.50084	−0.07876	−8.31768	<60
patented					<80

Fig. 5.52.
C78D. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.25…0.90.

Plasticity by torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	46.81	475.84	10.77	7811.7	
100	46.14	489.63	11.05	7785.8	
200	44.96	503.15	11.83	7756.3	
300	41.98	523.36	12.39	7724.6	
400	38.4	547.89	12.92	7690.6	
500	34.76	575.0	13.4	7654.2	
600	31.21	604.31	13.96	7615.4	
700	27.87	635.52	14.50	7573.8	
800	23.33	698.24	13.87	7551.7	
900	25.11	695.73	15.00	7495.3	
1000	26.49	693.23	16.02	7436.2	
1100	27.82	690.74	16.95	7374.7	
1200	29.28	688.26	17.81	7310.8	

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Steel symbol/number: 11SMn30/1.0715

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S
0.00…0.14	0.00…0.05	0.90…1.30	0.000…0.110	0.270…0.330

International comparison of standards

ISO		Euronorm		
~ 11SMn28	683–9 (1988)	11SMn30	10087 (09/1998)	
		11SMn30	10277–3 (07/1999)	
United Kingdom		Russia		
11SMn30	EN 10087 (09/1998)			
11SMn30	EN 10277–3 (07/1999)			
Japan		China		
~ SUM 22	G 4804 (1999)			
USA				
ASTM		AISI	SAE	UNS
~ A 29 (1215)	A 29–99	~ 1213	~ 1213	~ G12130
~ A 510 (1213)	A 510–02	~ 1215	~ 1215	~ G12150

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

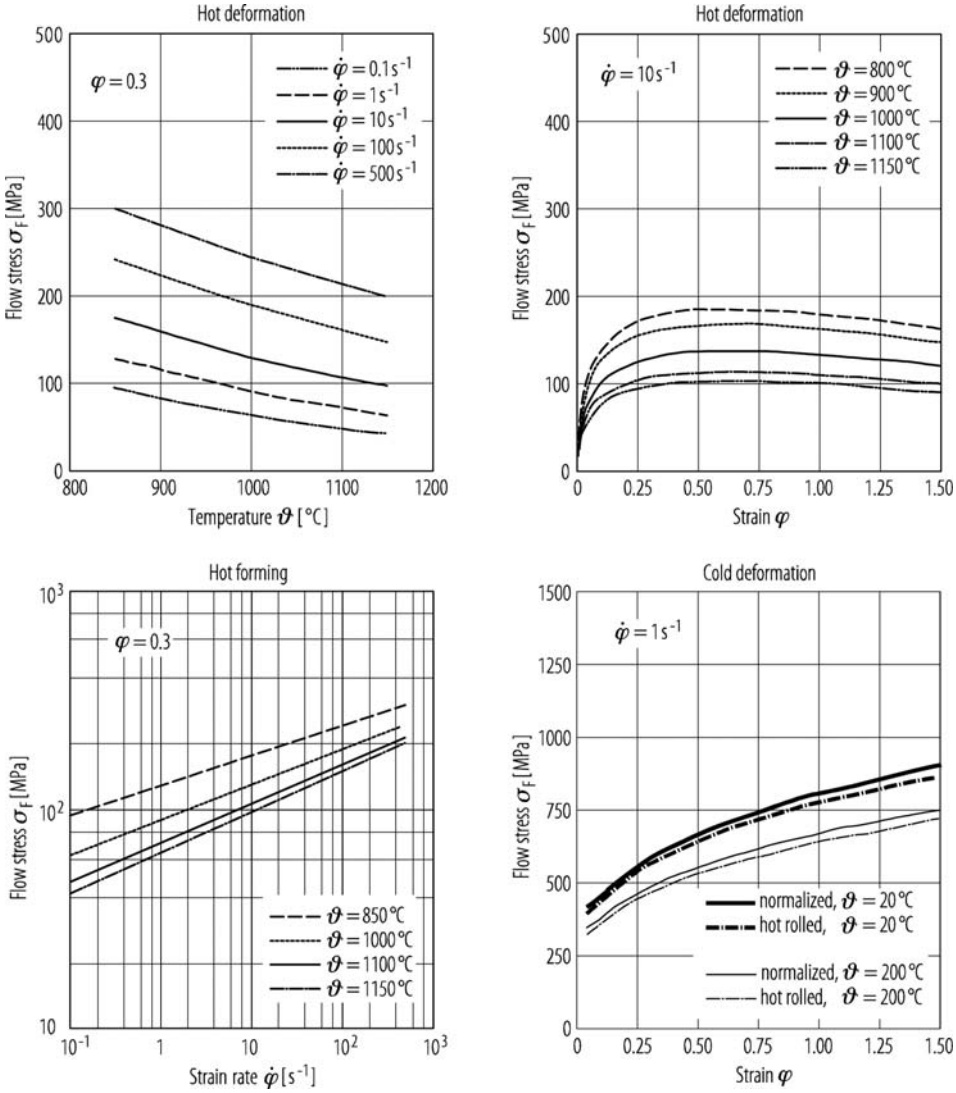
DOI: 10.1007/978-3-540-44760-3_38
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	normalized	hot rolled
	austenite		
σ_{F0} [MPa]	102.14	472.4	484.5
A	1473.43	814.386	789.098
Effect of temperature K_ϑ			
m_1	−0.00239	−0.00103	−0.00112
Effect of strain K_φ			
m_2	0.22924	0.28664	0.27314
m_4	−0.00870	0.01082	0.00754
m_5	0.00010		
m_7	−0.44065		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01207	0.01187
m_8	0.000161		
Range of validity			
ϑ [°C]	850…1150	20…300	20…300
φ	<1.50	0.04…1.50	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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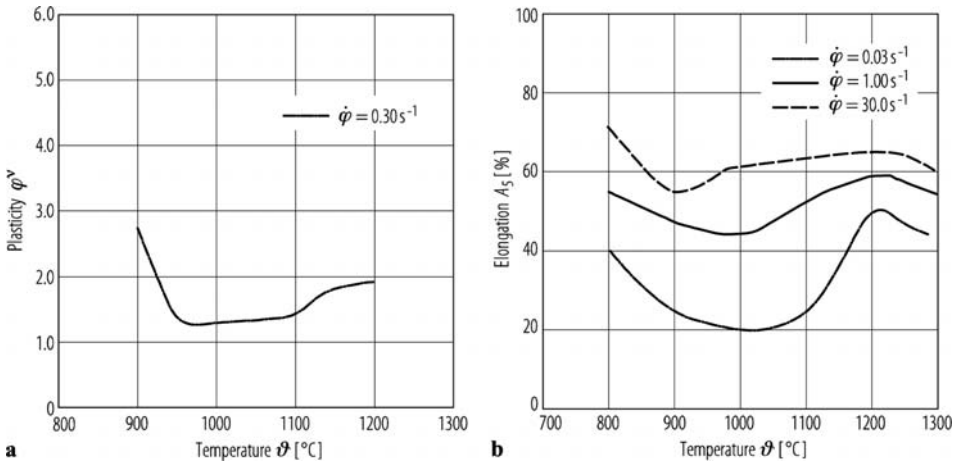
Fig. 5.53.
11SMn30. Flow stress curves by hot and cold forming.



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Fig. 5.54.
11SMn30. Hot plasticity of as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity in torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	48.98	472.13	11.43	7829.7	
100	47.21	485.17	11.80	7802.0	
200	46.58	498.31	12.42	7771.4	
300	44.37	518.23	12.94	7738.5	
400	41.5	542.45	13.45	7703.3	
500	38.42	569.3	14.0	7665.7	
600	35.30	598.19	14.50	7625.4	
700	32.28	629.04	15.04	7582.4	
800	24.15	693.06	12.16	7601.3	
900	26.46	690.57	12.98	7555.2	
1000	27.80	688.09	13.73	7507.3	
1100	28.81	685.62	14.40	7457.7	
1200	29.89	683.15	15.02	7406.3	

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Steel symbol/number: 11SMnPb30/1.0718

Metal Forming Data - Ferrous Alloys - deformation behaviour

C	Si	Mn	P	S	Pb
0.00…0.14	0.00…0.05	0.90…1.30	0.000…0.110	0.270…0.330	0.200…0.350

International comparison of standards

ISO		Euronorm		
~ 11SMnPb30	683–9 (1988)	11SMnPb30	10087 (09/1998)	
		11SMnPb30	10277–3 (07/1999)	
United Kingdom		Russia		
11SMnPb30	EN 10087 (09/1998)			
11SMnPb30	EN 10277–3 (07/1999)			
Japan		China		
~ SUM 22 L	G 4804 (1999)			
~ SUM 24 L	G 4804 (1999)			
USA				
ASTM		AISI	SAE	UNS
~ A 29 (12L13)	A 29–99	~ 12L13	~ 12L13	~ G12134
~ A 331 (12L13)	A 331–00			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

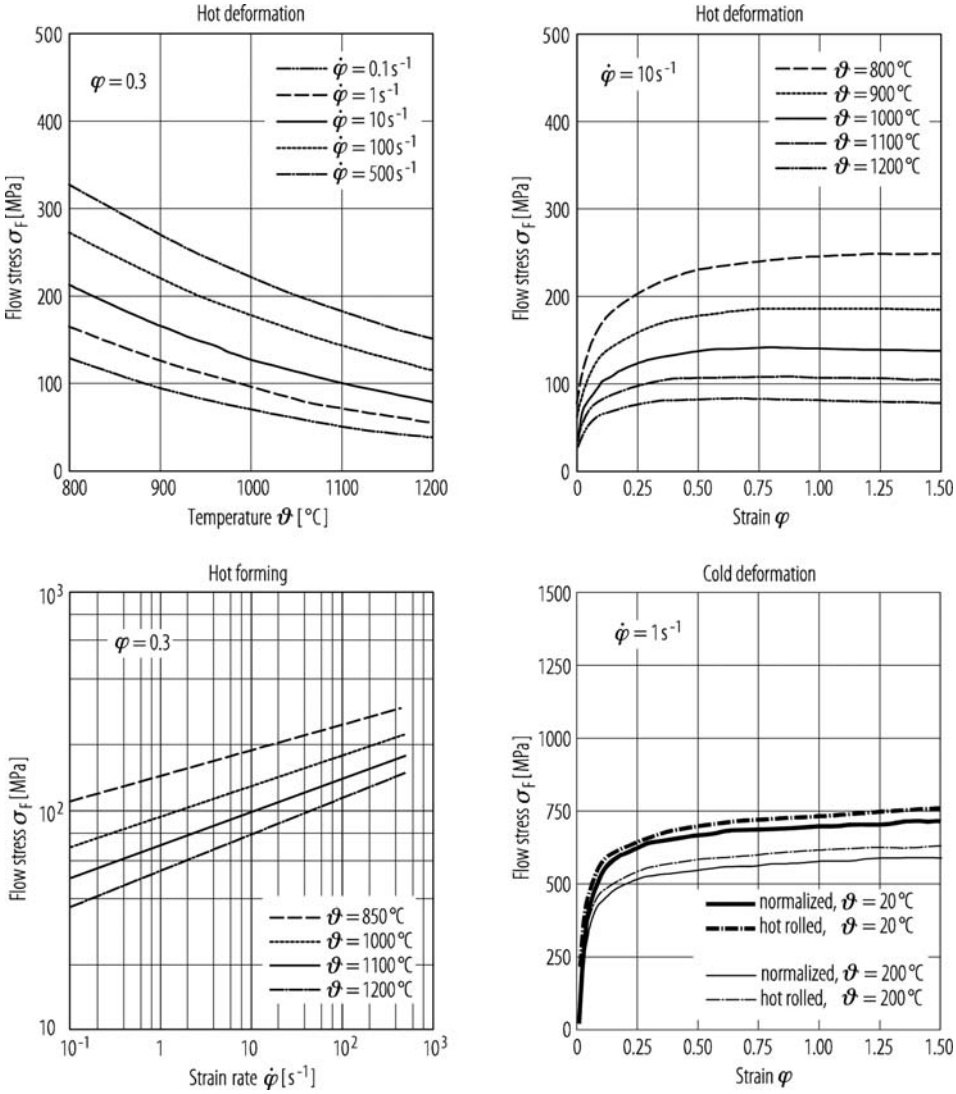
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	normalized	hot rolled
	austenite		
σ_{F0} [MPa]	102.28	555.00	576.46
A	2247.56	727.31	762.32
Effect of temperature K_ϑ			
m_1	−0.00265	−0.00107	−0.00104
Effect of strain K_φ			
m_2	0.30273	0.03803	0.05065
m_4	0.00025	−0.01925	−0.01685
m_5	−0.00063		
m_7	−0.00693		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01309	0.01111
m_8	0.000137		
Range of validity			
ϑ [°C]	800…1200	20…300	20…300
φ	<1.50	0.04…1.50	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.55.
11SMnPb30. Flow stress curves hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
normalized	300…340	42.4960	0.59367	420…460	17.3113	0.75466

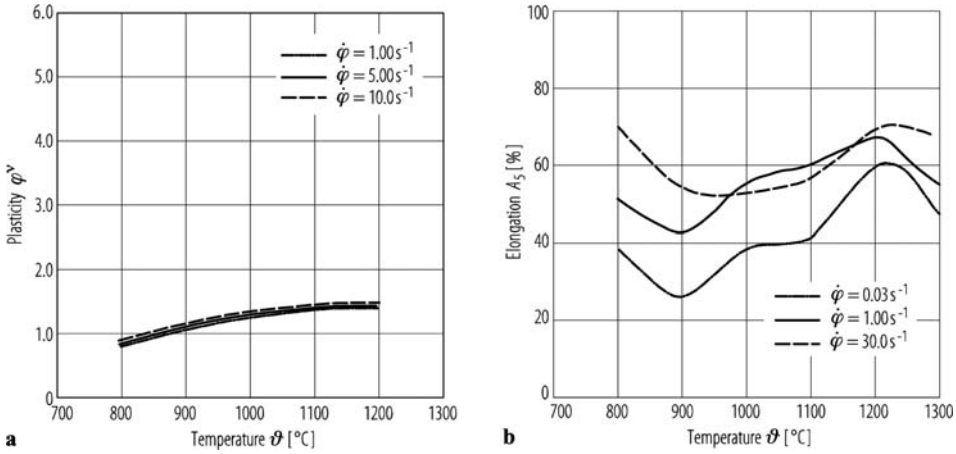
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
normalized	28…32	26.34504	0.03656	−6.50142	<60

Fig. 5.56.
11SMnPb30. Hot plasticity of as a function of the temperature. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	48.98	472.22	11.43	7829.7	
100	47.21	485.18	11.80	7802.0	
200	46.58	498.31	12.42	7771.4	
300	44.37	518.23	12.94	7738.5	
400	41.5	542.45	13.45	7703.3	
500	38.42	569.3	14.0	7665.7	
600	35.30	598.19	14.50	7625.4	
700	32.28	629.04	15.04	7582.4	
800	24.15	693.06	12.16	7601.3	
900	26.46	690.57	12.98	7555.2	
1000	27.80	688.09	13.73	7507.3	
1100	28.81	685.62	14.40	7457.7	
1200	29.89	683.15	15.02	7406.3	

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Steel symbol/number: 10S20/1.0721

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S
0.07…0.13	0.00…0.40	0.70…1.10	0.000…0.060	0.150…0.250

International comparison of standards

ISO		Euronorm		
~ 10S20	683–9 (1988)	10S20	10087 (09/1998)	
		10S20	10277 (07/1999)	
United Kingdom		Russia		
10S20	EN 10087 (09/1998)			
10S20	EN 10277 (07/1999)			
Japan		China		
		~ Y 12	T 8731 (1988)	
		~ U71122	T 8731 (1988)	
USA				
ASTM		AISI	SAE	UNS
~ A 510 (1108)	A 510–02	~ B 1111	~ 1108	~ G11080
~ A 510 (1109)	A 510–02	~ 1109	~ 1109	~ G11090

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

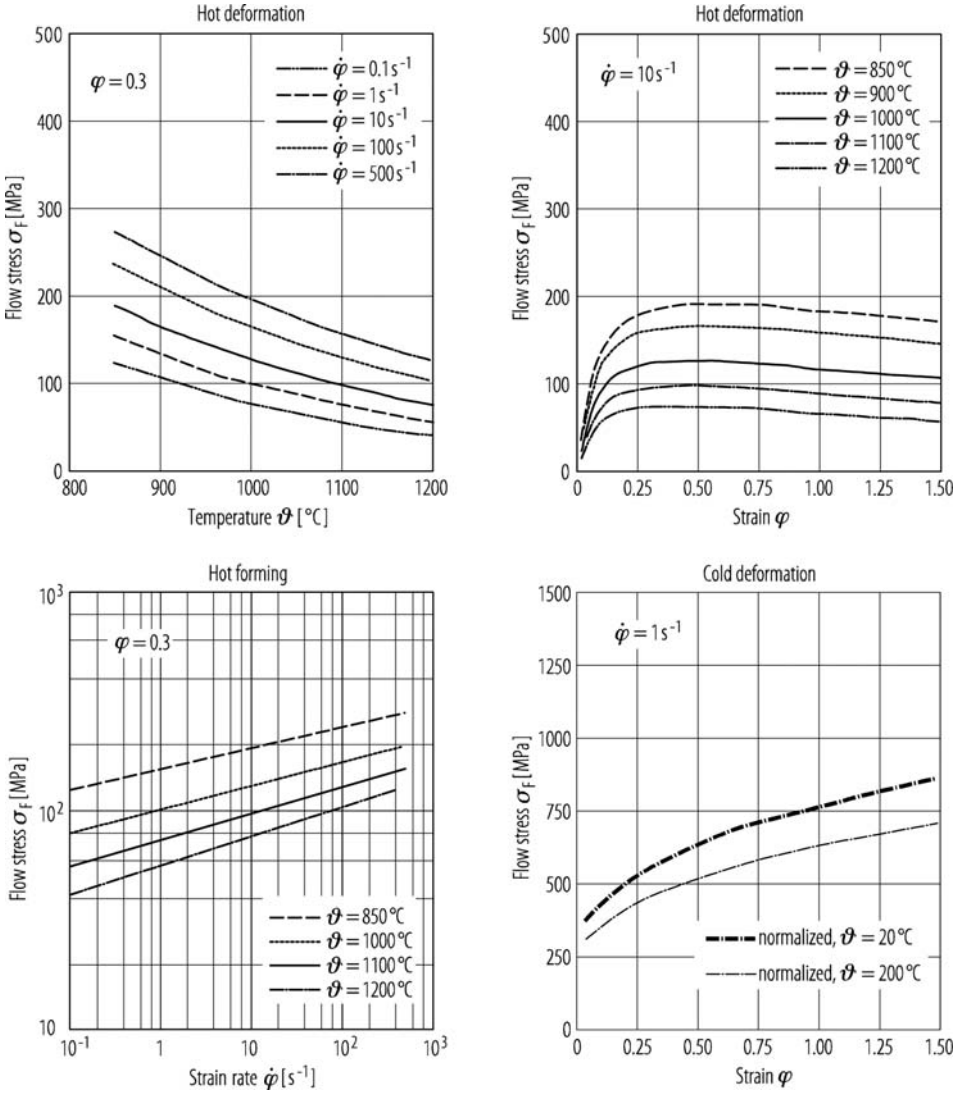
DOI: 10.1007/978-3-540-44760-3_40
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Flow curves

State of material	Hot deformation	Cold deformation
	deformed state	normalized
	austenite	
σ_{F0} [MPa]	101.33	438.7
A	2350.97	780.151
Effect of temperature K_ϑ		
m_1	−0.00268	−0.00114
Effect of strain K_φ		
m_2	0.13789	0.28653
m_4	−0.03193	0.00810
m_5	−0.00086	
m_7	0.01333	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01126
m_8	0.000110	
Range of validity		
ϑ [°C]	850…1200	20…300
φ	<1.20	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.57.
10S20. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
normalized	290…320	57.1792	0.46286	420…470	6.1292	0.91566

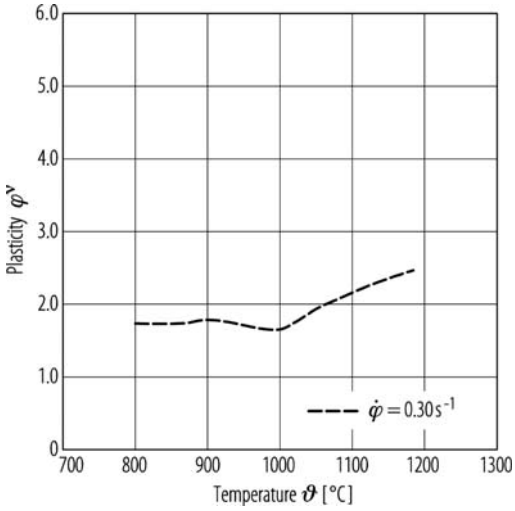
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
normalized	35…40	26.48292	−0.11226	−7.10179	<60

Fig. 5.58.
10S20. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.85.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	48.69	472.31	11.41	7819.3	
100	47.07	485.18	11.79	7791.6	
200	46.46	498.42	12.41	7761.1	
300	44.26	518.35	12.93	7728.3	
400	41.4	542.57	13.44	7693.2	
500	38.33	569.4	14.0	7655.6	
600	35.22	598.33	14.49	7615.4	
700	32.21	629.19	15.03	7572.4	
800	24.12	693.19	12.17	7590.9	
900	26.44	690.70	13.00	7544.8	
1000	27.79	688.22	13.75	7496.8	
1100	28.81	685.75	14.43	7447.0	
1200	29.90	683.28	15.05	7395.6	

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Steel symbol/number: M 350–50A/1.0810

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Mn	Si	P	S	N
		~ 3.0			
the chemical composition are up to the producers choice					

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
		2411	21427.2 (1983)	
Japan		China		
50–A–350	C2552 (1986)	W12		
USA				
ASTM		AISI	SAE	UNS
47F 507M	A677 M (1989)	M–43		
47F 230	A677 M (1989)			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

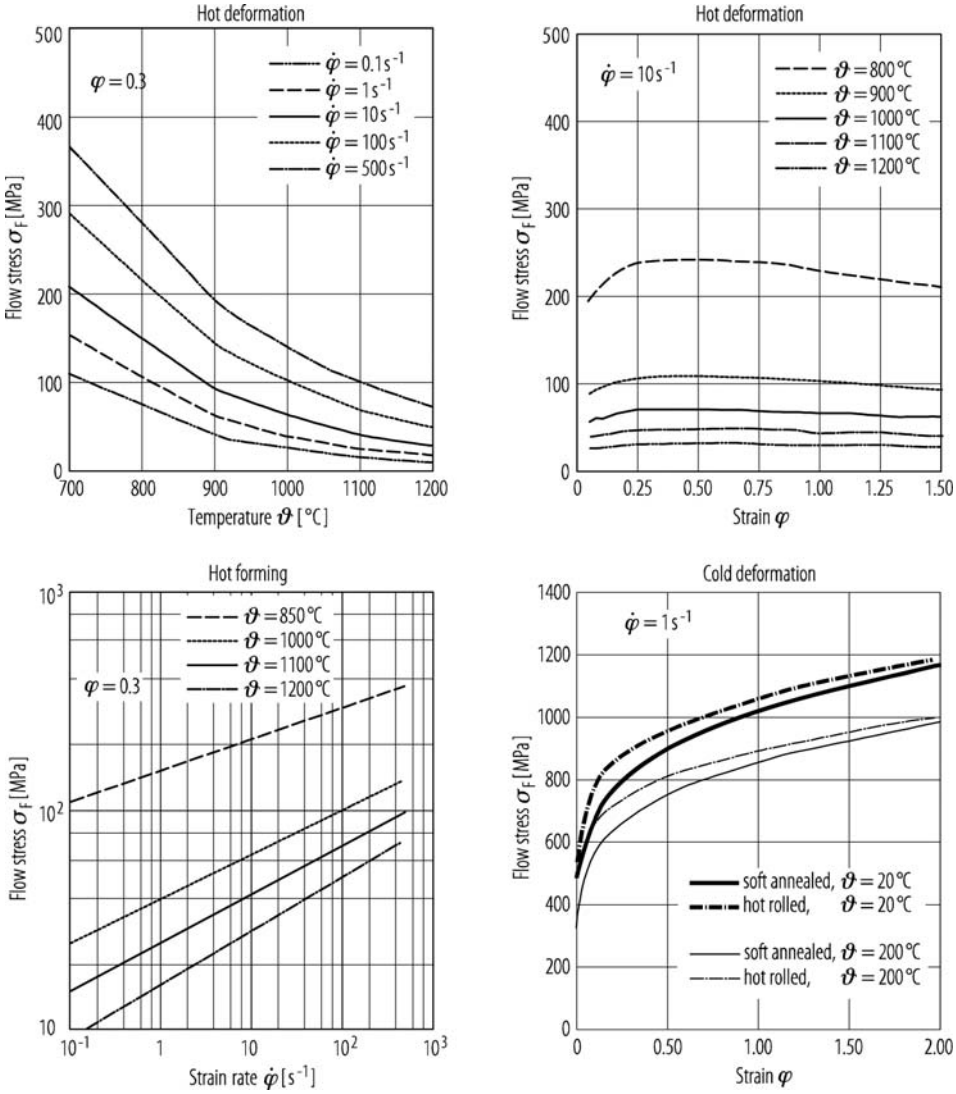
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	hot rolled
	ferrite		
σ_{F0} [MPa]	63.60	669.71	782.24
A	5259.13	1036.360	1086.860
Effect of temperature K_ϑ			
m_1	−0.00451	−0.00096	−0.00100
Effect of strain K_φ			
m_2	0.14219	0.19087	0.14594
m_4	−0.00139	0.00005	0.00076
m_5	0.00002		
m_7	−0.30841		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.19087	0.00825
m_8	0.000202		
Range of validity			
ϑ [°C]	700 … 1200	20…300	20…180
φ	0.04…1.50	0.04…1.60	0.04…1.60
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.59.
M 350–50A. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
hot rolled	450…500	102.030	0.34584	520…560	61.753	0.44671

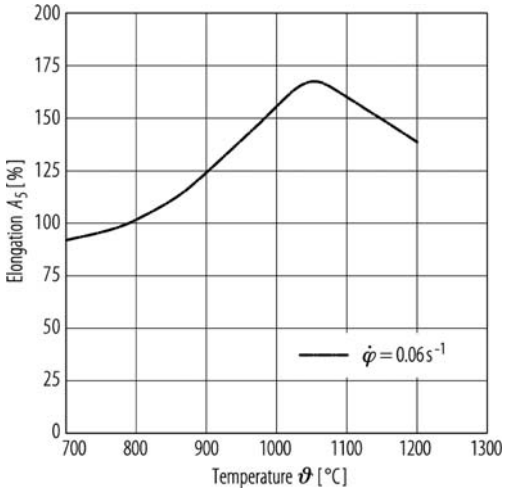
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
hot rolled	25…30	14.443	0.11658	0.46865	< 85

Fig. 5.60.
M 350–50A. Hot plasticity as a function of the temperature. Deformed state. Austenitised at 1150 [°C]. Note: At hot deformation the relation of plasticity between as–cast and as-deformed state is: 0.60…0.90.

Plasticity by tensile test



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	23.50	444.8	10.50	7654.9	186.5
100	25.02	475.2	12.29	7631.5	185.0
200	27.89	535.8	13.15	7599.3	181.2
300	28.77	576.3	13.68	7565.5	175.2
400	29.74	626.8	14.07	7530.5	167.1
500	31.96	722.9	14.38	7494.6	156.7
600	32.15	829.0	14.63	7458.0	144.2
700	26.65	1026.2	14.86	7420.8	129.5
800	25.38	808.8	15.05	7383.1	112.7
900	26.83	738.0	15.22	7344.9	93.6
1000	26.89	707.7	15.38	7306.3	72.4
1100	28.29	707.7	15.53	7267.3	49.0
1200	27.62	707.7	15.66	7228.0	

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

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Steel symbol/number: M 700–50A/1.0815

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Mn	Si	P	S	N
		~ 1.30			
the chemical composition are up to the producers choice					

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
		2111	21427.2 (1983)	
Japan		China		
50–A–700	C2552 (1986)			
USA				
ASTM		AISI	SAE	UNS
47F 992M	A677 M (1989)			
47F 450	A677 M (1989)			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

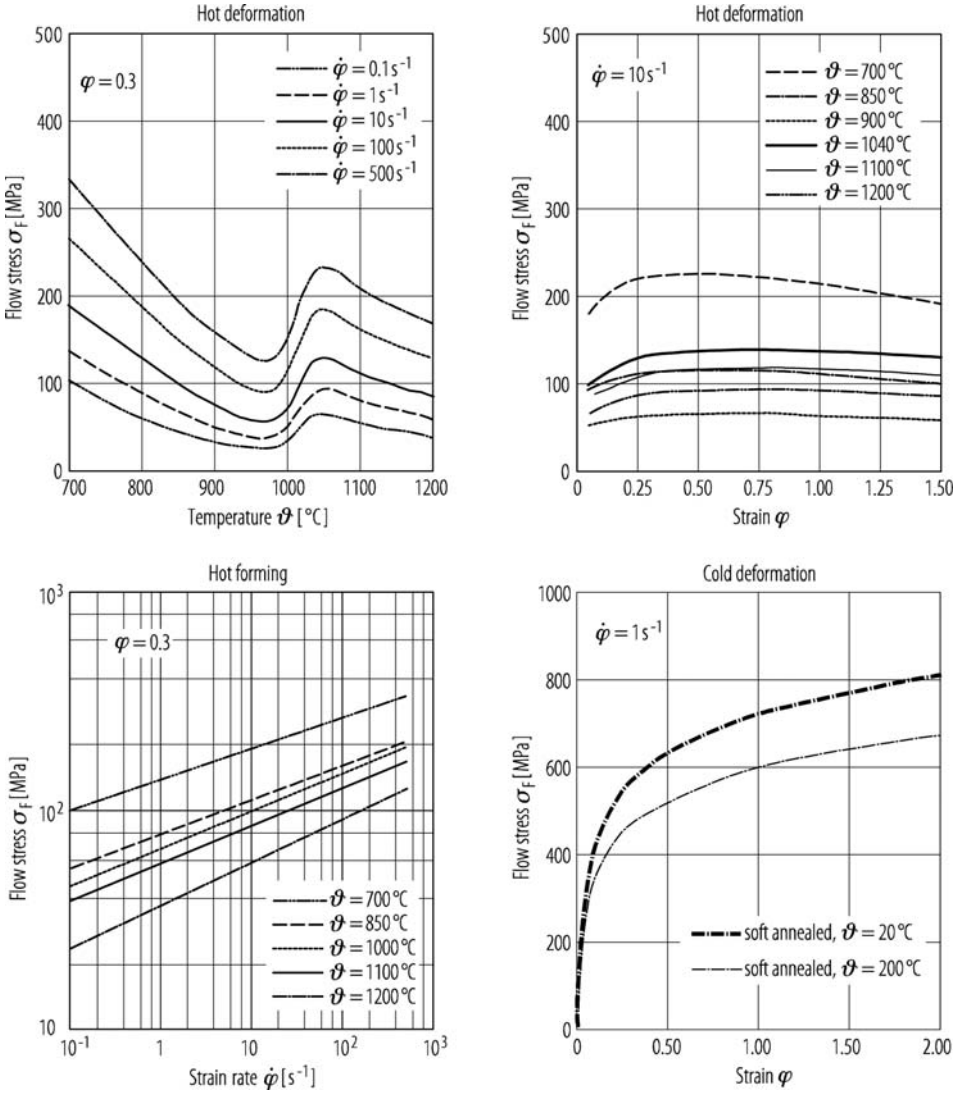
DOI: 10.1007/978-3-540-44760-3_42
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Flow curves

State of material	Hot deformation		Cold deformation
	deformed state		soft annealed
	austenite	ferrite+Fe_3C	
σ_{F0} [MPa]	120.65	(51.41)	409.97
A	2418.1	6873.1	754.97
Effect of temperature K_ϑ			
m_1	−0.00277	−0.00493	−0.00107
Effect of strain K_φ			
m_2	0.22203	0.17735	0.15206
m_4	−0.00094	0.00056	−0.02503
m_5	−0.00014	0.00015	
m_7	−0.23135	−0.41921	
Effect of strain rate $K_{\dot\varphi}$			
m_3			0.00488
m_8	0.000143	0.000202	
Range of validity			
ϑ [°C]	1040 … 1200	700 … 975	20…200
φ	0.04…1.50	0.04…1.50	0.04…1.60
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.61.
M 700–50 A. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_P [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
normalized						
hot rolled	300…350	82.909	0.42069	400…450	20.135	0.69077

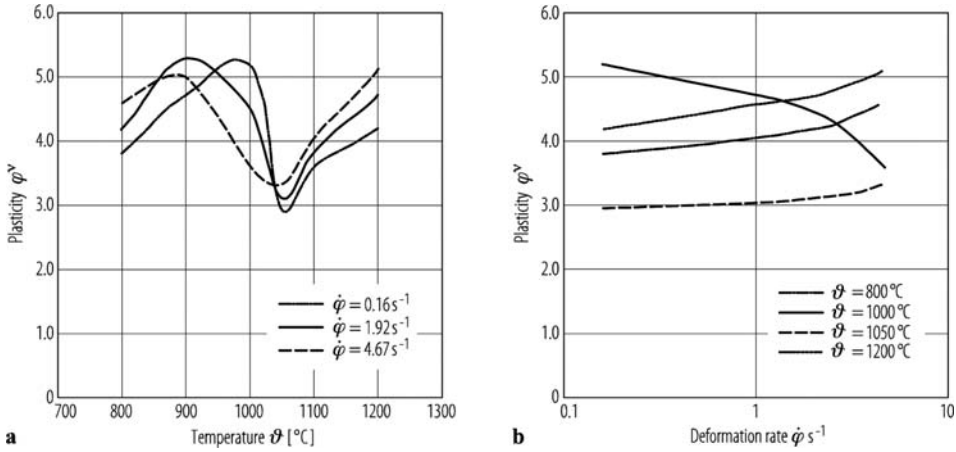
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
normalized					
hot rolled	25…33	66.902	−0.19804	−6.77479	< 85

Fig. 5.62.
M 700–50A. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity by torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	34.67	445.5	11.82	7782.9	184.2
100	37.50	486.0	14.06	7755.6	180.6
200	38.19	526.4	15.15	7717.6	174.9
300	39.04	566.9	15.82	7677.5	167.8
400	38.01	627.7	16.32	7635.9	159.3
500	36.86	698.6	16.71	7593.1	149.4
600	33.63	809.9	17.05	7549.4	138.2
700	28.87	961.8	17.33	7505.0	125.5
800	27.53	820.0	17.58	7459.8	111.4
900	29.04	739.1	17.81	7414.0	95.9
1000	30.54	708.7	18.01	7367.6	79.0
1100	30.83	658.1	18.19	7320.8	60.7
1200	31.83	668.2	18.37	7273.5	

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

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Steel symbol/number: DC06/1.0873

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Mn	P	S	Ti
0.00…0.02	0.00…0.25	0.000…0.020	0.000…0.020	0.00…0.30

International comparison of standards

ISO		Euronorm		
		DC06	10130 (05/1998)	
		DC06	10139 (11/1997)	
United Kingdom		Russia		
DC06	EN 10130 (05/1998)			
DC06	EN 10139 (11/1997)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

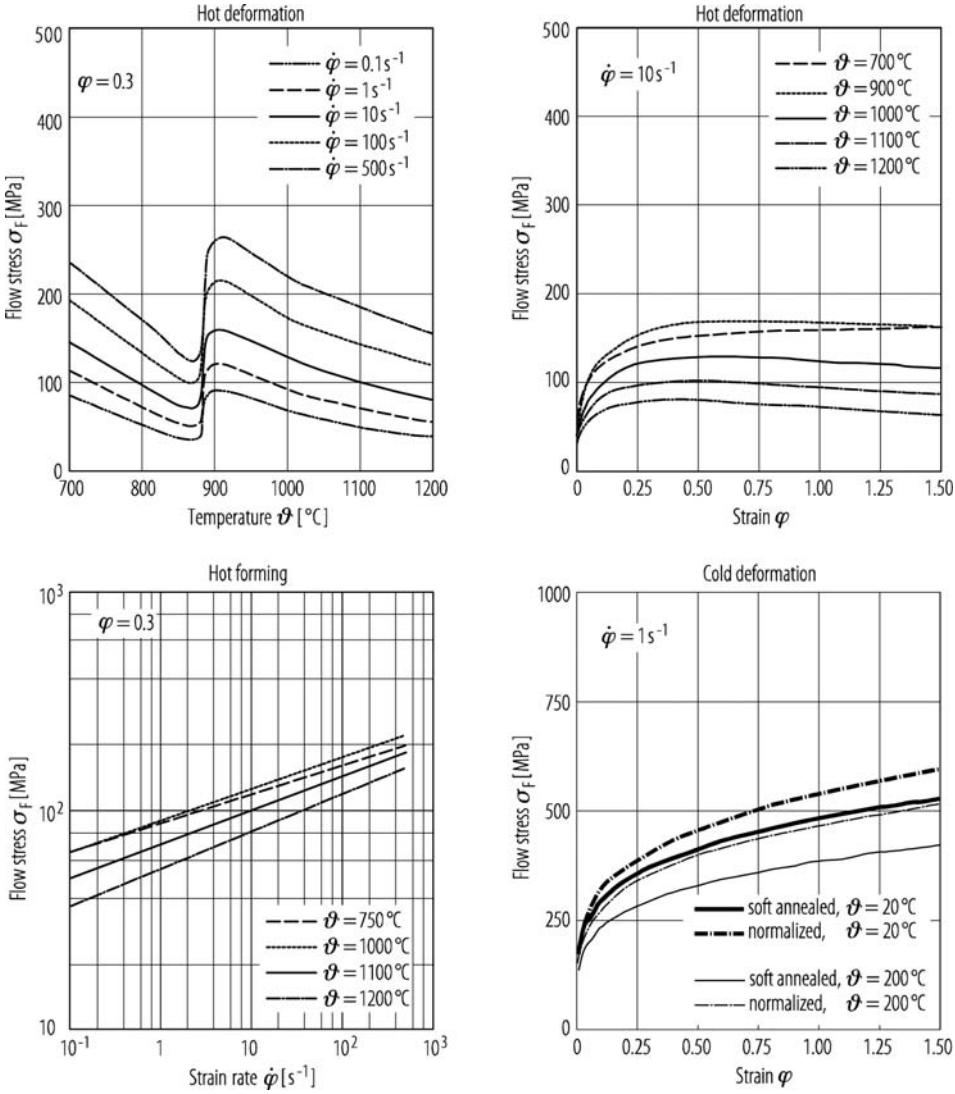
DOI: 10.1007/978-3-540-44760-3_43
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Flow curves

	Hot deformation		Cold deformation	
	deformed state		soft annealed	normalized
State of material	austenite	ferrite+Fe_3C		
σ_{F0} [MPa]	122.68	(37.12)	304.3	319.0
A	1794.64	3283.84	495.609	548.512
Effect of temperature K_ϑ				
m_1	−0.00224	−0.00419	−0.00129	−0.00081
Effect of strain K_φ				
m_2	0.38333	0.25640	0.21565	0.23314
m_4	0.00189	−0.00078	0.00046	0.00027
m_5	−0.00128	−0.00116		
m_7	0.13291	0.19336		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.01299	0.00358
m_8	0.000141	0.000172		
Range of validity				
ϑ [°C]	895…1200	700…875	20…120	20…300
φ	0.04…1.50	0.04…1.50	0.04…1.50	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.63.
DC06. Flow stress curves by hot and cold forming.



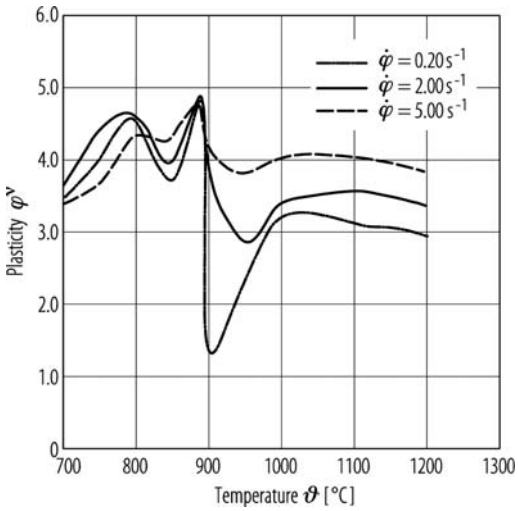
Mechanical properties after cold deformation

State of material	Yield stress ΔR_P [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
hot rolled				280…300	26.1830	0.65511	<85

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Fig. 5.64.
DC06. Hot plasticity as a fuction of the temperature (and deformation rate); deformed state and austenitized at 1150 [°C].

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	66.89	469.6	12.62	7855.6	207.1
100	53.40	478.4	12.78	7825.5	204.1
200	51.60	491.1	13.04	7794.1	198.2
300	48.82	510.7	13.45	7760.5	189.9
400	45.51	534.6	13.91	7724.5	181.9
500	42.03	561.0	14.40	7685.9	171.6
600	38.57	589.4	14.92	7644.6	160.8
700	35.24	619.8	15.46	7600.6	145.8
800	26.88	683.8	12.98	7610.9	127.0
900	28.61	681.4	13.54	7568.4	106.0
1000	29.38	678.9	14.05	7524.5	86.5
1100	29.88	676.5	14.52	7479.3	73.7
1200	30.52	674.0	14.95	7432.8	62.9

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: S340MC/1.0974

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.00…0.12	0.00…0.50	0.00…1.30	0.000…0.030	0.000…0.030	> 0.015
Nb	Ti				
0.00…0.09	0.00…0.22				

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

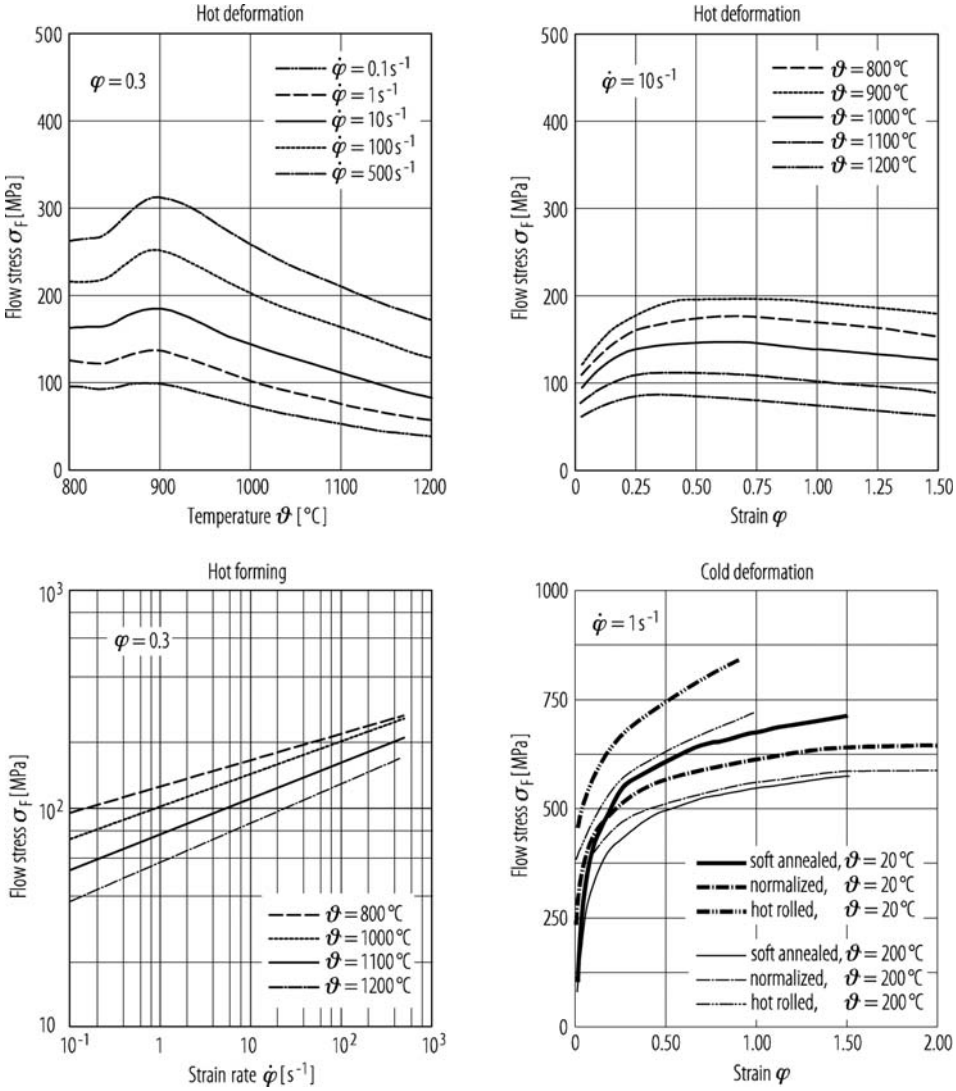
DOI: 10.1007/978-3-540-44760-3_44
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Flow curves

State of material	Hot deformation		Cold deformation		
	deformed state		soft annealed	normalized	hot rolled
	austenite	ferrite+Fe_3C			
σ_{F0} [MPa]	114.70	(102.50)	414.7	436.1	601.6
A	3222.49	850.72	713.111	627.926	866.206
Effect of temperature K_ϑ					
m_1	−0.00258	−0.00158	−0.00118	−0.00055	−0.00097
Effect of strain K_φ					
m_2	0.47578	0.35903	0.09434	0.10423	0.19283
m_4	0.01255	0.00885	−0.03408	−0.01314	0.00201
m_5	−0.00142	−0.00158			
m_7	0.06682	0.06682			
Effect of strain rate $K_{\dot\varphi}$					
m_3			0.01242	0.00776	0.01185
m_8	0.000149	0.000150			
Range of validity					
ϑ [°C]	900…1200	800…840	20…120	20…320	20…200
φ	0.04…1.50	0.04…1.50	0.04…1.50	0.04…2.50	0.04…0.55
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<275

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Fig. 5.65.
S340MC. Flow stress curves by hot and cold forming.



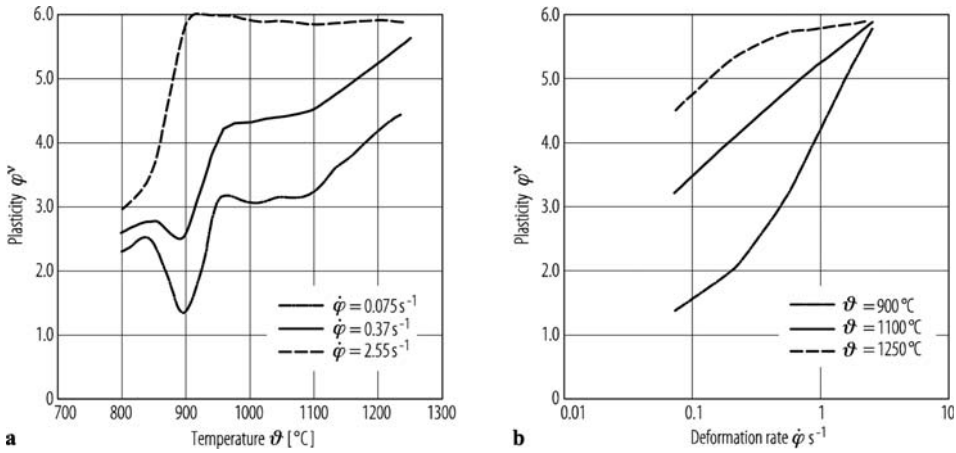
Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
hot rolled				430…460	34.3252	0.59249	<85

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Fig. 5.66.
S340MC. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	66.89	465.78	12.63	7855.6	208.2
100	53.40	478.44	12.78	7825.5	203.0
200	51.60	491.14	13.04	7794.1	197.0
300	48.82	510.72	13.45	7760.5	190.5
400	45.5	534.55	13.91	7724.5	182.6
500	42.03	561.0	14.4	7685.9	172.7
600	38.57	589.42	14.92	7644.6	160.2
700	35.24	619.79	15.46	7600.6	145.1
800	26.88	683.82	12.98	7610.9	127.3
900	28.61	681.36	13.54	7568.4	107.1
1000	29.38	678.91	14.05	7524.5	86.5
1100	29.88	676.48	14.52	7479.3	73.7
1200	30.52	674.04	14.95	7432.8	61.9

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: S355NC/1.0977

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.00…0.18	0.00…0.50	0.00…1.60	0.000…0.025	0.000…0.015	>0.0150
V	Tu	Nb			
0.00…0.10	0.00…0.15	0.00…0.09			

International comparison of standards

ISO		Euronorm		
		S355NC	10149 (09/1995)	
United Kingdom		Russia		
S355NC	EN 10149 (09/1995)			
~ 43/35CS	1449 Part 1 (1991)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

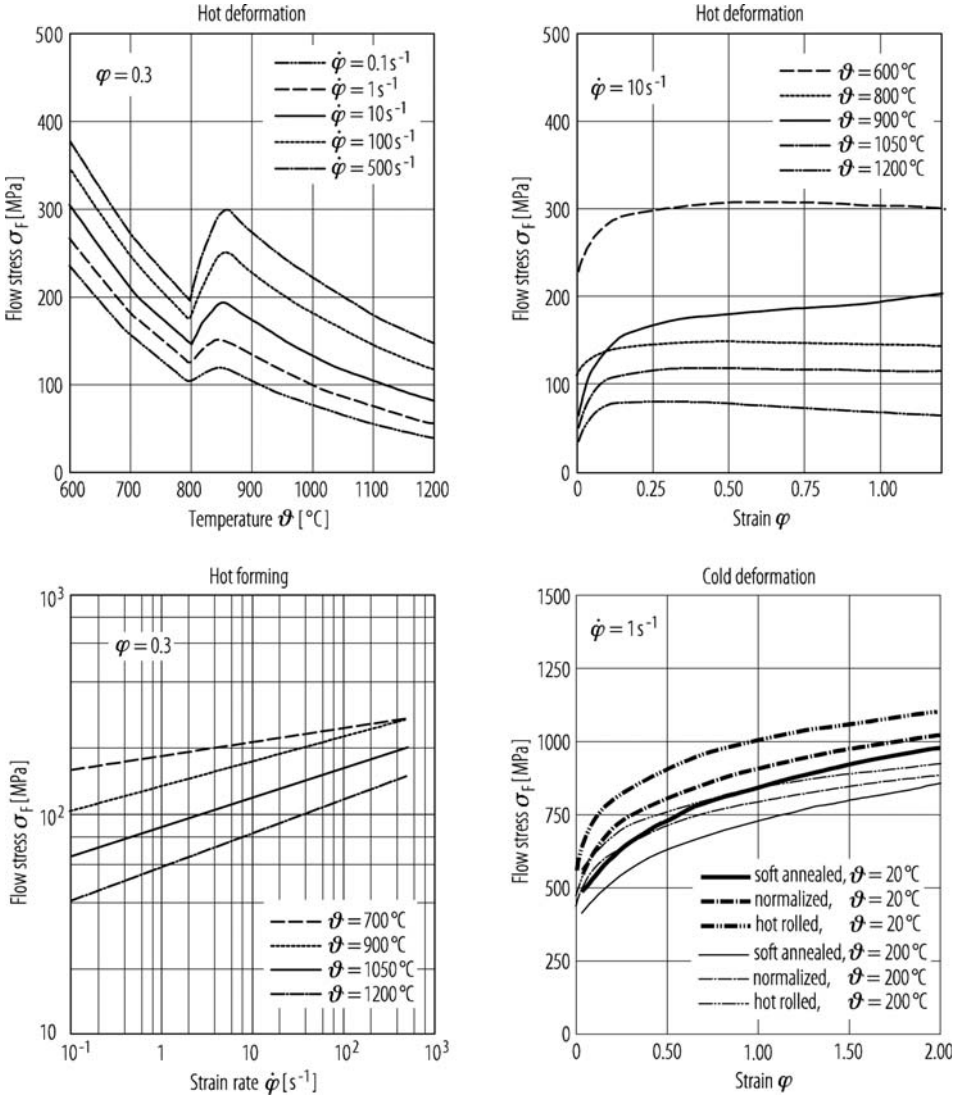
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Flow curves

State of material	Hot deformation		Cold deformation		
	deformed state		soft annealed	normalized	hot rolled
	austenite	ferrite+Fe_3C			
σ_{F0} [MPa]	114.34	(66.26)	561.8	595.2	719.7
A	1893.93	3113.60	851.643	919.477	1017.950
Effect of temperature K_ϑ					
m_1	−0.00219	−0.00382	−0.00082	−0.00076	−0.00098
Effect of strain K_φ					
m_2	0.33771	0.09665	0.22367	0.16326	0.13812
m_4	0.00036	0.00028	0.00707	0.00171	0.00014
m_5	−0.00238	−0.00014			
m_7	0.91215	−0.11048			
Effect of strain rate $K_{\dot\varphi}$					
m_3			0.01121	0.01186	0.00963
m_8	0.000127	0.000093			
Range of validity					
ϑ [°C]	840…1200	600…820	20…140	20…140	20…140
φ	0.04…1.20	0.04…1.20	0.04…2.20	0.04…2.20	0.04…2.20
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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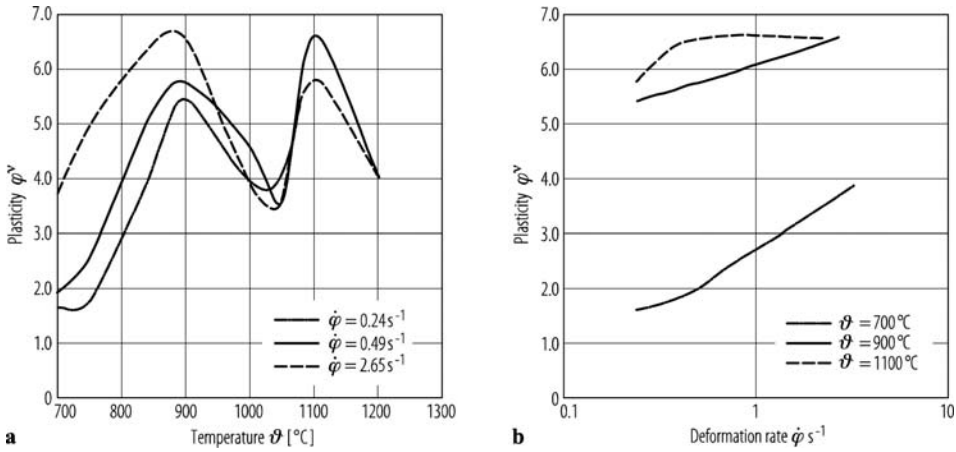
Fig. 5.67.
S355NC. Flow stress curves by hot and cold forming.



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Fig. 5.68.
S355NC. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	47.13	472.84	11.31	7815.9	216.3
100	46.28	485.92	11.69	7788.5	207.8
200	45.78	499.04	12.34	7758.0	200.6
300	43.65	519.00	12.87	7725.4	195.5
400	40.8	543.26	13.38	7690.4	190.7
500	37.82	570.1	13.9	7652.9	184.8
600	34.76	599.10	14.43	7612.9	176.9
700	31.78	630.00	14.98	7570.1	166.1
800	23.96	693.91	12.26	7585.9	152.2
900	26.34	691.42	13.12	7539.0	135.0
1000	27.76	688.93	13.90	7490.1	115.0
1100	28.83	686.45	14.60	7439.4	92.6
1200	29.97	683.99	15.25	7386.9	68.9

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.
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Steel symbol/number: S380MC/1.0978

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.00…0.12	0.00…0.50	0.00…1.50	0.000…0.025	0.000…0.020	> 0.015
Nb	Ti	V			
0.00…0.09	0.00…0.22	0.00…0.20			

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

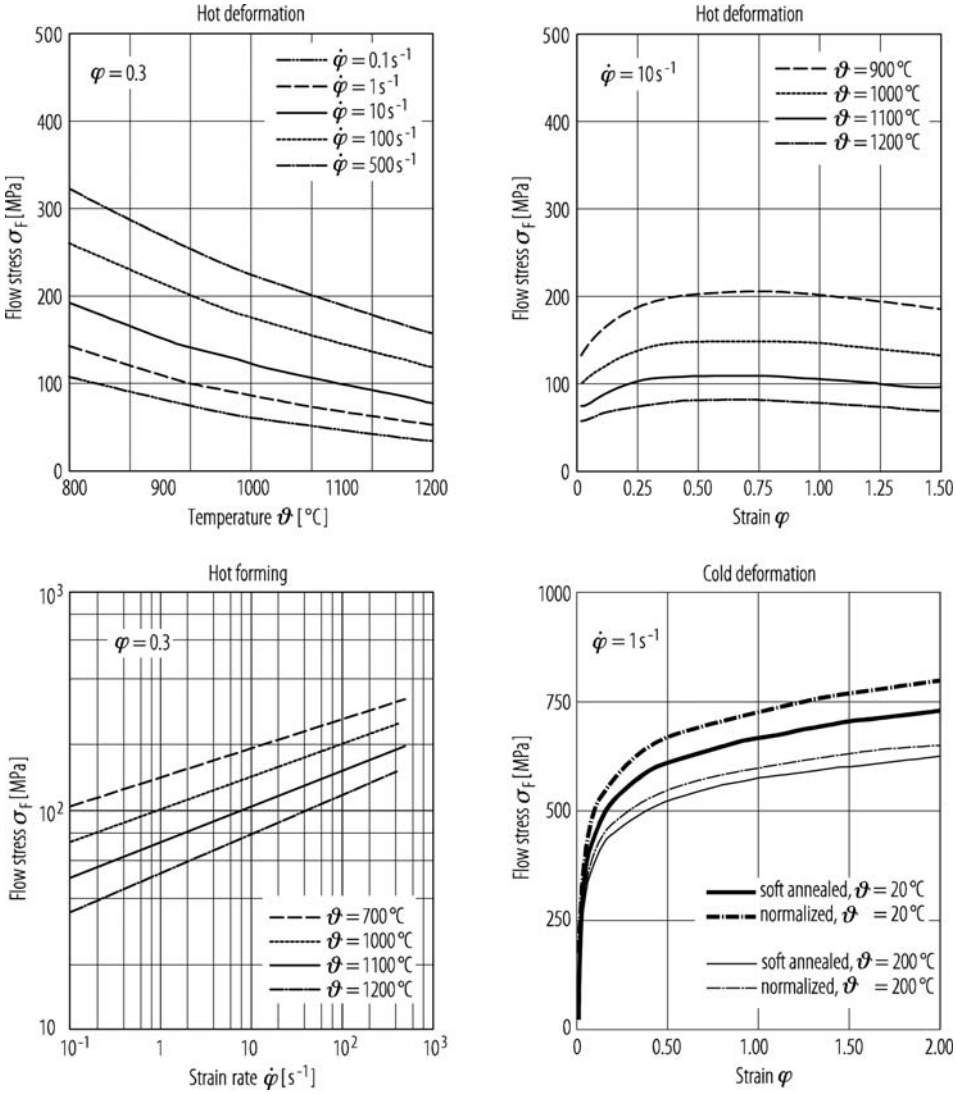
DOI: 10.1007/978-3-540-44760-3_46
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	normalized
	austenite		
σ_{F0} [MPa]	115.82	436.6	482.7
A	4453.92	689.818	758.155
Effect of temperature K_ϑ			
m_1	−0.00382	−0.00084	−0.00112
Effect of strain K_φ			
m_2	0.35270	0.11113	0.11268
m_4	0.00926	−0.01596	−0.01599
m_5	−0.00049		
m_7	−0.24026		
Effect of strain rate $K_{\dot\varphi}$			
m_3		−0.01095	−0.00524
m_8	0.000148		
Range of validity			
ϑ [°C]	890…1200	20…320	20…200
φ	0.04…1.50	0.04…2.20	0.04…2.20
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.69.
S380MC. Flow stress curves by hot and cold forming.



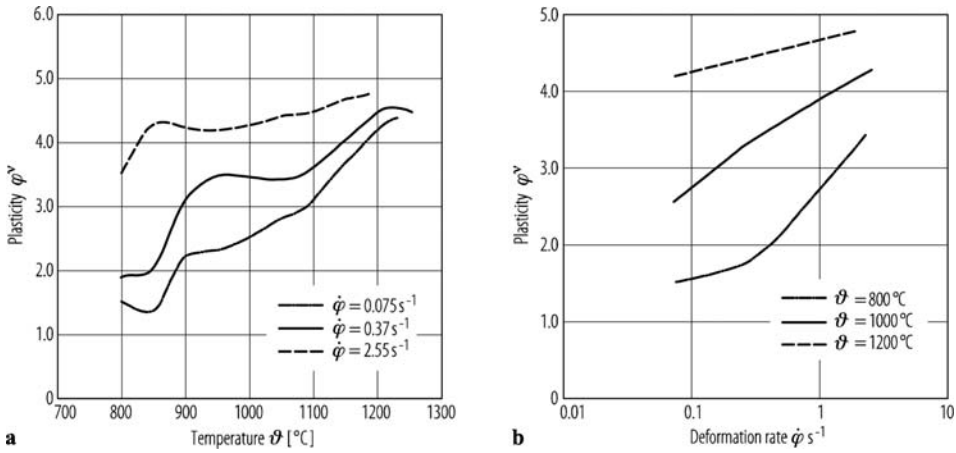
Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
hot rolled				560…600	25.1908	0.67162	<85

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Fig. 5.70.
S380MC. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properities

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	52.05	472.91	11.43	7834.2	
100	50.62	485.77	11.80	7806.5	
200	48.52	498.31	12.42	7778.7	
300	45.07	518.23	12.94	7743.0	
400	41.14	542.45	13.45	7707.8	
500	37.15	569.27	13.97	7670.1	
600	33.32	598.19	14.50	7629.8	
700	29.73	629.04	15.04	7586.7	
800	24.10	693.06	12.16	7605.6	
900	25.72	690.57	12.98	7559.6	
1000	26.97	688.09	13.73	7511.6	
1100	28.17	685.62	14.40	7462.0	
1200	29.53	683.15	15.02	7410.6	

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Steel symbol/number: S420MC/1.0980

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.00…0.12	0.00…0.50	0.00…1.60	0.000…0.025	0.000…0.015	> 0.015
Nb	Ti	V			
0.00…0.09	0.00…0.15	0.00…0.20			

International comparison of standards

ISO		Euronorm		
FeE420	6930–1 (2001)	S420MC	10149–2 (09/1995)	
United Kingdom		Russia		
S420MC	EN 10149–2 (09/1995)			
50F45 HR	1449 Part 1 (1991)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

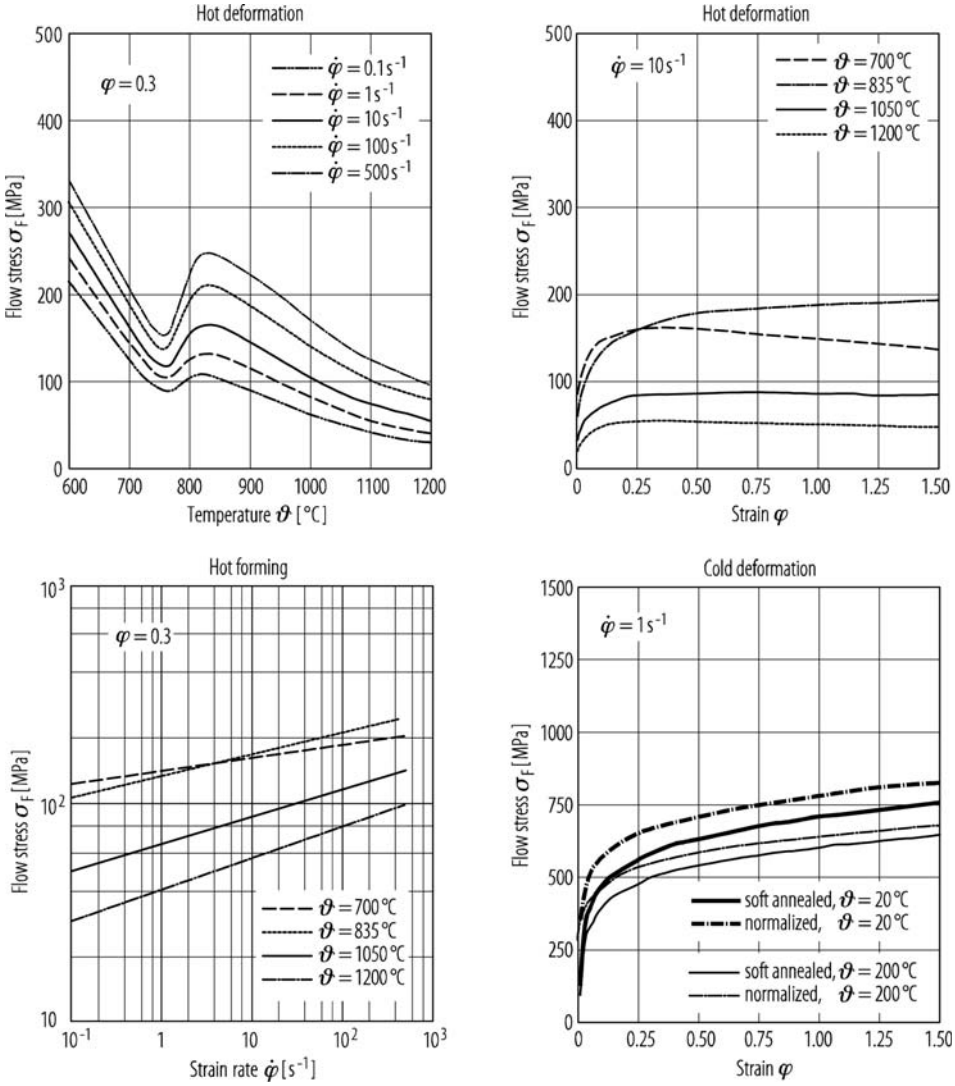
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Flow curves

State of material	Hot deformation			Cold deformation	
	deformed state		casting state	soft annealed	normalized
	austenite	ferrite+Fe_3C			
σ_{F0} [MPa]	113.13	(48.90)	118.23	465.9	515.1
A	2743.20	7920.93	2276.71	722.733	799.104
Effect of temperature K_ϑ					
m_1	−0.00264	−0.00510	−0.00277	−0.00088	−0.00114
Effect of strain K_φ					
m_2	0.31761	0.21806	0.16017	0.15198	0.13346
m_4	0.00030	0.00003	−0.00861	−0.00641	−0.00085
m_5	−0.00129	−0.00041	0.00017		
m_7	0.28953	−0.04860	−0.39312		
Effect of strain rate $K_{\dot\varphi}$					
m_3				0.00325	0.00043
m_8	0.000119	0.000086	0.000126		
Range of validity					
ϑ [°C]	835…1200	600…760	900…1250	20…320	20…320
φ	0.04…1.50	0.04…1.50	0.04…1.50	0.04…2.20	0.04…2.20
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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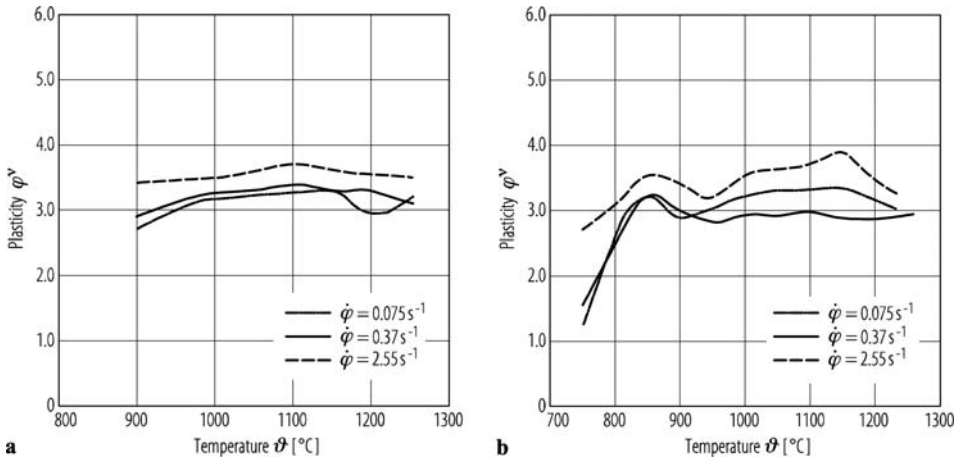
Fig. 5.71.
S420MC. Flow stress curves by hot and cold forming.



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Fig. 5.72.
S420MC. Hot plasticity as a function of the temperature. (a) Casting state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	47.68	472.3	11.09	7816.7	
100	46.56	485.9	11.73	7789.2	
200	46.02	498.8	12.36	7758.8	
300	43.87	518.8	12.89	7726.1	
400	41.05	543.0	13.40	7691.0	
500	38.00	569.9	13.92	7653.5	
600	34.92	598.8	14.45	7613.4	
700	31.94	629.7	15.00	7570.5	
800	24.02	693.7	12.23	7587.4	
900	26.37	691.2	13.08	7540.7	
1000	27.77	688.7	13.84	7492.2	
1100	28.82	686.2	14.53	7441.9	
1200	29.94	683.7	15.17	7389.8	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: S460MC/1.0982

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.00…0.12	0.00…0.50	0.00…1.60	0.000…0.025	0.000…0.015	>0.0150
V	Ti	Nb			
0.00…0.20	0.00…0.15	0.000…0.090			

International comparison of standards

ISO		Euronorm		
~ FeE460	6930–1 (2001)	S460MC	10149 (09/1995)	
United Kingdom		Russia		
S460MC	EN 10149 (09/1995)			
~ 50/45 HR	1449 Part 1 (1991)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

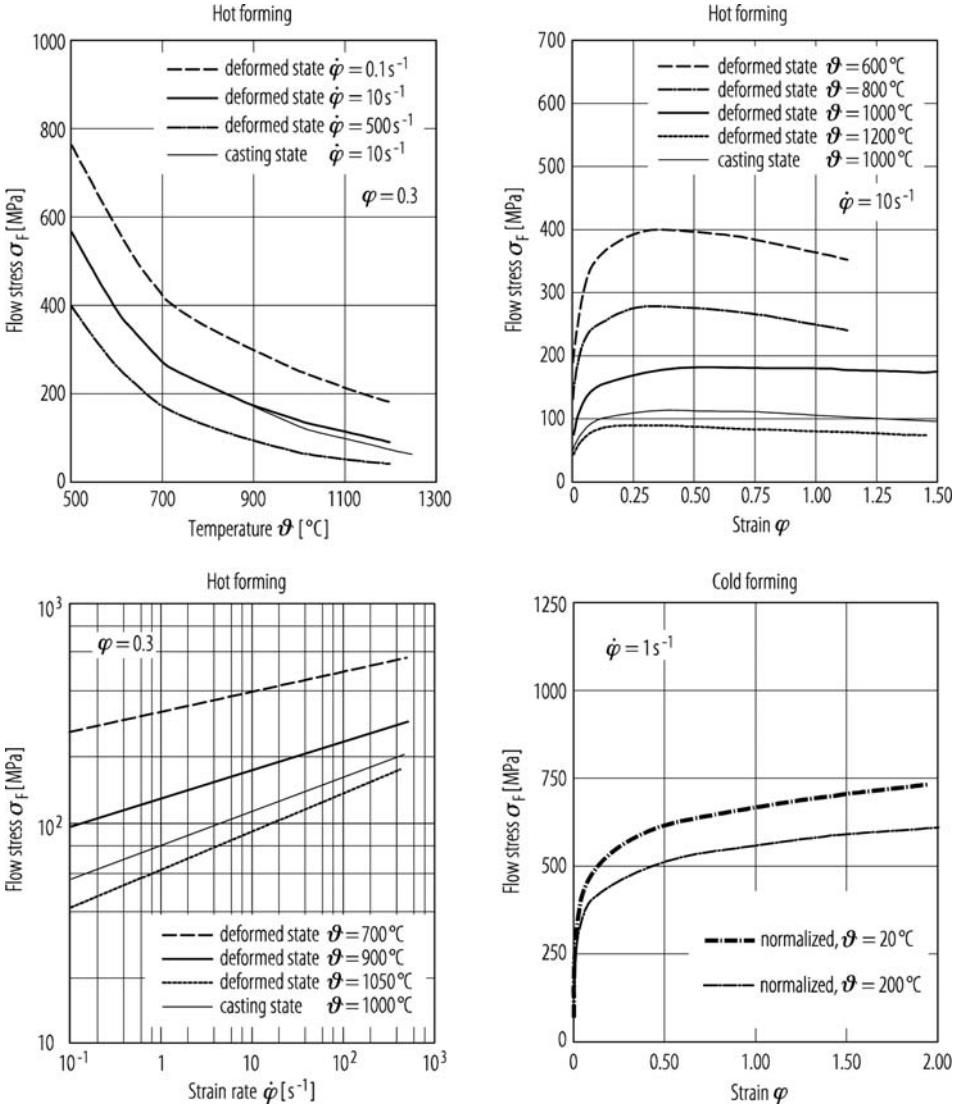
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Flow curves

State of material	Hot deformation			Cold deformation
	deformed state		casting state	normalized
	austenite	ferrite+Fe_3C	austenite	
σ_{F0} [MPa]	120.67	(84.93)	107.60	470.7
A	1637.36	4796.49	3089.74	693.113
Effect of temperature K_ϑ				
m_1	–0.00222	-0.00384	-0.00282	-0.00102
Effect of strain K_φ				
m_2	0.27579	0.20586	0.33436	0.11943
m_4	0.00018	-0.00059	0.00027	-0.01038
m_5	–0.00116	-0.00032	-0.00129	
m_7	0.19866	-0.35681	0.16538	
Effect of strain rate $K_{\dot\varphi}$				
m_3				0.01053
m_8	0.000146	0.000153	0.000146	
Range of validity				
ϑ [°C]	830…1200	500…720	900…1250	20…320
φ	0.04…1.50	0.04…1.50	0.04…1.20	0.04…2.20
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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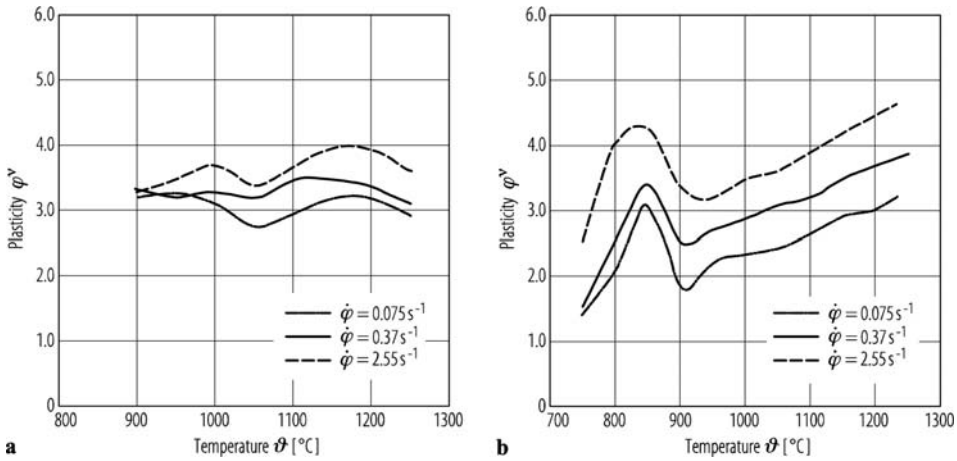
Fig. 5.73.
S460MC. Flow stress curves by hot and cold forming.



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Fig. 5.74.
S460MC. Hot plasticity as a function of the temperature. (a) Casting state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	48.49	474.1	11.01	7798.4	214.9
100	47.62	487.4	11.43	7771.6	209.8
200	46.14	500.8	12.14	7744.9	203.3
300	43.02	520.8	12.69	7709.3	196.8
400	39.34	545.2	13.21	7674.8	190.3
500	35.57	572.2	13.73	7637.8	183.2
600	31.92	601.3	14.26	7598.3	174.9
700	28.50	632.3	14.80	7556.0	164.3
800	23.58	695.8	12.71	7560.6	150.0
900	25.31	693.3	13.66	7510.7	130.4
1000	26.65	690.8	14.52	7458.6	100.7
1100	27.93	688.3	15.31	7404.5	88.7
1200	29.36	685.9	16.03	7348.5	75.0

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: C42D2/1.1154

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.40…0.44	0.10…0.30	0.50…0.70	0.000…0.020	0.000…0.025	0.000…0.010
Cr	Cu	Mo	N	Ni	
0.00…0.10	0.00…0.15	0.00…0.03	0.000…0.007	0.00…0.10	

International comparison of standards

ISO		Euronorm		
~ 3CD43A	8457–2 (1989)	C42D2	10016–4 (12/1994)	
~ C42D2	16120–4 (2001)			
United Kingdom		Russia		
C42D2	EN 10016–4 (12/1994)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

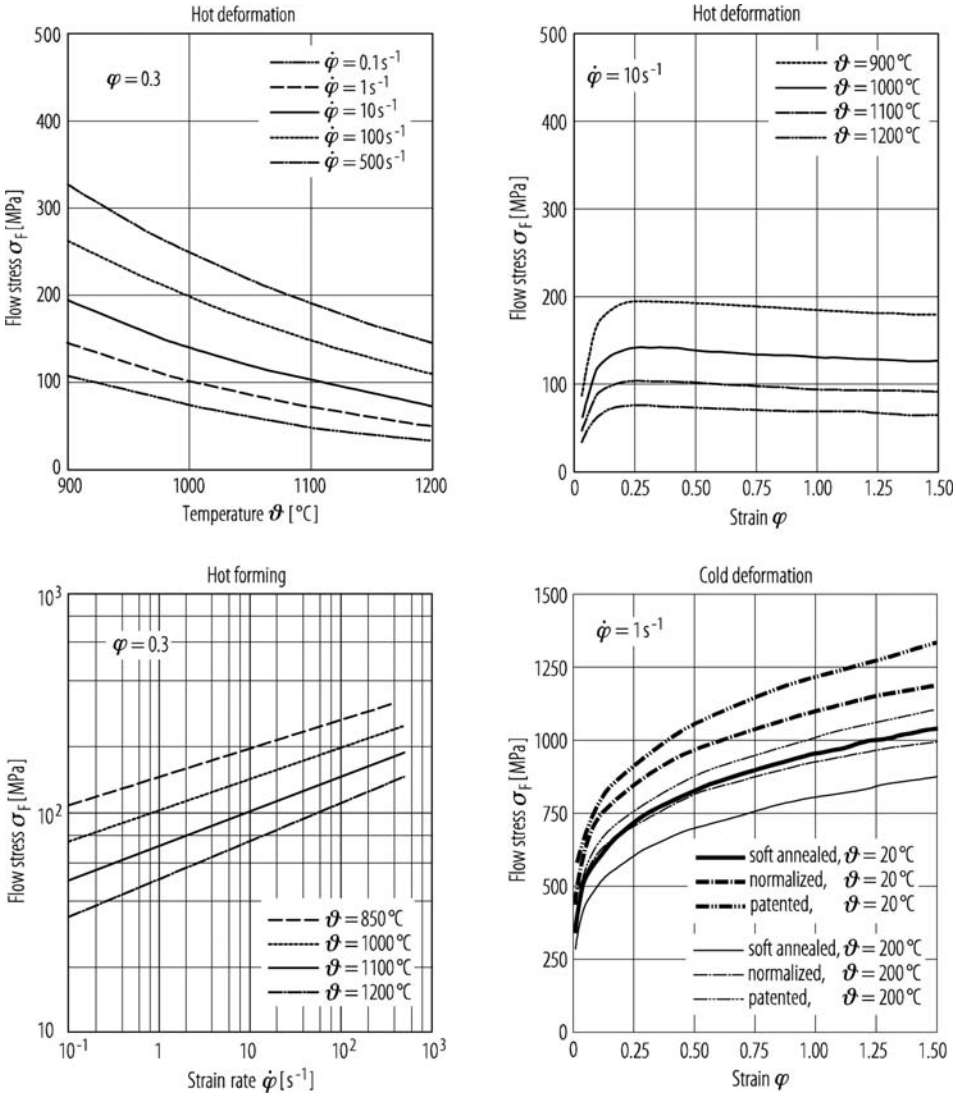
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Flow curves

	Hot deformation	Cold deformation		
	deformed state	soft annealed	normalized	patented
State of material	austenite			
σ_{F0} [MPa]	119.1	607.5	732.1	806.9
A	3430.03	971.063	1121.121	1275.856
Effect of temperature K_ϑ				
m_1	−0.00351	−0.00097	−0.00099	−0.00105
Effect of strain K_φ				
m_2	−0.15598	0.20681	0.18743	0.21176
m_4	−0.05303	0.00010	0.00002	0.00224
m_5	−0.00026			
m_7	0.14166			
Effect of strain rate $K_{\dot\varphi}$				
m_3		0.01110	0.01086	0.01217
m_8	0.000144			
Range of validity				
ϑ [°C]	900…1250	20…150	20…150	20…150
φ	0.04…1.50	0.04…1.00	0.04…1.00	0.04…1.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.75.
C42D2. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

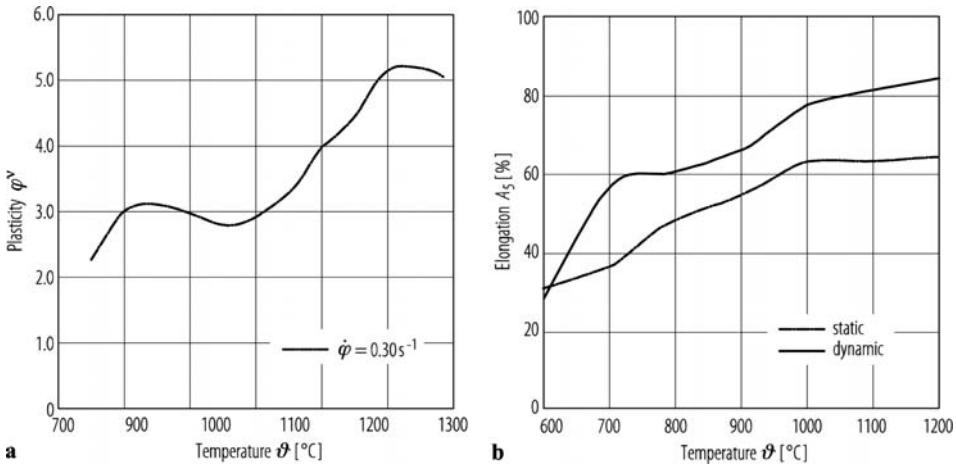
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
soft annealed	340…370	80.9774	0.48298	590…630	13.4394	0.8251
hot rolled	360…400	115.9930	0.44353	640…680	31.0476	0.64039
patented				750…800	17.2771	0.77094

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
soft annealed	20…25	33.00470	0.07075	−11.3763	<70
hot rolled					<80
patented					<80

Fig. 5.76.
C42D2. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformation rate: 0.2 [s^{-1}]. Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	47.92	474.65	10.91	7808.4	
100	47.12	488.04	11.35	7781.9	
200	45.75	501.31	12.07	7751.9	
300	42.67	521.41	12.62	7719.7	
400	39.0	545.82	13.14	7685.3	
500	35.30	572.8	13.7	7648.4	
600	31.68	601.97	14.19	7608.9	
700	28.29	633.04	14.74	7566.8	
800	23.50	696.41	12.91	7566.5	
900	25.24	693.91	13.91	7515.2	
1000	26.60	691.41	14.80	7461.8	
1100	27.89	688.93	15.61	7406.2	
1200	29.33	686.45	16.36	7348.6	

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

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Steel symbol/number: G46Mn4/1.1159

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S
0.42…0.50	0.25…0.50	0.90…1.20	0.000…0.035	0.000…0.035

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
Japan		China		
~ SCMn5	G 5111 (1991)			
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

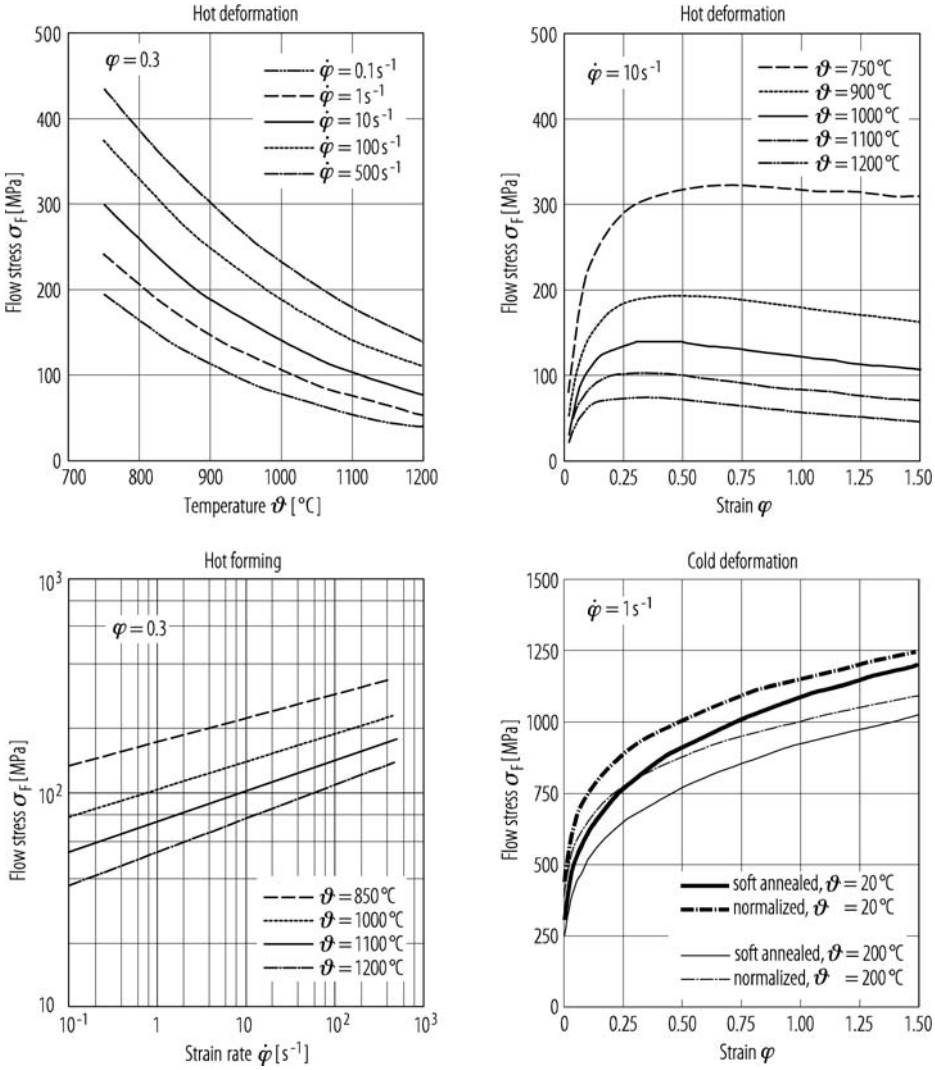
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	normalized
	austenite		
σ_{F0} [MPa]	108.60	616.8	754.9
A	4548.49	1102.606	1172.979
Effect of temperature K_ϑ			
m_1	−0.00291	−0.00089	−0.00079
Effect of strain K_φ			
m_2	0.35966	0.25184	0.19258
m_4	−0.01486	0.00013	0.00009
m_5	−0.00176		
m_7	0.22550		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.00673	0.00765
m_8	0.000129		
Range of validity			
ϑ [°C]	750…1200	20…300	20…300
φ	<1.50	0.04…1.50	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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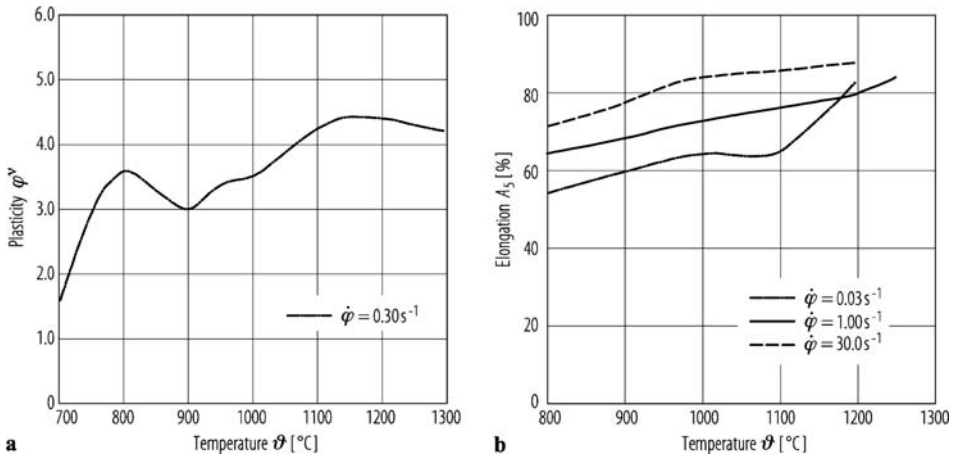
Fig. 5.77.
G46Mn4. Flow stress curves by hot and cold forming.



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Fig. 5.78.
G46Mn4. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	41.75	474.61	10.96	7811.2	
100	43.22	488.68	11.34	7784.6	
200	43.10	501.35	12.07	7754.6	
300	41.20	521.44	12.62	7722.5	
400	38.6	545.85	13.14	7688.0	
500	35.78	572.9	13.7	7651.1	
600	32.90	602.01	14.19	7611.7	
700	30.10	633.08	14.73	7569.5	
800	23.53	696.44	12.93	7568.9	
900	26.15	693.94	13.92	7517.5	
1000	27.81	691.45	14.82	7464.0	
1100	29.09	688.96	15.63	7408.3	
1200	30.43	686.49	16.38	7350.6	

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Steel symbol/number: 36Mn5/1.1167

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S
0.32…0.40	0.00…0.40	1.20…1.50	0.000…0.035	0.000…0.035

International comparison of standards

ISO		Euronorm		
~ 36Mn6	683–18 (1996)			
United Kingdom		Russia		
~150 M 36	PD 970 (2001)	~ 35GL	977 (1988)	
		~ 35G2	4543 (1971)	
Japan		China		
~ SMn 438 M	G 3311 (1998)			
~ SCMn3	G 5111 (1991)			
USA				
ASTM		AISI	SAE	UNS
~ A 29 (1335)	A 29–99	~1541	~1541	~ H13350
~ A 29 (1541)	A 29–99		~1335	~ H15410

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

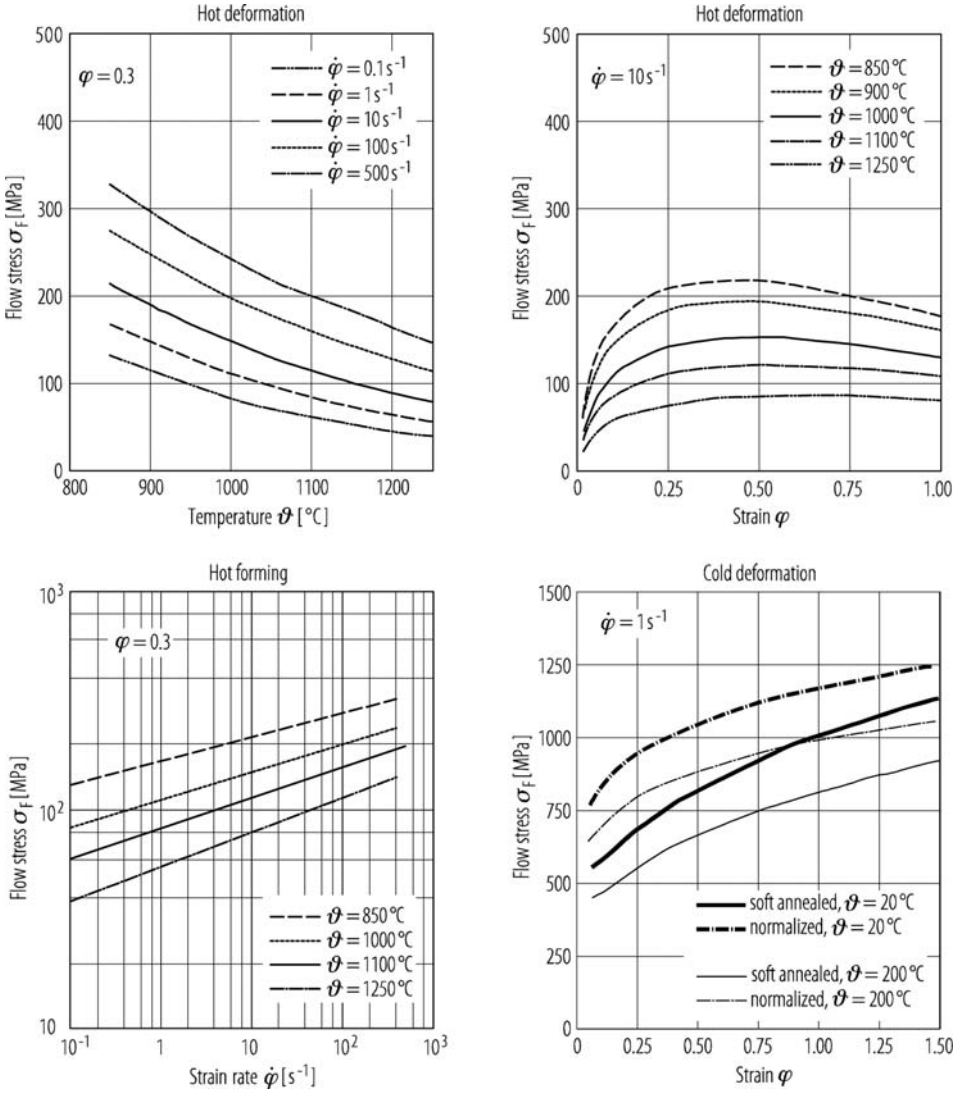
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	normalized
	austenite		
σ_{F0} [MPa]	109.95	591.3	844.4
A	3612.67	1011.39	1190.933
Effect of temperature K_ϑ			
m_1	−0.00306	−0.00118	−0.00096
Effect of strain K_φ			
m_2	0.23887	0.31696	0.16254
m_4	−0.01487	0.01881	0.00256
m_5	0.00108		
m_7	−1.28813		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01241	0.01040
m_8	0.000127		
Range of validity			
ϑ [°C]	850…1250	20…300	20…300
φ	<1.00	0.04…1.50	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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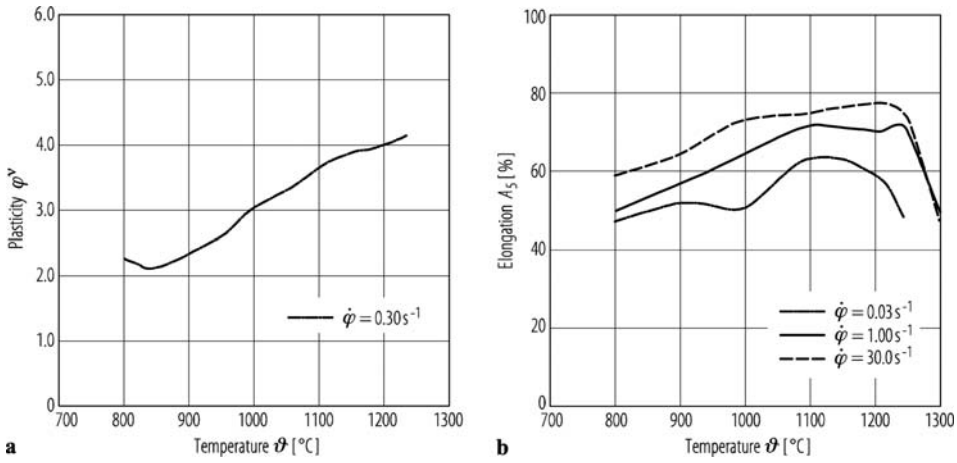
Fig. 5.79.
36Mn5. Flow stress curves by hot and cold forming.



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Fig. 5.80.
36Mn5. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	43.19	474.05	11.02	7819.8	
100	44.09	487.45	11.44	7793.0	
200	43.87	500.69	12.15	7762.8	
300	41.91	520.74	12.69	7730.5	
400	39.3	545.11	13.22	7695.8	
500	36.36	572.1	13.7	7658.7	
600	33.44	601.17	14.27	7619.0	
700	30.58	632.20	14.81	7576.6	
800	23.62	695.75	12.68	7581.8	
900	26.18	693.25	13.63	7531.9	
1000	27.77	690.76	14.49	7479.9	
1100	28.99	688.27	15.27	7425.8	
1200	30.27	685.80	15.99	7369.8	

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Steel symbol/number: C72D2/1.1242

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.70…0.74	0.10…0.30	0.50…0.70	0.000…0.020	0.000…0.025	0.00…0.10
Mo	Ni	Al	Cu	N	
0.00…0.02	0.00…0.10	0.000…0.010	0.00…0.15	0.00…0.007	

International comparison of standards

ISO		Euronorm		
~ 3CD73A	8457–2 (1989)	C72D2	10016–4 (12/1994)	
~ C72D2	16120–4 (2001)			
United Kingdom		Russia		
C72D2	EN 10016–4 (12/1994)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

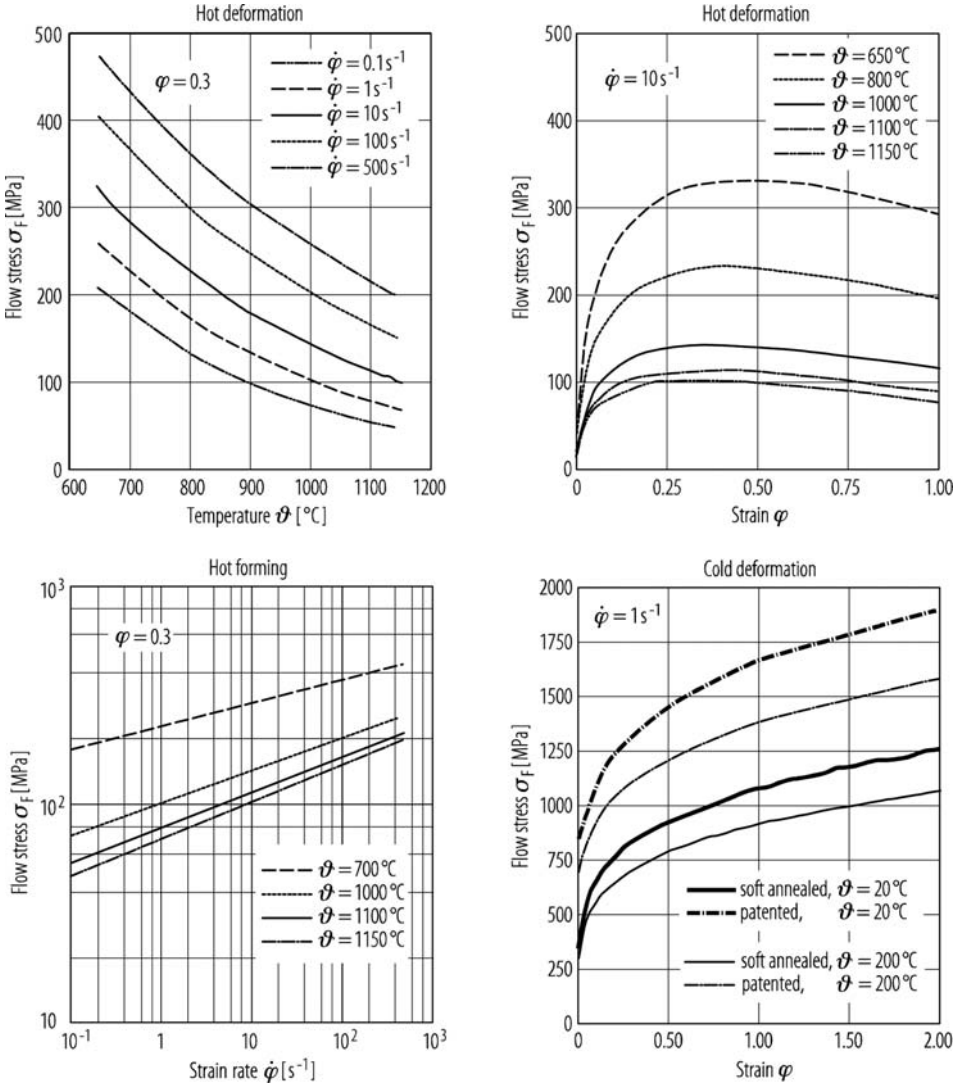
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Flow curves

State of material	Hot deformation		Cold deformation
	deformed state	soft annealed	patented
	austenite		
σ_{F0} [MPa]	114.97	675.1	1116.1
A	2708.04	1100.961	1694.173
Effect of temperature K_ϑ			
m_1	−0.00249	−0.00091	−0.00104
Effect of strain K_φ			
m_2	0.37311	0.21673	0.19389
m_4	−0.00343	0.00003	0.00230
m_5	−0.00072		
m_7	−0.50363		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01210	0.01168
m_8	0.000149		
Range of validity			
ϑ [°C]	650…1150	20…300	20…300
φ	0.04…1.00	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.81.
C72D2. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
normalized				550…600	1.8057	1.20746
patented				1150…1200	7.8463	0.94856

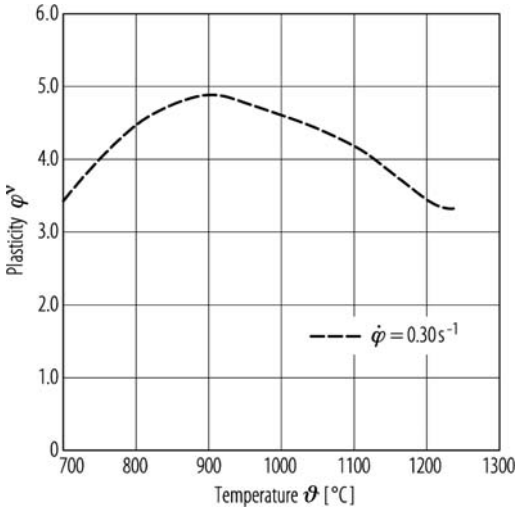
DOI: 10.1007/978-3-540-44760-3_52
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
normalized	20…25	11.41559	0.15798	−10.0839	<60
patented					<80

Fig. 5.82.
C72D2. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.95.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	47.30	475.34	10.77	7817.3	
100	46.57	488.95	11.22	7791.0	
200	45.31	502.10	11.97	7761.1	
300	42.29	522.24	12.53	7729.1	
400	38.7	546.70	13.05	7694.8	
500	35.00	573.8	13.6	7658.1	
600	31.42	602.96	14.10	7618.9	
700	28.06	634.10	14.64	7576.9	
800	23.41	697.21	13.27	7568.3	
900	25.16	694.71	14.32	7515.0	
1000	26.54	692.21	15.26	7459.3	
1100	27.85	689.72	16.12	7401.4	
1200	29.31	687.25	16.91	7341.3	

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Steel symbol/number: C100S/1.1274

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.95…1.05	0.15…0.35	0.30…0.60	0.000…0.025	0.000…0.025	0.00…0.40
Mo	Ni				
0.00…0.10	0.00…0.40				

International comparison of standards

ISO		Euronorm		
~ CS 95	4960 (1999)	C100S	10132–4 (02/2000)	
		~ 2 CS 100	132 (1979)	
United Kingdom		Russia		
C100S	EN 10132–4 (02/2000)			
Japan		China		
~ SK 4–CSP	G 4802 (1999)			
USA				
ASTM		AISI	SAE	UNS
~ A 29 (1095)	A 29–99	~ 1095	~ 1095	~ G10950
~ A 331 (1095)	A 331–00			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

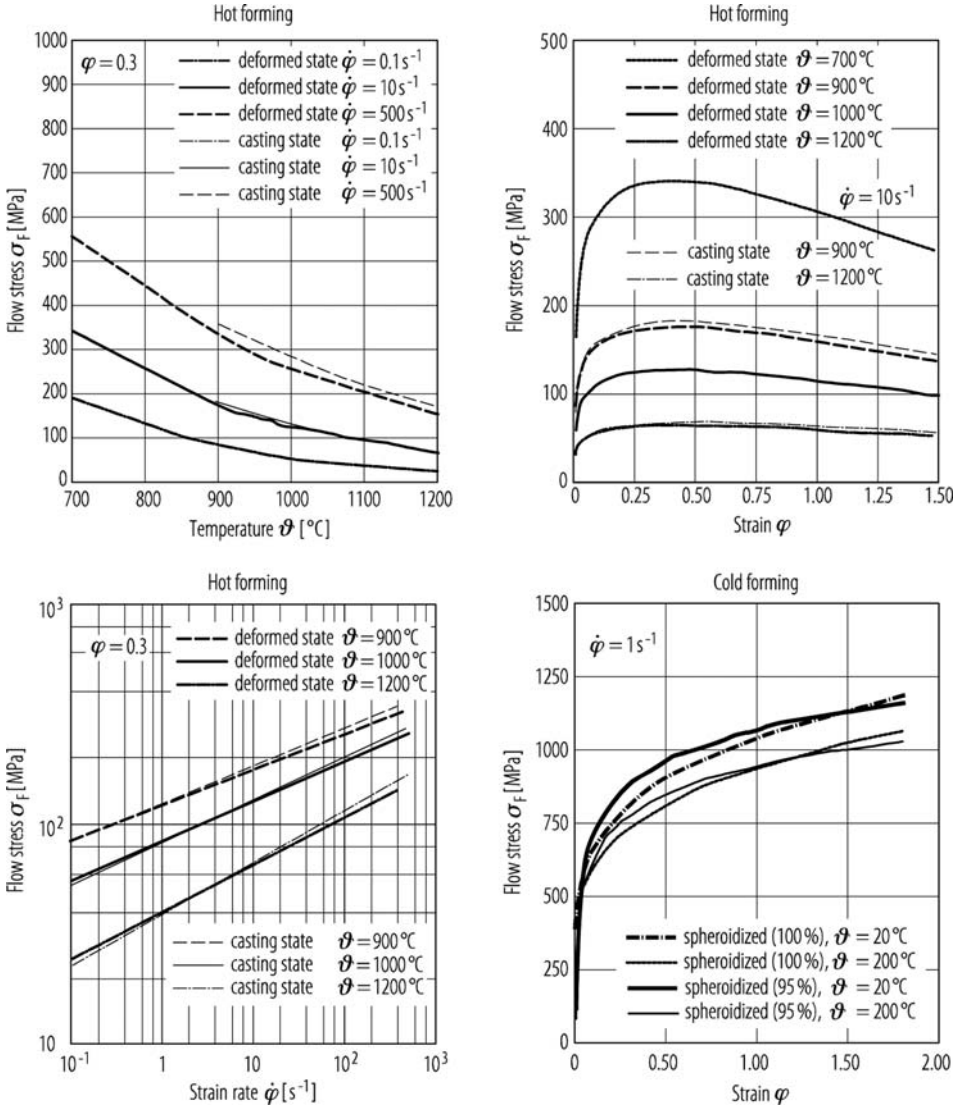
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Flow curves

	Hot deformation		Cold deformation	
	deformed state	casting state	spheroidized 100%	spheroidized 95%
State of material	austenite	austenite		
σ_{F0} [MPa]	112.51	114.91	664.1	721.4
A	5291.45	4851.24	1053.862	1094.242
Effect of temperature K_ϑ				
m_1	−0.00376	−0.00376	−0.00061	−0.00069
Effect of strain K_φ				
m_2	0.16505	0.16631	0.20672	0.13907
m_4	−0.00129	−0.00156	0.00104	−0.01013
m_5	0.00015	0.00016		
m_7	−0.50332	−0.48527		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.00649	0.00812
m_8	0.000181	0.000195		
Range of validity				
ϑ [°C]	700…1200	900…1200	20…300	20…300
φ	0.04…1.50	0.04…1.50	0.04…1.80	0.04…1.80
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.83.
C100S. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

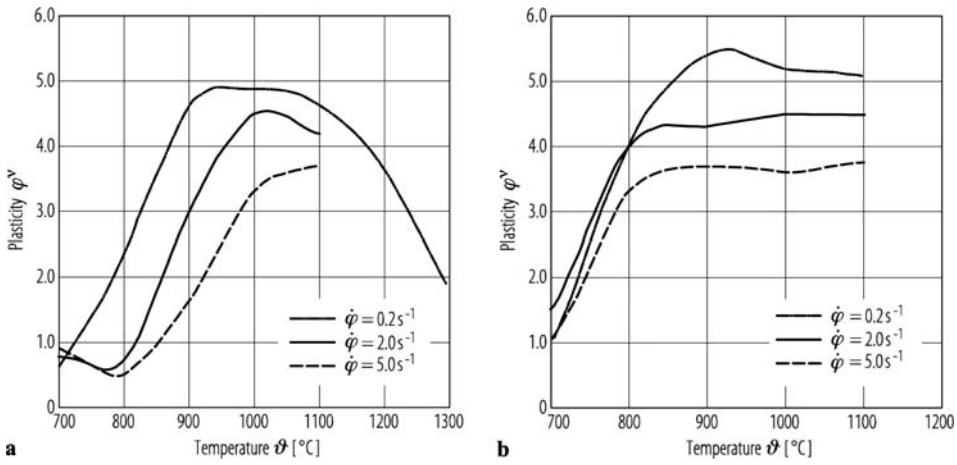
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
normalized	580…630	36.6568	0.70879			
annealed cold-rolled strip	400…450	71.2803	0.50702			
soft annealed	400…450	61.7961	0.60373	570…610	25.9533	0.77479

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
normalized					<60
annealed cold-rolled strip					<60
soft annealed	35…40	125.19218	−0.27192	−14.3165	<60

Fig. 5.84.
C100S. Hot plasticity as a function of the temperature. (a) Casting state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	46.71	476.64	10.47	7814.0	202.5
100	46.04	490.27	10.94	7788.4	193.6
200	44.88	503.82	11.73	7759.0	187.9
300	41.92	524.08	12.30	7727.5	184.2
400	38.4	548.66	12.83	7693.7	179.1
500	34.71	575.9	13.3	7657.6	170.3
600	31.17	605.17	13.87	7618.9	156.4
700	27.83	636.44	14.41	7577.6	137.2
800	23.32	698.87	14.33	7545.3	113.4
900	25.09	696.36	15.53	7486.4	86.7
1000	26.48	693.86	16.61	7424.7	60.0
1100	27.81	691.36	17.59	7360.5	37.1
1200	29.28	688.88	18.49	7293.8	22.8

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Steel symbol/number: C105U/1.1545

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S
1.00…1.10	0.10…0.30	0.10…0.40	0.000…0.030	0.000…0.030

International comparison of standards

ISO		Euronorm		
~ C105U	4957 (1999)	C105U	ISO 4957 (12/1999)	
		~ CT 105	96 (1979)	
United Kingdom		Russia		
C105U	EN ISO 4957 (12/1999)			
Japan		China		
		~ T00103	5063 (1963)	
		~ T00103	T 1298 (1986)	
USA				
ASTM		AISI	SAE	UNS
		~ W1/C1,0%)	~W 110	~ T72301

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

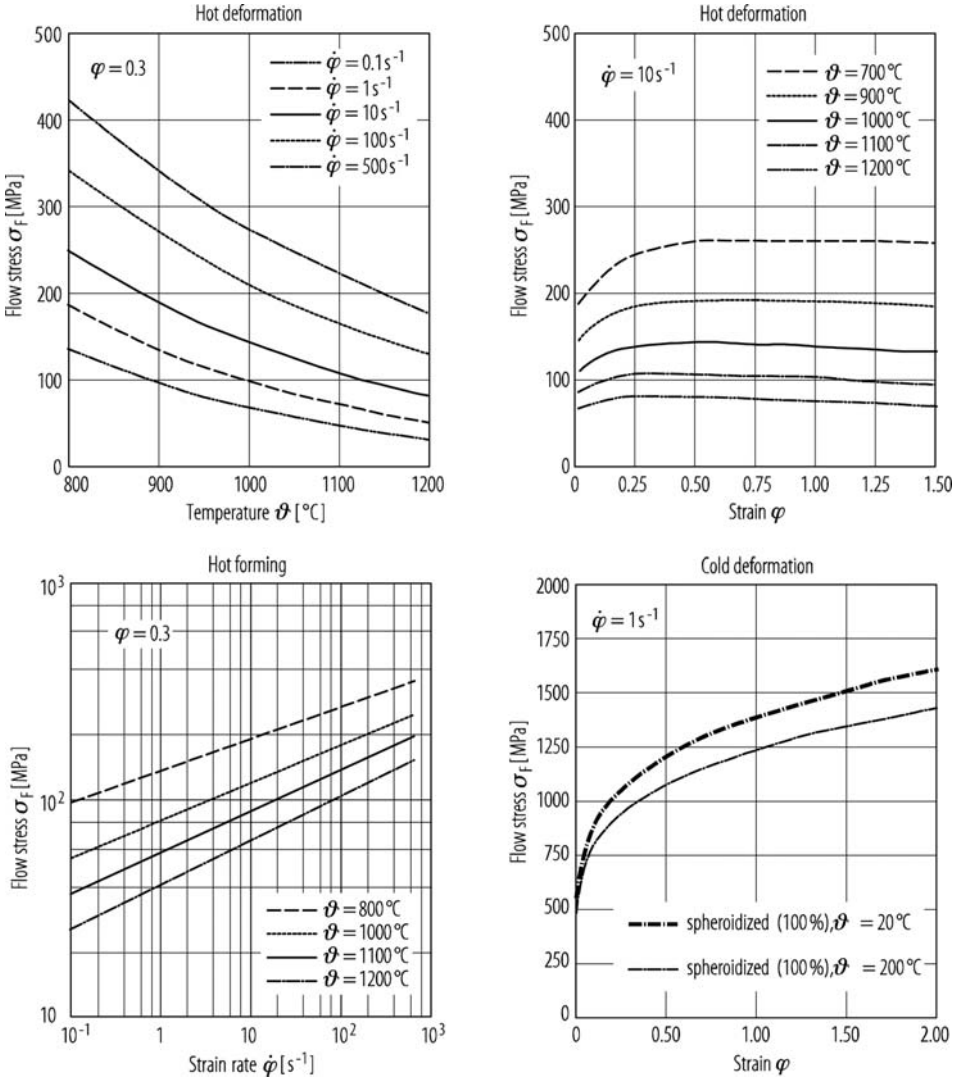
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Flow curves

State of material	Hot deformation	Cold deformation
	deformed state	spheroidized
	austenite	
σ_{F0} [MPa]	126.16	670.0
A	3048.21	1055.418
Effect of temperature K_ϑ		
m_1	−0.00300	−0.00064
Effect of strain K_φ		
m_2	0.23951	0.20145
m_4	0.00494	0.00061
m_5	−0.00075	
m_7	0.04322	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00702
m_8	0.000167	
Range of validity		
ϑ [°C]	800…1200	20…250
φ	0.04…1.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.85.
C105U. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
soft annealed	400…450	24.0182	0.79491	600…650	17.2746	0.83516

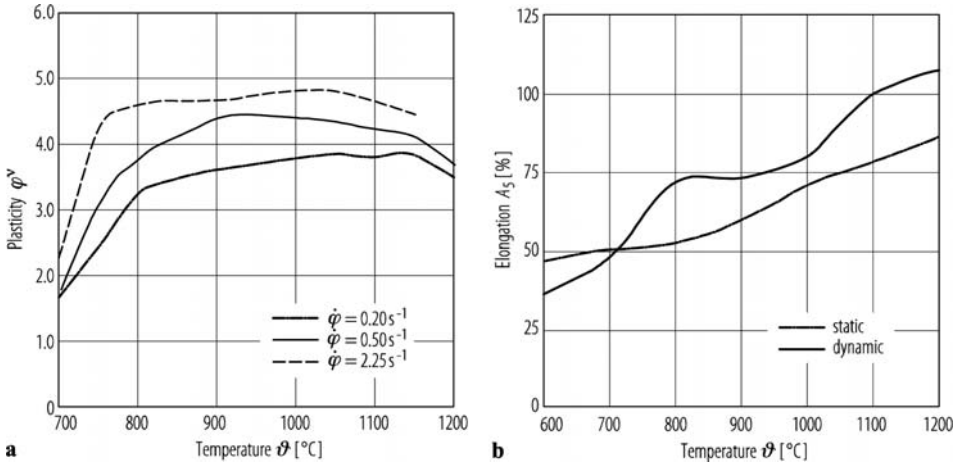
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
soft annealed	25…30	24.43924	0.05474	−5.49987	<60

Fig. 5.86.
C105U. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformation rate: 0.2 [s^{-1}]. Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	46.78	476.22	10.56	7800.1	
100	46.11	489.65	11.03	7774.3	
200	44.93	503.28	11.81	7744.9	
300	41.96	523.50	12.38	7713.3	
400	38.4	548.04	12.90	7679.4	
500	34.75	575.2	13.4	7643.1	
600	31.20	604.47	13.95	7604.3	
700	27.86	635.69	14.48	7562.9	
800	23.33	698.36	13.95	7539.0	
900	25.10	695.85	15.10	7482.2	
1000	26.49	693.35	16.13	7422.7	
1100	27.81	690.86	17.07	7360.8	
1200	29.28	688.38	17.93	7296.6	

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Steel symbol/number: C120U/1.1555

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S
1.15…1.25	0.10…0.30	0.10…0.40	0.000…0.030	0.000…0.030

International comparison of standards

ISO		Euronorm		
~ C120U	4957 (1999)	C120U	ISO 4957 (12/1999)	
United Kingdom		Russia		
C120U	EN ISO 4957 (12/1999)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

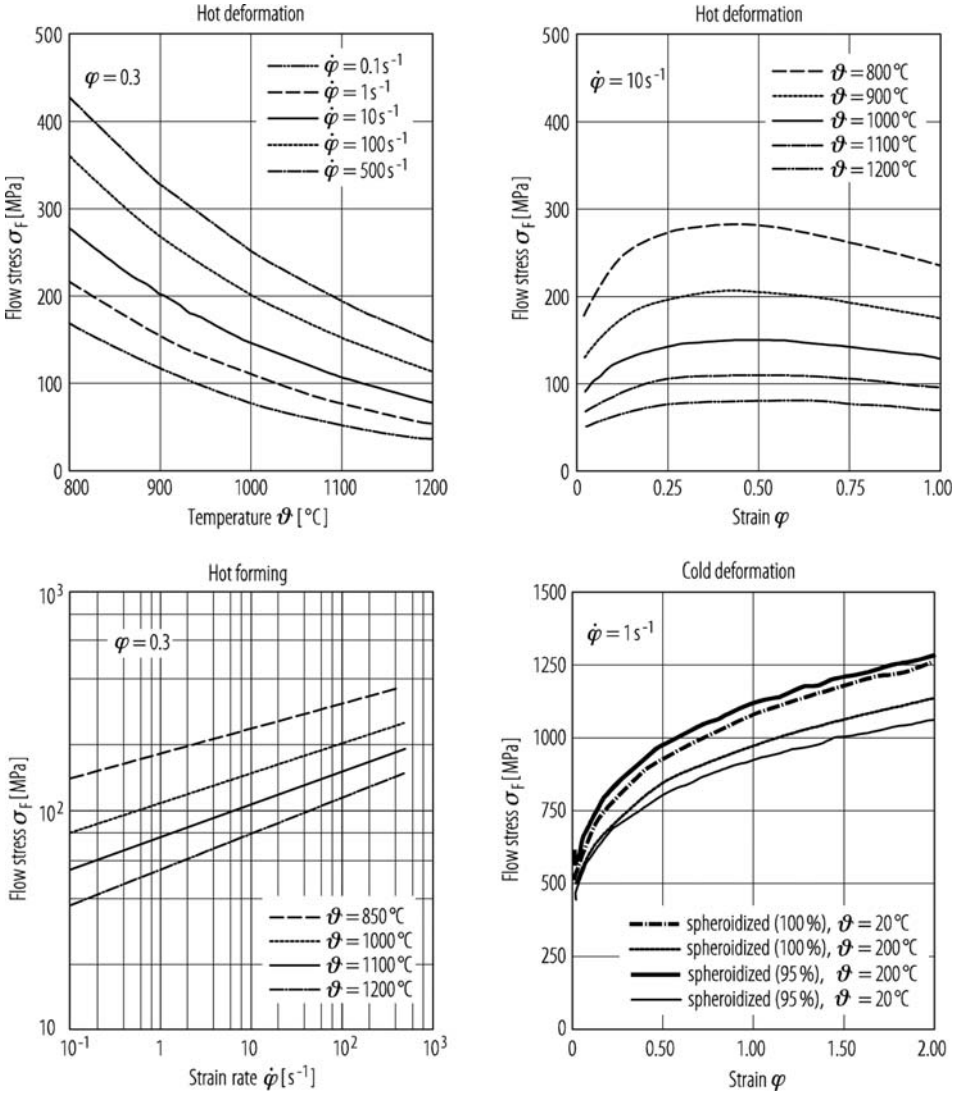
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	spheroidized 100%	spheroidized 95%
	austenite		
σ_{F0} [MPa]	121.11	672.9	720.7
A	6888.55	1089.004	1110.232
Effect of temperature K_ϑ			
m_1	−0.00364	−0.00058	−0.00105
Effect of strain K_φ			
m_2	0.30456	0.21824	0.19992
m_4	0.00389	0.00230	0.00254
m_5	0.00045		
m_7	−0.97705		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.00421	0.01035
m_8	0.000137		
Range of validity			
ϑ [°C]	800…1200	20…250	20…120
φ	0.04…1.00	0.04…1.80	0.04…1.80
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.87.
C120U. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

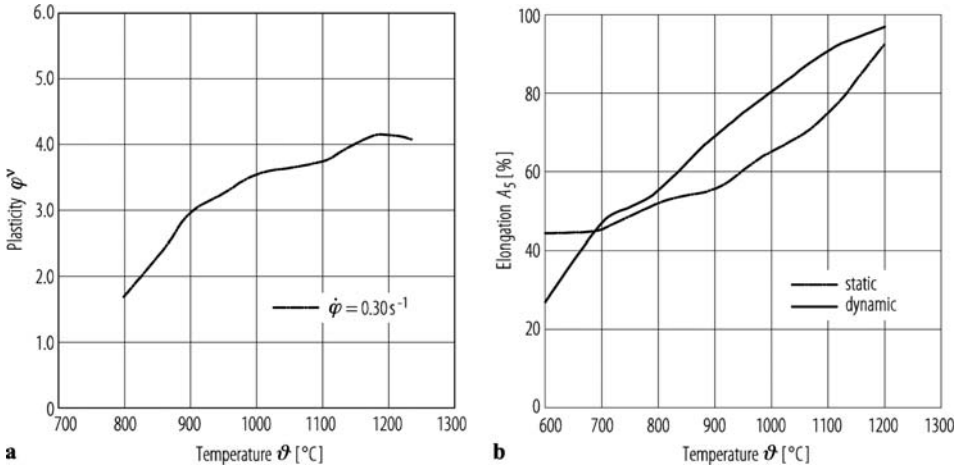
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
soft annealed	530…590	25.9601	0.76473	650…700	21.1470	0.77479
sorbite	950…1000	36.3935	0.76476	1180…1200	23.9335	0.79478
pearlite	800…850	42.7141	0.77539	1050…1100	20.5411	0.84163

Mechanical properties after cold deformation

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
soft annealed	20…25	39.09287	0.10013	−10.3944	<60
sorbite	6…8	0.53447	0.43323	1.44148	<70
pearlite	8…10	0.21587	0.84845	0.00087	<30

Fig. 5.88.
C120U. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformation rate: 0.2 [s^{-1}]. Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



DOI: 10.1007/978-3-540-44760-3_55
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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	46.71	476.81	10.43	7793.6	
100	46.04	490.21	10.91	7768.1	
200	44.88	504.02	11.70	7738.9	
300	41.92	524.29	12.27	7707.5	
400	38.4	548.89	12.80	7673.9	
500	34.71	576.1	13.3	7637.9	
600	31.17	605.43	13.84	7599.4	
700	27.83	636.71	14.38	7558.3	
800	23.32	699.05	14.48	7522.7	
900	25.09	696.54	15.70	7463.2	
1000	26.49	694.04	16.80	7400.9	
1100	27.81	691.54	17.79	7336.0	
1200	29.28	689.06	18.71	7268.6	

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DOI: 10.1007/978-3-540-44760-3_55
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Steel symbol/number: 145CrV6/1.2063

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
1.40…1.60	0.15…0.30	0.50…0.70	0.000…0.035	0.000…0.035	1.30…1.50

International comparison of standards

ISO		Euronorm	
United Kingdom		Russia	
Japan		China	
USA			
ASTM	AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

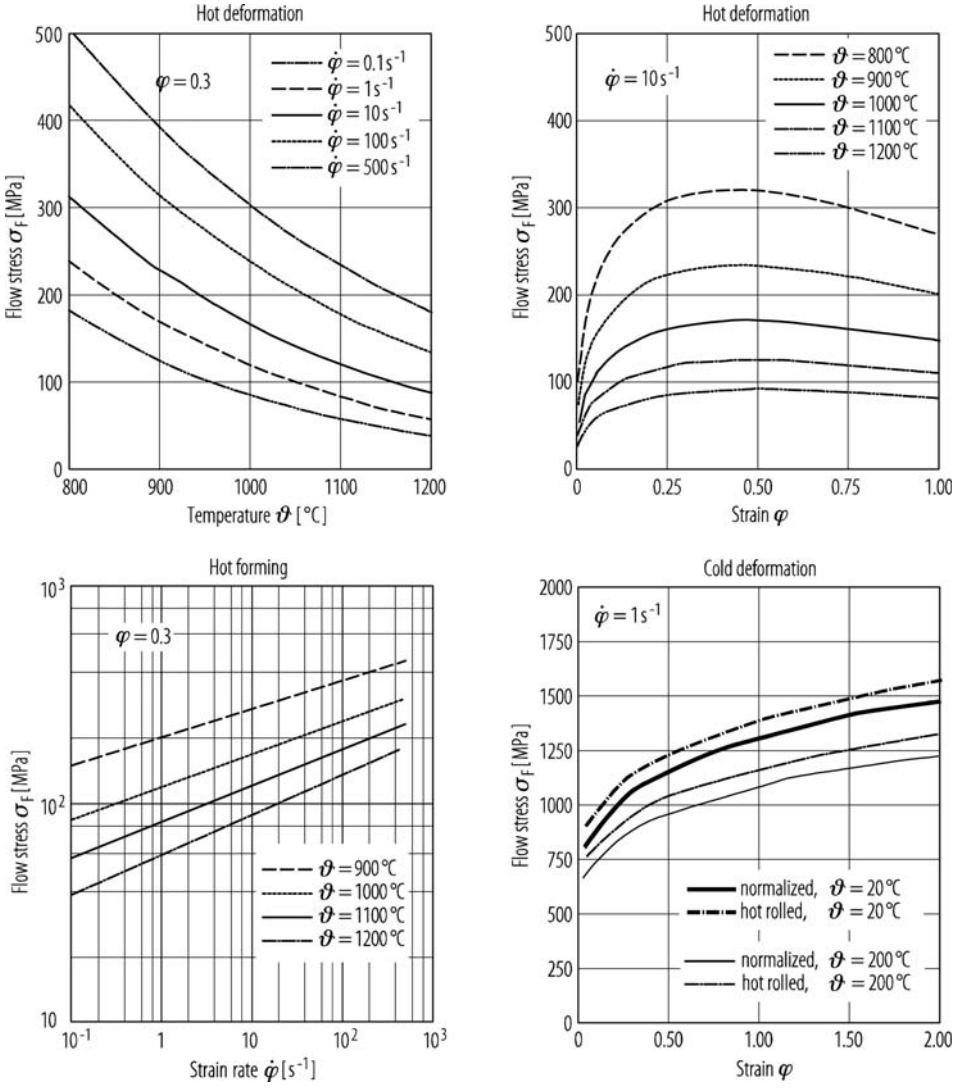
DOI: 10.1007/978-3-540-44760-3_56
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	normalized	hot rolled
	austenite		
σ_{F0} [MPa]	132.60	912.2	984.9
A	7826.81	1326.886	1403.256
Effect of temperature K_ϑ			
m_1	−0.00365	−0.00105	−0.00097
Effect of strain K_φ			
m_2	0.31076	0.18405	0.18518
m_4	−0.00056	0.00463	0.00688
m_5	0.00046		
m_7	−0.98375		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01031	0.00998
m_8	0.000151		
Range of validity			
ϑ [°C]	800…1200	20…250	20…250
φ	0.04…1.00	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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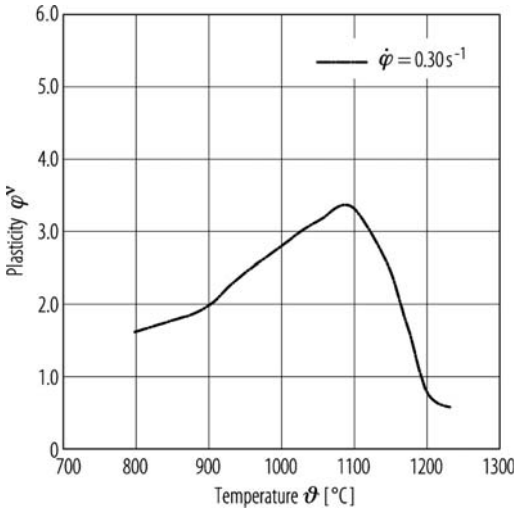
Fig. 5.89.
146CrV6. Flow stress curves by hot and cold forming.



DOI: 10.1007/978-3-540-44760-3_56
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Fig. 5.90.
145CrV6. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.30…0.85.

Plasticity in torsion



DOI: 10.1007/978-3-540-44760-3_56
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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	34.09	479.07	9.87	7765.5	
100	37.90	493.09	10.38	7741.3	
200	38.30	507.10	11.23	7713.2	
300	36.78	527.60	11.81	7683.0	
400	34.5	552.42	12.33	7650.6	
500	32.05	579.9	12.8	7615.9	
600	29.50	609.45	13.35	7578.9	
700	27.00	640.98	13.87	7539.3	
800	23.26	701.62	17.70	7435.7	
900	26.35	699.10	19.31	7360.6	
1000	28.44	696.59	20.76	7281.8	
1100	30.12	694.08	22.09	7199.5	
1200	31.82	691.59	23.31	7113.9	

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Steel symbol/number: X210Cr12/1.2080

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
1.90…2.20	0.10…0.60	0.20…0.60	0.000…0.030	0.000…0.030	11.00…13.00

International comparison of standards

ISO		Euronorm		
~ X210Cr12	4957 (1999)	X210Cr12	ISO 4957 (12/1999)	
United Kingdom		Russia		
X210Cr12	EN ISO 4957 (12/1999)	~ Ch12	5950 (2000)	
Japan		China		
~ SKD 1	G 4404 (2000)	~ Cr12	T 1299 (2000)	
		~T21200	T 1299 (2000)	
USA				
ASTM		AISI	SAE	UNS
~A 681 (D3)	A 681–99	~ D3	~ D3	~ T30403

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

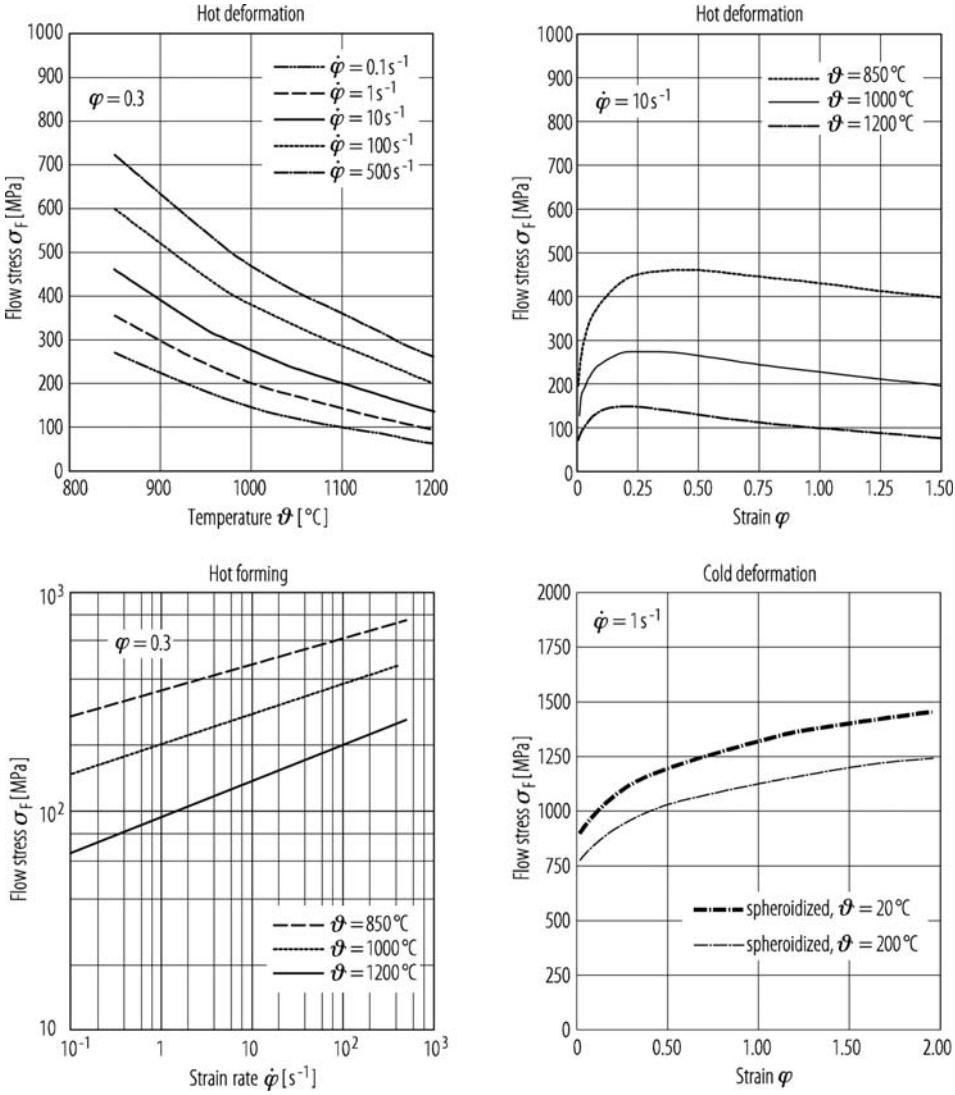
DOI: 10.1007/978-3-540-44760-3_57
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation spheroidized
σ_{F0} [MPa]	256.69	1000.6
A	10794.2	1341.060
Effect of temperature K_ϑ		
m_1	−0.00314	−0.00089
Effect of strain K_φ		
m_2	0.32302	0.14956
m_4	0.00024	0.00492
m_5	−0.00238	
m_7	0.53224	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00874
m_8	0.000137	
Range of validity		
ϑ [°C]	850…1200	20…200
φ	0.04…1.20	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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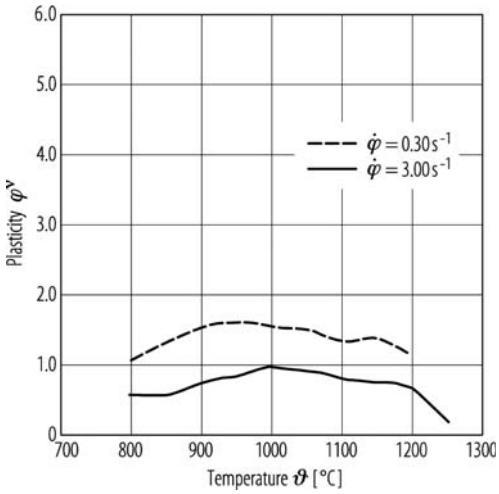
Fig. 5.91.
X210Cr12. Flow stress curves by hot and cold forming.



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Fig. 5.92.
X210Cr12. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.20…0.70.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	31.68	459.84	10.02	7639.8	
100	33.32	475.14	10.18	7616.5	
200	34.78	493.21	10.43	7592.0	
300	34.88	511.72	10.76	7565.8	
400	34.3	532.07	11.10	7538.0	
500	33.39	552.4	11.5	7508.5	
600	32.24	573.17	11.82	7477.3	
700	30.98	594.54	12.19	7444.2	
800	28.77	616.59	12.57	7409.2	
900	29.51	639.40	12.97	7372.2	
1000	29.96	663.00	13.38	7333.1	
1100	30.48	687.44	13.80	7291.8	
1200	31.27	712.76	14.24	7248.1	

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Steel symbol/number: 90SiCr5/1.2108

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.85…0.95	1.05…1.25	0.60…0.80	0.000…0.035	0.000…0.035	1.10…1.30

International comparison of standards

ISO		Euronorm	
United Kingdom		Russia	
Japan		China	
	~9SiCr	T 095 (1997)	
	~T30100	T 1299 (2000)	
USA			
ASTM	AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

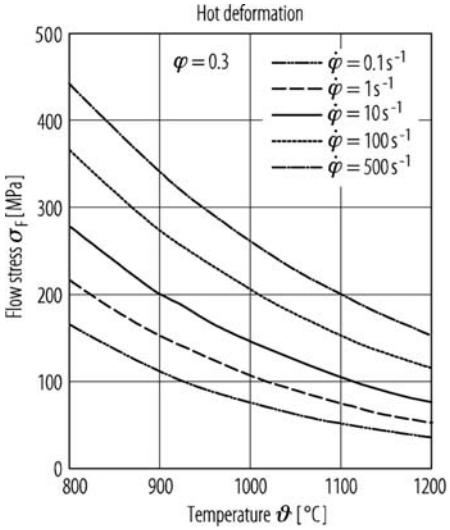
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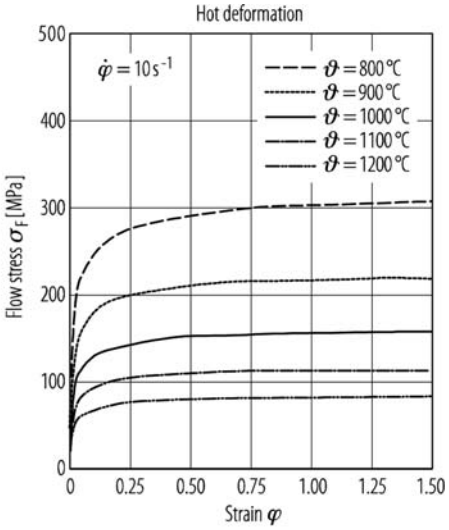
Flow curves

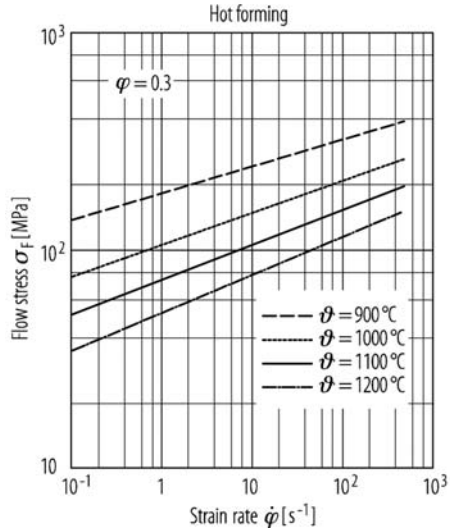
State of material	Hot deformation deformed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	129.91	793.9
A	4350.47	1169.453
Effect of temperature K_ϑ		
m_1	−0.00356	−0.00069
Effect of strain K_φ		
m_2	0.09646	0.17616
m_4	−0.00533	0.00066
m_5	−0.00009	
m_7	−0.03409	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01107
m_8	0.000146	
Range of validity		
ϑ [°C]	800…1200	20…260
φ	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

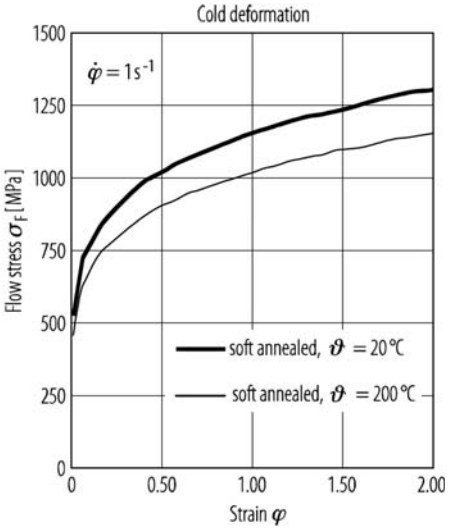
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Fig. 5.93.
90SiCr5. Flow stress curves by hot and cold forming.





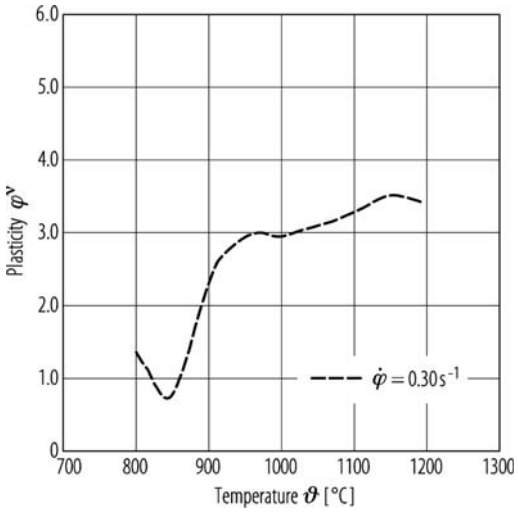




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Fig. 5.94.
90SiCr5. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.35…0.90.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	30.02	478.44	10.04	7742.2	
100	32.17	492.19	10.54	7717.8	
200	33.67	506.16	11.38	7689.4	
300	33.81	526.58	11.96	7658.9	
400	33.3	551.33	12.48	7626.3	
500	32.38	578.7	13.0	7591.3	
600	31.27	608.21	13.51	7554.0	
700	30.05	639.67	14.04	7514.0	
800	31.83	700.88	16.52	7435.3	
900	32.19	698.36	17.99	7366.2	
1000	32.31	695.85	19.32	7293.6	
1100	32.57	693.35	20.52	7217.9	
1200	33.16	690.86	21.64	7139.2	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: 31CrV2/1.2208

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.28…0.35	0.25…0.40	0.40…0.60	0.000…0.030	0.000…0.030	0.40…0.70
V					
0.07…0.12					

International comparison of standards

ISO		Euronorm	
United Kingdom		Russia	
Japan		China	
USA			
ASTM	AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

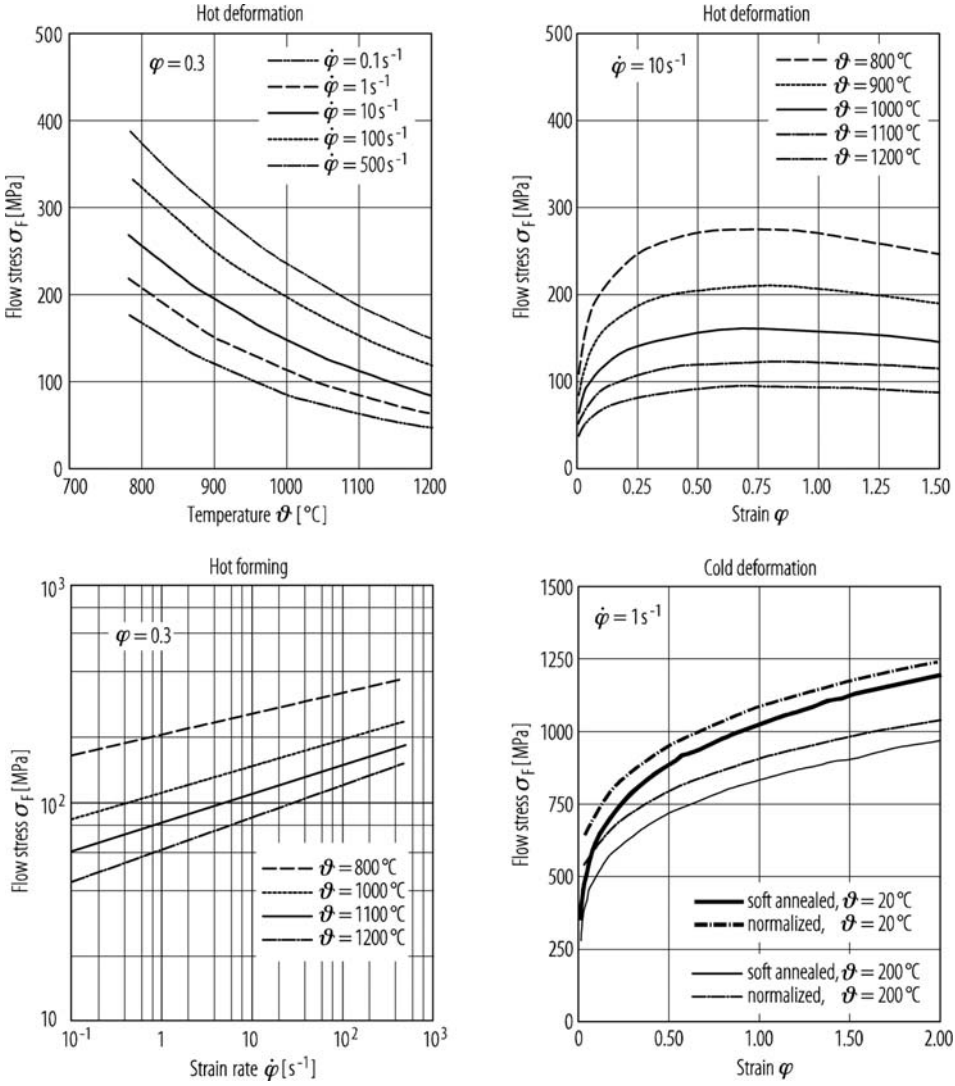
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	normalized
	austenite		
σ_{F0} [MPa]	116.68	646.9	740.8
A	3624.22	1053.08	1103.688
Effect of temperature K_ϑ			
m_1	−0.00311	−0.00117	−0.00102
Effect of strain K_φ			
m_2	0.25446	0.21439	0.19753
m_4	0.00043	0.00011	0.00494
m_5	0.00026		
m_7	−0.48097		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01246	0.01179
m_8	0.000121		
Range of validity			
ϑ [°C]	780…1200	20..300	20…300
φ	0.04…1.50	0.04…1.80	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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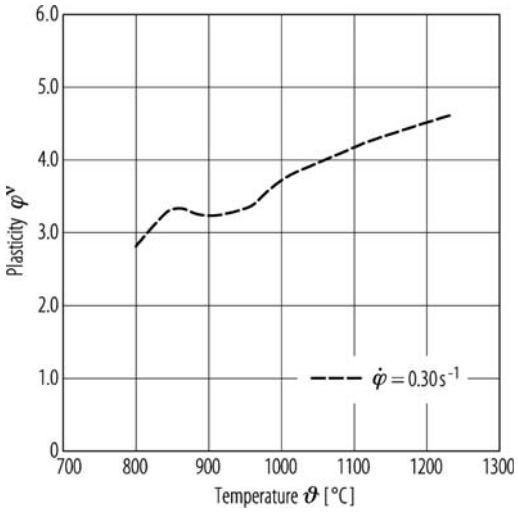
Fig. 5.95.
31CrV2. Flow stress curves by hot and cold forming.



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Fig. 5.96.
31CrV2. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.30…0.90.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	43.93	473.96	11.08	7819.2	
100	44.53	487.40	11.49	7792.2	
200	44.25	500.37	12.19	7762.0	
300	42.25	520.40	12.73	7729.6	
400	39.6	544.75	13.25	7694.9	
500	36.65	571.7	13.8	7657.7	
600	33.70	600.77	14.30	7617.9	
700	30.82	631.77	14.84	7575.4	
800	23.68	695.40	12.58	7583.2	
900	26.20	692.90	13.51	7533.9	
1000	27.76	690.41	14.35	7482.6	
1100	28.95	687.93	15.11	7429.3	
1200	30.20	685.45	15.81	7374.1	

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Steel symbol/number: 80CrV2/1.2235

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.75…0.85	0.15…0.35	0.30…0.50	0.000…0.025	0.000…0.025	0.40…0.60
Mo	Ni	V			
0.00…0.10	0.00…0.40	0.15…0.25			

International comparison of standards

ISO		Euronorm		
		80CrV2	10132–4 (02/2000)	
United Kingdom		Russia		
80CrV2	EN 10132–4 (02/2000)	~ 8Ch	5950 (2000)	
		~ 9ChF	5950 (2000)	
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

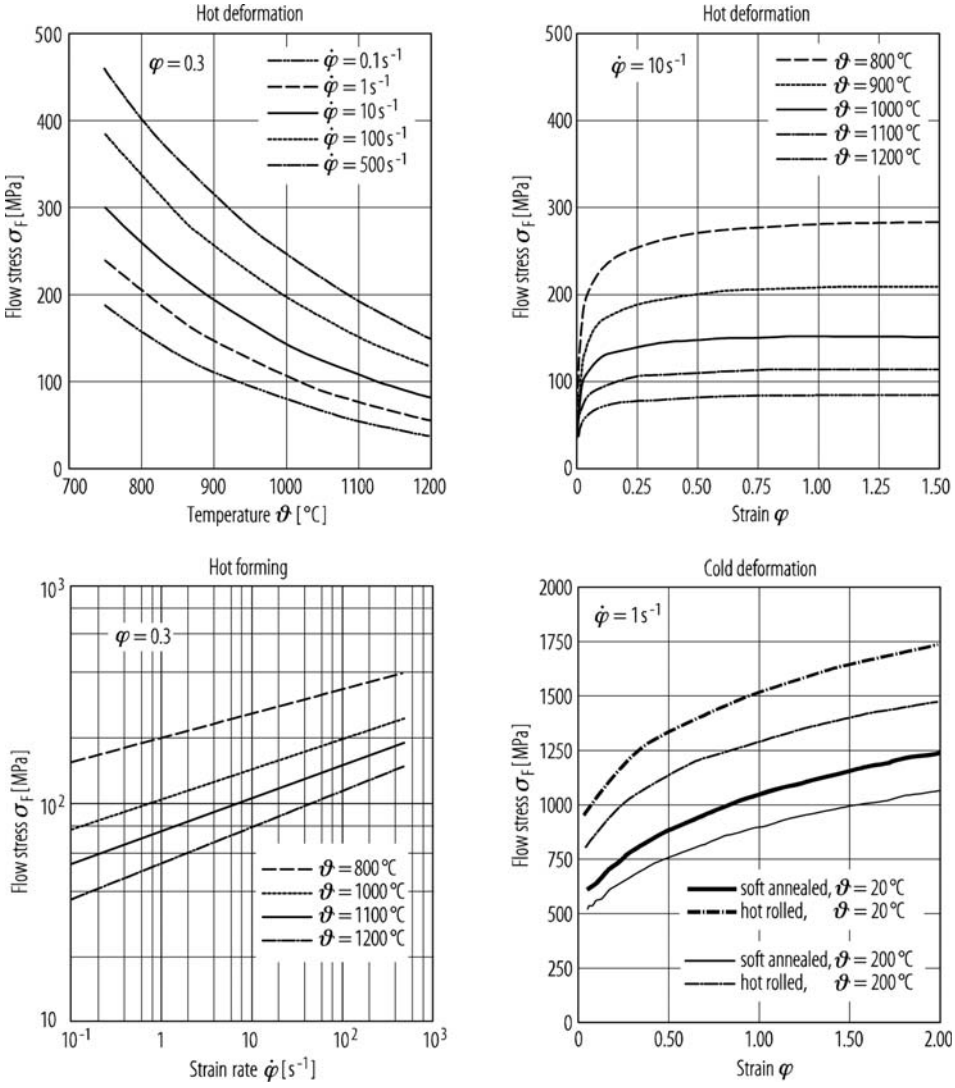
DOI: 10.1007/978-3-540-44760-3_60
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	hot rolled
	austenite		
σ_{F0} [MPa]	124.76	660.0	1052.3
A	3303.31	1017.722	1543.796
Effect of temperature K_ϑ			
m_1	−0.00329	−0.00086	−0.00093
Effect of strain K_φ			
m_2	0.10047	0.25838	0.19493
m_4	−0.00592	0.01230	0.00615
m_5	−0.00011		
m_7	−0.02998		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.00941	0.00985
m_8	0.000138		
Range of validity			
ϑ [°C]	750…1200	20…300	20…300
φ	0.04…1.50	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.97.
80CrV2. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
soft annealed	310…350	87.1534	0.49305	580…630	18.2488	0.80498

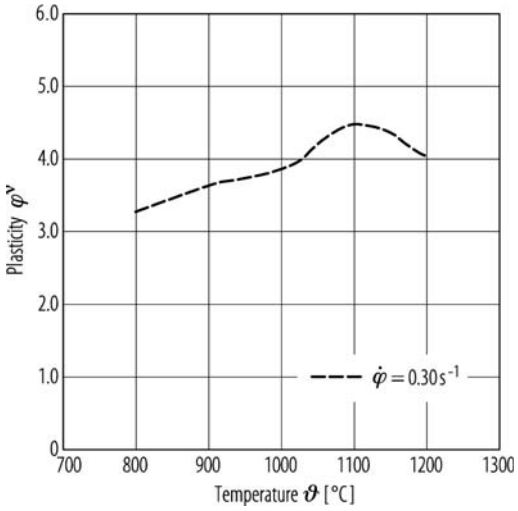
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
soft annealed	32…38	26.05579	0.07063	−5.37997	<70

Fig. 5.98.
80CrV2. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.30…0.85.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	35.84	476.31	10.53	7806.2	
100	36.07	489.68	11.00	7780.4	
200	37.42	503.46	11.78	7751.0	
300	37.45	523.69	12.35	7719.4	
400	36.8	548.24	12.88	7685.6	
500	35.79	575.4	13.4	7649.3	
600	34.55	604.70	13.92	7610.6	
700	33.18	635.94	14.46	7569.2	
800	25.04	698.53	14.07	7542.6	
900	26.53	696.02	15.23	7485.1	
1000	27.65	693.52	16.28	7424.9	
1100	28.73	691.03	17.23	7362.3	
1200	30.01	688.54	18.11	7297.2	

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Steel symbol/number: X40CrMoV5–1/1.2344

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.35…0.42	0.80…1.20	0.25…0.50	0.000…0.030	0.000…0.020	4.80…5.50
Mo	V				
1.20…1.50	0.85…1.15				

International comparison of standards

ISO		Euronorm		
~ X40CrMoV5–1	4957 (1999)	X40CrMoV5–1	ISO 4957 (12/1999)	
		~ X 40 CrMoV 5 1 1	96 (1979)	
United Kingdom		Russia		
X40CrMoV5–1	EN ISO 4957 (12/1999)	~ 4Ch5MF1S	5950 (2000)	
Japan		China		
~ SKD 61	G 4404 (2000)	~ 4Cr5MoSiV1	T 1299 (2000)	
		~ T20502	T 1299 (2000)	
USA				
ASTM		AISI	SAE	UNS
~ A 681 (H 13)	A681–99	~ H13	~ H13	~ T20813

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

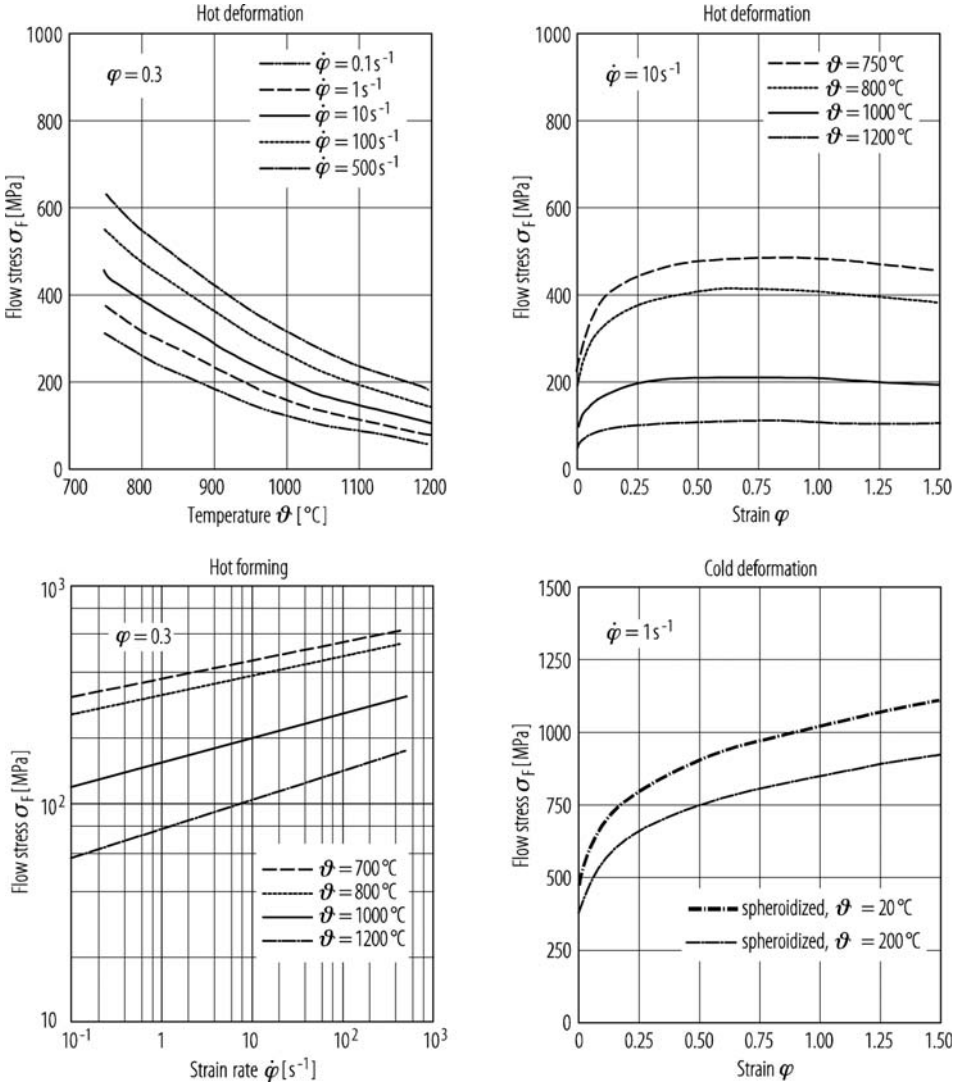
DOI: 10.1007/978-3-540-44760-3_61
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation spheroidized
σ_{F0} [MPa]	167.00	687.4
A	7533.00	1053.709
Effect of temperature K_ϑ		
m_1	−0.00346	−0.00110
Effect of strain K_φ		
m_2	0.24779	0.18994
m_4	0.00091	0.00106
m_5	−0.00020	
m_7	−0.24942	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00938
m_8	0.000111	
Range of validity		
ϑ [°C]	750…1200	20…260
φ	0.04…1.50	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500

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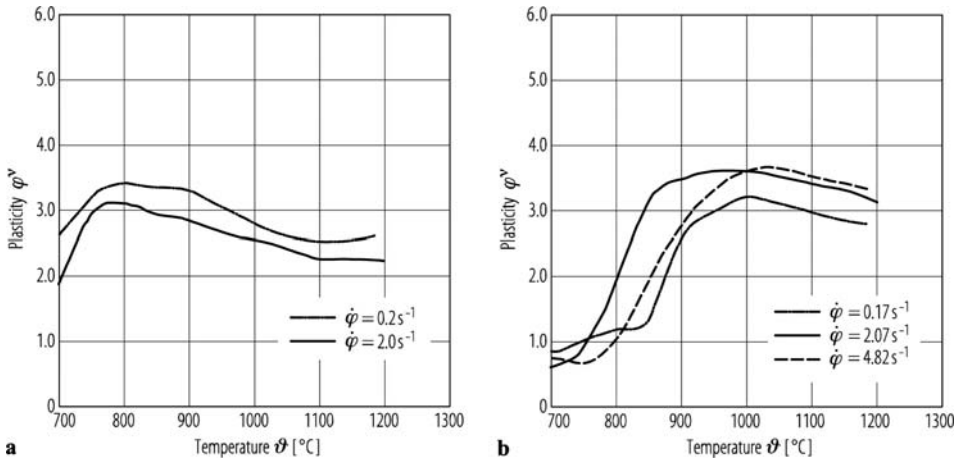
Fig. 5.99.
X40CrMoV5–1. Flow stress curves by hot and cold forming.



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Fig. 5.100.
X40CrMoV5–1. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	22.95	428.40	10.08	7755.6	213.8
100	23.13	473.81	10.95	7730.1	209.8
200	23.36	495.61	11.53	7702.0	205.2
300	23.59	515.32	12.05	7671.5	199.6
400	23.82	535.01	12.55	7638.8	192.0
500	24.06	555.12	13.05	7603.7	181.6
600	24.29	575.81	13.57	7566.2	168.2
700	24.53	597.18	20.32	7424.6	151.8
800	24.77	619.27	22.24	7341.7	132.8
900	25.02	642.13	23.97	7253.7	111.8
1000	25.27	665.80	25.55	7161.1	90.1
1100	25.51	690.32	27.01	7064.4	69.1
1200	25.77	715.72	27.70	6982.2	50.7

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: X50CrMoV8–1–1/1.2360

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.45…0.50	0.70…0.90	0.35…0.45	0.000…0.020	0.000…0.005	7.30…7.80
Mo	V				
1.30…1.50	1.30…1.50				

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

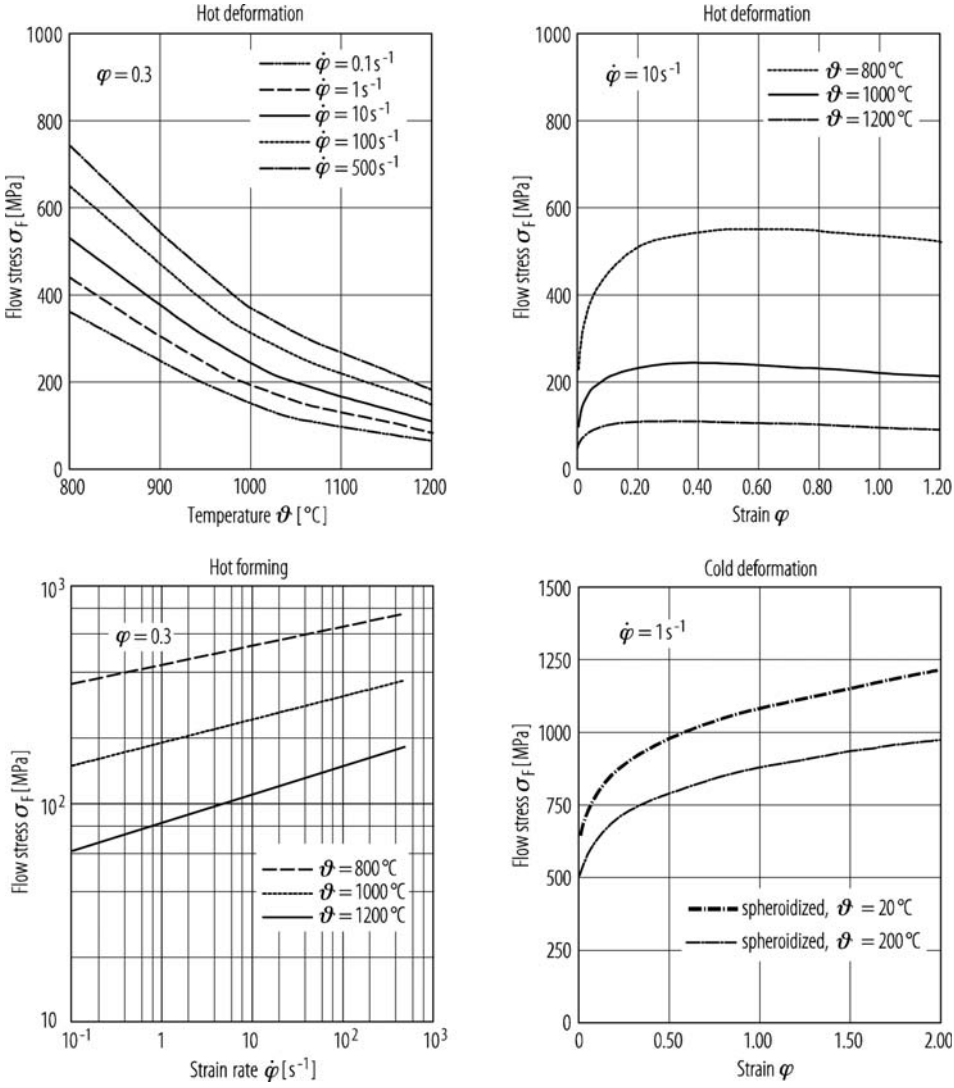
DOI: 10.1007/978-3-540-44760-3_62
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation spheroidized
σ_{F0} [MPa]	213.79	790.8
A	16229.8	1110.097
Effect of temperature K_ϑ		
m_1	−0.00389	−0.00121
Effect of strain K_φ		
m_2	0.25884	0.15538
m_4	0.0000025	0.00197
m_5	−0.00102	
m_7	0.06492	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01004
m_8	0.000107	
Range of validity		
ϑ [°C]	800…1200	20…260
φ	0.04…1.20	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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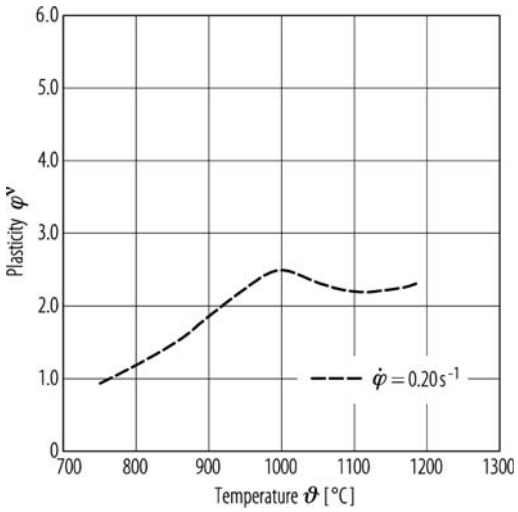
Fig. 5.101.
X50CrMoV8–1–1. Flow stress curves by hot and cold forming.



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Fig. 5.102.
X50CrMoV8–1–1. Hot plasticity as a function of the temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.80.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	24.12	432.60	9.71	7747.4	
100	24.31	478.45	10.60	7722.8	
200	24.55	500.47	11.17	7695.5	
300	24.79	520.37	11.69	7665.9	
400	25.04	540.25	12.18	7634.2	
500	25.28	560.56	12.67	7600.1	
600	25.53	581.46	13.17	7563.7	
700	25.78	603.03	24.58	7347.5	
800	26.04	625.33	26.99	7245.6	
900	26.29	648.42	29.16	7137.4	
1000	26.55	672.32	31.15	7023.4	
1100	26.81	697.08	32.99	6904.0	
1200	27.08	722.73	33.86	6803.0	

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Steel symbol/number: X100CrMoV5–1/1.2363

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.95…1.05	0.10…0.40	0.40…0.80	0.000…0.030	0.000…0.030	4.80…5.50
Mo	V				
0.90…1.20	0.15…0.35				

International comparison of standards

ISO		Euronorm		
~ X100CrMoV5	4957 (1999)	X100CrMoV5	ISO 4957 (12/1999)	
United Kingdom		Russia		
X100CrMoV5	EN ISO 4957 (12/1999)			
Japan		China		
~ SKD 12	G 4404 (2000)	~ T20503	T 1299 (2000)	
		~ Cr5Mo1V	T 1299 (2000)	
USA				
ASTM		AISI	SAE	UNS
~ A 681 (A2)	A 681–99	~ A 2	~ A 2	~ T30102

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

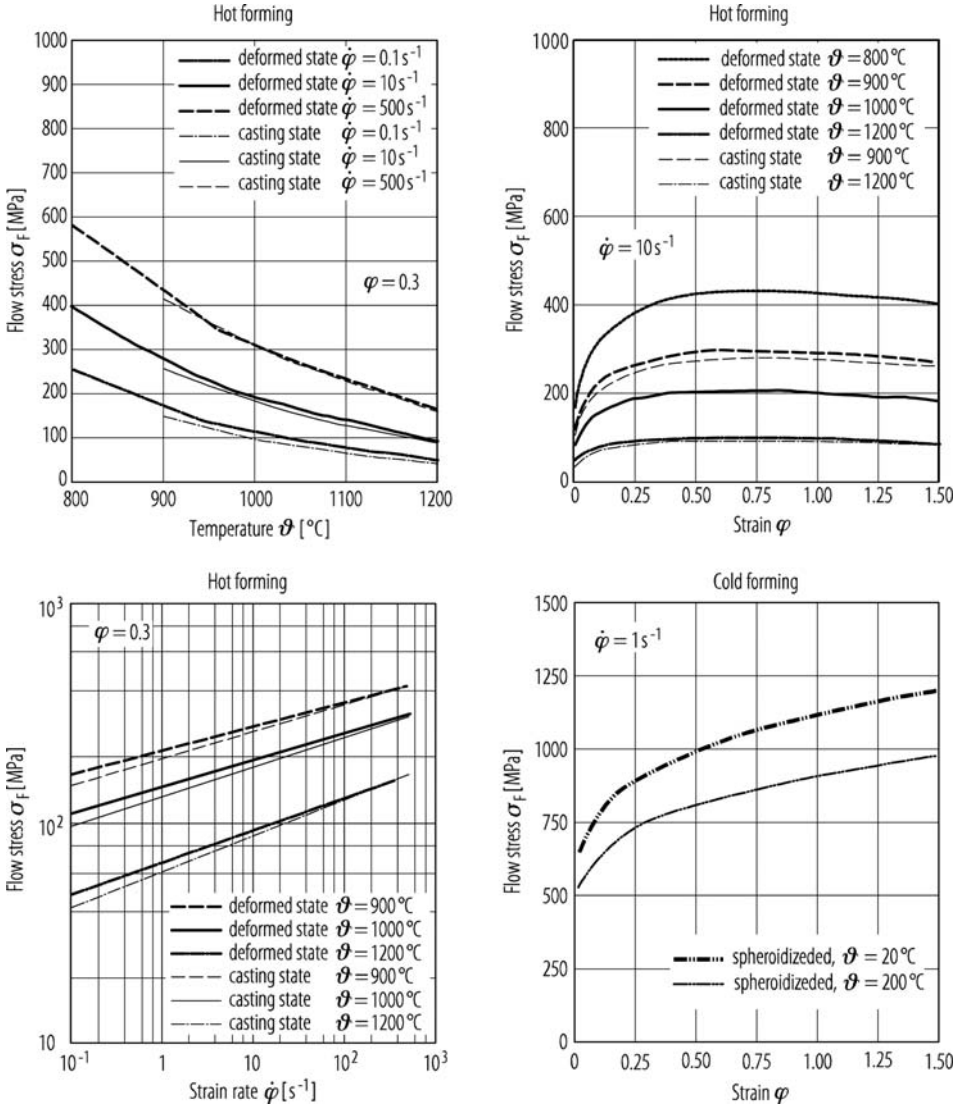
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Flow curves

State of material	Hot deformation		Cold deformation
	deformed state	casting state	spheroidized
	austenite	austenite	
σ_{F0} [MPa]	152.27	141.53	794.7
A	11199.6	10107.44	1144.171
Effect of temperature K_ϑ			
m_1	−0.00379	−0.00379	−0.00116
Effect of strain K_φ			
m_2	0.32124	0.32250	0.16732
m_4	0.00134	0.00107	0.00221
m_5	−0.00038	−0.00037	
m_7	−0.25082	−0.23277	
Effect of strain rate $K_{\dot\varphi}$			
m_3			0.00951
m_8	0.000121	0.000135	
Range of validity			
ϑ [°C]	800…1200	900 … 1200	20…260
φ	0.04…1.50	0.04…1.50	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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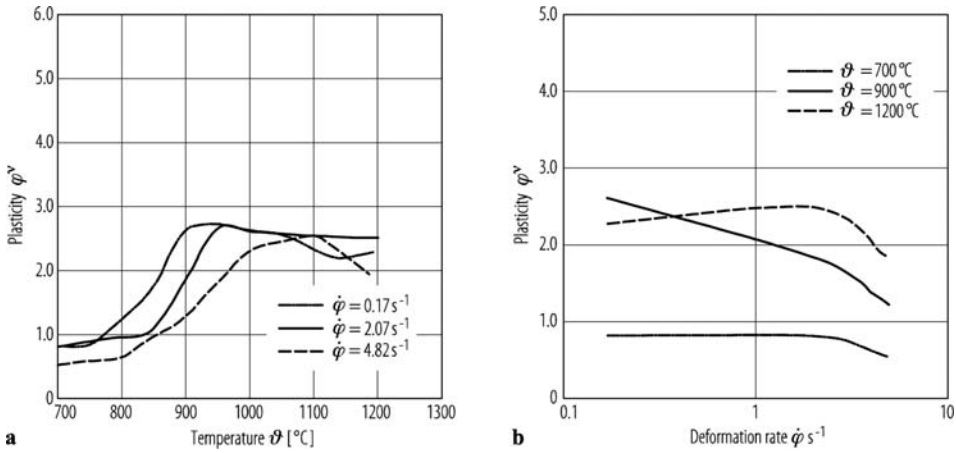
Fig. 5.103.
X100CrMoV5–1. Flow stress curves by hot and cold forming.



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Fig. 5.104.
X100CrMoV5–1. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	23.21	429.36	10.00	7777.6	
100	23.40	474.87	10.87	7752.2	
200	23.63	496.72	11.45	7724.2	
300	23.86	516.47	11.97	7693.8	
400	24.10	536.21	12.47	7661.2	
500	24.33	556.36	12.97	7626.3	
600	24.57	577.10	13.48	7588.9	
700	24.81	598.51	21.14	7432.3	
800	25.06	620.65	23.15	7345.4	
900	25.31	643.56	24.97	7253.2	
1000	25.55	667.29	26.63	7156.3	
1100	25.81	691.86	28.16	7054.8	
1200	26.06	717.32	28.89	6968.8	

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Steel symbol/number: X32CrMoV3–3/1.2365

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.28…0.35	0.10…0.40	0.15…0.45	0.000…0.030	0.000…0.020	2.70…3.20
Mo	V				
2.50…3.00	0.40…0.70				

International comparison of standards

ISO		Euronorm		
~ 32CrMoV12–28	4957 (1999)	32CrMoV12–28	ISO 4957 (12/1999)	
		~ 30 CrMoV 12 11	96 (1979)	
United Kingdom		Russia		
32CrMoV12–28	EN ISO 4957 (12/1999)	~ 3Ch3M3F	5950 (2000)	
Japan		China		
~ SKD 7	G 4404 (2000)	~ T20303	T 1299 (2000)	
		~ 4Cr3Mo3SiV	T 1299 (2000	
USA				
ASTM		AISI	SAE	UNS
~ A 681 (H 10)	A 681–99	~ H 10		

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

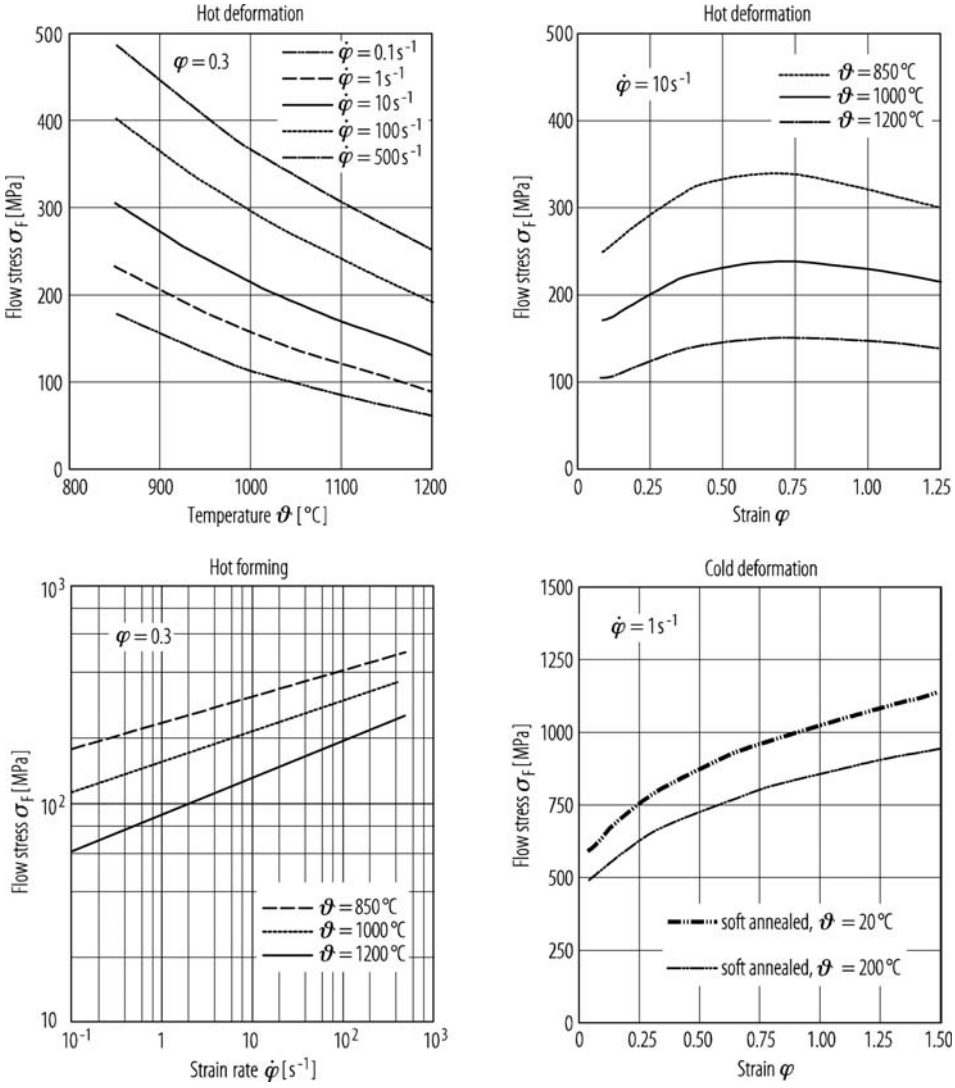
DOI: 10.1007/978-3-540-44760-3_64
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	172.50	653.2
A	5184.91	1041.861
Effect of temperature K_ϑ		
m_1	−0.00285	−0.00104
Effect of strain K_φ		
m_2	0.52332	0.23980
m_4	0.03829	0.00831
m_5	0.00041	
m_7	−0.900125	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00997
m_8	0.000139	
Range of validity		
ϑ [°C]	850…1200	20…260
φ	0.04…1.25	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500

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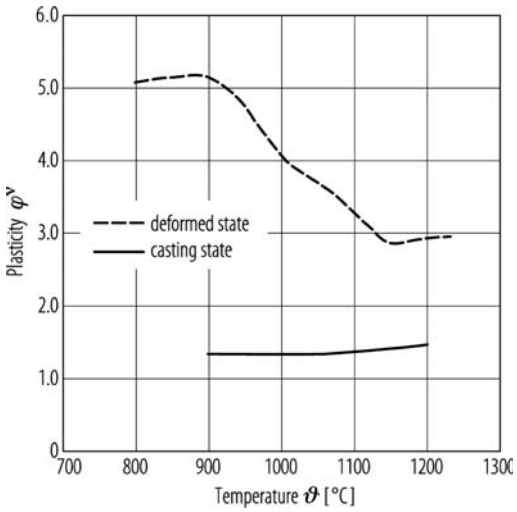
Fig. 5.105.
X32CrMoV3–3. Flow stress curves by hot and cold forming.



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Fig. 5.106.
X32CrMoV3–3. Hot plasticity as a function of the temperature. Deformation rate: 0.3 s^{-1}. Direct heating on deformation temperature.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	31.28	467.84	9.98	7864.1	215.6
100	33.05	486.65	10.64	7839.0	208.8
200	34.52	505.56	11.47	7810.0	200.0
300	34.63	525.94	12.05	7778.9	191.2
400	34.1	550.65	12.57	7745.5	182.5
500	33.15	578.0	13.1	7709.8	174.1
600	32.01	607.43	13.61	7671.5	165.9
700	30.76	638.84	14.14	7630.7	157.5
800	29.40	700.40	15.87	7564.7	148.7
900	30.06	697.88	17.26	7497.6	138.9
1000	30.43	695.37	18.51	7427.3	
1100	30.89	692.87	19.66	7354.0	
1200	31.64	690.38	20.71	7277.8	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: 105WCr6/1.2419

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
1.00…1.10	0.10…0.40	0.80…1.10	0.000…0.030	0.000…0.030	0.90…1.10
W					
1.00…1.30					

International comparison of standards

ISO		Euronorm		
		~ 107 WCr 5	96 (1979)	
United Kingdom		Russia		
		~ ChWG	5950 (2000)	
		~ ChW1G	Not standardized	
Japan		China		
~ SKS 2 M	G 3311 (1998)	~ T20111	T 095 (1997)	
~ SKS 31	G 4404 (2000)	~ CrWMn	T 1299 (2000)	
USA				
ASTM		AISI	SAE	UNS
~ A 681 (H 10)	A 681–99	~ H 10		~ T20810

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

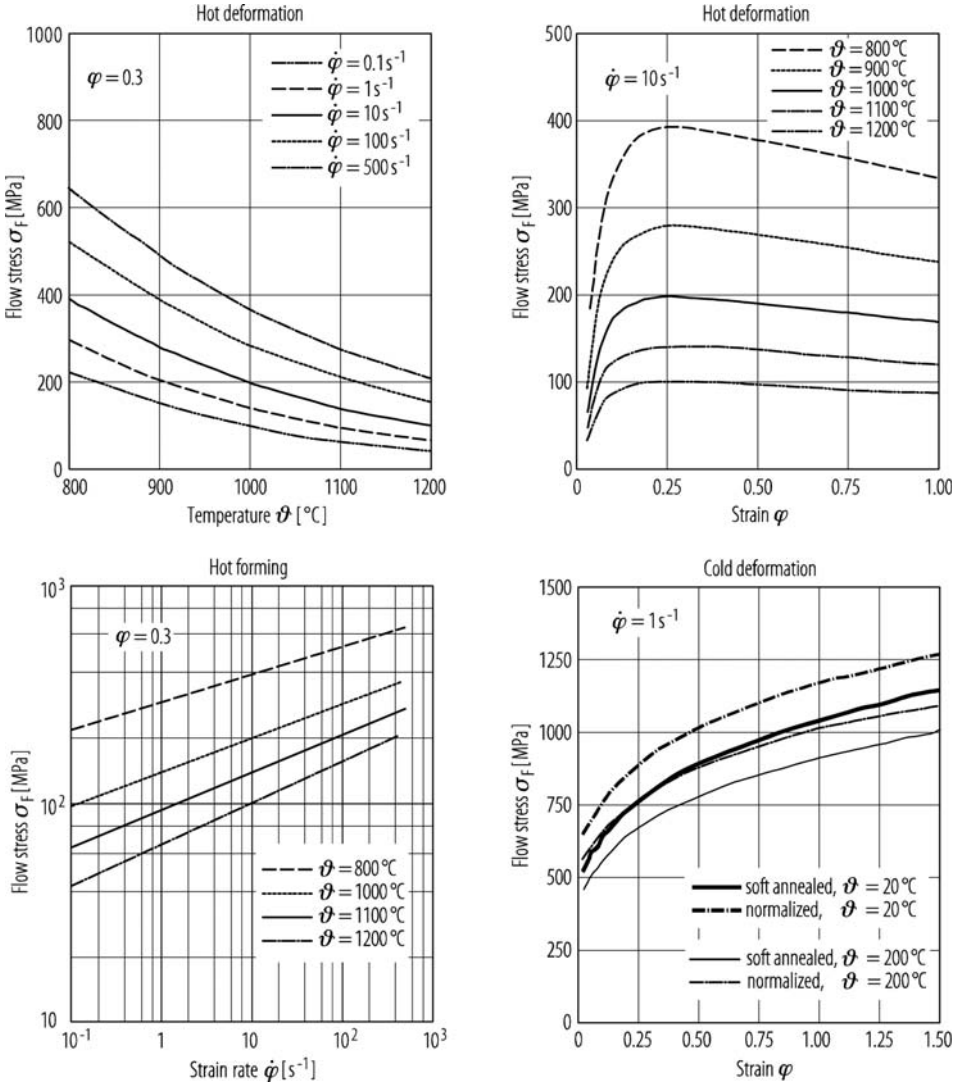
DOI: 10.1007/978-3-540-44760-3_65
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	normalized
	austenite		
σ_{F0} [MPa]	140.01	647.1	766.6
A	6135.26	1049.033	1177.342
Effect of temperature K_ϑ			
m_1	−0.00375	−0.00073	−0.00081
Effect of strain K_φ			
m_2	−0.14532	0.23332	0.20795
m_4	−0.05086	0.00447	0.00435
m_5	−0.00007		
m_7	−0.10956		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01043	0.00976
m_8	0.000156		
Range of validity			
ϑ [°C]	800…1200	20…320	20…260
φ	0.04…1.00	0.04…1.50	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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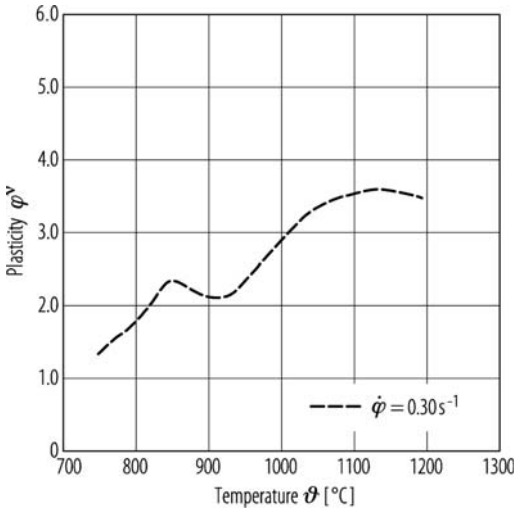
Fig. 5.107.
105WCr6. Flow stress curves by hot and cold forming.



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Fig. 5.108.
105WCr6. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.80.

Plasticity in torsion



DOI: 10.1007/978-3-540-44760-3_65
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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	31.24	477.96	10.14	7931.6	
100	33.02	491.67	10.64	7906.3	
200	34.49	505.58	11.47	7877.1	
300	34.60	525.97	12.04	7845.7	
400	34.0	550.67	12.57	7812.0	
500	33.12	578.0	13.1	7776.0	
600	31.99	607.46	13.60	7737.4	
700	30.73	638.87	14.13	7696.2	
800	29.47	700.41	15.89	7629.2	
900	30.12	697.89	17.28	7561.5	
1000	30.49	695.39	18.54	7490.5	
1100	30.94	692.89	19.68	7416.4	
1200	31.68	690.40	20.74	7339.4	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: X210CrW12/1.2436

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
2.00…2.30	0.10…0.40	0.30…0.60	0.000…0.030	0.000…0.030	11.00…13.00
W					
0.60…0.80					

International comparison of standards

ISO		Euronorm		
~ X210CrW12	4957 (1999)	X210CrW12	ISO 4957 (12/1999)	
		~ X 210 CrW 12 1	96 (1979)	
United Kingdom		Russia		
X210CrW12	EN ISO 4957 (12/1999)			
Japan		China		
~ SKD 2	G 4404 (2000)			
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

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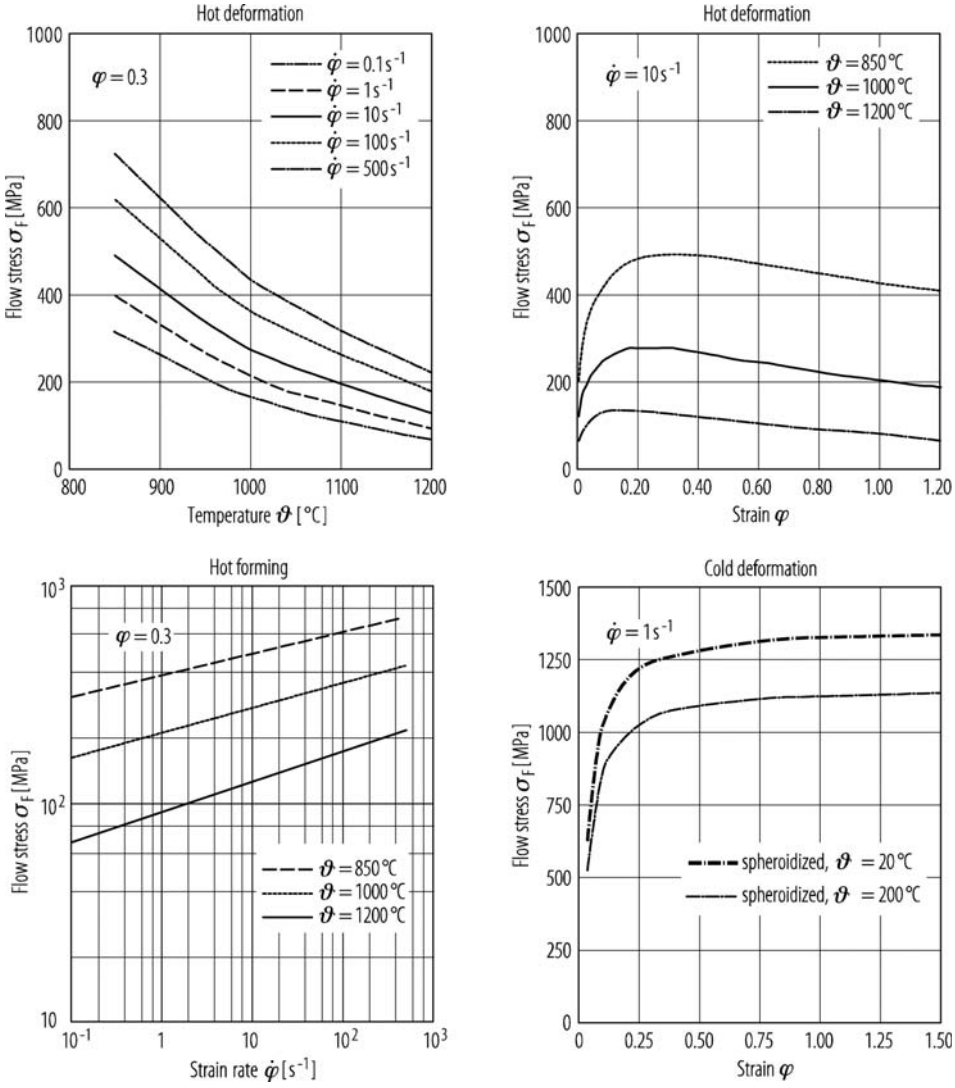
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation spheroidized
σ_{F0} [MPa]	256.89	1023.8
A	17468.4	1393.138
Effect of temperature K_ϑ		
m_1	−0.00348	−0.00093
Effect of strain K_φ		
m_2	0.35668	−0.00941
m_4	0.00048	−0.03307
m_5	−0.00247	
m_7	0.46903	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00851
m_8	0.000115	
Range of validity		
ϑ [°C]	850…1200	20…180
φ	0.04…1.20	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500

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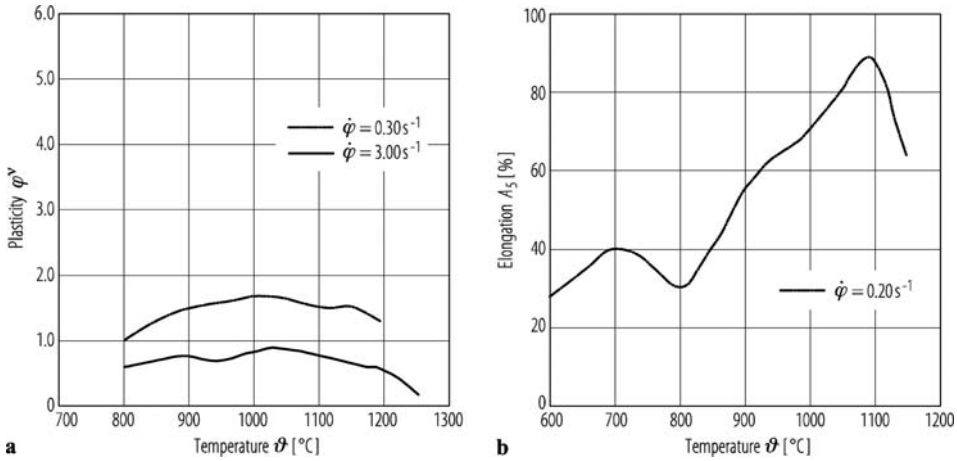
Fig. 5.109.
X210CrW12. Flow stress curves by hot and cold forming.



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Fig. 5.110.
X210CrW12. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	32.04	461.30	10.02	7737.6	
100	33.56	478.68	10.18	7714.0	
200	35.02	494.62	10.43	7689.2	
300	35.11	512.15	10.76	7662.7	
400	34.5	532.52	11.10	7634.5	
500	33.60	552.9	11.5	7604.7	
600	32.45	573.65	11.82	7573.1	
700	31.18	595.04	12.19	7539.6	
800	28.25	617.11	12.57	7504.1	
900	29.06	639.94	12.97	7466.6	
1000	29.57	663.56	13.38	7427.0	
1100	30.14	688.02	13.80	7385.1	
1200	30.98	713.36	14.24	7341.0	

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Steel symbol/number: 120WV4/1.2516

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
1.15…1.25	0.15…0.30	0.20…0.35	0.000…0.035	0.000…0.035	0.15…0.25
W	V				
0.90…1.10	0.07…0.12				

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

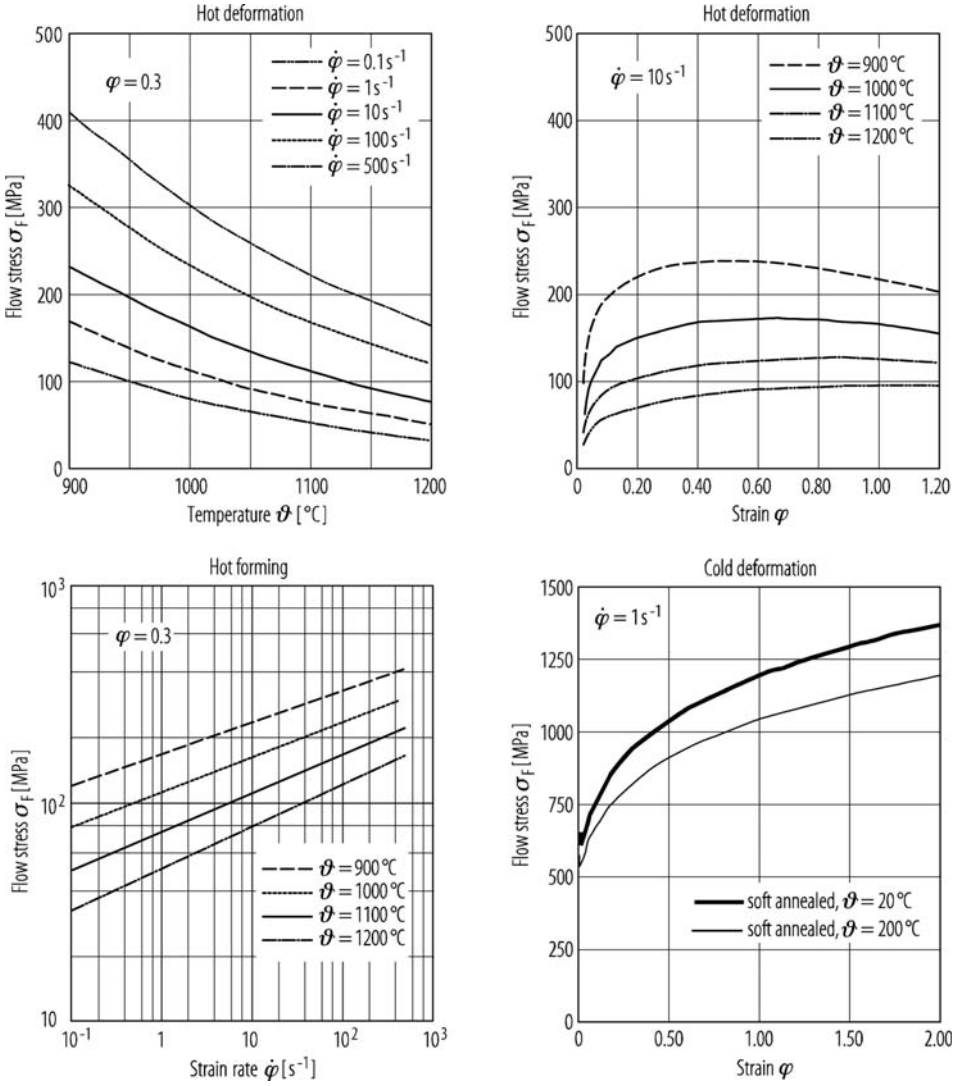
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	130.52	780.5
A	9794.63	1205.378
Effect of temperature K		
m_1	−0.00458	−0.00076
Effect of strain K_φ		
m_2	−0.00752	0.19992
m_4	−0.01907	0.00254
m_5	0.00210	
m_7	−1.30930	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00674
m_8	0.000159	
Range of validity		
ϑ [°C]	900…1200	20…260
φ	0.04…1.20	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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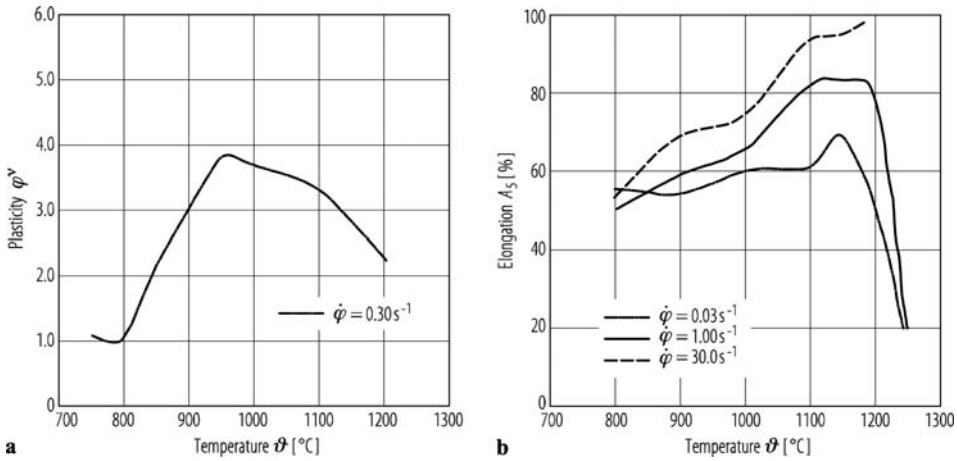
Fig. 5.111.
120WV4. Flow stress curves by hot and cold forming.



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Fig. 5.112.
120WV4. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	34.44			8008.3	
100	35.16	497.28	10.89	7982.1	
200	36.55	504.10	11.69	7952.1	
300	36.61	524.37	12.26	7919.9	
400	36.0	548.97	12.79	7885.4	
500	35.00	576.2	13.3	7848.4	
600	33.79	605.53	13.83	7808.9	
700	32.46	636.82	14.36	7766.7	
800	25.80	699.12	14.54	7728.8	
900	27.05	696.61	15.77	7667.4	
1000	27.95	694.11	16.87	7603.0	
1100	28.85	691.61	17.87	7535.9	
1200	29.96	689.13	18.80	7466.3	

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Steel symbol/number: 50WCrV8/1.2549

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.45…0.55	0.70…1.00	0.15…0.45	0.000…0.030	0.000…0.030	0.90…1.20
V	W				
0.10…0.20	1.70…2.20				

International comparison of standards

ISO		Euronorm		
~ 50WCrV8	4957 (1999)	50WCrV8	ISO 4957 (12/1999)	
United Kingdom		Russia		
50WCrV8	EN ISO 4957 (12/1999)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

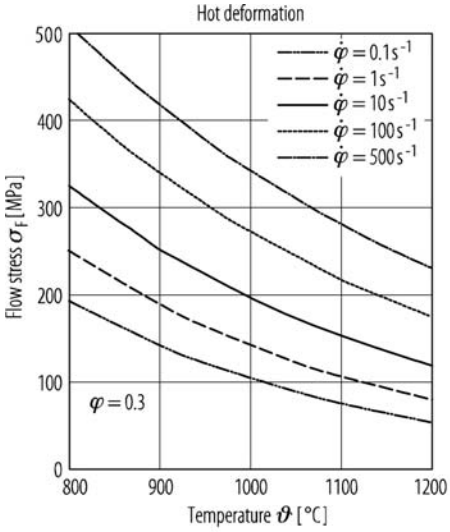
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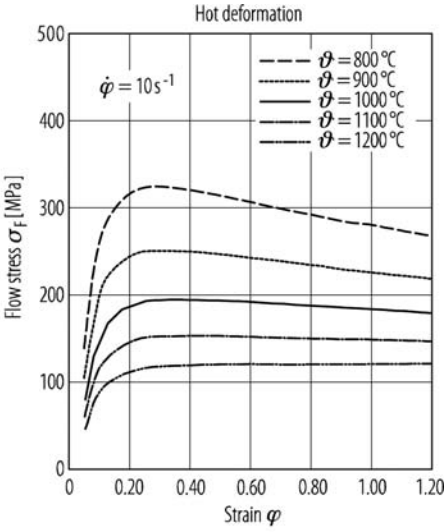
Flow curves

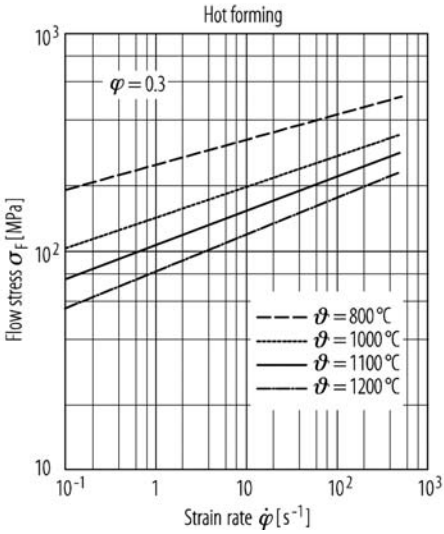
State of material	Hot deformation deformed state austenite	Cold deformation
σ_{F0} [MPa]	150.02	
A	2147.36	
Effect of temperature K_ϑ		
m_1	−0.00312	
Effect of strain K_φ		
m_2	−0.43742	
m_4	−0.09440	
m_5	0.00101	
m_7	−0.27641	
Effect of strain rate $K_{\dot\varphi}$		
m_3		
m_8	0.000142	
Range of validity		
ϑ [°C]	800…1200	
φ	0.04…1.20	
$\dot\varphi$ [s^{-1}]	<500	

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Fig. 5.113.
50WCrV8. Flow stress curves by hot forming.



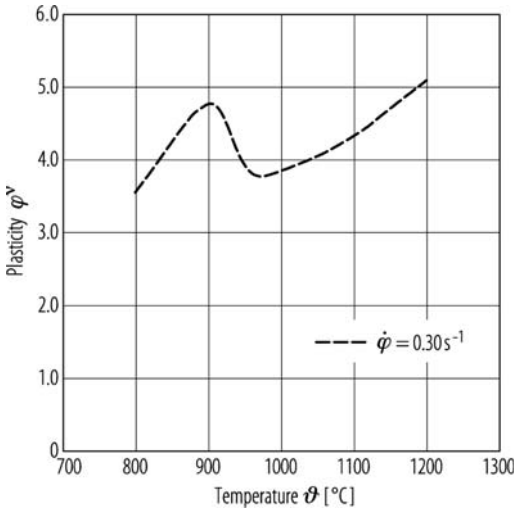




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Fig. 5.114.
50WCrV8. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.80.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	37.56	476.84	10.42	8078.8	
100	37.16	490.54	11.13	8051.8	
200	38.46	502.68	11.89	8021.1	
300	38.46	522.86	12.45	7988.2	
400	37.8	547.36	12.98	7953.0	
500	36.73	574.5	13.5	7915.2	
600	35.45	603.70	14.03	7874.8	
700	34.04	634.88	14.57	7831.7	
800	24.64	697.78	13.58	7815.5	
900	26.44	695.28	14.67	7758.7	
1000	27.83	692.78	15.66	7699.3	
1100	29.15	690.29	16.55	7637.4	
1200	30.66	687.81	17.38	7573.3	

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

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Steel symbol/number: 142WV13/1.2562

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
1.35…1.50	0.15…0.30	0.20…0.40	0.000…0.035	0.000…0.035	0.20…0.50
V	W				
0.20…0.30	2.80…3.30				

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
Japan		China		
~ SKS 11	G4404 (2000)			
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

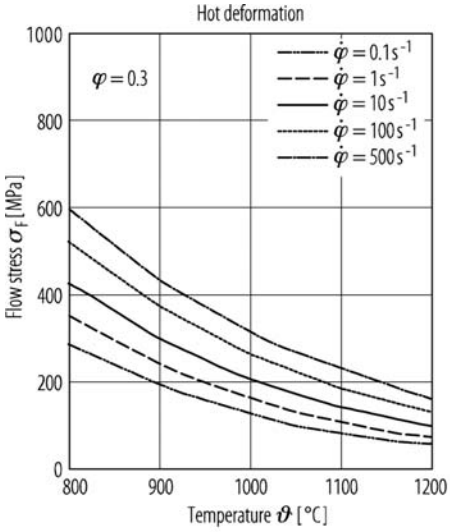
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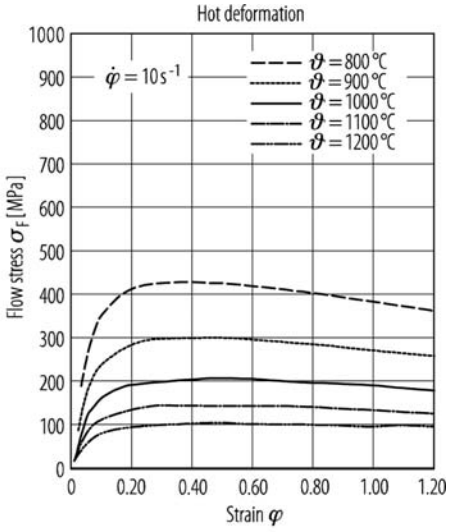
Flow curves

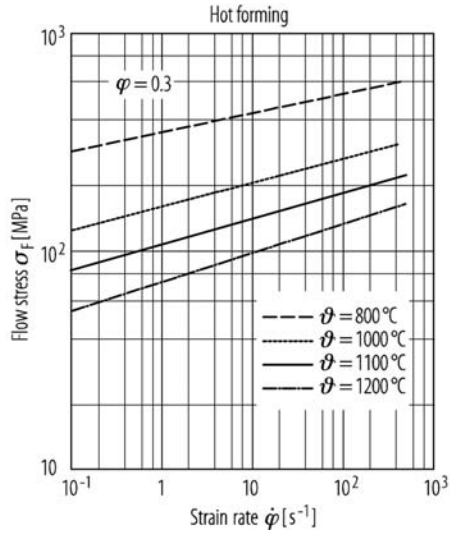
State of material	Hot deformation deformed state austenite	Cold deformation
σ_{F0} [MPa]	161.94	
A	9957.79	
Effect of temperature K_ϑ		
m_1	−0.00405	
Effect of strain K_φ		
m_2	−0.06124	
m_4	−0.04597	
m_5	0.00046	
m_7	−0.42694	
Effect of strain rate $K_{\dot\varphi}$		
m_3		
m_8	0.000108	
Range of validity		
ϑ [°C]	800…1200	
φ	0.04…1.20	
$\dot\varphi$ [s^{-1}]	<500	

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Fig. 5.115.
142WV13. Flow stress curves by hot forming.



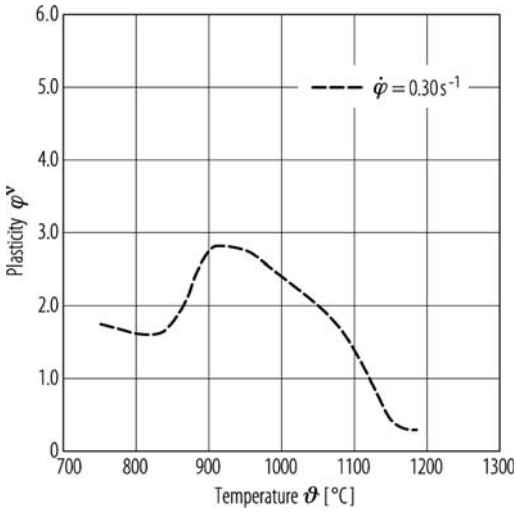




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Fig. 5.116.
142WV13. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.30…0.80.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	34.34	478.73	9.95	8149.0	
100	38.09	492.65	10.46	8123.4	
200	38.48	506.64	11.30	8093.7	
300	36.94	527.10	11.88	8061.9	
400	34.7	551.89	12.40	8027.7	
500	32.18	579.3	12.9	7991.1	
600	29.62	608.84	13.43	7952.0	
700	27.12	640.34	13.95	7910.2	
800	23.26	701.26	17.10	7814.6	
900	26.33	698.74	18.64	7738.9	
1000	28.41	696.23	20.03	7659.4	
1100	30.07	693.73	21.29	7576.4	
1200	31.76	691.24	22.46	7490.1	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

DOI: 10.1007/978-3-540-44760-3_69
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Steel symbol/number: X30WCrV9–3/1.2581

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.25…0.35	0.10…0.40	0.15…0.45	0.000…0.030	0.000…0.020	2.50…3.20
V	W				
0.30…0.50	8.50…9.50				

International comparison of standards

ISO		Euronorm		
~ X30WCrV9–3	4957 (1999)	X30WCrV9–3	ISO 4957 (12/1999)	
		~ X 30WCrV 9 3	96 (1979)	
United Kingdom		Russia		
X30WCrV9–3	EN ISO 4957 (12/1999)	~ 3Ch3W8F	Not standardized	
Japan		China		
~ SKD 5	G 4404 (2000)	~ 3Cr2W8V	T 1299 (2000)	
		~ T20280	T 1299 (2000)	
USA				
ASTM		AISI	SAE	UNS
~ A 681 (H 21)	A 681–99	~ H21	~ H21	~ T20821

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

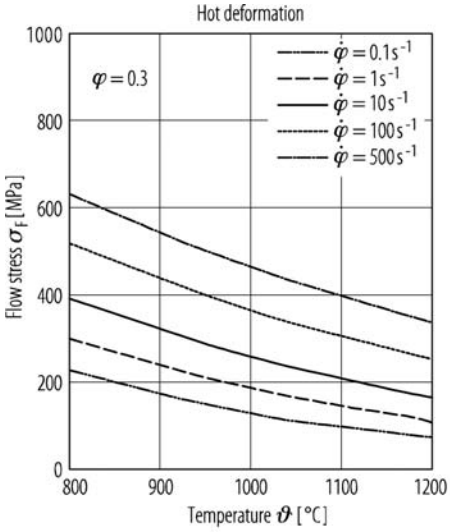
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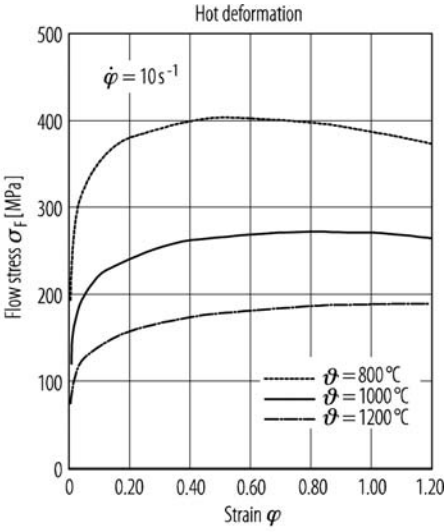
Flow curves

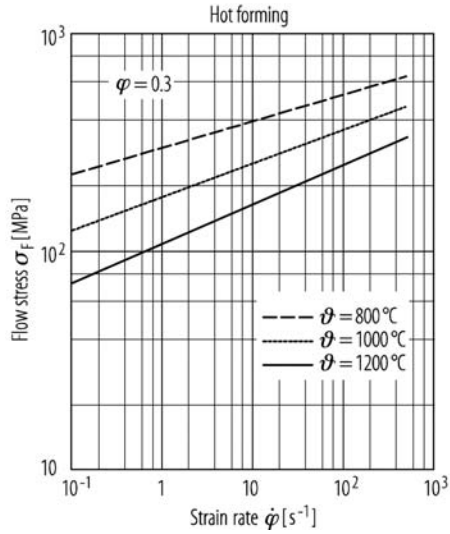
State of material	Hot deformation deformed state austenite	Cold deformation
σ_{F0} [MPa]	222.69	
A	2899.14	
Effect of temperature K_ϑ		
m_1	−0.00273	
Effect of strain K_φ		
m_2	0.07953	
m_4	−0.00242	
m_5	0.00084	
m_7	−0.57312	
Effect of strain rate $K_{\dot\varphi}$		
m_3		
m_8	0.000151	
Range of validity		
ϑ [°C]	800…1200	
φ	0.04…1.20	
$\dot\varphi$ [s^{-1}]	1.00…500	

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Fig. 5.117.
X30WCrV9–3. Flow stress curves by hot forming.



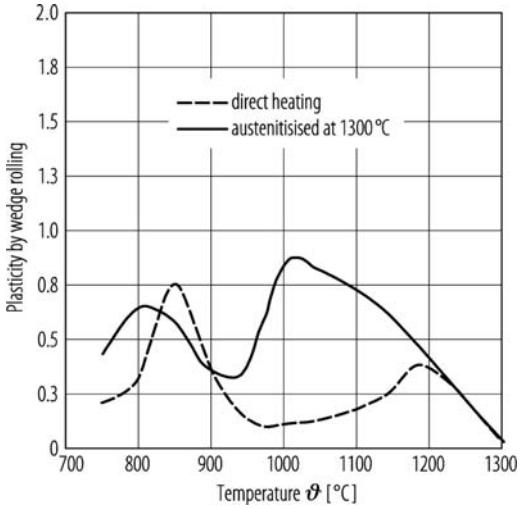




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Fig. 5.118.
Hot plasticity of X30WCrV9–3. Deformation rate: 15.0 [s^{-1}]. Deformed state. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.65.

Plasticity by wedge rolling



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	34.56			8877.5	215.9
100	35.24	422.58	10.18	8850.4	211.9
200	36.63	467.37	10.43	8821.9	207.3
300	36.68	488.88	10.76	8791.5	201.7
400	36.1	508.32	11.10	8759.2	194.1
500	35.07	527.7	11.5	8724.9	183.7
600	33.86	547.58	11.82	8688.6	170.3
700	32.52	567.99	12.19	8650.2	153.9
800	25.71	589.06	12.57	8609.5	134.9
900	26.99	610.85	12.97	8566.5	113.9
1000	27.91	633.40	13.38	8521.1	92.2
1100	28.82	656.75	13.80	8473.0	71.2
1200	29.95	680.93	14.24	8422.3	52.8

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: X165CrMoV12/1.2601

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
1.55…1.75	0.25…0.40	0.20…0.40	0.000…0.030	0.000…0.030	11.00…12.00
Mo	V	W			
0.50…0.70	0.10…0.50	0.40…0.60			

International comparison of standards

ISO		Euronorm		
		~ X 160 WCrV 12 1	96 (1979)	
United Kingdom		Russia		
Japan		China		
		~ Cr12MoV	T 1299 (2000)	
		~ T21201	T 1299 (2000)	
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

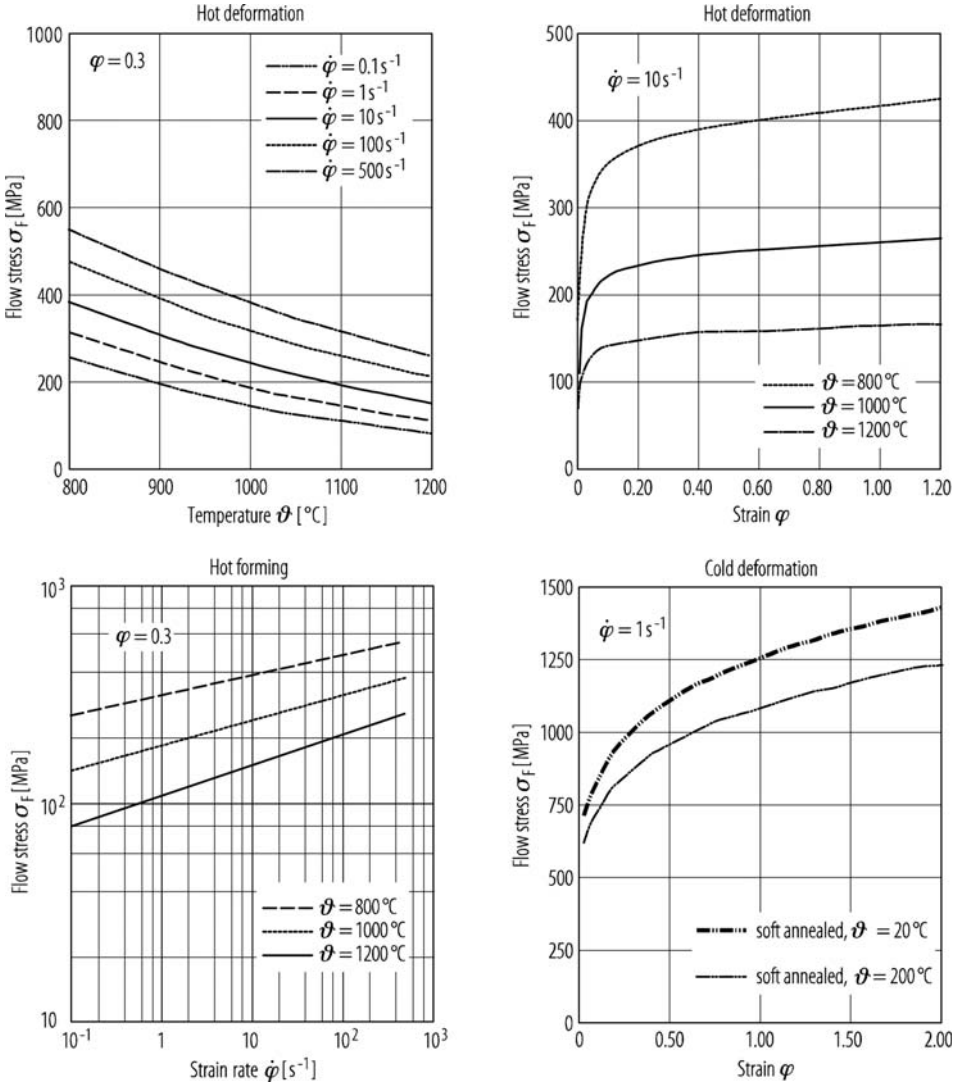
DOI: 10.1007/978-3-540-44760-3_71
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	224.34	867.3
A	2587.56	1275.293
Effect of temperature K_ϑ		
m_1	−0.00256	−0.00082
Effect of strain K_φ		
m_2	0.05320	0.18642
m_4	−0.00377	0.00329
m_5	−0.00007	
m_7	0.05325	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01183
m_8	0.000114	
Range of validity		
ϑ [°C]	800…1200	20…260
φ	0.04…1.20	0.04…2.00
$\dot\varphi$ [s^{-1}]	1.00…500	<500

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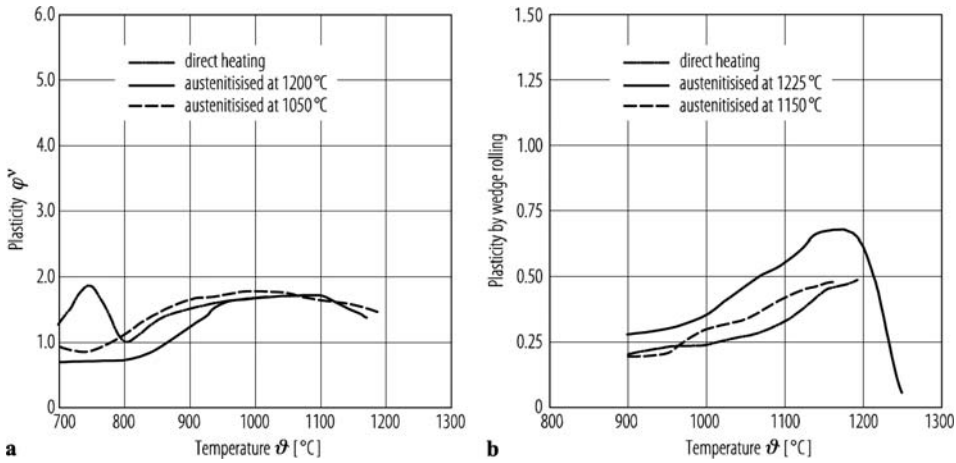
Fig. 5.119.
X165CrMoV12. Flow stress curves by hot and cold forming.



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Fig. 5.120.
X165CrMoV12. Hot plasticity as a function of the temperature. (a) Deformation rate: 15.0 [s^{-1}]. Deformed state. (b) Deformation rate: 0.20 [s^{-1}]. Casting state.

Plasticity by torsion and wedge rolling



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	31.9	457.86		7755.0	217.2
100	33.47	474.97	10.18	7731.3	208.5
200	34.92	492.29	10.43	7706.4	201.3
300	35.02	509.72	10.76	7679.8	195.6
400	34.5	529.99	11.10	7651.6	189.2
500	33.52	550.2	11.5	7621.7	180.3
600	32.37	570.92	11.82	7590.0	168.0
700	31.10	592.21	12.19	7556.5	151.9
800	28.44	614.18	12.57	7520.9	132.2
900	29.23	636.89	12.97	7483.4	109.9
1000	29.72	660.41	13.38	7443.6	86.5
1100	30.27	684.75	13.80	7401.7	64.2
1200	31.09	709.97	14.24	7357.4	45.8

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Steel symbol/number: 55NiCrMoV6/1.2713

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.50…0.60	0.10…0.40	0.65…0.95	0.000…0.030	0.000…0.030	0.60…0.80
Mo	Ni	V			
0.25…0.35	1.50…1.80	0.07…0.12			

International comparison of standards

ISO		Euronorm		
		~55 NiCrMoV 7	96 (1979)	
United Kingdom		Russia		
		~ 5ChNM	5950 (2000)	
Japan		China		
		~ 5CrNiMo	T 1299 (2000)	
		~ T20103	T 1299 (2000)	
USA				
ASTM		AISI	SAE	UNS
~ A 681 (L 6)	A 681–99	~ L 6	~ L 6	~ T61206

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

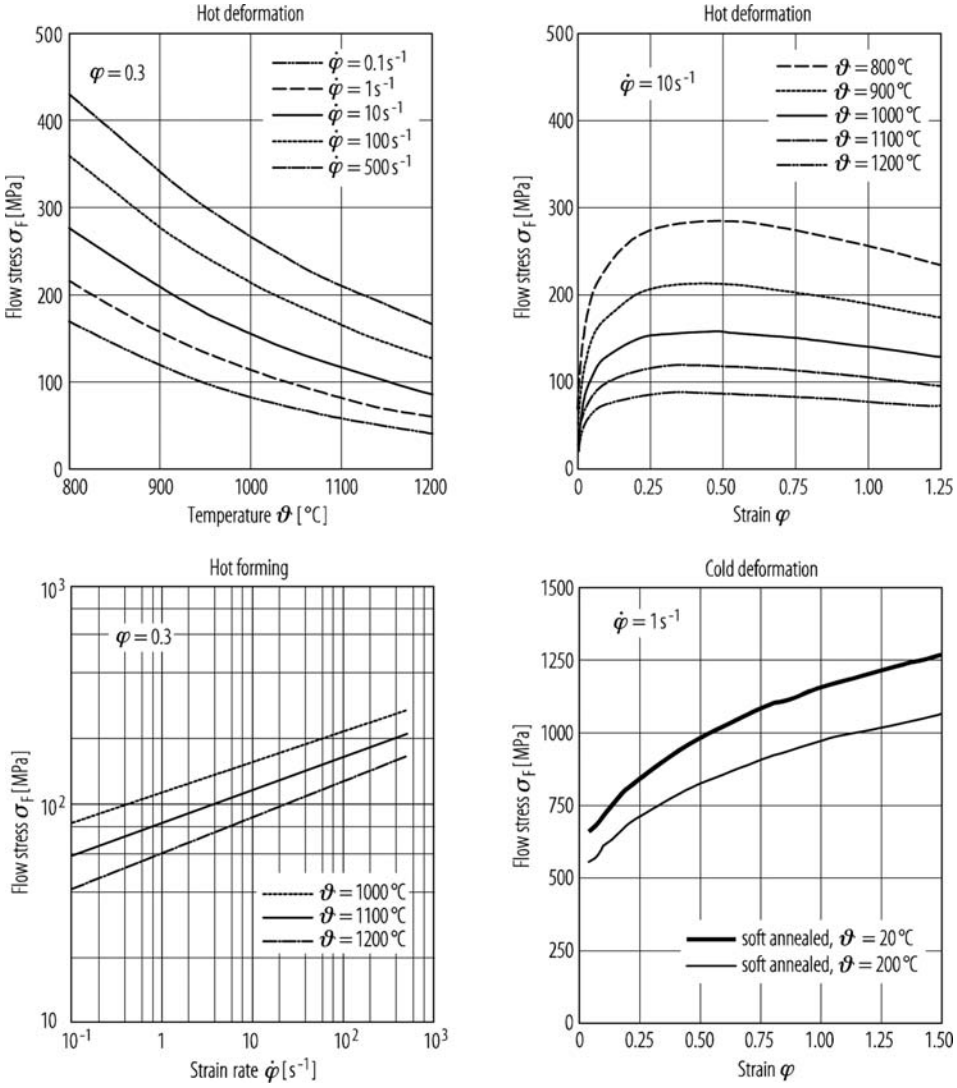
DOI: 10.1007/978-3-540-44760-3_72
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	130.44	740.7
A	4571.57	1164.550
Effect of temperature K_ϑ		
m_1	−0.00320	−0.00097
Effect of strain K_φ		
m_2	0.24957	0.24001
m_4	−0.00369	0.00913
m_5	−0.00012	
m_7	−0.51459	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01226
m_8	0.000138	
Range of validity		
ϑ [°C]	800…1200	20…260
φ	0.04…1.25	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500

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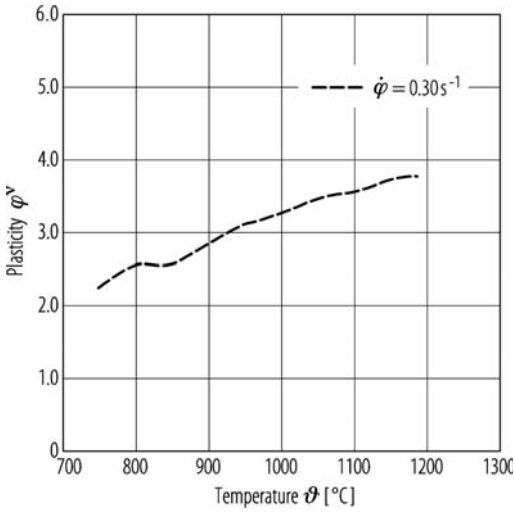
Fig. 5.121.
55NiCrMoV6. Flow stress curves by hot and cold forming.



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Fig. 5.122.
55NiCrMoV6. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.85.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	33.78	477.18	10.36	7833.2	207.7
100	34.73	490.56	10.84	7807.7	202.4
200	36.14	504.40	11.65	7778.5	196.2
300	36.21	524.70	12.22	7747.1	189.5
400	35.6	549.32	12.75	7713.4	181.1
500	34.63	576.6	13.3	7677.4	170.6
600	33.43	605.92	13.79	7638.8	157.6
700	32.11	637.23	14.32	7597.7	142.1
800	26.31	699.39	14.78	7555.3	124.4
900	27.45	696.88	16.04	7494.0	105.2
1000	28.25	694.37	17.17	7429.7	85.5
1100	29.06	691.88	18.20	7362.7	66.5
1200	30.09	689.39	19.15	7293.2	49.8

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: X19NiCrMo4/1.2764

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.16…0.22	0.10…0.40	0.15…0.45	0.000…0.030	0.000…0.030	1.10…1.40
Mo	Ni				
0.15…0.25	3.80…4.30				

International comparison of standards

ISO		Euronorm	
United Kingdom		Russia	
		~ 18Ch2N4MA	4543 (1971)
Japan		China	
USA			
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

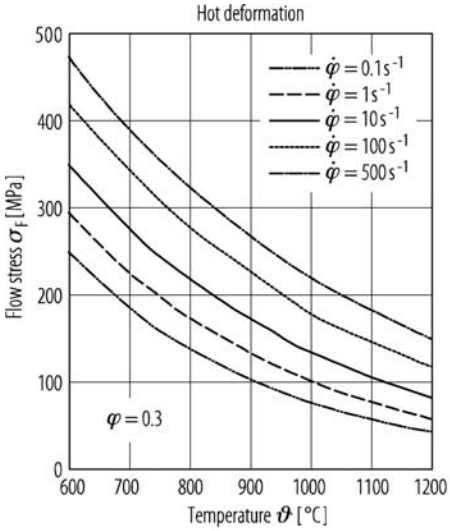
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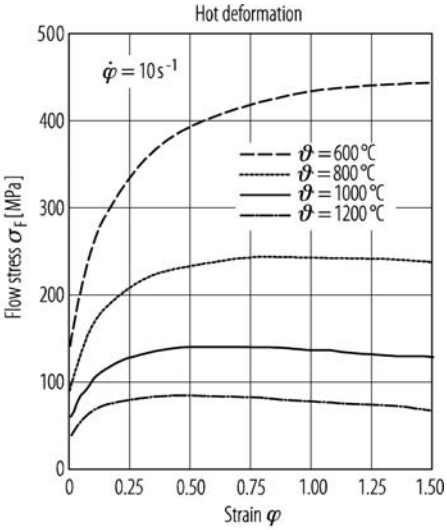
Flow curves

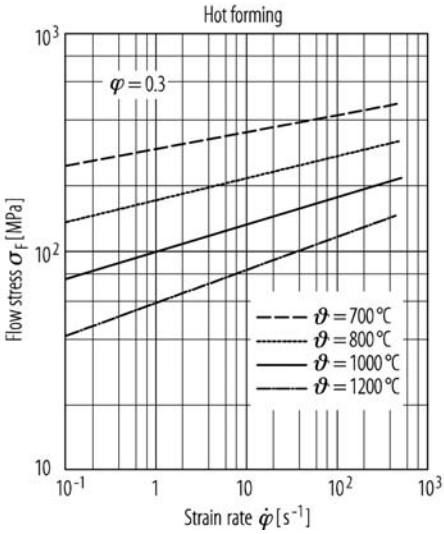
State of material	Hot deformation deformed state austenite	Cold deformation
σ_{F0} [MPa]	103.63	
A	2404.32	
Effect of temperature K_ϑ		
m_1	−0.00244	
Effect of strain K_φ		
m_2	0.40314	
m_4	0.00312	
m_5	−0.00103	
m_7	−0.00222	
Effect of strain rate $K_{\dot\varphi}$		
m_3		
m_8	0.000126	
Range of validity		
ϑ [°C]	600…1200	
φ	0.04…1.50	
$\dot\varphi$ [s^{-1}]	<500	

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Fig. 5.123.
X19NiCrMo4. Flow stress curves by hot forming.



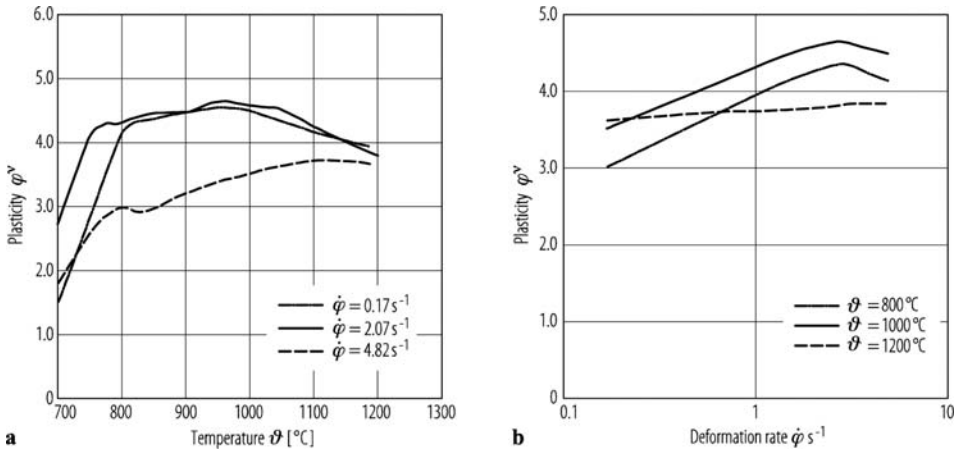




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Fig. 5.124.
X19NiCrMo4. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	32.65	477.45	10.27	7873.3	
100	33.98	491.06	10.75	7847.9	
200	35.41	504.92	11.57	7818.6	
300	35.50	525.26	12.14	7787.2	
400	34.9	549.92	12.67	7753.6	
500	33.96	577.2	13.2	7717.6	
600	32.80	606.60	13.71	7679.0	
700	31.51	637.95	14.24	7637.9	
800	27.46	699.85	15.24	7585.3	
900	28.40	697.34	16.56	7521.3	
1000	29.01	694.83	17.74	7454.2	
1100	29.67	692.33	18.82	7384.3	
1200	30.58	689.85	19.81	7311.7	

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Steel symbol/number: X45NiCrMo4/1.2767

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.40…0.50	0.10…0.40	0.20…0.50	0.000…0.030	0.000…0.030	1.20…1.50
Mo	Ni				
0.15…0.35	3.80…4.30				

International comparison of standards

ISO		Euronorm		
~ 45NiCrMo16	4957 (1999)	45NiCrMo16	ISO 4957 (12/1999)	
		~ 40 NiCrMoV 16	96 (1979)	
United Kingdom		Russia		
45NiCrMo16	EN ISO 4957 (12/1999)			
Japan		China		
~ SKT 6	G 4404 (2000)			
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

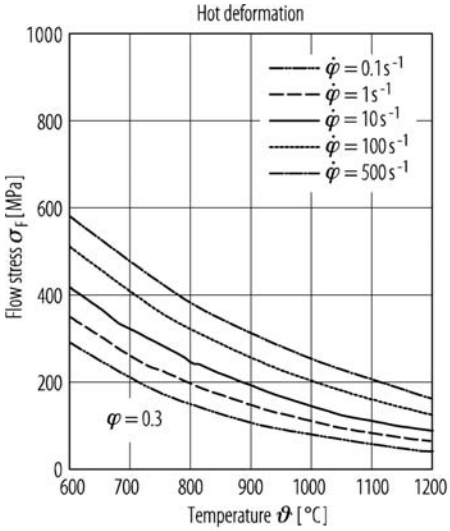
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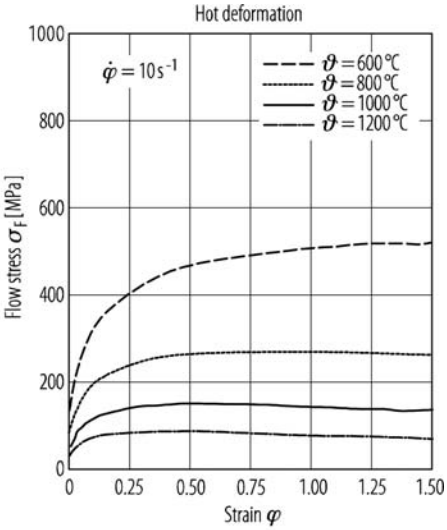
Flow curves

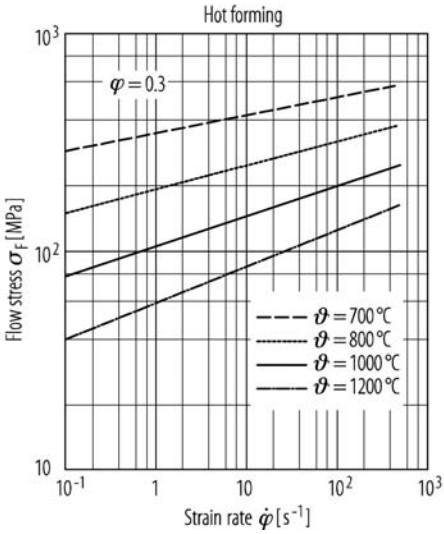
State of material	Hot deformation deformed state austenite	Cold deformation
σ_{F0} [MPa]	115.05	
A	3204.1	
Effect of temperature K_ϑ		
m_1	−0.00268	
Effect of strain K_φ		
m_2	0.37714	
m_4	0.00103	
m_5	−0.00116	
m_7	0.05342	
Effect of strain rate $K_{\dot\varphi}$		
m_3		
m_8	0.000137	
Range of validity		
ϑ [°C]	600…1200	
φ	0.04…1.50	
$\dot\varphi$ [s^{-1}]	<500	

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Fig. 5.125.
X45NiCrMo4. Flow stress curves by hot forming.



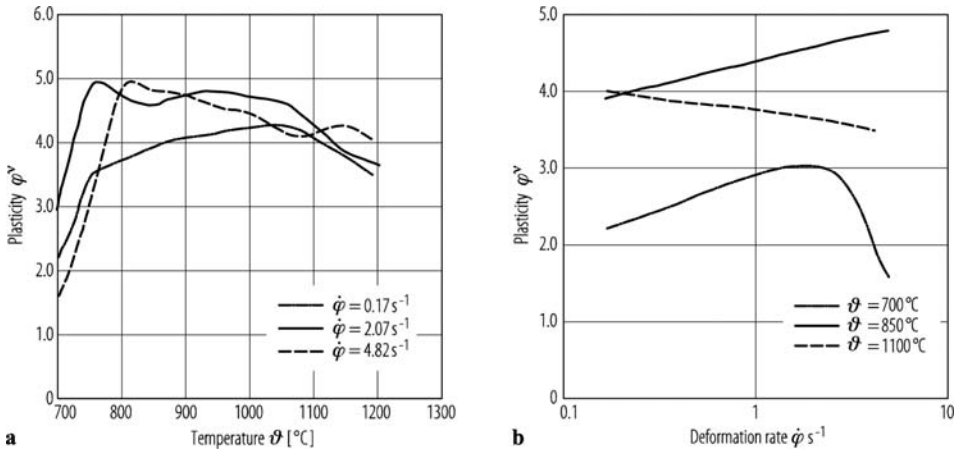




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Fig. 5.126.
X45NiCrMo4. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	31.71	477.83	10.18	7873.5	
100	33.34	491.47	10.68	7848.3	
200	34.80	505.36	11.50	7819.2	
300	34.90	525.73	12.08	7787.9	
400	34.3	550.42	12.60	7754.4	
500	33.40	577.7	13.1	7718.5	
600	32.26	607.17	13.64	7680.2	
700	30.99	638.56	14.17	7639.2	
800	28.73	700.23	15.66	7577.5	
900	29.47	697.71	17.03	7511.4	
1000	29.93	695.20	18.26	7442.1	
1100	30.45	692.71	19.39	7369.8	
1200	31.25	690.22	20.42	7294.7	

DOI: 10.1007/978-3-540-44760-3_74
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Steel symbol/number: HS10–4–3–10/1.3207

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
1.20…1.35	0.00…0.45	0.00…0.40	0.000…0.030	0.000…0.030	3.80…4.50
Mo	V	Co	W		
3.20…3.90	3.00…3.50	9.50…10.50	9.00…10.00		

International comparison of standards

ISO		Euronorm	
~HS10–4–3–10	4957 (12/1999)	~ HS10–4–3–10	96 (1976)
		HS10-4-3-10	ISO 4957 (12/1999)
United Kingdom		Russia	
HS10–4–3–10	EN ISO 4957 (12/1999)	~ R12F3K10M3–SCh	Not standardized
Japan		China	
~SKH57	G 4403 (2000)		
USA			
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

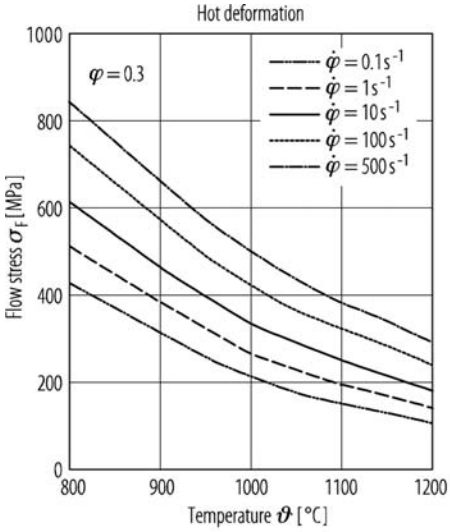
DOI: 10.1007/978-3-540-44760-3_75
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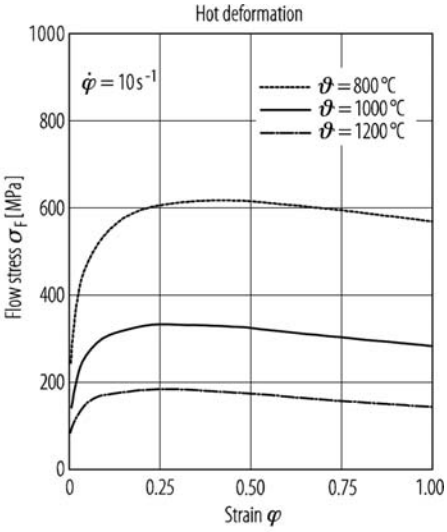
Flow curves

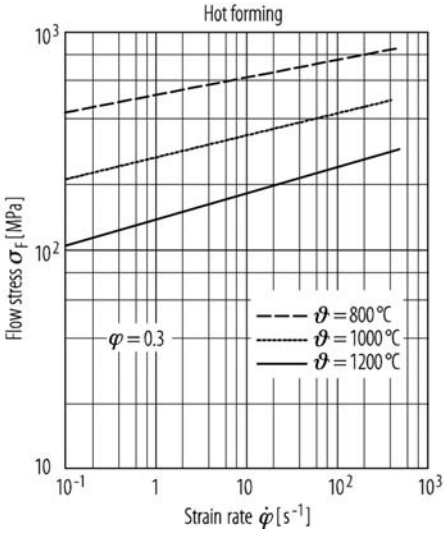
State of material	Hot deformation deformed state austenite	Cold deformation
σ_{F0} [MPa]	304.60	
A	9145.07	
Effect of temperature K_ϑ		
m_1	−0.00301	
Effect of strain K_φ		
m_2	0.22294	
m_4	−0.00153	
m_5	−0.00097	
m_7	−0.01742	
Effect of strain rate $K_{\dot\varphi}$		
m_3		
m_8	0.000100	
Range of validity		
ϑ [°C]	800…1200	
φ	0.04…1.00	
$\dot\varphi$ [s^{-1}]	<500	

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Fig. 5.127.
HS10–4–3–10. Flow stress curves by hot forming.



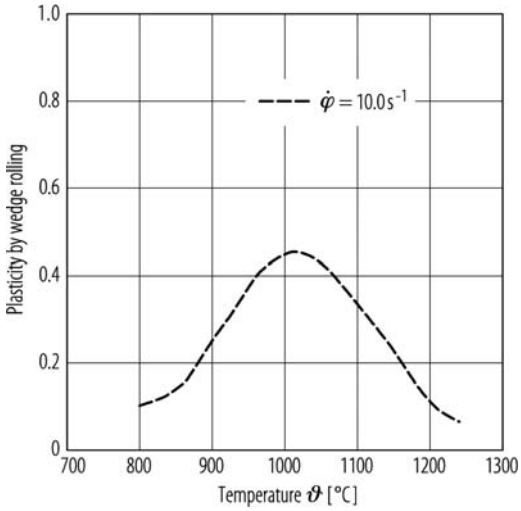




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Fig. 5.128.
HS10–4–3–10. Hot plasticity as a fuction of the temperature; deformed state and austenitized at 1200 [°C]. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.70.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	19.43	445.94	9.68	8977.6	
100	20.89	493.21	9.83	8951.1	
200	22.35	515.90	10.06	8924.6	
300	23.81	536.42	10.40	8893.5	
400	25.27	556.92	10.65	8862.8	
500	26.73	577.85	10.87	8831.2	
600	28.19	599.39	11.09	8798.4	
700	30.10	621.63	11.37	8763.1	
800	30.39	644.62	11.67	8726.1	
900	30.69	668.42	11.98	8687.1	
1000	30.99	693.06	12.40	8643.5	
1100	31.30	718.58	12.74	8600.1	
1200	31.61	745.02	13.19	8551.3	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: HS 6–5–2–5/1.3243

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.87…0.95	0.00…0.45	0.00…0.40	0.000…0.030	0.000…0.030	3.80…4.50
Mo	V	Co	W		
4.70…5.20	1.70…2.10	4.50…5.00	5.90…6.70		

International comparison of standards

ISO		Euronorm		
~ HS 6–5–2–5	4957 (1999)	HS 6–5–2–5	ISO 4957 (12/1999)	
United Kingdom		Russia		
HS 6–5–2–5	EN ISO 4957 (12/1999)	~ R6M5K5	19265 (1973)	
Japan		China		
~ SKH 55	G 4403 (2000)	~W6Mo5Cr4V2Co5	T 9943 (1988)	
		~ T76545	T 9943 (1988)	
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

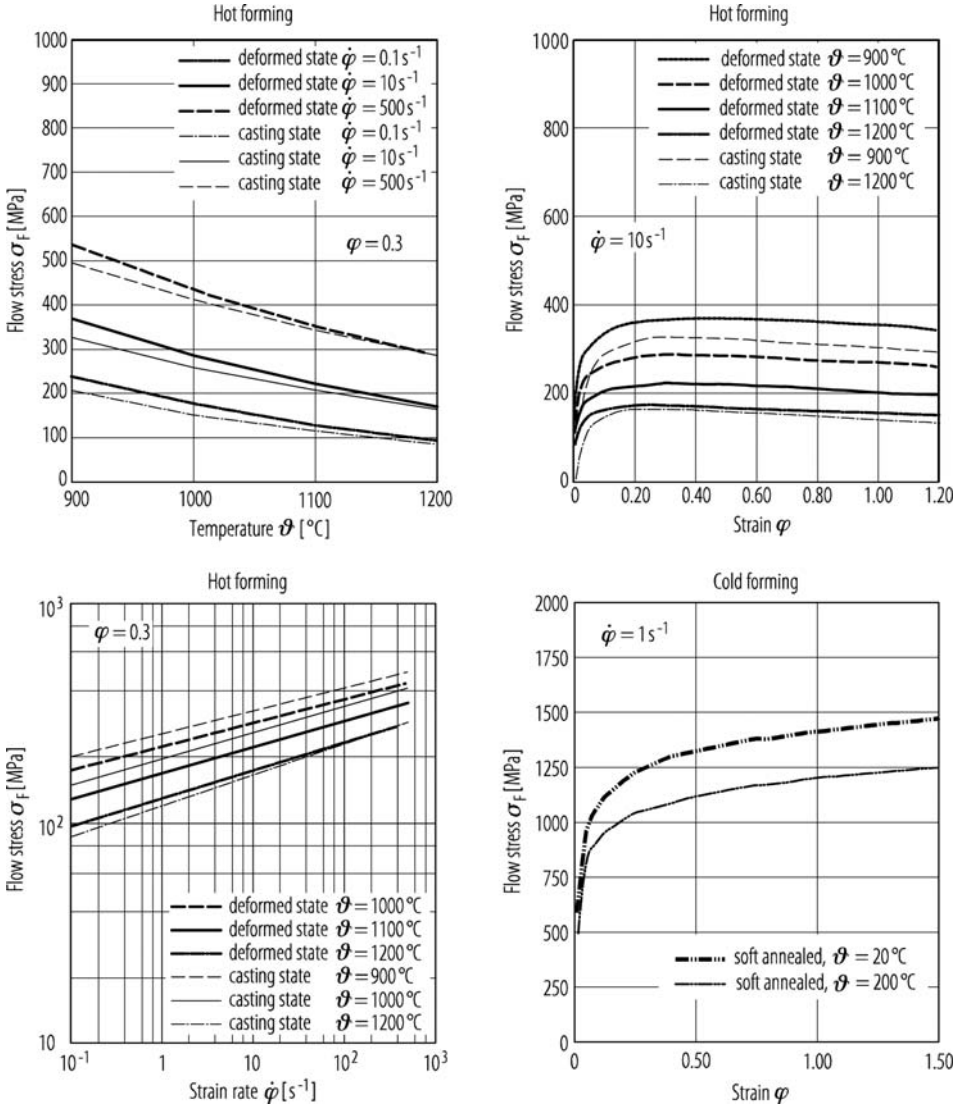
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Flow curves

State of material	Hot deformation		Cold deformation
	deformed state	casting state	soft annaeled
	austenite	austenite	
σ_{F0} [MPa]	261.86	207.8	1099.0
A	4301.2	3052.35	1447.00
Effect of temperature K_ϑ			
m_1	−0.00261	−0.00239	−0.00090
Effect of strain K_φ			
m_2	0.15721	0.09985	0.08950
m_4	−0.00172	−0.01736	−0.00690
m_5	−0.00059	−0.00062	
m_7	−0.00278	−0.00277	
Effect of strain rate $K_{\dot\varphi}$			
m_3			0.00440
m_8	0.000107	0.000117	
Range of validity			
ϑ [°C]	900…1200	900…1200	20…350
φ	0.04…1.20	0.04…1.20	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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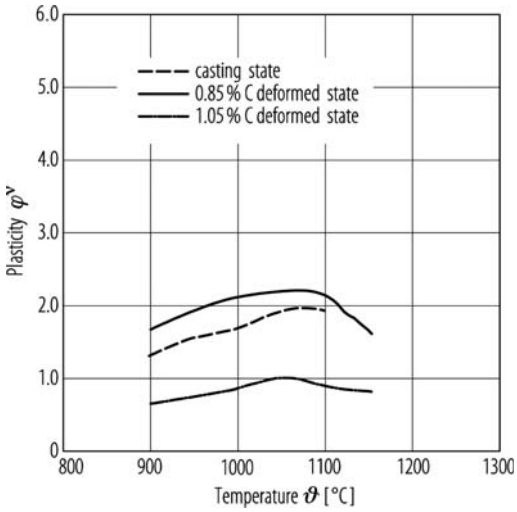
Fig. 5.129.
HS 6–5–2–5. Flow stress curves by hot and cold forming.



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Fig. 5.130.
HS 6–5–2–5. Hot plasticity as a function of the temperature. Deformation rate: 0.3 [s^{-1}]. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.70.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	20.12	439.73	11.18	8167.6	
100	21.42	486.33	11.33	8139.8	
200	22.64	508.71	11.56	8110.9	
300	23.98	528.94	11.90	8080.1	
400	26.45	549.15	12.15	8048.5	
500	27.06	569.79	12.37	8016.1	
600	27.75	591.04	12.59	7982.5	
700	28.02	612.96	12.87	7946.8	
800	28.30	635.64	13.17	7909.4	
900	28.57	659.10	13.48	7870.3	
1000	28.86	683.40	13.90	7826.9	
1100	29.14	708.56	14.24	7783.8	
1200	29.43	734.64	14.69	7735.6	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: HS2–9–1–8/1.3247

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
1.05…1.15	0.00…0.70	0.00…0.40	0.000…0.030	0.000…0.030	3.50…4.50
Co	Mo	V	W		
7.50…8.50	9.00…10.00	0.90…1.30	1.20…1.90		

International comparison of standards

ISO		Euronorm		
~ HS2–9–1–8	4957 (1999)	~ HS2–9–1–8	96 (1979)	
		HS2–9–1–8	ISO 4957 (12/1999)	
United Kingdom		Russia		
HS2–9–1–8	EN ISO 4957 (12/1999)			
Japan		China		
~ SKH59	G 4403(2000)	~ W2Mo9Cr4VCo8	T 9943 (1988)	
		~ T72948	T 9943 (1988)	
USA				
ASTM		AISI	SAE	UNS
~ A 600 (M 42)	A 600–99	~ M 42		~ T11342

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

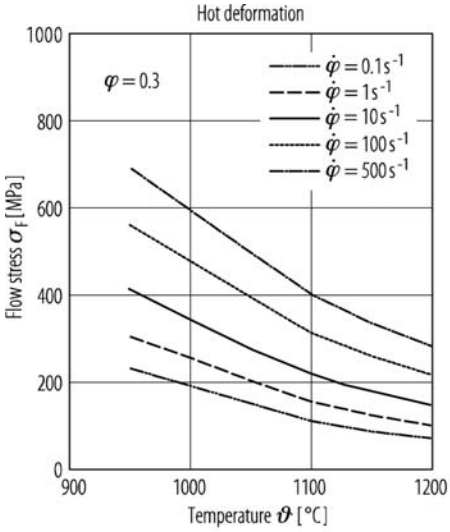
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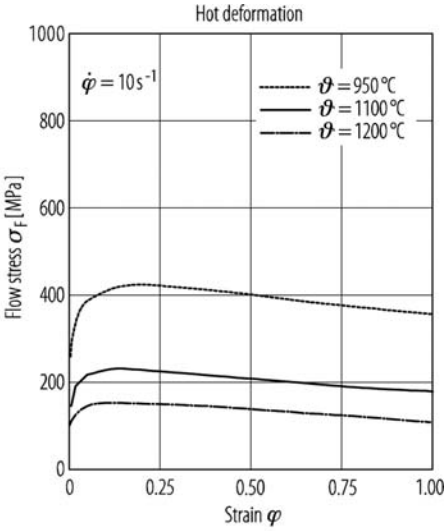
Flow curves

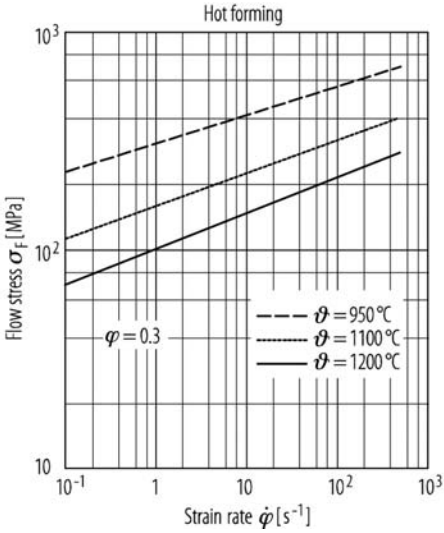
State of material	Hot deformation deformed state austenite	Cold deformation
σ_{F0} [MPa]	226.82	
A	22817.9	
Effect of temperature K_ϑ		
m_1	−0.00410	
Effect of strain K_φ		
m_2	0.14430	
m_4	−0.00090	
m_5	−0.00130	
m_7	0.29180	
Effect of strain rate $K_{\dot\varphi}$		
m_3		
m_8	0.000137	
Range of validity		
ϑ [°C]	950…1200	
φ	0.04…1.00	
$\dot\varphi$ [s^{-1}]	<500	

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Fig. 5.131.
HS2–9–1–8. Flow stress curves by hot forming.



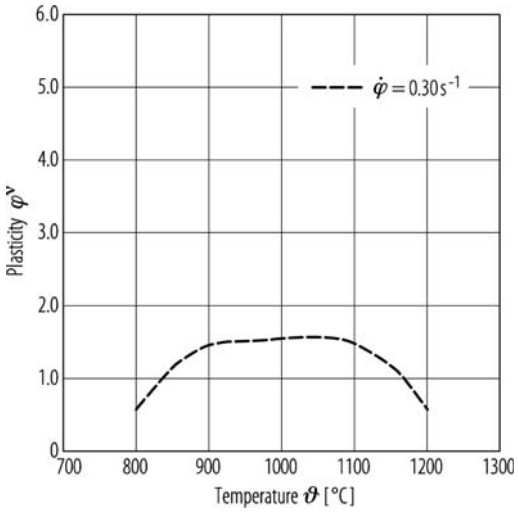




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Fig. 5.132.
HS2–9–1–8. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.35…0.60.

Plasticity in torsion.



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	18.59	442.89	11.18	8234.1	
100	20.05	489.83	11.33	8206.1	
200	21.52	512.37	11.56	8178.1	
300	22.98	532.75	11.90	8145.9	
400	24.45	553.10	12.15	8114.0	
500	25.91	573.89	12.37	8081.4	
600	27.38	595.29	12.59	8047.5	
700	29.06	617.37	12.87	8011.5	
800	29.35	640.21	13.17	7973.8	
900	29.64	663.84	13.48	7934.4	

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Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
1000	29.93	688.31	13.90	7890.7	
1100	30.22	713.66	14.24	7847.2	
1200	30.52	739.92	14.69	7798.7	

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: HS12–1–2/1.3318

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.90…1.00	0.00…0.45	0.00…0.40	0.000…0.030	0.000…0.030	3.80…4.50
Mo	V	W			
0.70…1.00	2.30…2.60	11.50…12.50			

International comparison of standards

ISO		Euronorm	
United Kingdom		Russia	
		~ R12F3	19265 (1973)
Japan		China	
USA			
ASTM	AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

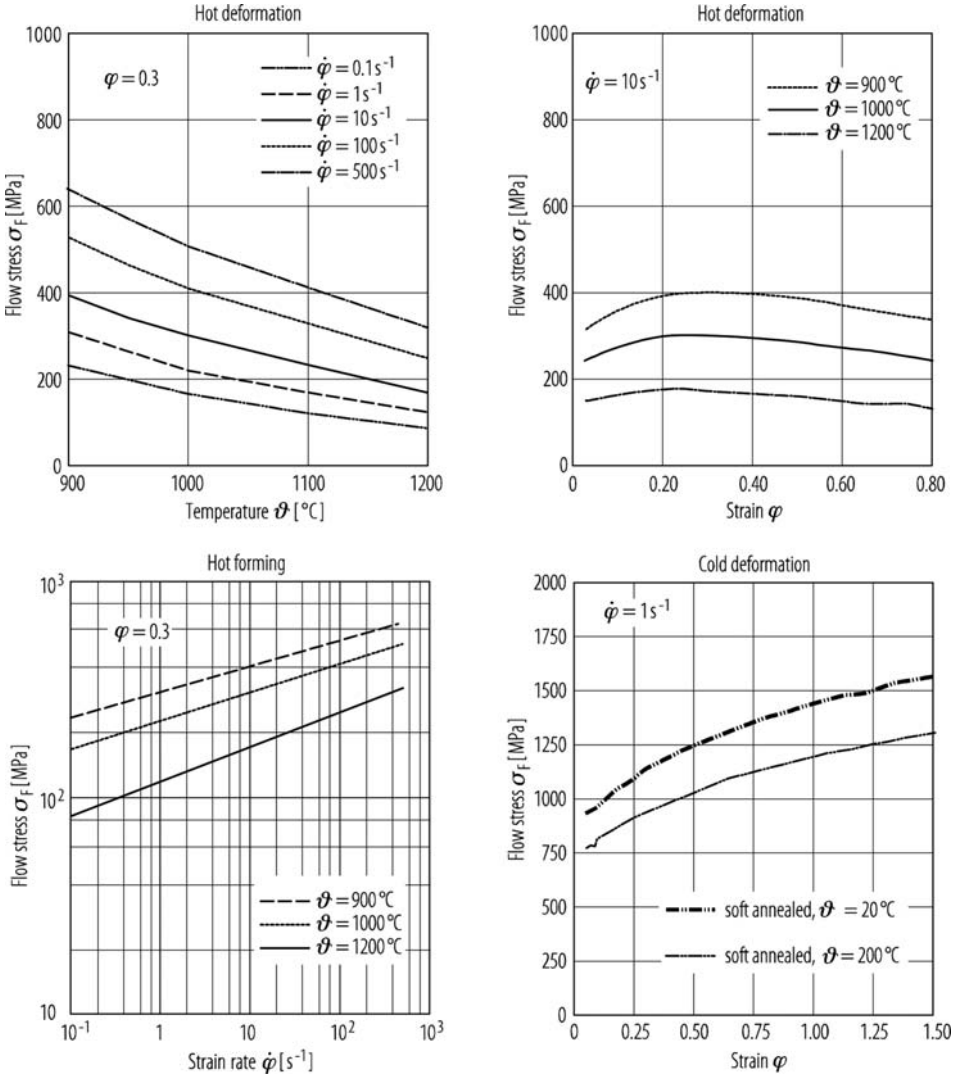
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	272.22	983.6
A	9319.27	1451.013
Effect of temperature K_ϑ		
m_1	−0.00289	−0.00104
Effect of strain K_φ		
m_2	0.40177	0.21802
m_4	0.01186	0.01149
m_5	−0.00096	
m_7	−0.52050	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00830
m_8	0.000133	
Range of validity		
ϑ [°C]	900…1200	20…350
φ	0.04…0.80	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.133.
HS12–1–2. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
soft annealed	270…300	76.2593	0.61379	650…700	12.4499	0.91566

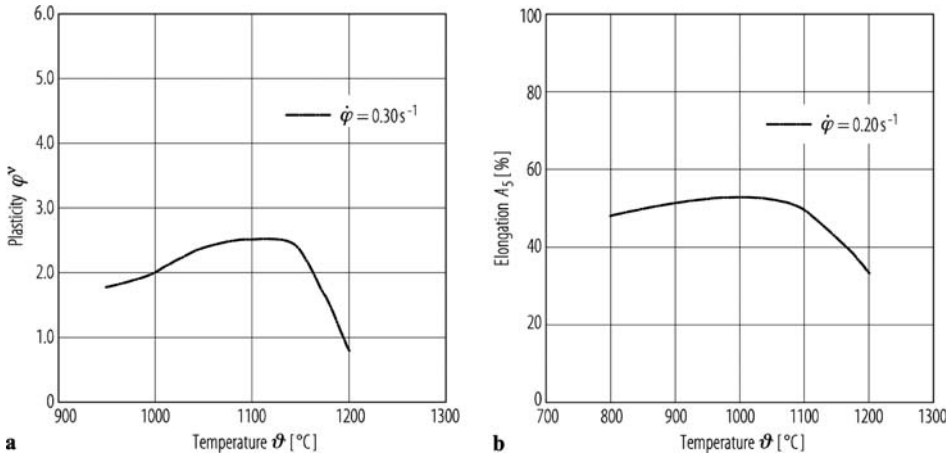
DOI: 10.1007/978-3-540-44760-3_78
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
soft annealed	18…22	8.62513	0.17082	−0.6255	<70

Fig. 5.134.
HS12–1–2. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	24.84	435.09	11.18	8164.9	
100	25.03	481.20	11.33	8137.1	
200	25.28	503.35	11.56	8108.3	
300	25.53	523.36	11.90	8077.4	
400	25.78	543.36	12.15	8045.8	
500	26.03	563.78	12.37	8013.5	
600	26.29	584.80	12.59	7979.9	
700	26.55	606.50	12.87	7944.2	
800	26.81	628.93	13.17	7906.8	
900	27.07	652.15	13.48	7867.7	
1000	27.34	676.19	13.90	7824.3	
1100	27.61	701.09	14.24	7781.2	
1200	27.88	726.89	14.69	7733.1	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

DOI: 10.1007/978-3-540-44760-3_78
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Steel symbol/number: HS3–3–2/1.3333

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.95…1.03	0.00…0.45	0.00…0.40	0.000…0.030	0.000…0.030	3.80…4.50
Mo	V	W			
2.50…2.90	2.20…2.50	2.70…3.00			

International comparison of standards

ISO		Euronorm		
~ HS3–3–2	4957 (1999)	HS3–3–2	ISO 4957 (12/1999)	
United Kingdom		Russia		
HS3–3–2	EN ISO 4957 (12/1999)	~ 11R3AM3F2	19265 (1973)	
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

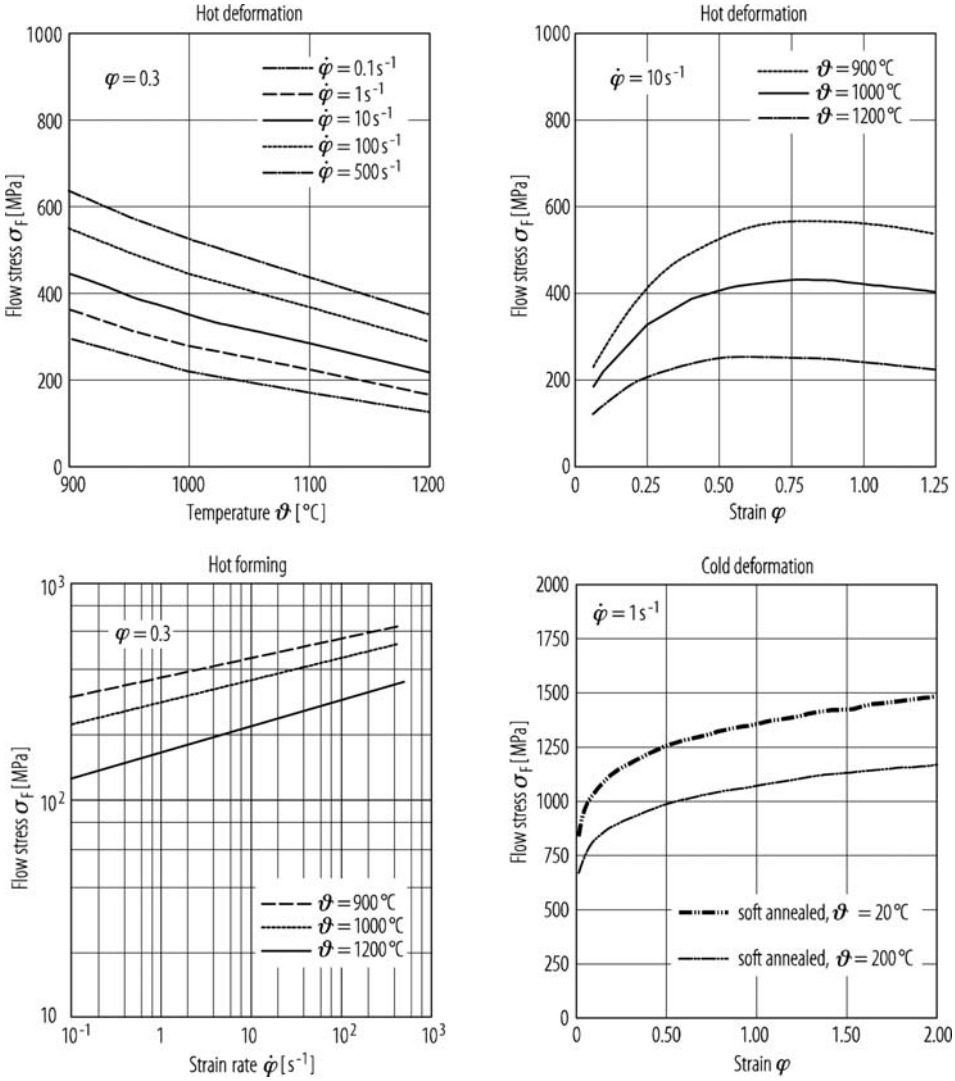
DOI: 10.1007/978-3-540-44760-3_79
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	218.82	1064.5
A	10846.26	1391.394
Effect of temperature K_ϑ		
m_1	−0.00230	−0.00131
Effect of strain K_φ		
m_2	0.86627	0.11897
m_4	0.03066	0.00077
m_5	−0.00110	
m_7	−0.44691	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01070
m_8	0.000101	
Range of validity		
ϑ [°C]	900…1200	20…350
φ	0.04…1.25	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.135.
HS3–3–2. Flow stress curves by hot and cold forming.

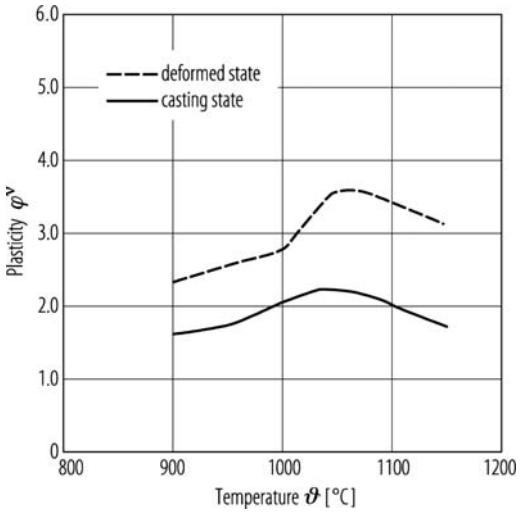


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Fig. 5.136.

HS3–3–2. Hot plasticity as a function of the temperature. Deformation rate: 0.3 [s^{-1}]. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.70.

Plasticity in torsion.



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	24.25	433.05	11.18	7929.1	
100	24.44	478.95	11.33	7902.2	
200	24.68	500.99	11.56	7874.1	
300	24.92	520.91	11.90	7844.2	
400	25.17	540.82	12.15	7813.5	
500	25.42	561.14	12.37	7782.0	
600	25.67	582.06	12.59	7749.4	
700	25.92	603.66	12.87	7714.7	
800	26.17	625.99	13.17	7678.5	
900	26.43	649.09	13.48	7640.5	
1000	26.69	673.02	13.90	7598.4	
1100	26.96	697.81	14.24	7556.5	
1200	27.22	723.48	14.69	7509.8	

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Steel symbol/number: HS6–5–2/1.3343

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.86…0.94	0.00…0.45	0.00…0.40	0.000…0.030	0.000…0.030	3.80…4.50
Mo	V	W			
4.70…5.20	1.70…2.10	5.90…6.70			

International comparison of standards

ISO		Euronorm		
~ HS6–5–2 C	4957 (1999)	HS6–5–2C	ISO 4957 (12/1999)	
United Kingdom		Russia		
HS6–5–2C	EN ISO 4957 (12/1999)	~ R6M5	19265 (1973)	
Japan		China		
~ SKH 51	G 4403 (2000)	~ W6Mo5Cr4V2	T 084 (1996)	
		~ T66541	T 084 (1996)	
USA				
ASTM		AISI	SAE	UNS
~ A 597 (CM-2)	A 597–99	~ M 2	~ M 2	~ T11302
~ A 600 (M 2)	A 600–99	~ 611		

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

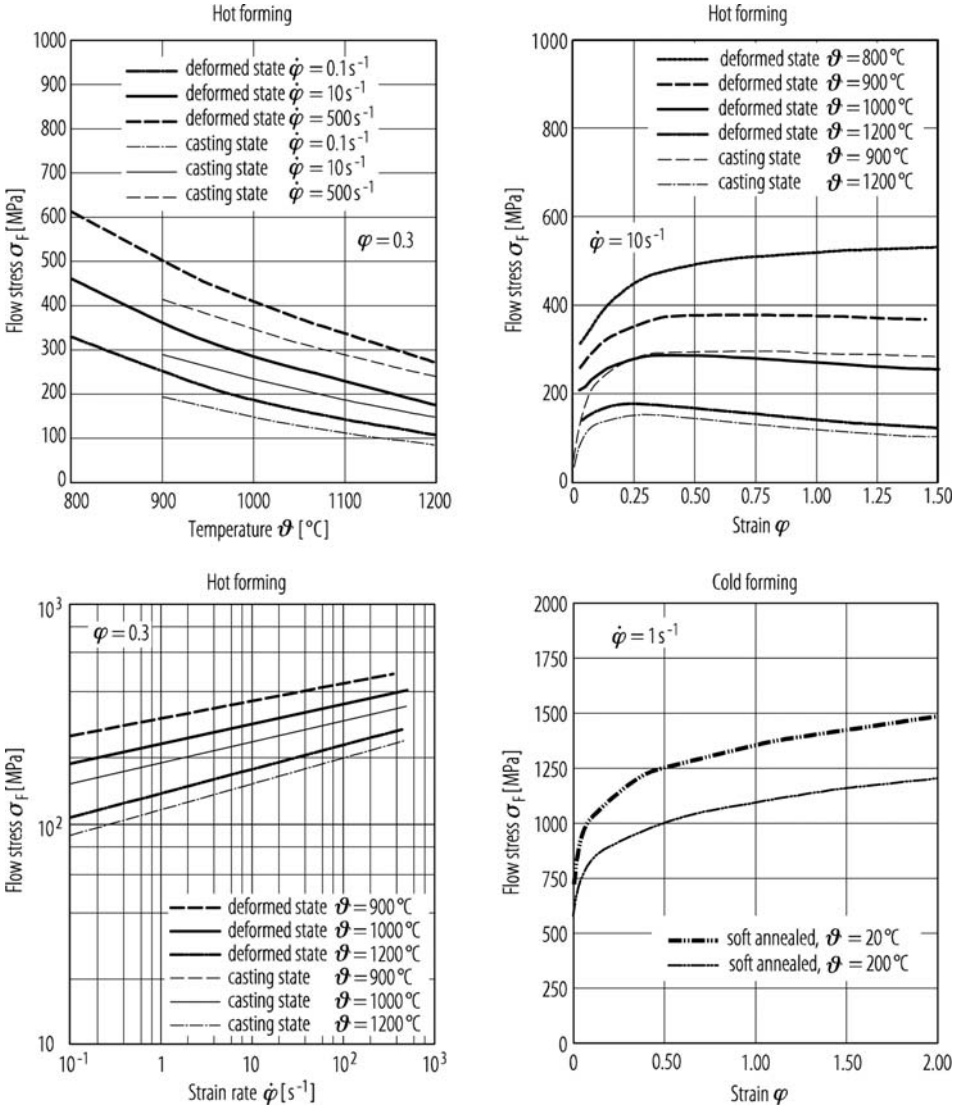
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Flow curves

State of material	Hot deformation		Cold deformation
	deformed state	casting state	soft annealed
	austenite	austenite	
σ_{F0} [MPa]	241.38	216.25	1022.9
A	4663.12	3383.94	1389.33
Effect of temperature K_ϑ			
m_1	−0.00211	−0.00189	−0.00121
Effect of strain K_φ			
m_2	0.45663	0.39928	0.1284
m_4	0.01351	−0.00215	0.0000618
m_5	−0.00191	−0.00191	
m_7	0.37022	0.37024	
Effect of strain rate $K_{\dot\varphi}$			
m_3			0.00010
m_8	0.000091	0.000098	
Range of validity			
ϑ [°C]	800…1200	900 … 1200	20…350
φ	0.04…1.50	0.04…1.50	0.04…2.0
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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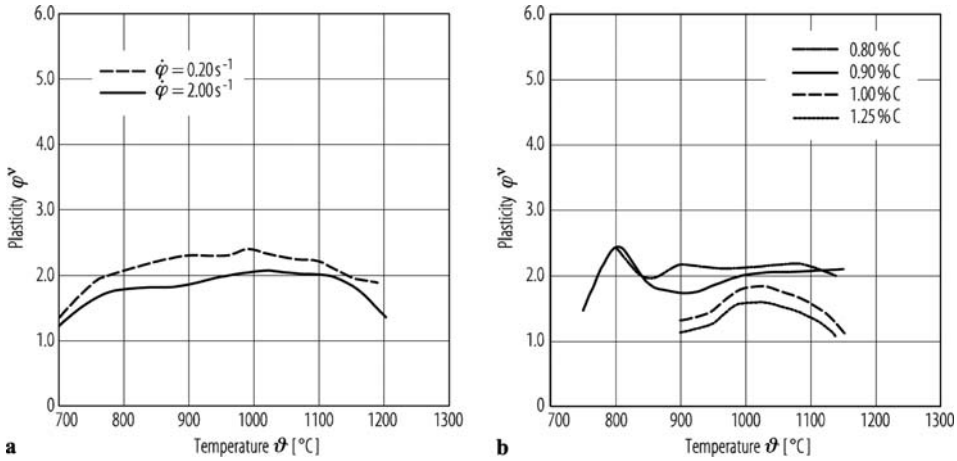
Fig. 5.137.
HS6–5–2. Flow stress curves by hot and cold forming.



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Fig. 5.138.
HS6–5–2. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformation rate: 0.2 [s^{-1}]. Deformed state. Austenitised at 1050 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	20.24	434.89	11.18	8117.0	224.0
100	21.58	480.98	11.33	8089.4	219.9
200	22.75	503.12	11.56	8060.7	213.9
300	24.05	523.13	11.90	8030.1	207.1
400	25.06	543.12	12.15	7998.6	199.4
500	25.97	563.53	12.37	7966.5	190.5
600	26.23	584.54	12.59	7933.1	180.4
700	26.49	606.22	12.87	7897.6	168.6
800	26.75	628.65	13.17	7860.4	155.0
900	27.01	651.85	13.48	7821.6	139.1
1000	27.28	675.88	13.90	7778.4	120.4
1100	27.54	700.77	14.24	7735.6	98.5
1200	27.82	726.56	14.69	7687.7	72.7

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: HS18–0–1/1.3355

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.70…0.83	0.00…0.45	0.00…0.40	0.000…0.030	0.000…0.030	3.80…4.50
V	W				
1.00…1.20	17.20…18.70				

International comparison of standards

ISO		Euronorm		
~ HS18–0–1	4957 (1999)	~ HS18–0–1	96 (1979)	
		HS18–0–1	ISO 4957 (12/1999)	
United Kingdom		Russia		
HS18–0–1	EN ISO 4957 (12/1999)	~ R18	19265 (1973)	
Japan		China		
~ SKH 2	G 4403 (2000)	~ W18Cr4V	T 084 (1996)	
		~ T51841	T 3080 (2000)	
USA				
ASTM		AISI	SAE	UNS
~ A 600 (T 1)	A 597–99	~ T 1	~ T 1	~ T12001

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

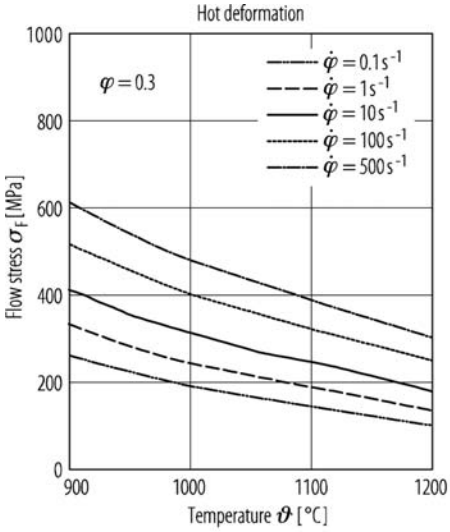
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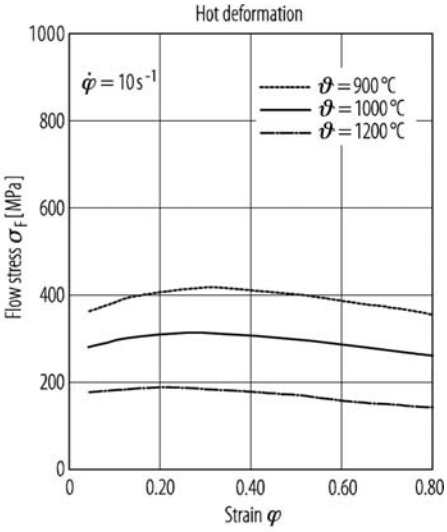
Flow curves

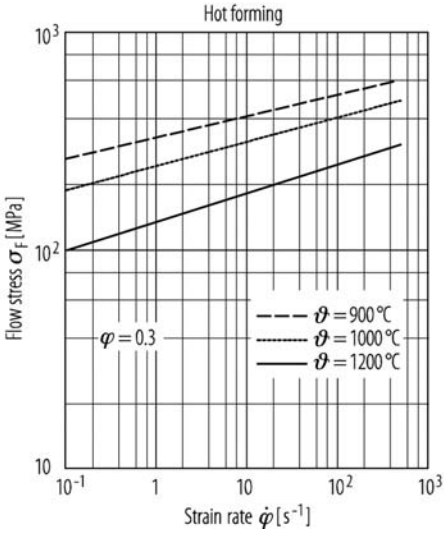
State of material	Hot deformation deformed state austenite	Cold deformation
σ_{F0} [MPa]	295.67	
A	7530.37	
Effect of temperature K_ϑ		
m_1	−0.00261	
Effect of strain K_φ		
m_2	0.38090	
m_4	0.01456	
m_5	−0.00136	
m_7	−0.17748	
Effect of strain rate $K_{\dot\varphi}$		
m_3		
m_8	0.000109	
Range of validity		
ϑ [°C]	900…1200	
φ	0.04…0.80	
$\dot\varphi$ [s^{-1}]	<500	

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Fig. 5.139.
HS18–0–1. Flow stress curves by hot forming.



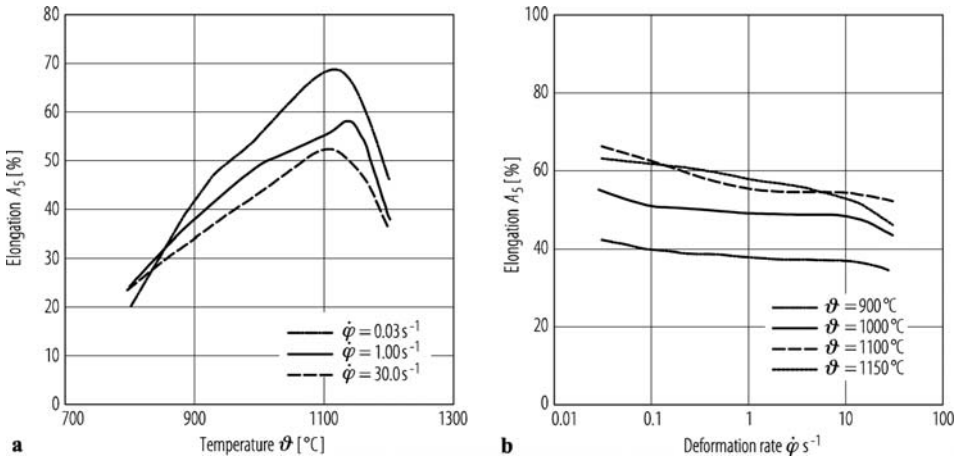




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Fig. 5.140.
HS18–0–1. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity in tensile test



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	24.48	433.86	11.18	8688.3	
100	24.67	479.84	11.33	8658.8	
200	24.92	501.92	11.56	8628.0	
300	25.16	521.88	11.90	8595.2	
400	25.41	541.82	12.15	8561.6	
500	25.66	562.19	12.37	8527.2	
600	25.91	583.15	12.59	8491.4	
700	26.17	604.78	12.87	8453.4	
800	26.42	627.15	13.17	8413.7	
900	26.68	650.30	13.48	8372.1	
1000	26.95	674.28	13.90	8325.9	
1100	27.21	699.11	14.24	8280.0	
1200	27.48	724.83	14.69	8228.8	

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Steel symbol/number: X120Mn12/1.3401

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
1.10…1.30	0.30…0.50	12.00…13.00	0.000…0.100	0.000…0.040	0.00…1.50

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
~ BW 10	3100 (1991)	~ 110G13L	977 (1988)	
		~ 110G13L	21357 (1987)	
Japan		China		
~ SCMnH 1	G 5131 (1991)	~ ZGMn13–1	T 5680 (1998)	
~ SCMnH 11	G 5131 (1991)	~ C40134	T 5680 (1998)	
USA				
ASTM		AISI	SAE	UNS
~ A 128 (A)	A 128–98			~ J91109
~ A 128 (B-3)	A 128–98			~ J91149

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

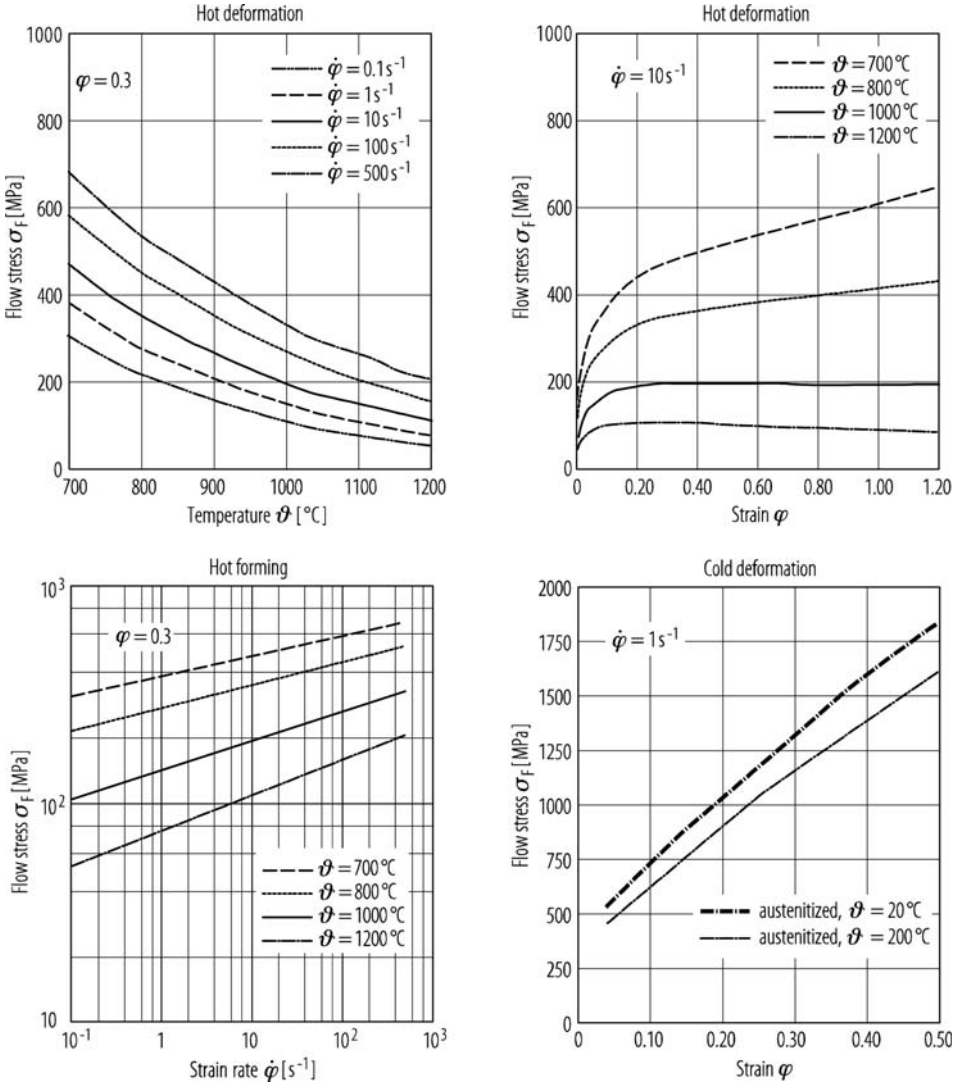
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation austenitized
σ_{F0} [MPa]	169.0	752.9
A	4354.67	2948.634
Effect of temperature K_ϑ		
m_1	−0.00271	−0.00173
Effect of strain K_φ		
m_2	0.31143	0.69423
m_4	−0.00028	0.02148
m_5	−0.00206	
m_7	0.71095	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.02311
m_8	0.000133	
Range of validity		
ϑ [°C]	700…1200	20…120
φ	0.04…1.20	0.04…0.50
$\dot\varphi$ [s^{-1}]	<500	<500

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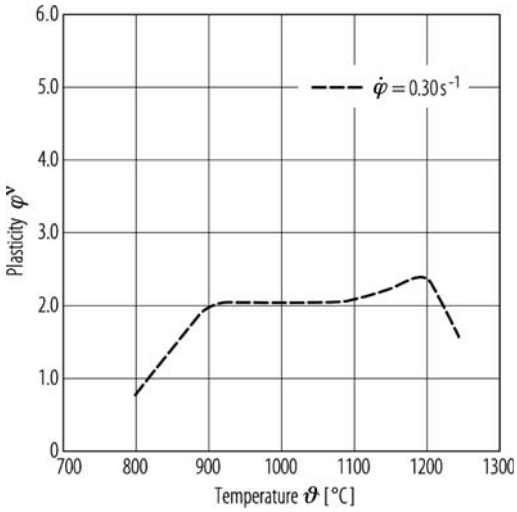
Fig. 5.142.
X120Mn12. Flow stress curves by hot and cold forming.



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Fig. 5.142.
X120Mn12. Hot plasticity as a function of the temperature. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.70.

Plasticity in torsion



DOI: 10.1007/978-3-540-44760-3_82
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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	15.46	493.31	16.97	7878.8	
100	17.07	500.10	18.01	7836.3	
200	18.44	508.73	19.37	7787.3	
300	19.72	517.50	20.71	7732.0	
400	21.01	526.43	21.70	7673.7	
500	22.33	535.51	20.76	7633.5	
600	23.70	544.74	19.86	7597.2	
700	25.13	554.14	20.49	7539.8	
800	26.63	563.69	21.86	7465.5	
900	28.20	573.42	23.45	7380.0	
1000	29.85	583.31	23.13	7332.1	
1100	31.59	593.37	23.61	7265.0	
1200	33.41	603.60	25.00	7169.7	

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

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Steel symbol/number: 100Cr6/1.3505

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.93…1.05	0.15…0.35	0.25…0.45	0.000…0.025	0.000…0.015	1.35…1.60
Mo	Al	Cu			
0.00…0.10	0.000…0.050	0.00…0.30			

International comparison of standards

ISO		Euronorm		
~ 100Cr6	683–17 (04/2000)	100Cr6	ISO 683–17 (04/2000)	
United Kingdom		Russia		
100Cr6	EN ISO 683–17 (04/2000)	~ SchCh15	801 (1978)	
~ 2 S. 135	Aerospace materials			
Japan		China		
~ SUJ 2	G 4805 (1999)	~ B00150	T 18254 (2002)	
~ SUJ 4	G 4805 (1999)	~ GCr15	T 18254 (2002)	
USA				
ASTM		AMS	SAE	UNS
~ A 506 (E 52100)	A 506–00	~ 6440K	~ E52100	~ G52986
~ A 711 (E 52100)	A 711–01			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

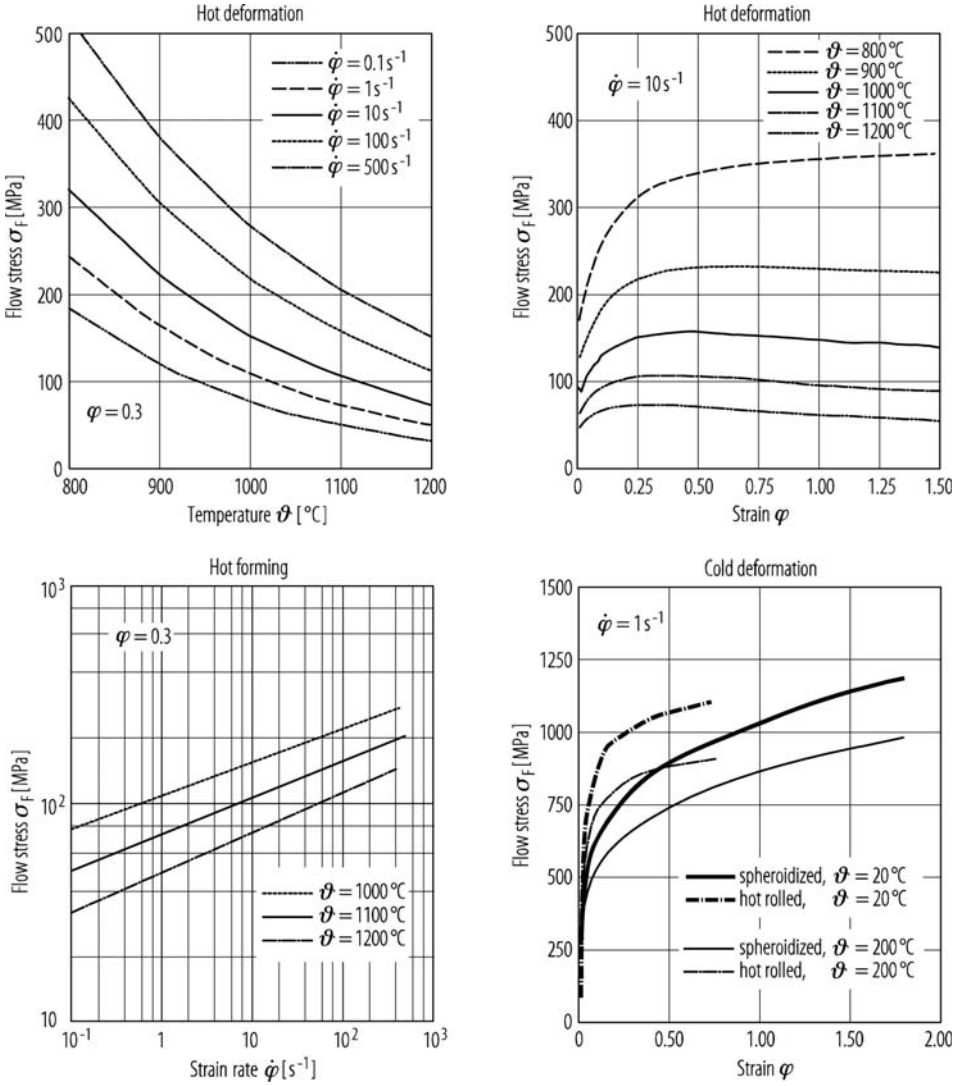
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	spheroidized	hot rolled
	austenite		
σ_{F0} [MPa]	129.79	645.2	893.0
A	8422.43	1060.945	1167.654
Effect of temperature K_ϑ			
m_1	−0.00361	−0.00108	−0.00110
Effect of strain K_φ			
m_2	0.36013	0.22065	0.06240
m_4	0.00367	0.00065	−0.01283
m_5	−0.00160		
m_7	0.32298		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01121	0.01121
m_8	0.000152		
Range of validity			
ϑ [°C]	800…1200	20. . .300	20…200
φ	<1.50	0.04…1.80	0.040…0.70
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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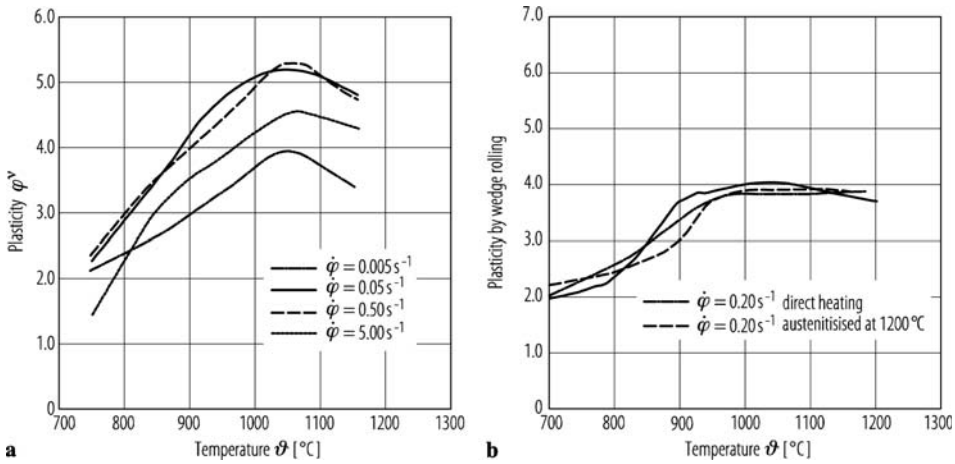
Fig. 5.144.
100Cr6. Flow stress curves by hot and cold forming.



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Fig. 5.144.
100Cr6. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	35.62	477.63	10.23	7791.8	213.2
100	39.05	491.46	10.72	7766.7	207.4
200	39.36	505.12	11.54	7737.8	201.5
300	37.76	525.46	12.11	7706.8	195.4
400	35.4	550.14	12.64	7673.6	187.4
500	32.87	577.4	13.2	7638.0	176.7
600	30.25	606.85	13.68	7600.0	162.6
700	27.69	638.22	14.21	7559.3	145.2
800	23.28	700.02	15.42	7503.4	124.9
900	26.26	697.50	16.76	7439.2	99.8
1000	28.25	695.00	17.96	7371.9	81.7
1100	29.84	692.50	19.06	7301.7	66.9
1200	31.46	690.01	20.07	7228.7	54.8

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Steel symbol/number: X2CrNiMnMoNNb21–16–5–3/1.3964

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.03	0.00…1.00	4.00…6.00	0.000…0.025	0.000…0.010	20.00…21.50
Mo	Ni	Nb	N		
3.00…3.50	15.00…17.00	0.000…0.250	0.200…0.350		

International comparison of standards

ISO		Euronorm	
United Kingdom		Russia	
Japan		China	
USA			
Spec	AISI	SAE	UNS
~ NITRONIC 50			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

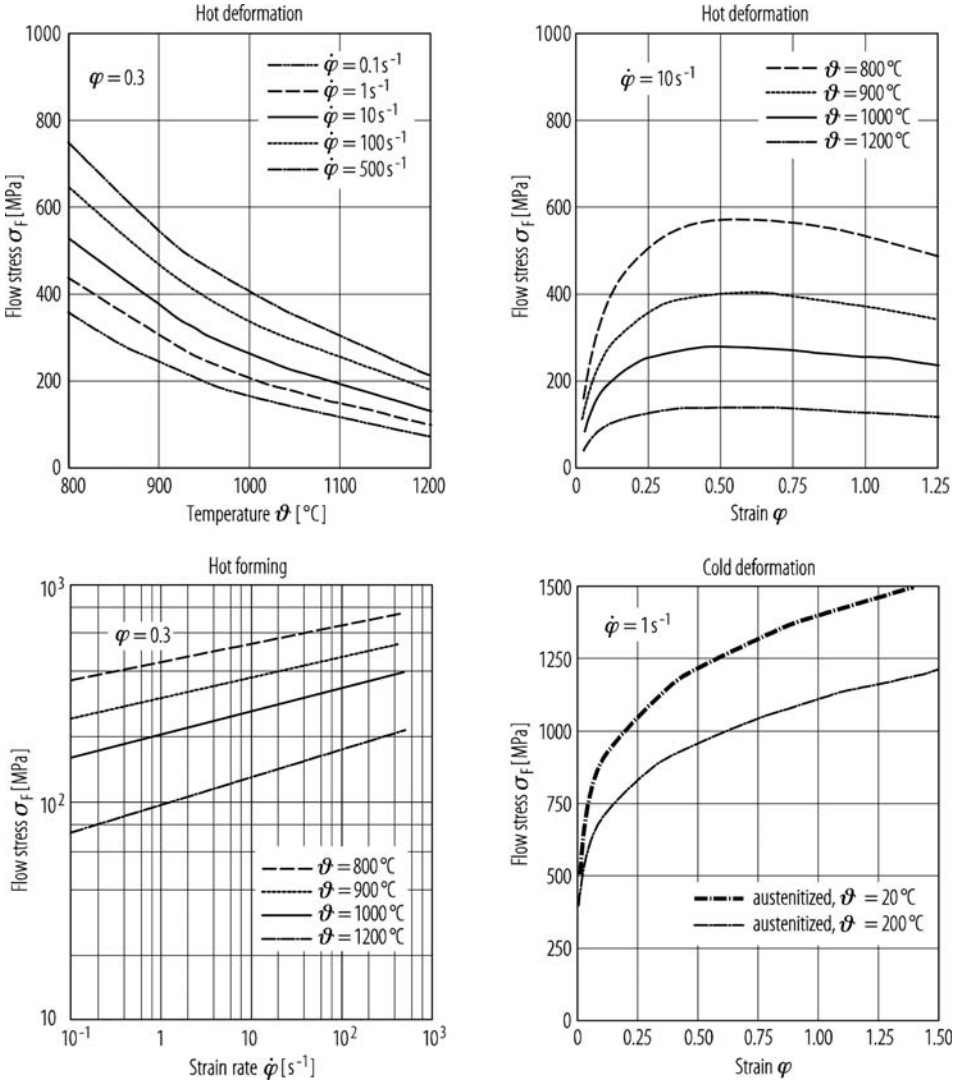
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation austenitized
σ_{F0} [MPa]	180.2	912.3
A	17613.70	1440.203
Effect of temperature K_ϑ		
m_1	−0.00371	−0.00131
Effect of strain K_φ		
m_2	0.36446	0.20116
m_4	−0.01979	0.00001
m_5	−0.00021	
m_7	−0.59463	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01416
m_8	0.000106	
Range of validity		
ϑ [°C]	800…1200	20…350
φ	0.04…1.25	0.04…1.25
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.145.
X2CrNiMnMoNNb21–16–5–3. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

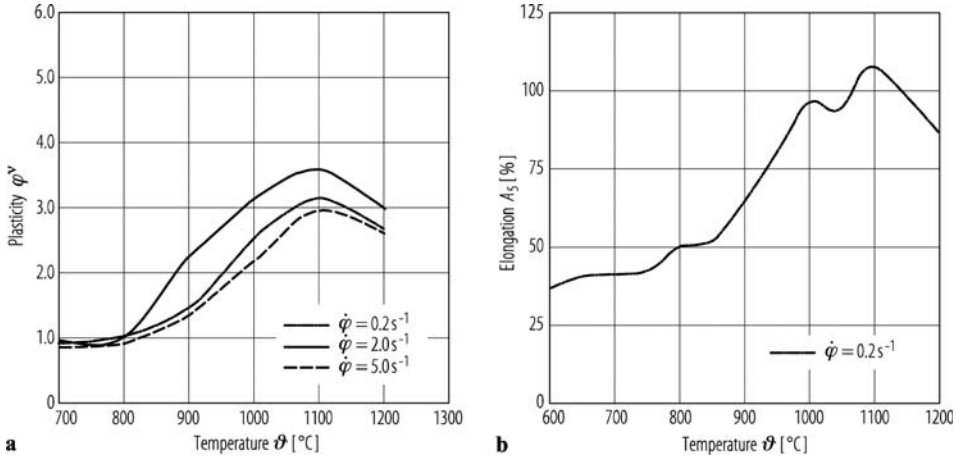
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	390…440	65.8915	0.65894	750…850	9.9459	1.05094

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	40…50	23.44882	0.16322	−5.28269	<80

Fig. 5.146.
X2CrNiMnMoNNb21–16–5–3. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Austenitised at 1200 [°C].

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	11.87	493.31	16.50	7891.4	195.6
100	14.12	500.10	16.73	7851.8	190.7
200	15.76	508.73	17.31	7809.4	183.1
300	17.18	517.50	17.02	7770.5	174.6
400	18.55	526.43	17.02	7730.2	165.9
500	19.92	535.51	17.92	7679.3	157.4
600	21.33	544.74	18.23	7632.5	148.9
700	22.78	554.14	18.54	7584.1	140.3
800	24.28	563.69	18.87	7534.1	131.1
900	25.86	573.42	19.19	7482.4	120.5
1000	27.51	583.31	19.53	7429.1	107.3
1100	29.24	593.37	19.86	7374.1	90.2
1200	31.05	603.60	20.21	7317.3	67.5

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Steel symbol/number: X7Cr14/1.4001

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.08	0.00…1.00	0.00…1.00	0.000…0.045	0.000…0.030	13.00…15.00

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
Japan		China		
~ SUS 429	G 4304 (1999)	~ H0Cr14	T 5092 (1996)	
~ SUS 429	G 4305 (1999)	~ W41148	T 5092 (1996)	
USA				
ASTM		AISI	SAE	UNS
~ A 182 (F 429)	A 182–02	~ 410 S	~ S41008	~ S41008
~ A 240 (410 S)	A 240–02	~429	~ S42900	~ S42900

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

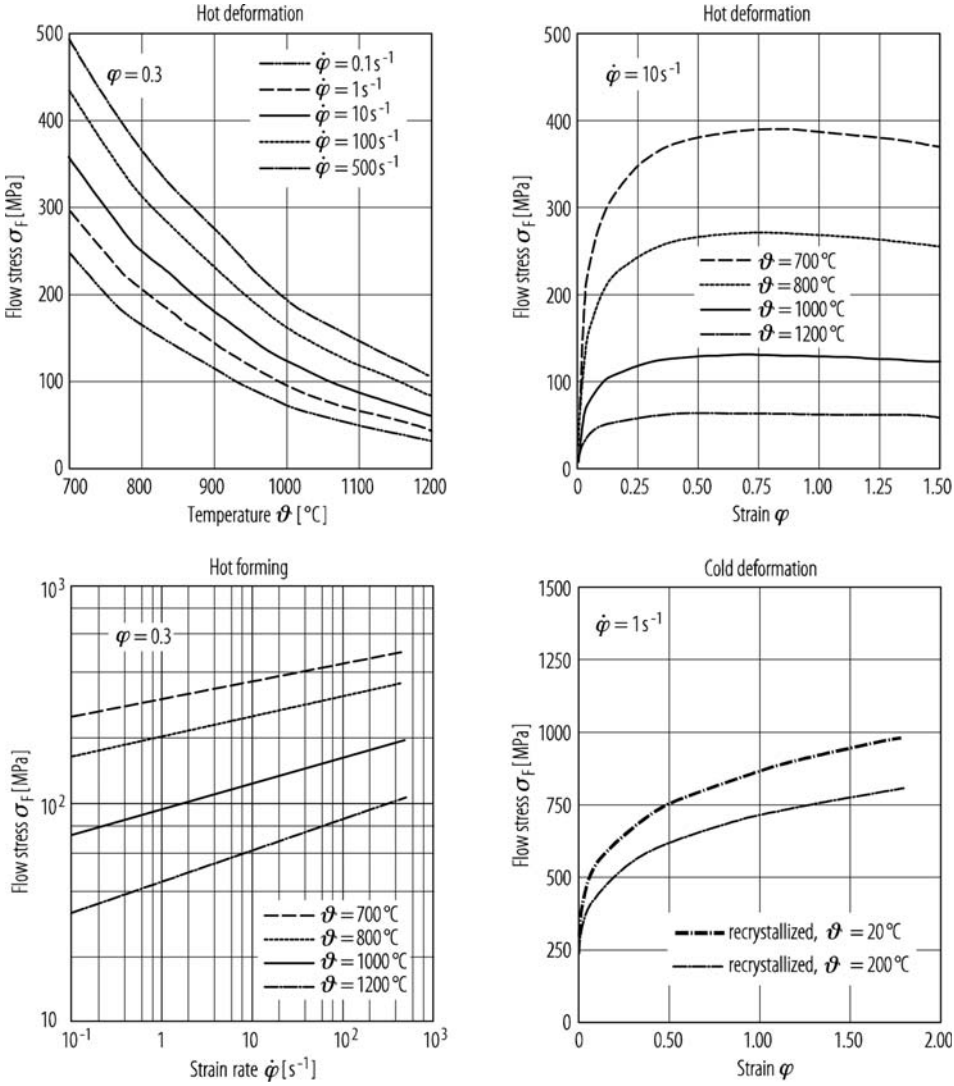
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Flow curves

State of material	Hot deformation deformed state ferrit+austenite	Cold deformation recrystallized
σ_{F0} [MPa]	98.3	551.43
A	6155.04	888.70
Effect of temperature K_ϑ		
m_1	−0.00377	−0.00112
Effect of strain K_φ		
m_2	0.22032	0.21782
m_4	−0.00904	0.00002
m_5	−0.00019	
m_7	−0.21646	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01981
m_8	0.000117	
Range of validity		
ϑ [°C]	700…1250	20…350
φ	0.04…1.50	0.04…1.80
$\dot\varphi$ [s^{-1}]	<500	< 500

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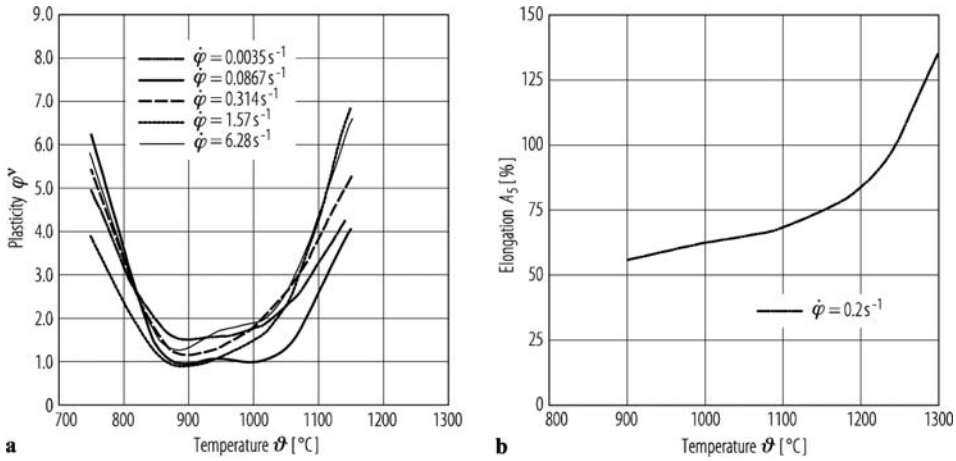
Fig. 5.147.
X7Cr14. Flow stress curves by hot and cold forming.



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Fig. 5.148.
X7Cr14. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	25.09	435.96	10.18	7692.8	
100	25.29	482.16	10.43	7668.8	
200	25.53	504.35	10.76	7643.2	
300	25.79	524.41	11.10	7616.0	
400	26.04	544.44	11.45	7587.1	
500	26.30	564.91	11.82	7556.5	
600	26.56	585.97	12.19	7524.1	
700	26.82	607.71	12.57	7489.7	
800	27.08	630.18	12.97	7453.3	
900	27.35	653.45	13.38	7414.9	
1000	27.62	677.53	13.80	7374.3	
1100	27.89	702.49	14.24	7331.3	
1200	28.16	728.33	14.69	7286.0	

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Steel symbol/number: X12Cr13/1.4006

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.08…0.15	0.00…1.00	0.00…1.50	0.000…0.040	0.000…0.015	11.50…13.50
Ni					
0.00…0.75					

International comparison of standards

ISO		Euronorm		
~ A	7153–1 (1991)	X12Cr13	10272 (10/2000)	
~ X12Cr13	TR 15510 (1997)	~ X 12 Cr 13 KD	119 (1974)	
United Kingdom		Russia		
X12Cr13	EN 10272 (10/2000)	~ 15Ch13L	977 (1988)	
~ 410 S 21	970 Part 1 (1996)	~ 12Ch13	5632 (1972)	
Japan		China		
~ SUS 410TKA	G 3446 (1994)	~ S40310	T 1220 (1992)	
~ SUS 410	G 4315 (2000)	~ ZG 15Cr13	T 6405 (1992)	
USA				
ASTM		AISI	SAE	UNS
~ A 182 (F 6a)	A 182–02	~ 614	~ S41000	~ S41000
~ A 240 (410)	A 240–02	~ 410	~ 410	~ J91171

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

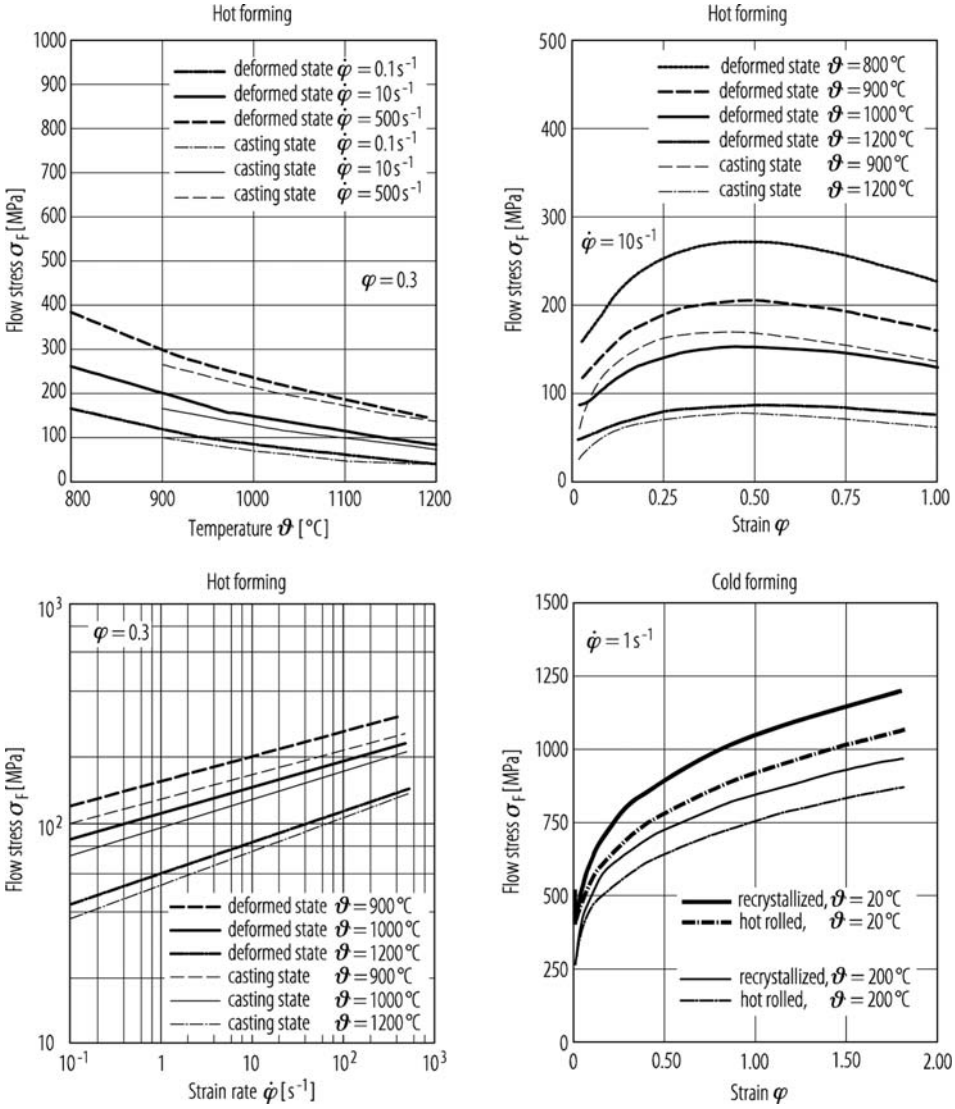
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Flow curves

State of material	Hot deformation		Cold deformation	
	deformed state	casting state	recrystallized	hot rolled
	austenite + ferrite	austenite + ferrite		
σ_{F0} [MPa]	111.98	97.06	576.9	647.6
A	6643.87	4239.37	940.641	1071.352
Effect of temperature K_ϑ				
m_1	−0.00329	−0.00308	−0.00109	−0.00115
Effect of strain K_φ				
m_2	0.48144	0.36963	0.23861	0.22854
m_4	0.01207	−0.00653	0.00392	0.00001
m_5	0.00037	0.00041		
m_7	−1.17964	−1.17951		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.01873	0.01986
m_8	0.000120	0.000129		
Range of validity				
ϑ [°C]	800...1200	900…1200	20…350	20…350
φ	0.04…1.00	0.04…1.00	0.04…1.80	0.04…1.80
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.149.
X12Cr13. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
soft annealed	300…330	69.7969	0.4528	500…550	16.3669	0.71442

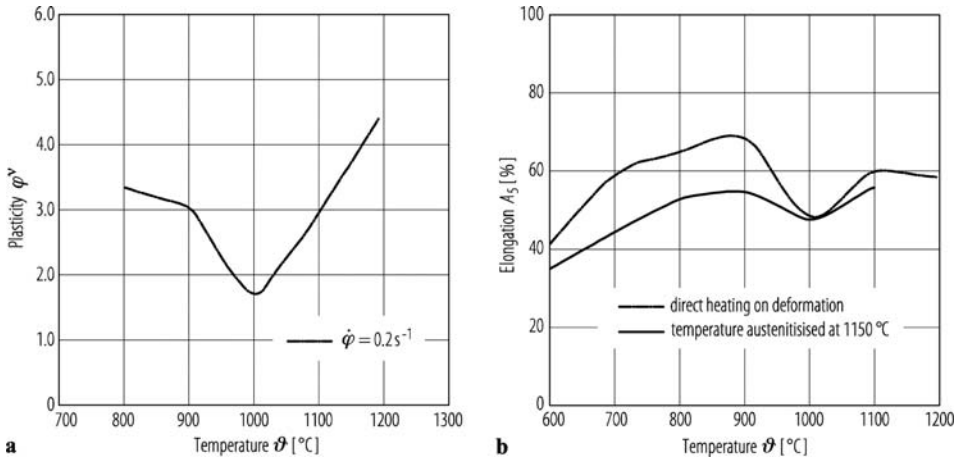
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Mechanical properties after cold deformation

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
soft annealed	24…28	42.31789	−0.14115	−12.2165	<70

Fig. 5.150.
X12Cr13. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformation rate: 0.2 [1/2]. Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ °C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	24.91	435.34	10.18	7708.4	215.4
100	25.10	481.48	10.43	7668.8	206.7
200	25.35	503.64	10.76	7658.7	199.5
300	25.60	523.67	11.10	7631.4	193.8
400	25.85	543.68	11.45	7602.5	187.4
500	26.11	564.11	11.82	7571.8	178.5
600	26.37	585.14	12.19	7539.3	166.2
700	26.63	606.85	12.57	7504.9	150.1
800	26.89	629.30	12.97	7468.5	130.4
900	27.15	652.53	13.38	7429.9	108.1
1000	27.42	676.58	13.80	7389.2	84.7
1100	27.69	701.50	14.24	7346.2	62.4
1200	27.96	727.31	14.69	7300.8	

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

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Steel symbol/number: X6CrNi17–1/1.4017

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.08	0.00…1.00	0.00…1.00	0.000…0.040	0.000…0.015	16.00…18.00
Ni					
1.20…1.60					

International comparison of standards

ISO		Euronorm		
		X6CrNi17–1	10088–2 (04/1995)	
United Kingdom		Russia		
X6CrNi17–1	EN 10088–2 (04/1995)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

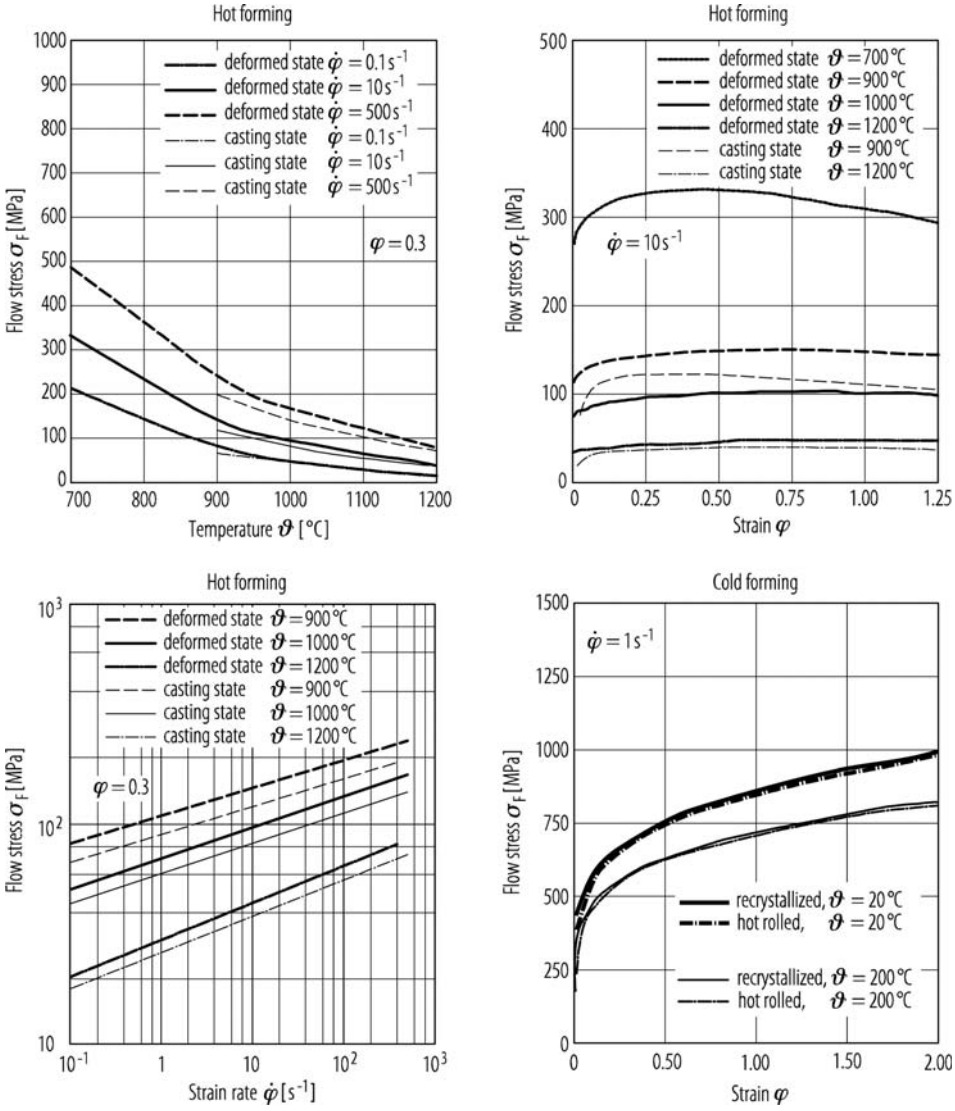
DOI: 10.1007/978-3-540-44760-3_87
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Flow curves

State of material	Hot deformation		Cold deformation	
	deformed state	casting state	recrystallized	hot rolled
	austenite + ferrite	austenite + ferrite		
σ_{F0} [MPa]	89.8	75.64	543.7	590.2
A	7148.36	4561.29	874.124	878.923
Effect of temperature K_ϑ				
m_1	−0.0046	−0.00438	−0.00101	−0.00104
Effect of strain K_φ				
m_2	0.05758	−0.05417	0.18693	0.19047
m_4	0.00001	−0.01862	−0.00289	0.00155
m_5	0.00081	0.00079		
m_7	−0.53815	−0.53809		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.00204	0.01982
m_8	0.000141	0.000139		
Range of validity				
ϑ [°C]	700…1200	900…1200	20…350	20…350
φ	0.04…1.25	0.04…1.25	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.151.
X6CrNi17–1. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
hot rolled	240…280	171.15850	0.22507	430…500	35.62900	0.48899

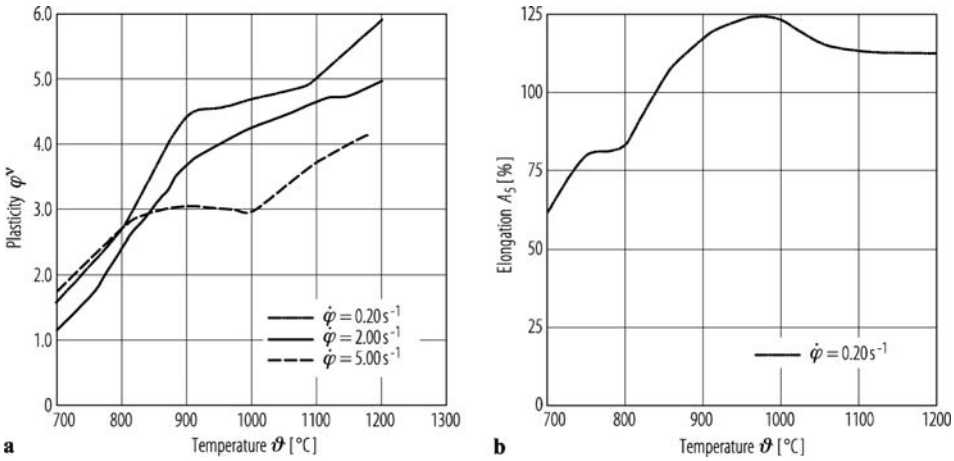
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
hot rolled	35…42	22.92642	0.07925	−1.81126	<70

Fig. 5.152.
X6CrNi17-1. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	26.46	440.54	10.18	7688.8	192.3
100	26.67	487.23	10.43	7684.3	188.4
200	26.93	509.65	10.76	7639.1	182.6
300	27.20	529.92	11.10	7611.9	175.2
400	27.46	550.17	11.45	7583.1	165.9
500	27.74	570.85	11.82	7552.5	154.5
600	28.01	592.13	12.19	7520.1	141.0
700	28.28	614.09	12.57	7485.7	126.0
800	28.56	636.81	12.97	7449.4	109.8
900	28.84	660.32	13.38	7411.0	93.3
1000	29.13	684.66	13.80	7370.3	77.4
1100	29.42	709.87	14.24	7327.4	63.4
1200	29.70	735.99	14.69	7282.1	52.7

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: X20Cr13/1.4021

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.16…0.25	0.00…1.00	0.00…1.50	0.000…0.040	0.000…0.015	12.00…14.00

International comparison of standards

ISO		Euronorm		
~ B	7153–1 (1991)	X20Cr13	10250–4 (1999)	
~ X20Cr13	TR 15510 (1997)	X20Cr13	10151 (06/2002)	
United Kingdom		Russia		
X20Cr13	EN 10250–4 (10/1999)	~ 20Ch13	5632 (1972)	
~ 420 S 37	970 Part 1 (1996)			
Japan		China		
~ SUS 420J1 TKA	G 3446 (1994)	~ SM 2Cr13	T 094 (1997)	
~ SUS 420J1	G 4309 (1999)	~ S42020	T 14975 (1994)	
USA				
ASTM		AISI	AMS	UNS
~ A 176 (420)	A 176–99	~ 420	~ 5506F	~ S42000
~ A 276 (420)	A 276–02	~ S42000	~ 5621E	

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

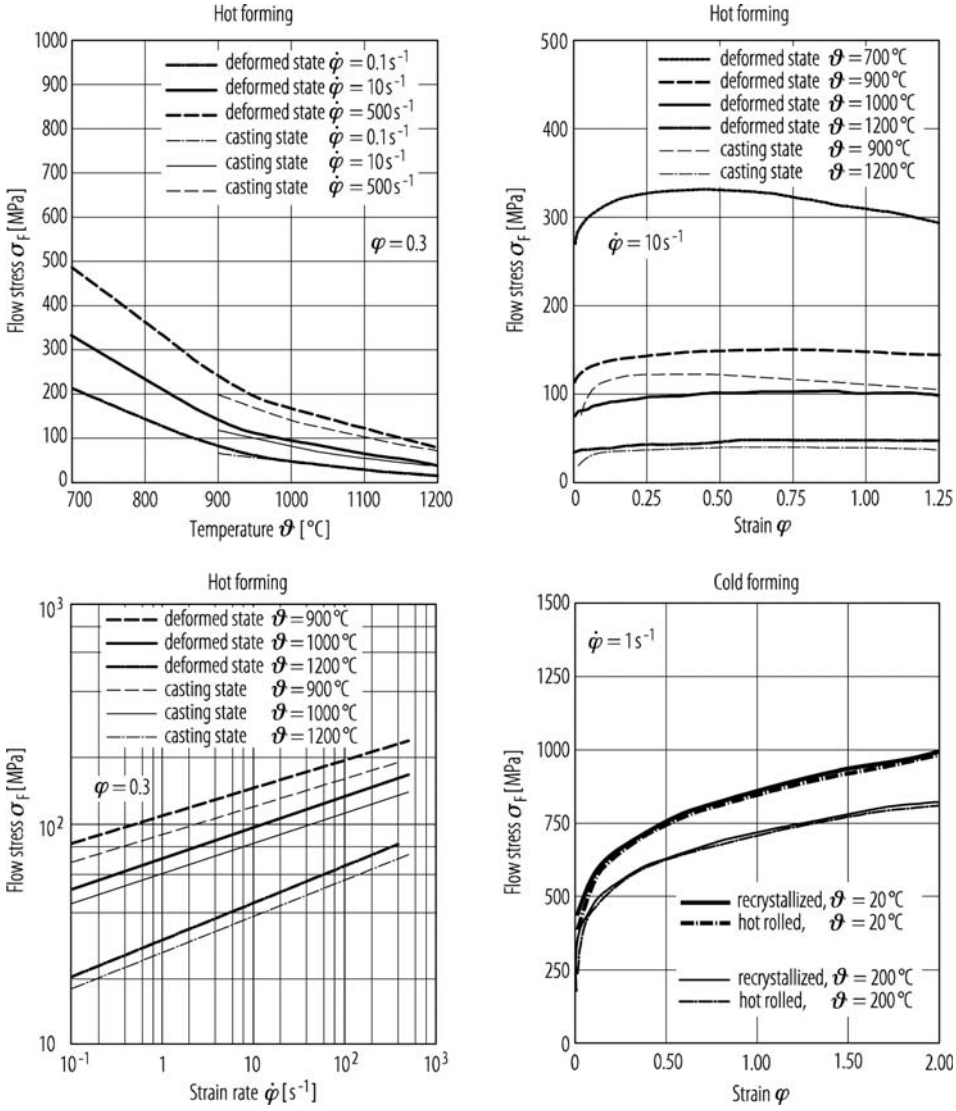
DOI: 10.1007/978-3-540-44760-3_88
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	recrystallized	hot rolled
	austenite		
σ_{F0} [MPa]	130.08	637.8	709.0
A	3867.07	896.304	967.914
Effect of temperature K_ϑ			
m_1	−0.00322	−0.00110	−0.00107
Effect of strain K_φ			
m_2	0.18640	0.15808	0.14417
m_4	0.00016	0.00001	0.00001
m_5	0.00021		
m_7	−0.46052		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01982	0.01823
m_8	0.000122		
Range of validity			
ϑ [°C]	900…1250	20…300	20…300
φ	0.04…1.50	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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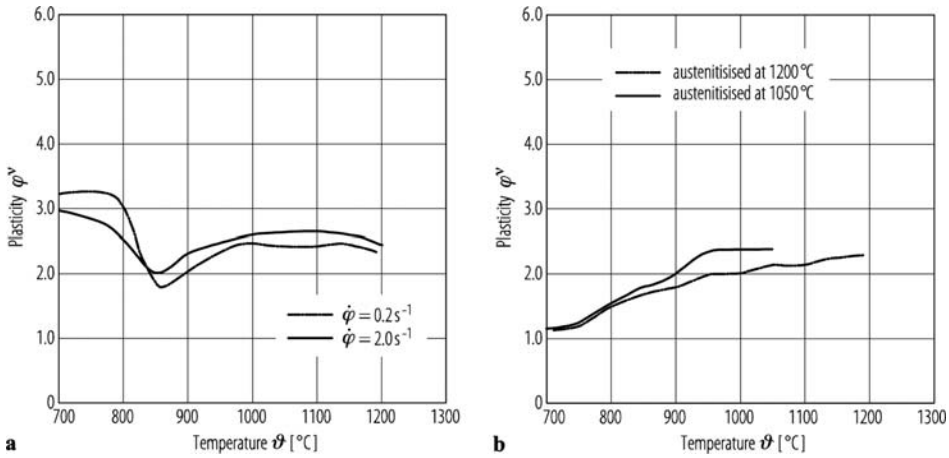
Fig. 5.153.
X20Cr13. Flow stress curves by hot and cold forming.



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Fig. 5.154.
X20Cr13. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deforamtion rate: [s^{-1}]. Deformed state.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	25.09	435.97	10.18	7691.8	213.2
100	25.29	482.18	10.43	7664.7	204.5
200	25.54	504.37	10.76	7642.1	197.3
300	25.79	524.43	11.10	7614.9	191.6
400	26.05	544.47	11.45	7586.0	185.2
500	26.30	564.93	11.82	7555.4	176.3
600	26.56	585.99	12.19	7523.0	164.0
700	26.82	607.73	12.57	7488.6	147.9
800	27.09	630.21	12.97	7452.3	128.2
900	27.35	653.47	13.38	7413.8	105.9
1000	27.62	677.56	13.80	7373.2	82.5
1100	27.89	702.51	14.24	7330.3	60.2
1200	28.17	728.36	14.69	7285.0	41.8

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: X46Cr13/1.4034

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.43…0.50	0.00…1.00	0.00…1.00	0.000…0.040	0.000…0.015	12.50…14.50

International comparison of standards

ISO		Euronorm		
~ D	7153–1 (1991)	X46Cr13	10088–2 (04/1995)	
~ X46Cr13	TR 15510 (1997)	X46Cr13	10088–3 (04/1995)	
United Kingdom		Russia		
X46Cr13	EN 10088–2 (04/1995)	~ 40Ch13	5632 (1972)	
X46Cr13	EN 10088–3 (04/1995)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

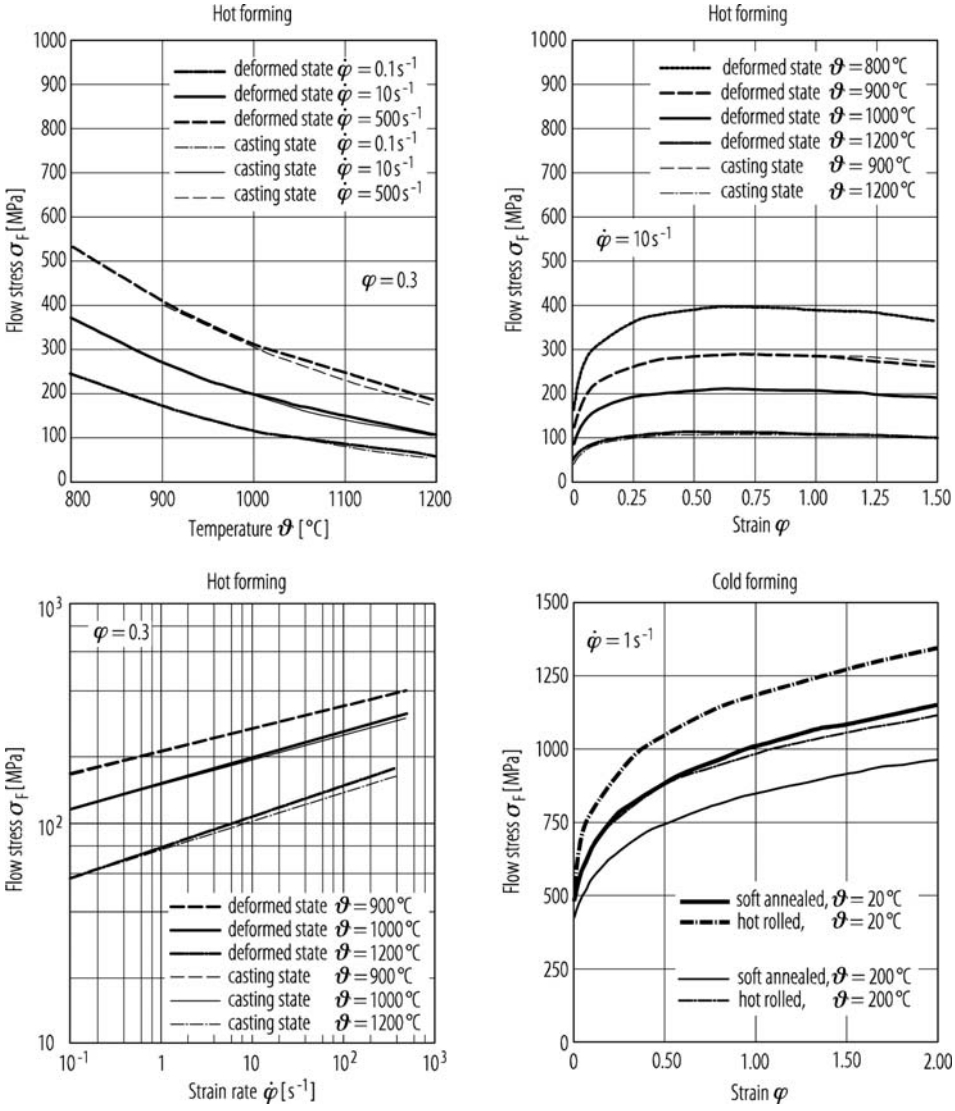
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Flow curves

	Hot deformation		Cold deformation	
	deformed state	casting state	soft annealed	hot rolled
State of material	austenite+carb.	austenite+carb.		
σ_{F0} [MPa]	162.2	158.8	668.6	804.6
A	6753.46	7402.48	1024.619	1208.257
Effect of temperature K_ϑ				
m_1	−0.00336	−0.00350	−0.00096	−0.00103
Effect of strain K_φ				
m_2	0.25732	0.24275	0.18944	0.17759
m_4	0.00022	−0.00054	0.00164	0.00005
m_5	−0.00015	−0.00001		
m_7	−0.29333	−0.32327		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.00526	0.00974
m_8	0.000115	0.000111		
Range of validity				
ϑ [°C]	780…1200	900…1200	20…300	20…300
φ	0.04…1.50	0.04…1.50	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.155.
X46Cr13. Flow stress curves by hot and cold forming.



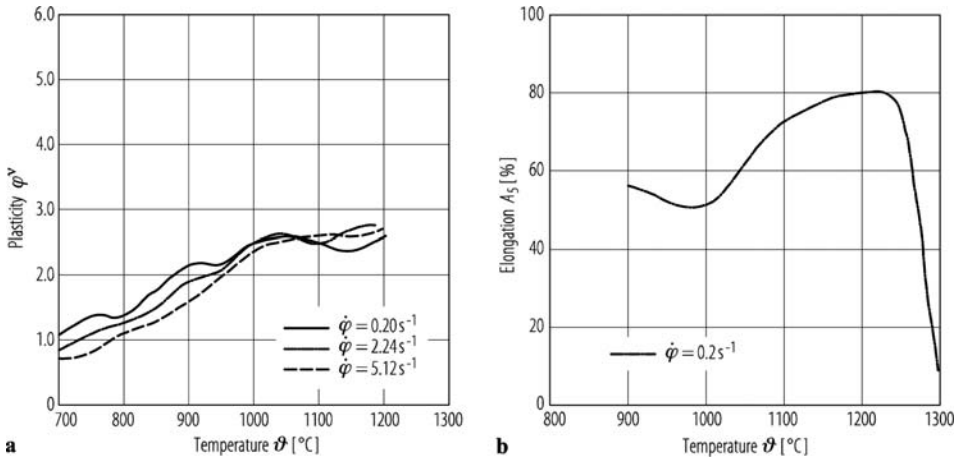
Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
soft annealed	400…450	16.8917	0.80254	700…750	12.8587	0.84012	<80

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Fig. 5.156.
X46Cr13. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	25.54	437.47	10.18	7679.4	222.2
100	25.74	483.83	10.43	7667.7	213.5
200	25.99	506.10	10.76	7629.8	206.3
300	26.25	526.23	11.10	7602.6	200.6
400	26.50	546.33	11.45	7573.8	194.2
500	26.77	566.87	11.82	7543.2	185.3
600	27.03	588.00	12.19	7510.9	173.0
700	27.29	609.82	12.57	7476.6	156.9
800	27.56	632.37	12.97	7440.3	137.2
900	27.84	655.72	13.38	7401.9	114.9
1000	28.11	679.89	13.80	7361.3	91.5
1100	28.39	704.93	14.24	7318.5	69.2
1200	28.67	730.86	14.69	7273.2	50.8

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Steel symbol/number: X14CrMoS17/1.4104

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.10…0.17	0.00…1.00	0.00…1.50	0.000…0.040	0.150…0.350	15.50…17.50
Mo					
0.20…0.60					

International comparison of standards

ISO		Euronorm		
X14CrMoS17	7153–1 (1991)	X14CrMoS17	10088–1 (1995)	
United Kingdom		Russia		
X14CrMoS17	EN 10088–1 (1995)			
Japan		China		
~ SUS 430F	G 4309 (1998)	~ Y1Cr17	T 1220 (1992)	
~ SUS 430F	G 4309 (1999)	~ S11714	T 4240 (1993)	
USA				
ASTM		AISI	SAE	UNS
~ A 314 (430 F)	A 314–02	~ 430 F		~ S43020
~ A 581 (430 F)	A 581–00			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

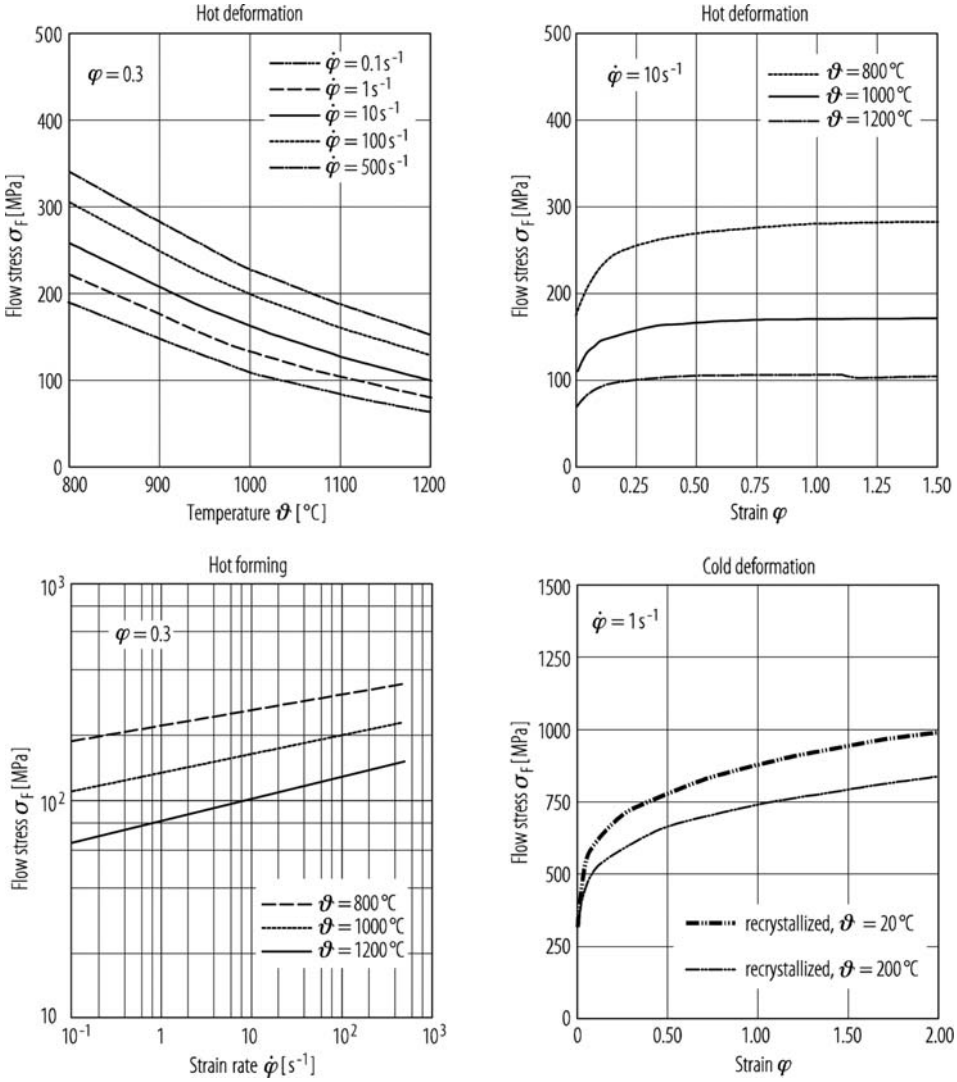
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Flow curves

State of material	Hot deformation deformed state austenite+ferrite	Cold deformation recrystallized
σ_{F0} [MPa]	145.1	615.1
A	1984.72	897.765
Effect of temperature K_ϑ		
m_1	−0.00248	−0.00098
Effect of strain K_φ		
m_2	0.13787	0.16526
m_4	0.00061	−0.00109
m_5	−0.00027	
m_7	0.00818	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01424
m_8	0.000087	
Range of validity		
ϑ [°C]	800…1100	20…350
φ	0.04…1.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.157.
X14CrMoS17. Flow stress curves by hot and cold forming.



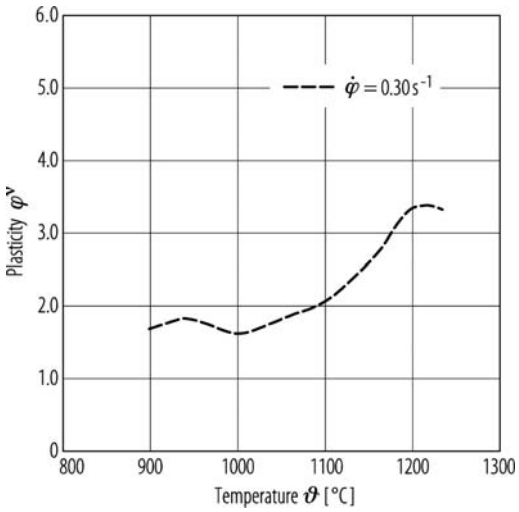
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Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
soft annealed				430…470	16.4489	0.74312	<70
hot rolled	350…400	23.5254	0.76259	530…600	16.7809	0.75824	<70

Fig. 5.158.
X14CrMoS17. Hot plasticity as a function of the temperature. Deformed state. Direct on heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.25…0.50.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	26.24	439.83	10.18	7683.0	215.9
100	26.45	486.45	10.43	7655.3	213.2
200	26.71	508.83	10.76	7633.4	206.7
300	26.97	529.07	11.10	7606.2	200.2
400	27.24	549.28	11.45	7577.4	196.9
500	27.51	569.93	11.82	7546.8	195.4
600	27.78	591.17	12.19	7514.4	189.4
700	28.05	613.11	12.57	7480.1	
800	28.33	635.78	12.97	7443.8	
900	28.61	659.25	13.38	7405.4	
1000	28.89	683.56	13.80	7364.8	
1100	29.17	708.73	14.24	7321.9	
1200	29.46	734.81	14.69	7276.7	

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Steel symbol/number: X90CrMoV18/1.4112

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.85…0.95	0.00…1.00	0.00…1.00	0.000…0.040	0.000…0.015	17.00…19.00
Mo	V				
0.90…1.30	0.07…0.12				

International comparison of standards

ISO		Euronorm		
~ K	7153–1 (1991)	X90CrMoV18	10088–3 (04/1995)	
United Kingdom		Russia		
X90CrMoV18	EN 10088–3 (04/1995)			
Japan		China		
~ SUS 440B	G 4303 (1998)	~ 9Cr18MoV	T 1220 (1992)	
		~ S46990	T 1220 (1992)	
USA				
ASTM		AISI	AMS	UNS
~ A 314 (440 B)	A 314–02	~ S44003	~ 7115D	~ S44003
~ A 580 (440 B)	A 580–98	~ 440 B		

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

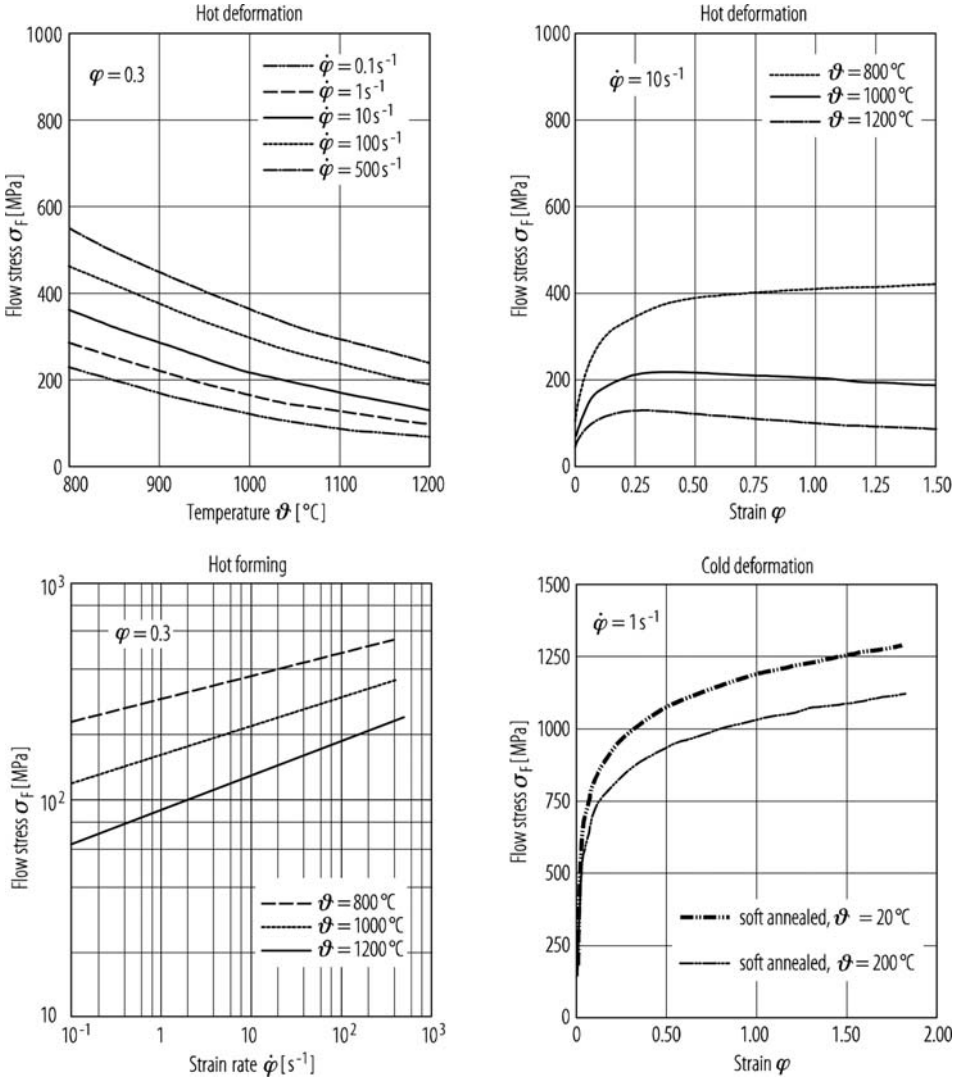
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Flow curves

State of material	Hot deformation deformed state austenite+carb.	Cold deformation soft annealed
σ_{F0} [MPa]	175.2	831.6
A	4118.72	1215.531
Effect of temperature K_ϑ		
m_1	−0.00232	−0.00079
Effect of strain K_φ		
m_2	0.43044	0.13103
m_4	0.00080	−0.00779
m_5	−0.00210	
m_7	0.46494	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01412
m_8	0.000130	
Range of validity		
ϑ [°C]	800…1200	20…300
φ	0.04…1.500	0.04…1.80
$\dot\varphi$ [s^{-1}]	<500	<500

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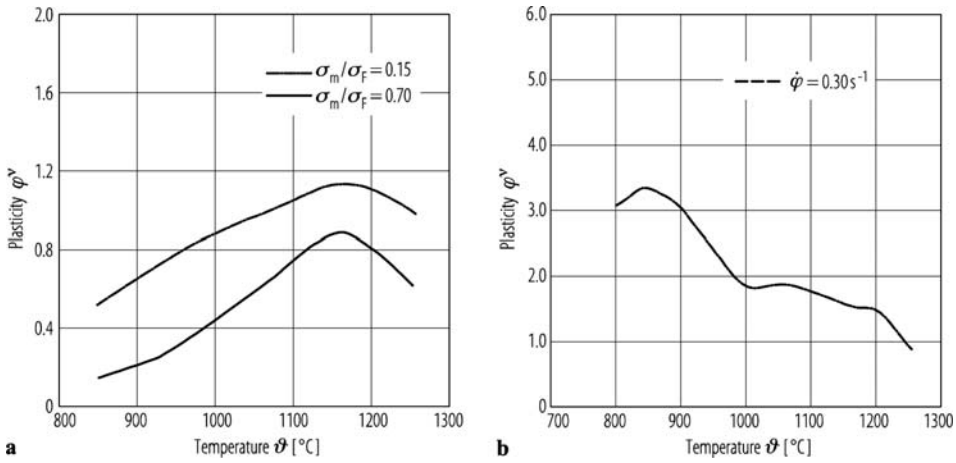
Fig. 5.159.
X90CrMoV18. Flow stress curves by hot and cold forming.



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Fig. 5.160.
X90CrMoV18. Hot plasticity as a function of the temperature. (a) Casting state. Austenitised at 1250 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	27.61	444.22	10.18	7656.1	223.0
100	27.82	491.30	10.43	7658.9	217.0
200	28.10	513.90	10.76	7606.6	209.0
300	28.37	534.34	11.10	7579.6	201.0
400	28.65	554.76	11.45	7550.8	192.0
500	28.93	575.61	11.82	7520.4	179.3
600	29.22	597.07	12.19	7488.1	158.6
700	29.51	619.22	12.57	7453.9	
800	29.80	642.12	12.97	7417.7	
900	30.09	665.83	13.38	7379.5	
1000	30.39	690.37	13.80	7339.0	
1100	30.69	715.80	14.24	7296.3	
1200	30.99	742.13	14.69	7251.2	

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Steel symbol/number: X50CrMoV15/1.4116

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.45…0.55	0.00…1.00	0.00…1.00	0.000…0.040	0.000…0.015	14.00…15.00
Mo	V				
0.50…0.80	0.10…0.20				

International comparison of standards

ISO		Euronorm		
~ I	7153–1 (1991)	X50CrMoV15	10088–3 (04/1995)	
United Kingdom		Russia		
X50CrMoV15	EN 10088–3 (04/1995)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

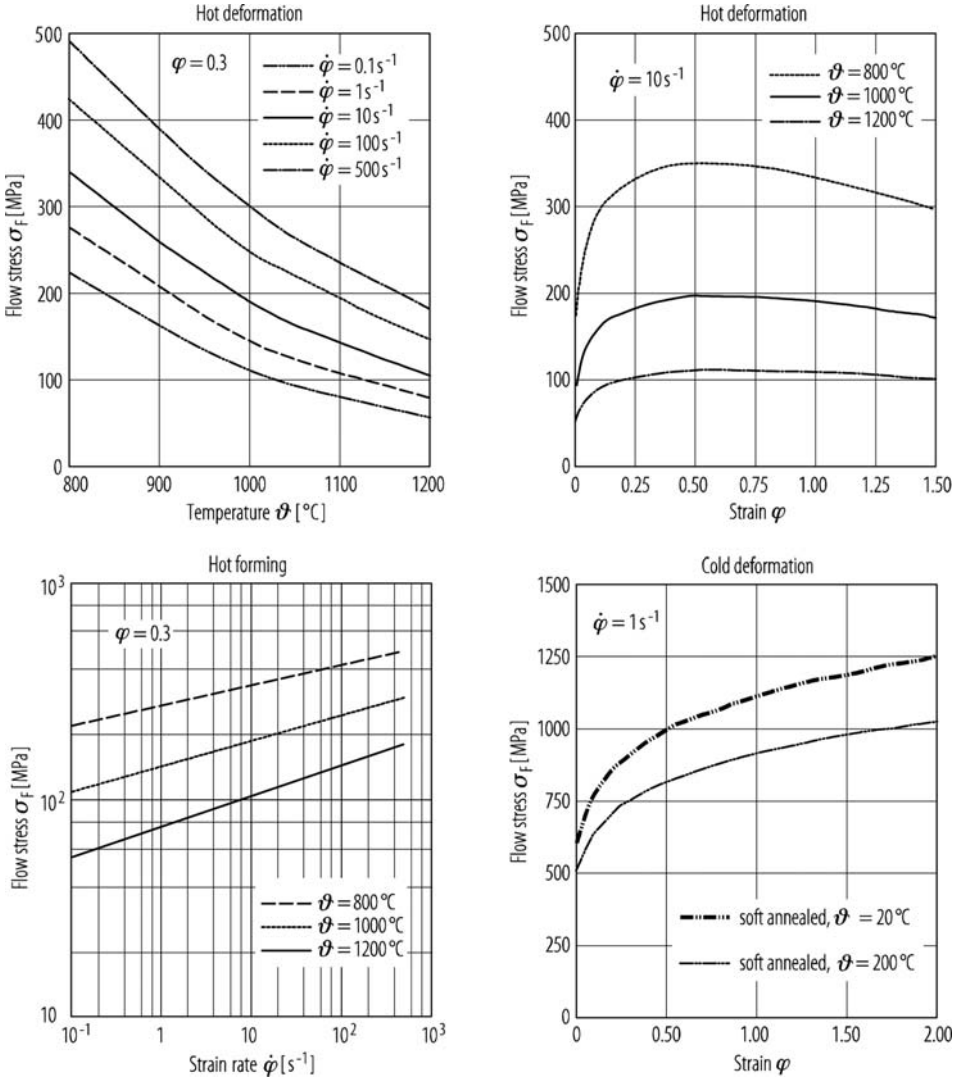
DOI: 10.1007/978-3-540-44760-3_92
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Flow curves

State of material	Hot deformation deformed state austenite+carb.	Cold deformation soft annaeled
σ_{F0} [MPa]	160.2	782.2
A	5219.57	1133.070
Effect of temperature K_ϑ		
m_1	−0.00330	−0.00108
Effect of strain K_φ		
m_2	0.18784	0.16594
m_4	−0.00015	0.00158
m_5	0.00034	
m_7	−0.51387	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00752
m_8	0.000117	
Range of validity		
ϑ [°C]	800…1250	20…300
φ	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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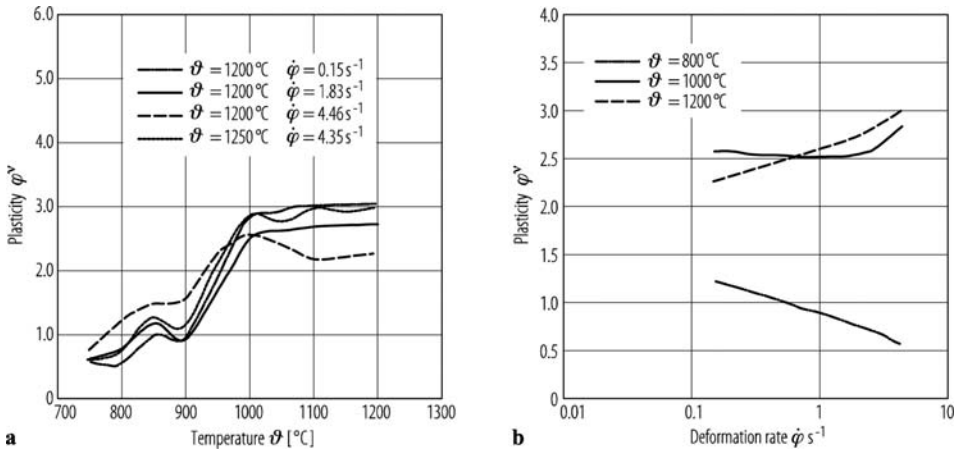
Fig. 5.161.
X50CrMoV15. Flow stress curves by hot and cold forming.



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Fig. 5.162.
X50CrMoV15. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Austenitised at 1200 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	26.03	439.14	10.18	7689.2	
100	26.24	485.68	10.43	7632.1	
200	26.50	508.03	10.76	7639.6	
300	26.76	528.23	11.10	7612.4	
400	27.02	548.41	11.45	7583.6	
500	27.29	569.03	11.82	7553.0	
600	27.56	590.24	12.19	7520.5	
700	27.83	612.14	12.57	7486.2	
800	28.10	634.78	12.97	7449.9	
900	28.38	658.21	13.38	7411.4	
1000	28.66	682.48	13.80	7370.8	
1100	28.94	707.61	14.24	7327.9	
1200	29.23	733.65	14.69	7282.6	

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Steel symbol/number: X5CrNi18–10/1.4301

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.07	0.00…1.00	0.00…2.00	0.000…0.045	0.000…0.015	17.00…19.50
Ni	N	Cu			
8.00…10.50	0.000…0.110	0.00…1.00			

International comparison of standards

ISO		Euronorm		
~ M	7153–1 (1991)	X5CrNi18–10	10263–5 (06/2001)	
~ X5CrNi18–9	9329–4 (1997)	X5CrNi18–10	10222–5 (02/2000)	
United Kingdom		Russia		
~ 304 S 15	970 Part 1 (1996)	~ 08Ch18N10	5632 (1972)	
X5CrNi18–10	EN 10263–5 (06/2001)			
Japan		China		
~ SUS 304	G 4315 (2000)	~ 0Cr18Ni9	T 085 (1996)	
~ SUS 304CSP	G 4313 (1996)	~ S30408	T 3090(2000)	
USA				
ASTM		AISI	SAE	UNS
~ A 182 (F 304)	A 182–02	~ 304	~ 304	~ S30400
~ A 249 (304)	A 249–02		~ 30400	~ J92610

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

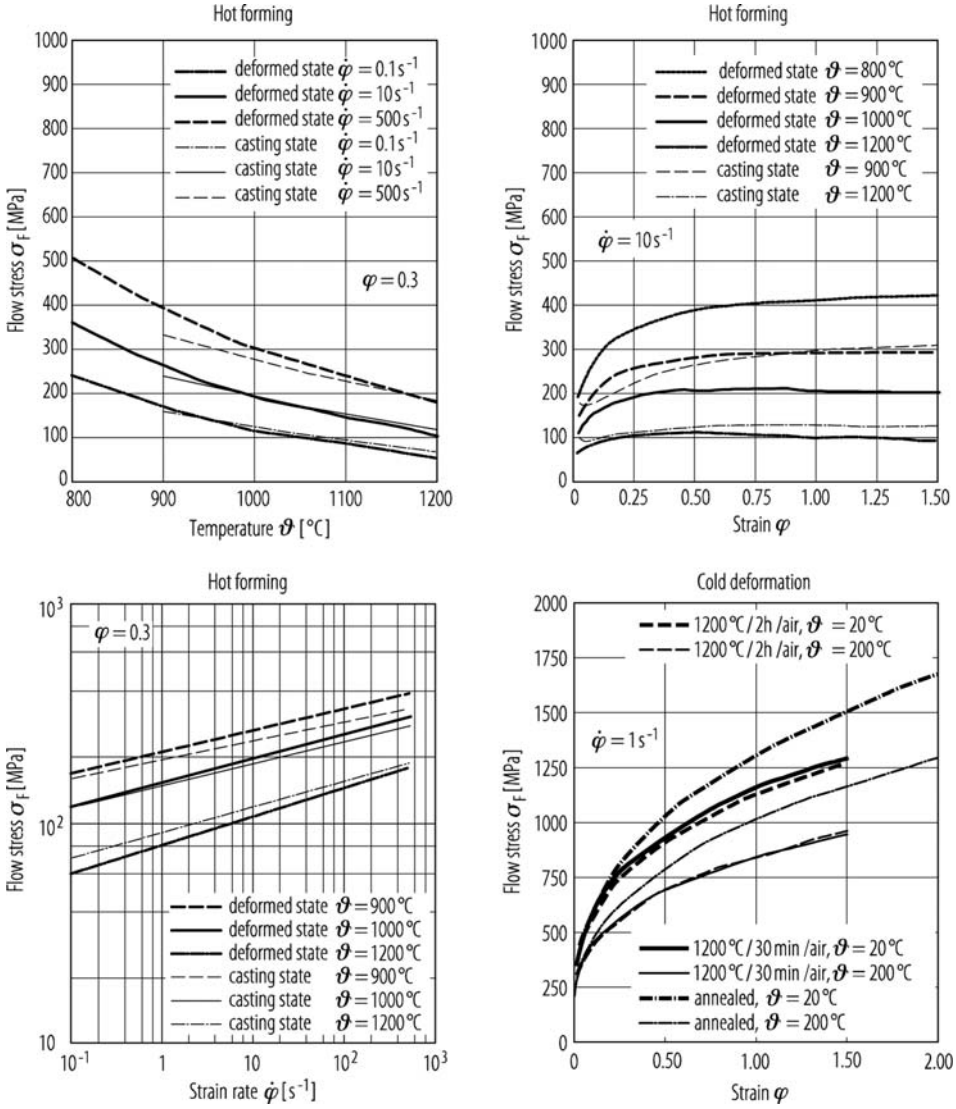
DOI: 10.1007/978-3-540-44760-3_93
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Flow curves

State of material	Hot deformation		Cold deformation		
	deformed state	casting state	1200°C/2h/air	1050°C/ 30min/air	austenitized
	austenite	austenite			
σ_{F0} [MPa]	158.4	148.15	568.3	593.5	597.2
A	5857.22	3072.23	1170.679	1188.736	1335.332
Effect of temperature K_ϑ					
m_1	−0.00300	−0.00223	−0.00168	−0.00173	−0.00148
Effect of strain K_φ					
m_2	0.34846	0.50496	0.30459	0.29211	0.36291
m_4	0.00277	0.02303	0.00021	0.00021	0.00372
m_5	−0.00105	−0.0011			
m_7	0.13542	0.13498			
Effect of strain rate $K_{\dot\varphi}$					
m_3			0.00441	0.00456	0.01014
m_8	0.000109	0.000096			
Range of validity					
ϑ [°C]	800…1250	900…1200	20…300	20…300	20…300
φ	0.04…1.50	0.04…1.50	0.04…1.50	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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Fig. 5.163.
X5CrNi18–10. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

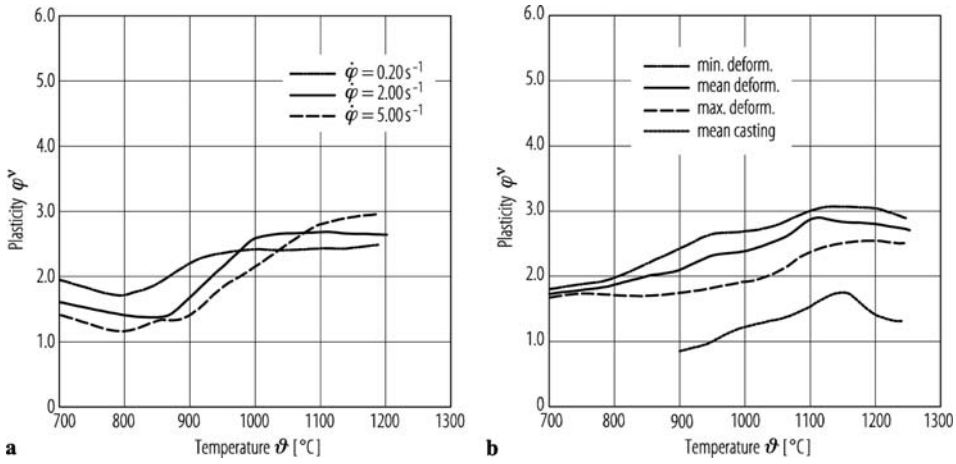
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	200…250	89.0092	0.65465	500…550	52.1560	0.78498
hot rolled				400…450	98.1003	0.67926

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	45…53	32.29492	0.09647	−5.76096	<80
hot rolled					<75

Fig. 5.164.
X5CrNi18–10. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformation rate: 0.2 [s^{-1}]. Deformed and casting state. Direct heating on deformation temperature.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.79	493.31	16.50	7766.2	198.7
100	15.73	500.10	16.73	7727.2	192.6
200	17.23	508.73	17.31	7685.5	185.3
300	18.58	517.50	17.02	7647.3	178.1
400	19.91	526.43	17.02	7607.6	171.0
500	21.26	535.51	17.92	7557.5	163.8
600	22.65	544.74	18.23	7511.4	156.4
700	24.09	554.14	18.54	7463.8	148.3
800	25.59	563.69	18.87	7414.6	139.3
900	27.16	573.42	19.19	7363.8	128.9
1000	28.82	583.31	19.53	7311.3	116.7
1100	30.55	593.37	19.86	7257.1	102.0
1200	32.37	603.60	20.21	7201.2	84.4

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Steel symbol/number: X8CrNiS18–9/1.4305

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.10	0.00…1.00	0.00…2.00	0.000…0.045	0.150…0.350	17.00…19.00
Ni	Cu	N			
8.00…10.00	0.00…1.00	0.000…0.110			

International comparison of standards

ISO		Euronorm		
~ N	7153–1 (1991)	X8CrNiS18–9	10088–2 (04/1995)	
~ X10CrNiS18-9	TR 15510 (1997)	X8CrNiS18–9	10088–3 (04/1995)	
United Kingdom		Russia		
X8CrNiS18-9	EN 10088–3 (04/1995)	~ 08Ch18N10	GOST 5632 (1972)	
~ 303 S 31	1554 (1990)			
Japan		China		
~ SUS 303	G 4303 (1998)	~ Y1Cr18Ni9	T 1220 (1992)	
~ SUS 303	G 4304 (1999)	~ S30314	T 1220 (1992)	
USA				
ASTM		AISI	SAE	UNS
~ A 314 (303)	A 314–02	~ 303		~ S30300
~ A 473 (303)	A 320–02	~ S30300		~ J92610

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

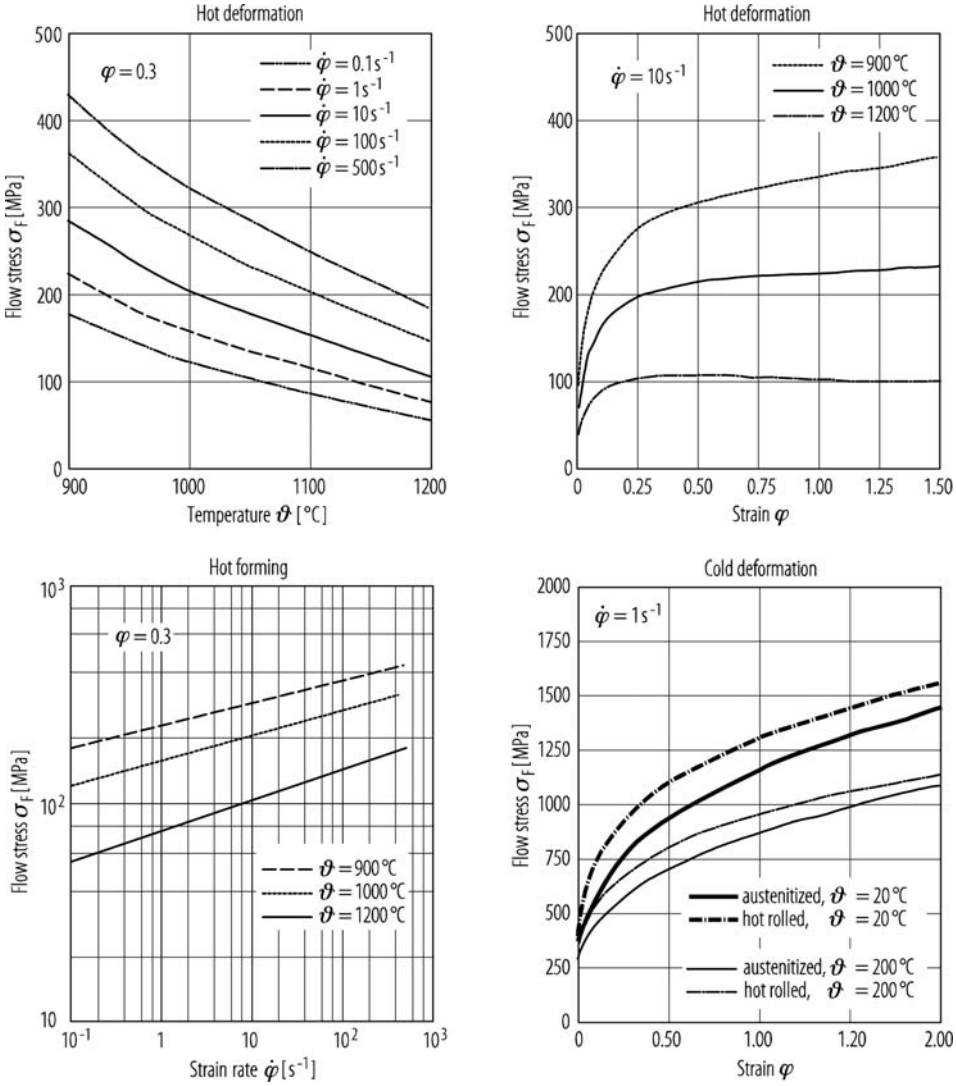
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	austenitized	hot rolled
	austenite		
σ_{F0} [MPa]	163.8	578.0	735.6
A	7501.19	1190.157	1350.733
Effect of temperature K_ϑ			
m_1	−0.00322	−0.00162	−0.00176
Effect of strain K_φ			
m_2	0.33786	0.32462	0.25847
m_4	0.00012	0.00451	0.000016
m_5	−0.00148		
m_7	0.46653		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.00543	0.00976
m_8	0.000116		
Range of validity			
ϑ [°C]	900…1200	20…300	20…300
φ	0.04…1.50	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.165.
X8CrNiS18–9. Flow stress curves by hot and cold forming.



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Mechanical properties after cold deformation

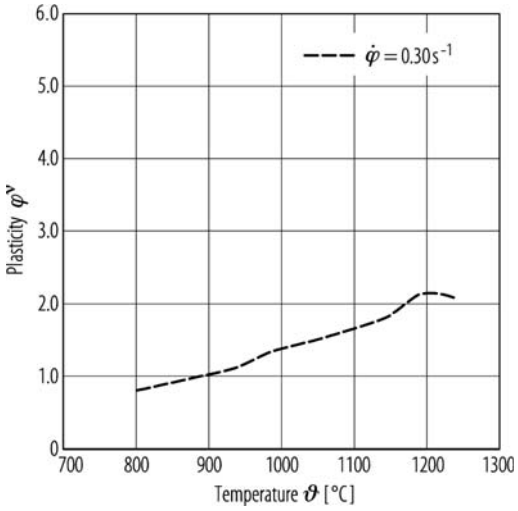
State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	240…270	29.7138	0.93051	570…650	4.4270	1.33322

Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	50…57	15.37065	0.31519	−4.82704	<80

Fig. 5.166.
X8CrNiS18–9. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as–cast and as-deformed state is: 0.30…0.60.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.78	493.31	16.50	7772.6	
100	15.71	500.10	16.73	7733.6	
200	17.22	508.73	17.31	7691.9	
300	18.57	517.50	17.02	7653.6	
400	19.90	526.43	17.02	7613.9	
500	21.25	535.51	17.92	7563.7	
600	22.64	544.74	18.23	7517.6	
700	24.08	554.14	18.54	7469.9	
800	25.58	563.69	18.87	7420.7	
900	27.15	573.42	19.19	7369.8	
1000	28.81	583.31	19.53	7317.3	
1100	30.54	593.37	19.86	7263.1	
1200	32.36	603.60	20.21	7207.1	

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Steel symbol/number: X2CrNi19–11/1.4306

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.03	0.00…1.00	0.00…2.00	0.000…0.045	0.000…0.015	18.00…20.00
Ni	N	Cu			
10.00…12.00	0.000…0.110	0.00…1.00			

International comparison of standards

ISO		Euronorm		
~ X2CrNi19–11	TR 15510 (1997)	X2CrNi19–11	10088–3 (04/1995)	
~ X2CrNi18–10E	4954 (1993)	X2CrNi19–11	10263–5 (06/2001)	
United Kingdom		Russia		
X2CrNi19–11	EN 10263–5 (06/2001)	~ 03Ch18N11	5632 (1972)	
Japan		China		
~ SUS 304L	G 4304 (1999)	~ 00Cr19Ni10	T 3090 (2000)	
~ SUS 304LTP	G 3459 (1997)	~ S30403	T 3090 (2000)	
USA				
ASTM		AISI	SAE	UNS
~ A 182 (F 304 L)	A 182–02	~ 304L	~ S30403	~ S30403
~ A 249 (304 L)	A 249–02		~ 304 L	~ J92500

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

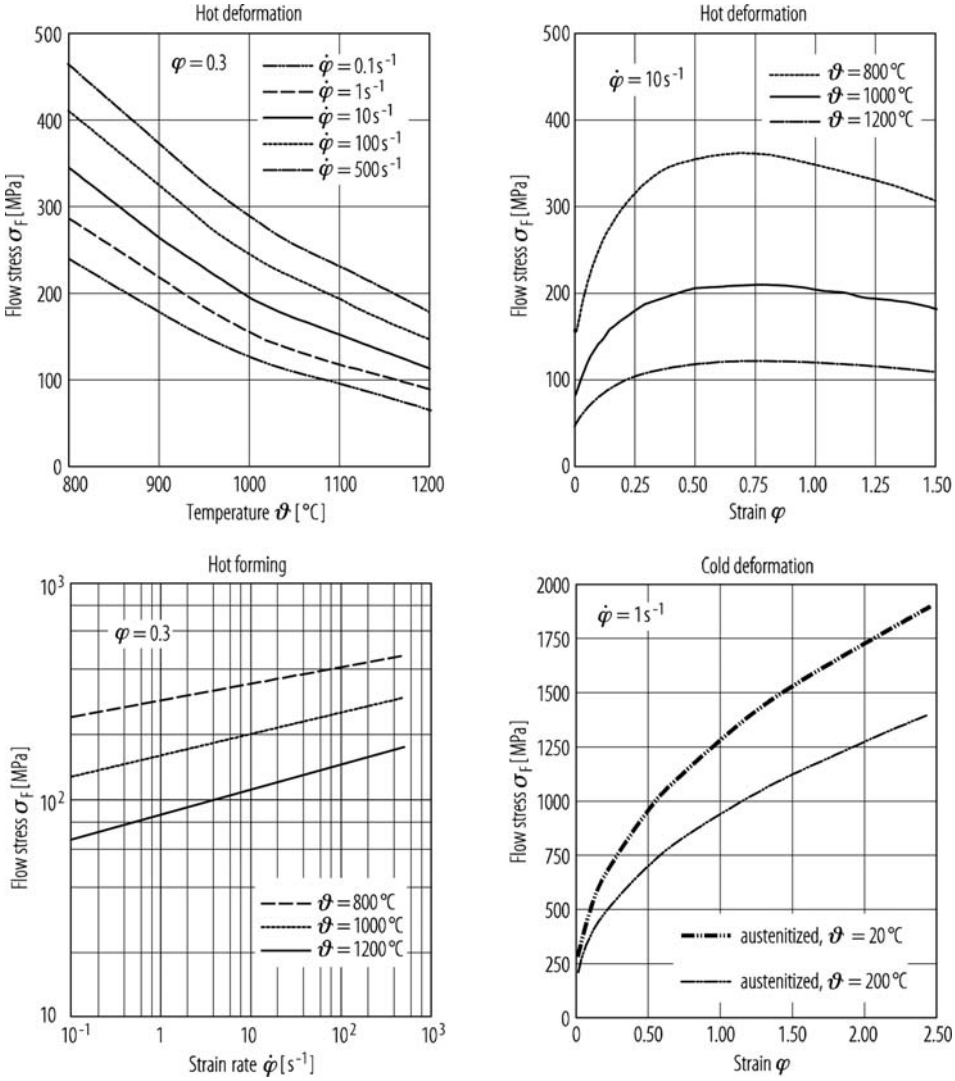
DOI: 10.1007/978-3-540-44760-3_95
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation austenitized
σ_{F0} [MPa]	149.9	498.5
A	6079.51	1323.046
Effect of temperature K_ϑ		
m_1	−0.00309	−0.00174
Effect of strain K_φ		
m_2	0.35227	0.43790
m_4	0.00227	0.00523
m_5	0.00037	
m_7	−0.83149	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00639
m_8	0.000097	
Range of validity		
ϑ [°C]	800…1200	20…300
φ	0.04…1.20	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.167.
X2CrNi19–11. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	200…250	49.8905	0.731		10.5528	1.05654
hot rolled	200…230	19.3753	0.94325	520…570	5.4700	1.20886

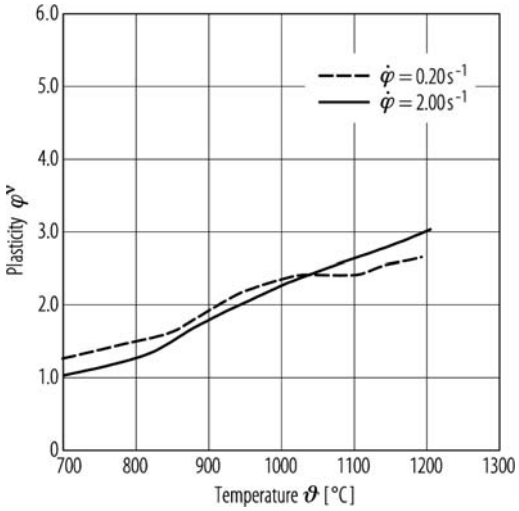
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	60…70	16.03943	0.32967	−4.29565	<80
hot rolled	50…58	5.45379	0.53462	−4.98049	<70

Fig. 5.168.
X2CrNi19–11. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.30…0.60.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.51	493.31	16.50	7779.9	
100	15.49	500.10	16.73	7740.9	
200	17.02	508.73	17.31	7699.1	
300	18.38	517.50	17.02	7660.8	
400	19.72	526.43	17.02	7621.0	
500	21.07	535.51	17.92	7570.8	
600	22.46	544.74	18.23	7524.6	
700	23.90	554.14	18.54	7476.9	
800	25.41	563.69	18.87	7427.7	
900	26.98	573.42	19.19	7376.7	
1000	28.63	583.31	19.53	7324.2	
1100	30.36	593.37	19.86	7269.9	
1200	32.19	603.60	20.21	7213.9	

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Steel symbol/number: X10CrNi18–8/1.4310

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.05…0.15	0.00…2.00	0.00…2.00	0.000…0.045	0.000…0.015	16.00…19.00
Mo	Ni	N			
0.00…0.80	6.00…9.50	0.000…0.110			

International comparison of standards

ISO		Euronorm		
~ O	7153–1 (1991)	X10CrNi18–8	10088–3 (04/1995)	
~ X12CrNi17–7	6931–2 (1989)	X10CrNi18–8	10263–5 (06/2001)	
United Kingdom		Russia		
X10CrNi18–8	EN 10088–3 (04/1995)			
X10CrNi18–8	EN 10263–5 (06/2001)			
Japan		China		
~ SUS 301	G 4305 (1999)	~ 1Cr17Ni7	T 110 (1997)	
~ SUS 301–CSP	G 4313 (1996)	~ S30110	T 1220 (1992)	
USA				
ASTM		AISI	SAE	UNS
~ A 240 (302)	A 240–02	~ 301	~ S30100	~ S30100
~ A 240 (301)	A 240–02	~ 302	~ S30200	~ S30200

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

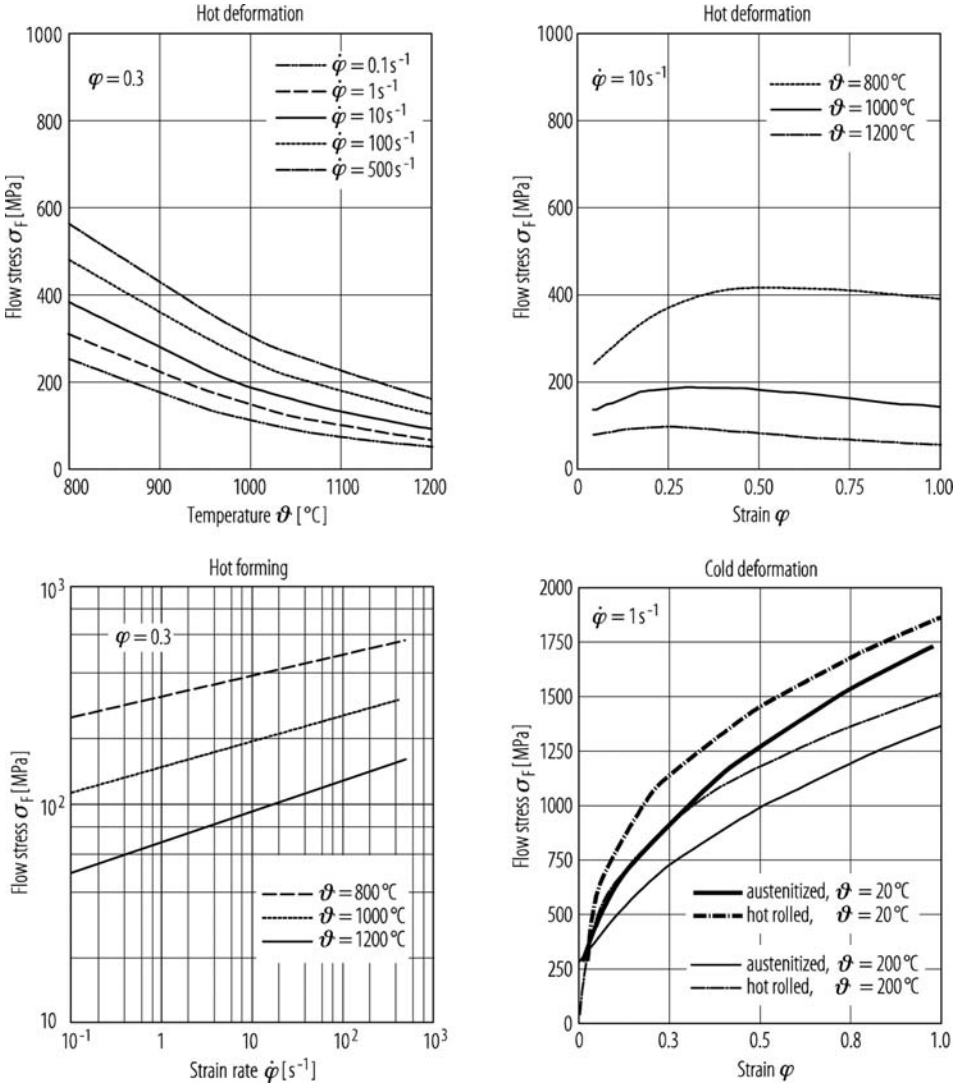
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	austenitized	hot rolled
	austenite		
σ_{F0} [MPa]	154.02	657.7	809.0
A	15224.481	1790.325	1919.672
Effect of temperature K_ϑ			
m_1	−0.00290	−0.00143	−0.00117
Effect of strain K_φ			
m_2	0.86863	0.46262	0.32804
m_4	0.03368	0.00314	−0.01311
m_5	−0.00353		
m_7	0.35731		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.02650	0.01986
m_8	0.000117		
Range of validity			
ϑ [°C]	800…1200	20…150	20…150
φ	0.04…1.00	0.04…1.00	0.04….1.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.169.
X10CrNi18–8. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	300…350	50.4721	0.82282	700…800	15.5603	1.05426
hot rolled				600…650	12.8108	1.16035
feather-hard	800…850	15.6389	1.00507			

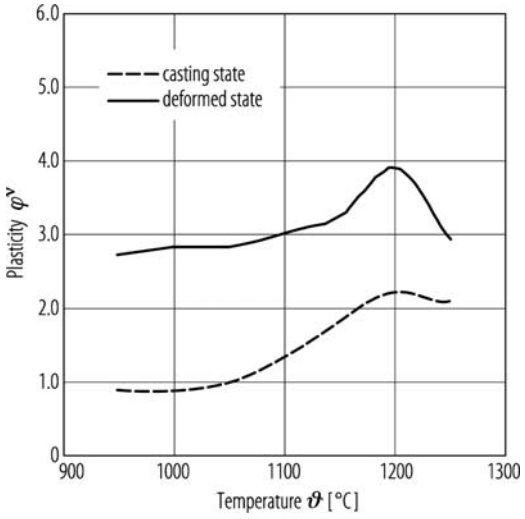
DOI: 10.1007/978-3-540-44760-3_96
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	45…55	24.44559	0.17365	−7.84183	<80
hot rolled					<75
feather-hard					<80

Fig. 5.170.
X10CrNi18–8. Hot plasticity as a function of the temperature. Deformation rate: 0.3 [s^{-1}]. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.30…0.60.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.33	493.31	16.50	7719.8	
100	15.35	500.10	16.73	7681.1	
200	17.23	508.73	17.31	7639.7	
300	18.58	517.50	17.02	7601.6	
400	19.91	526.43	17.02	7562.2	
500	21.26	535.51	17.92	7512.4	
600	22.65	544.74	18.23	7466.6	
700	24.09	554.14	18.54	7419.2	
800	25.59	563.69	18.87	7370.3	
900	27.17	573.42	19.19	7319.8	
1000	28.82	583.31	19.53	7267.6	
1100	30.55	593.37	19.86	7213.8	
1200	32.38	603.60	20.21	7158.2	

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Steel symbol/number: X2CrNi21–10/1.4331

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.025	0.00…1.00	0.00…2.00	0.000…0.025	0.000…0.025	20.00…22.00
Ni					
9.50…11.50					

International comparison of standards

ISO		Euronorm	
United Kingdom		Russia	
Japan		China	
		~ H00Cr21Ni10	T 5092 (1996)
		~ W43043	T 5092 (1996)
USA			
Spec	ASME	AWS	UNS
~ 308 LSi	~ SFA 5.9 (ER308LSi)	~ A 5.9(ER308LSi)	~ S30888

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

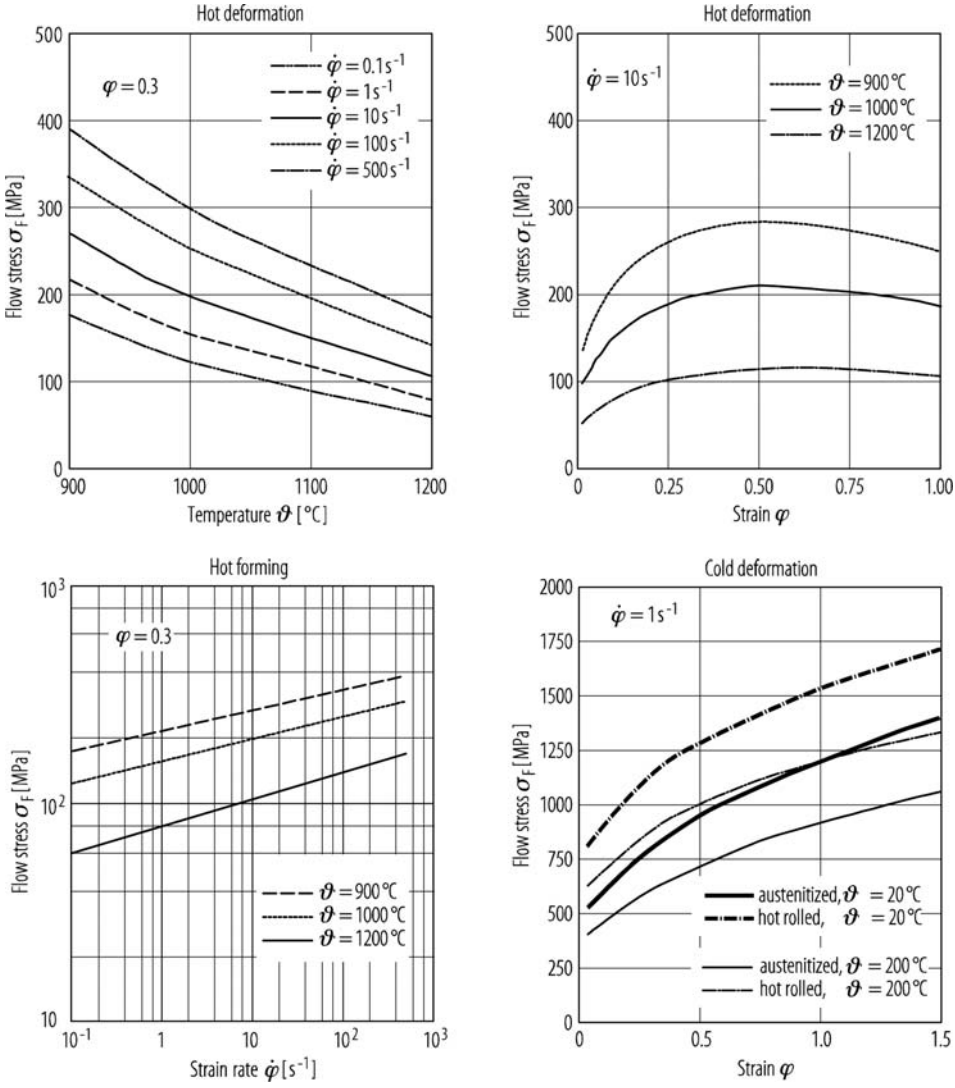
DOI: 10.1007/978-3-540-44760-3_97
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	austenitized	hot rolled
	austenite		
σ_{F0} [MPa]	150.1	590.8	936.6
A	9556.09	1220.999	1564.781
Effect of temperature K_ϑ			
m_1	−0.00351	−0.00151	−0.00140
Effect of strain K_φ			
m_2	0.38109	0.36944	0.27164
m_4	0.00445	0.01506	0.00945
m_5	0.00063		
m_7	−1.10475		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.00151	0.01986
m_8	0.000104		
Range of validity			
ϑ [°C]	900…1200	20…300	20…300
φ	0.04…1.00	0.04…1.50	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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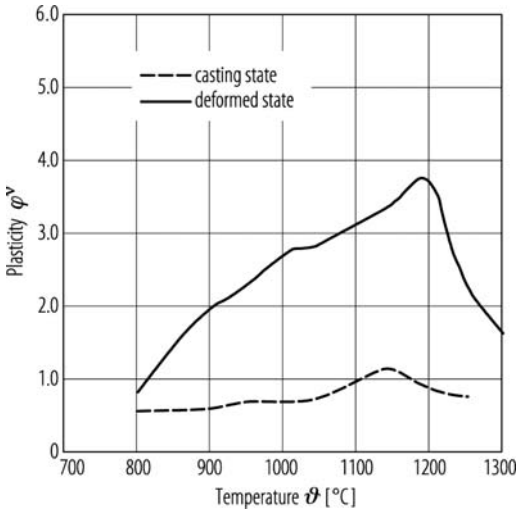
Fig. 5.171.
X2CrNi21–10. Flow stress curves by hot and cold forming.



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Fig. 5.172.
X2CrNi21–10. Hot plasticity as a function of the temperature. Deformation rate: 0.3 [s^{-1}]. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.25…0.50.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	12.64	493.31	16.50	7760.9	
100	14.78	500.10	16.73	7722.0	
200	16.89	508.73	17.31	7680.3	
300	18.26	517.50	17.02	7642.1	
400	19.60	526.43	17.02	7602.5	
500	20.95	535.51	17.92	7552.4	
600	22.34	544.74	18.23	7506.3	
700	23.79	554.14	18.54	7458.7	
800	25.29	563.69	18.87	7409.6	
900	26.87	573.42	19.19	7358.8	
1000	28.52	583.31	19.53	7306.3	
1100	30.25	593.37	19.86	7252.2	
1200	32.07	603.60	20.21	7196.3	

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Steel symbol/number: X5CrNiMo17–12–2/1.4401

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.07	0.00…1.00	0.00…2.00	0.000…0.045	0.000…0.015	16.50…18.50
Mo	Ni	N	Cu		
2.00…2.50	10.00…13.00	0.000…0.110	0.00…1.00		

International comparison of standards

ISO		Euronorm		
~ P	7153–1 (1991)	X5CrNiMo 17–12–2	10088–3 (04/1995)	
~ X5CrNiMo17–12	9329–4 (1997)	X5CrNiMo 17–12–2	10263–5 (06/2000)	
United Kingdom		Russia		
X5CrNiMo 17–12–2	EN 10263–5 (06/2000)	~ 08Ch16N11M3	5632 (1972)	
~ 316 S 31	970 Part 1 (1996)			
Japan		China		
~ SUS 316	G 4315 (2000)	~ 0Cr17Ni12Mo2	T 1220 (1992)	
~ SUS 316TP	G 3459 (1997)	~ S31608	T 3090 (2000)	
USA				
ASTM		AISI	SAE	UNS
~ A 182 (F 316 H)	A 182-02	~ 316	~ 31600	~ S31600
~ A 249 (316)	A 249-02	~ 316 H	~ 316 H	~ S31609

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

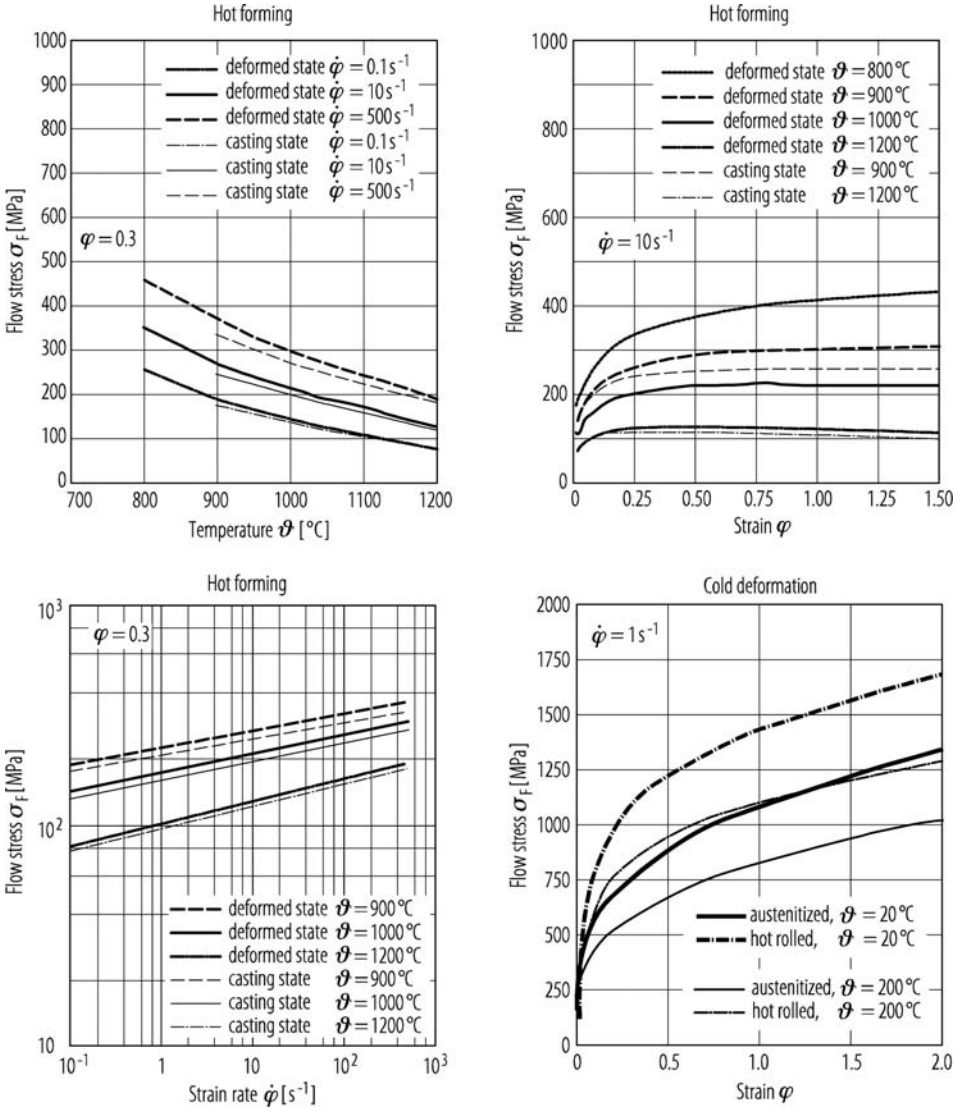
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Flow curves

	Hot deformation		Cold deformation	
	deformed state	casting state	austenitized	hot rolled
State of material	austenite	austenite		
σ_{F0} [MPa]	172.0	171.4	564.6	824.3
A	3661.04	2605.35	1118.40	1490.244
Effect of temperature K_ϑ				
m_1	−0.00237	−0.00221	−0.00155	−0.00146
Effect of strain K_φ				
m_2	0.35696	0.27450	0.30440	0.21471
m_4	0.00324	0.001739	0.00346	−0.00978
m_5	−0.00130	−0.00124		
m_7	0.27452	0.27416		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.00562	0.01272
m_8	0.000086	0.000084		
Range of validity				
ϑ [°C]	800…1200	900…1200	20…300	20…300
φ	0.04…1.50	0.04…1.50	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.173.
X5CrNiMo17–12–2. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_P [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	200…240	9.07134	1.12076	550…600	2.6394	1.36667

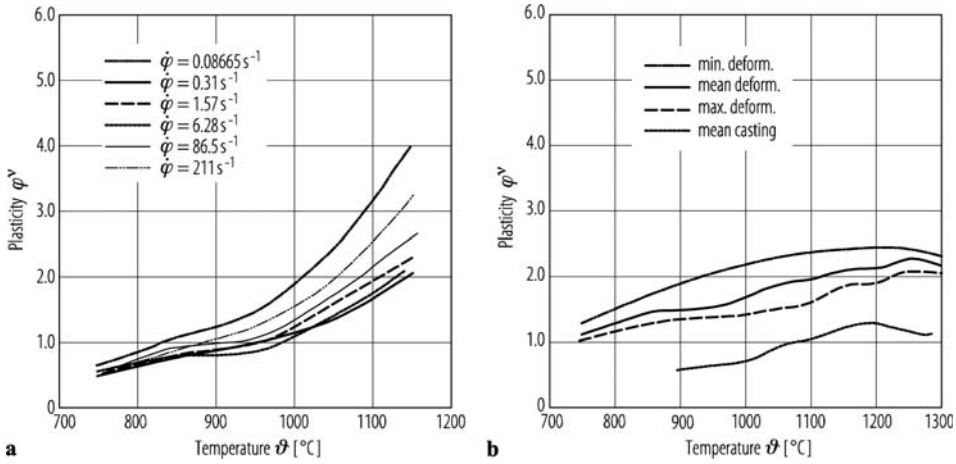
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	50…70	18.70760	0.30367	−7.62122	<70

Fig. 5.174.
X5CrNiMo17–12–2. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformation rate: 0.3 [s^{-1}]. Deformed and casting state. Direct heating on deformation temperature.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.29	493.31	16.50	7859.8	195.5
100	15.31	500.10	16.73	7820.3	191.0
200	16.97	508.73	17.31	7778.1	185.6
300	18.34	517.50	17.02	7739.4	179.8
400	19.67	526.43	17.02	7699.3	173.0
500	21.02	535.51	17.92	7648.5	164.9
600	22.41	544.74	18.23	7601.9	155.1
700	23.86	554.14	18.54	7553.7	143.9
800	25.36	563.69	18.87	7503.9	131.3
900	26.94	573.42	19.19	7452.5	117.8
1000	28.59	583.31	19.53	7399.4	104.2
1100	30.32	593.37	19.86	7344.5	91.2
1200	32.14	603.60	20.21	7287.9	79.9

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Steel symbol/number: X5CrNiMo19–11/1.4403

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.05	0.00…1.40	0.00…1.90	0.000…0.025	0.000…0.015	18.20…19.80
Mo	Ni				
2.50…3.00	10.20…11.80				

International comparison of standards

ISO		Euronorm	
~ X2CrNi19–11	TR 15510 (1997)	~ X6CrNiMo19 13 02 KE	144 (1979)
United Kingdom		Russia	
Japan		China	
~ SUS Y 316L	G 4316 (1991)	~ H0Cr19Ni12Mo2	T 5092 (1996)
		~ W43168	T 5092 (1996)
USA			
ASME	AWS	Spec	UNS
~ SFA 5.9 (ER316Si)	~ A5.9 (ER308Mo)	19–9–Mo Low Carbon	~ S30882
~ SFA 5.30 (IN316)	~ A5.9 (ER308MoL)		~ S30886

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

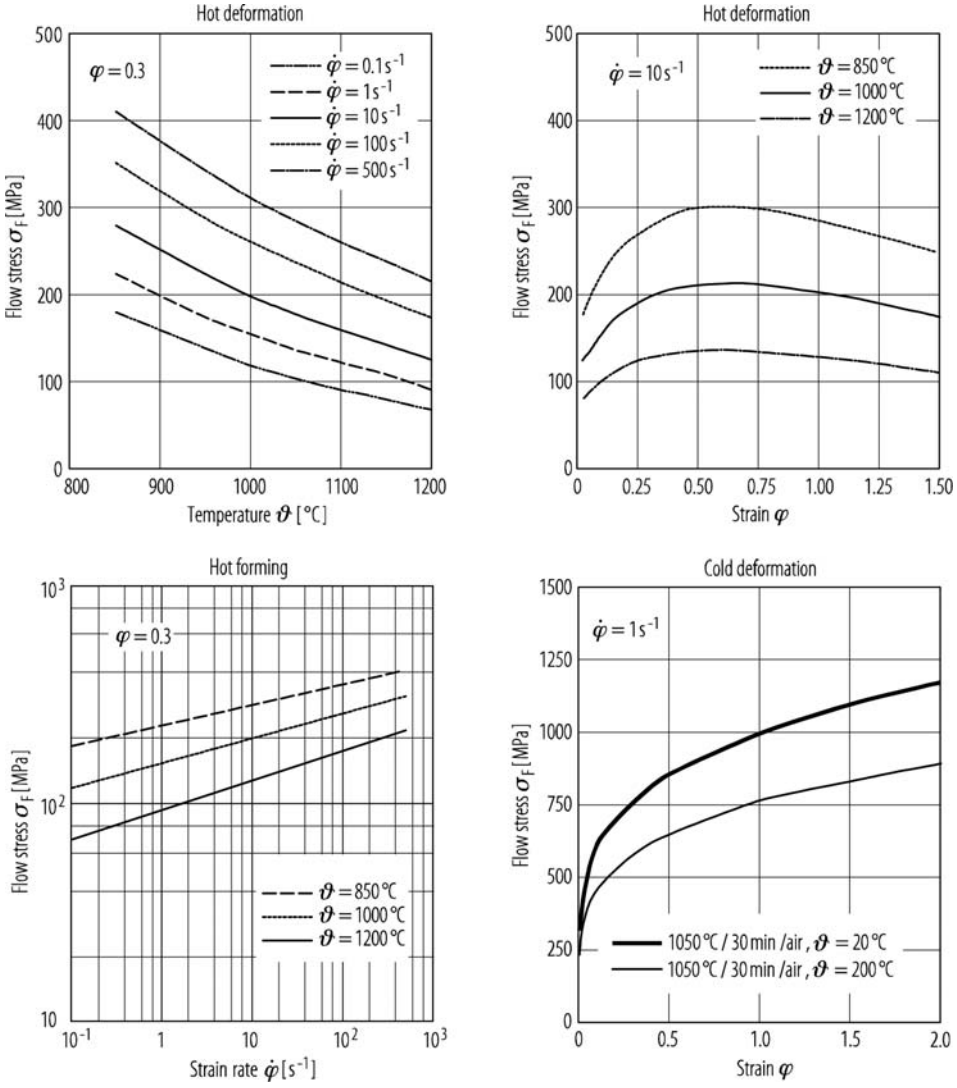
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation 1050°C/30min/air
σ_{F0} [MPa]	156.7	595.7
A	3516.52	1029.294
Effect of temperature K_ϑ		
m_1	−0.00252	−0.00155
Effect of strain K_φ		
m_2	0.38195	0.22976
m_4	0.00887	0.00002
m_5	−0.00002	
m_7	−0.58596	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00562
m_8	0.000113	
Range of validity		
ϑ [°C]	850…1200	20…300
φ	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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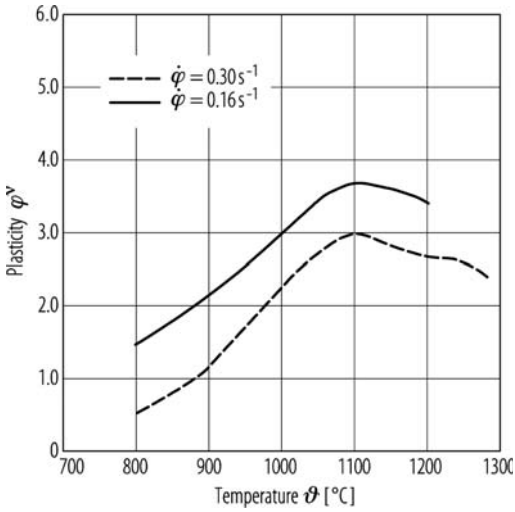
Fig. 5.175.
X5CrNiMo19–11. Flow stress curves by hot and cold forming.



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Fig. 5.176.
X5CrNiMo19–11. Hot plasticity as a fuction of the temperature (and deformation rate); deformed state and austenitized at 1200 [°C]. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.25…0.65.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.48	493.31	16.50	7830.2	
100	15.47	500.10	16.73	7790.9	
200	16.85	508.73	17.31	7748.9	
300	18.22	517.50	17.02	7710.3	
400	19.56	526.43	17.02	7670.3	
500	20.92	535.51	17.92	7619.8	
600	22.31	544.74	18.23	7573.3	
700	23.75	554.14	18.54	7525.3	
800	25.26	563.69	18.87	7475.7	
900	26.83	573.42	19.19	7424.4	
1000	28.48	583.31	19.53	7371.5	
1100	30.22	593.37	19.86	7316.9	
1200	32.04	603.60	20.21	7260.5	

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Steel symbol/number: X2CrNiMo17–12–2/1.4404

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.03	0.00…1.00	0.00…2.00	0.000…0.045	0.000…0.015	16.50…18.50
Mo	Ni	N			
2.00…2.50	10.00…13.00	0.00…0.11			

International comparison of standards

ISO		Euronorm		
X2CrNiMo17–12	9329–4 (1997)	X2CrNiMo17–12–2	10028–7 (2000)	
X2CrNiMo17–12–2	TR 15510 (1997)	X2CrNiMo17–12–2	10275 (10/2000)	
United Kingdom		Russia		
X2CrNiMo17–12–2	EN 10028–7 (2000)			
X2CrNiMo17–12–2	EN 10250–4 (10/1999)			
Japan		China		
~ SUS 316LTP	G 3459 (1997)	~ 00Cr17Ni14Mo2	T 3090 (2000)	
~ SUS 316L	G 4315 (2000)	~ S31603	T 3090 (2000)	
USA				
ASTM		AISI	SAE	UNS
~ A 182 (F316L)	A 182-02	~ 316 L	~ 316 N	~ S31603
~ A 351 (CF3M)	A 351-00		~ 316 L	~ J92700

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

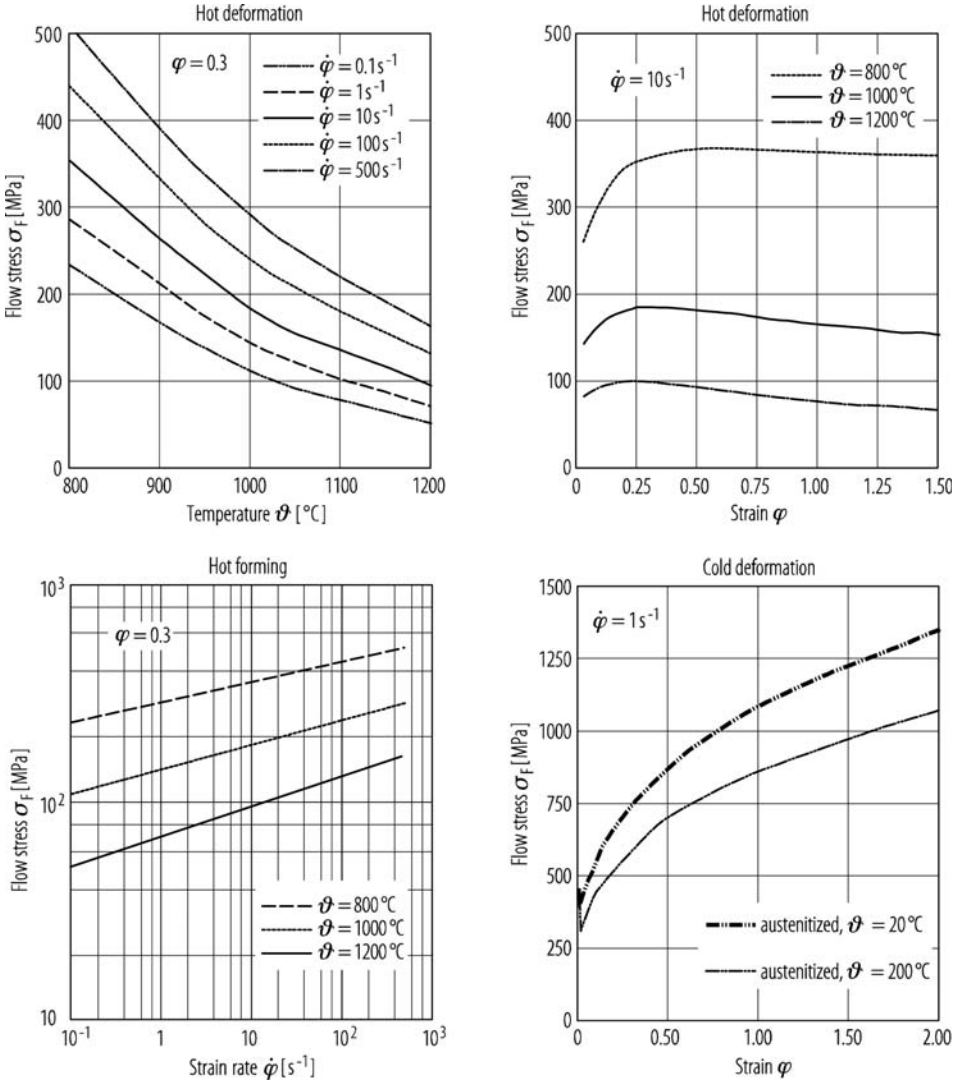
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation austenitized
σ_{F0} [MPa]	175.06	562.3
A	4885.72	1104.20
Effect of temperature K_ϑ		
m_1	−0.00286	−0.00131
Effect of strain K_φ		
m_2	0.28253	0.31552
m_4	0.002998	0.00468
m_5	−0.00145	
m_7	0.26707	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01301
m_8	0.000114	
Range of validity		
ϑ [°C]	800…1200	20…300
φ	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.177.
X2CrNiMo17–12–2. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_P [MPa]			Tensile strength ΔR_m [MP]a		
	A_0	A	n_1	B_0	B	n_2
chilled	240…280	35.1386	0.85397	540…620	8.2439	1.1479

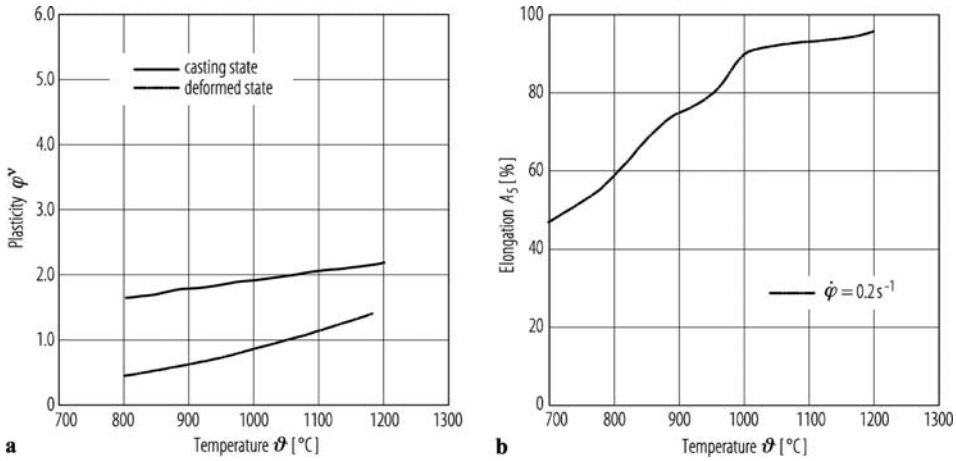
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	50…55	24.03978	0.18621	−7.86074	<80

Fig. 5.178.
X2CrNiMo17–12–2. Hot plasticity as a function of the temperature. (a) Deformation rate: 0.2 [s^{-1}]. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity in torsion and tensile test



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	14.73	493.31	16.50	7851.1	197.4
100	16.48	500.10	16.73	7811.7	191.1
200	17.00	508.73	17.31	7769.6	183.4
300	18.36	517.50	17.02	7730.9	176.1
400	19.70	526.43	17.02	7690.8	169.0
500	21.05	535.51	17.92	7640.1	162.0
600	22.44	544.74	18.23	7593.5	154.9
700	23.88	554.14	18.54	7545.4	147.3
800	25.39	563.69	18.87	7495.6	138.8
900	26.96	573.42	19.19	7444.3	129.0
1000	28.61	583.31	19.53	7391.2	117.4
1100	30.35	593.37	19.86	7336.4	103.2
1200	32.17	603.60	20.21	7279.9	85.8

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Steel symbol/number: X2CrNiMoN17–11–2/1.4406

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.03	0.00…1.00	0.00…2.00	0.000…0.045	0.000…0.015	16.50…18.50
Mo	Ni	N			
2.00…2.50	10.00…12.00	0.120…0.220			

International comparison of standards

ISO		Euronorm		
~ X2CrNiMoN17–11–2	TR 15510 (1997)	X2CrNiMoN17–11–2	10272 (10/2000)	
~ X2CrNiMoN17–12	9328–5 (1991)	X2CrNiMoN17–11–2	10088–3 (04/1995)	
United Kingdom		Russia		
X2CrNiMoN17–11–2	EN 10272 (10/2000)			
X2CrNiMoN17–11–2	EN 10088–3 (04/1995)			
Japan		China		
~ SUS 316LN	G 4303 (1998)	~ 00Cr17Ni13Mo2N	T 1220 (1992)	
~ SUS 316LN	G 4305 (1999)	~ S31653	T 1220 (1992)	
USA				
ASTM		AISI	SAE	UNS
~ A 182 (F 316 LN)	A 182–02	~ 316LN	~ S31653	~ S31653
~ A 249 (316 LN)	A 249–02		~ 316LN	

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

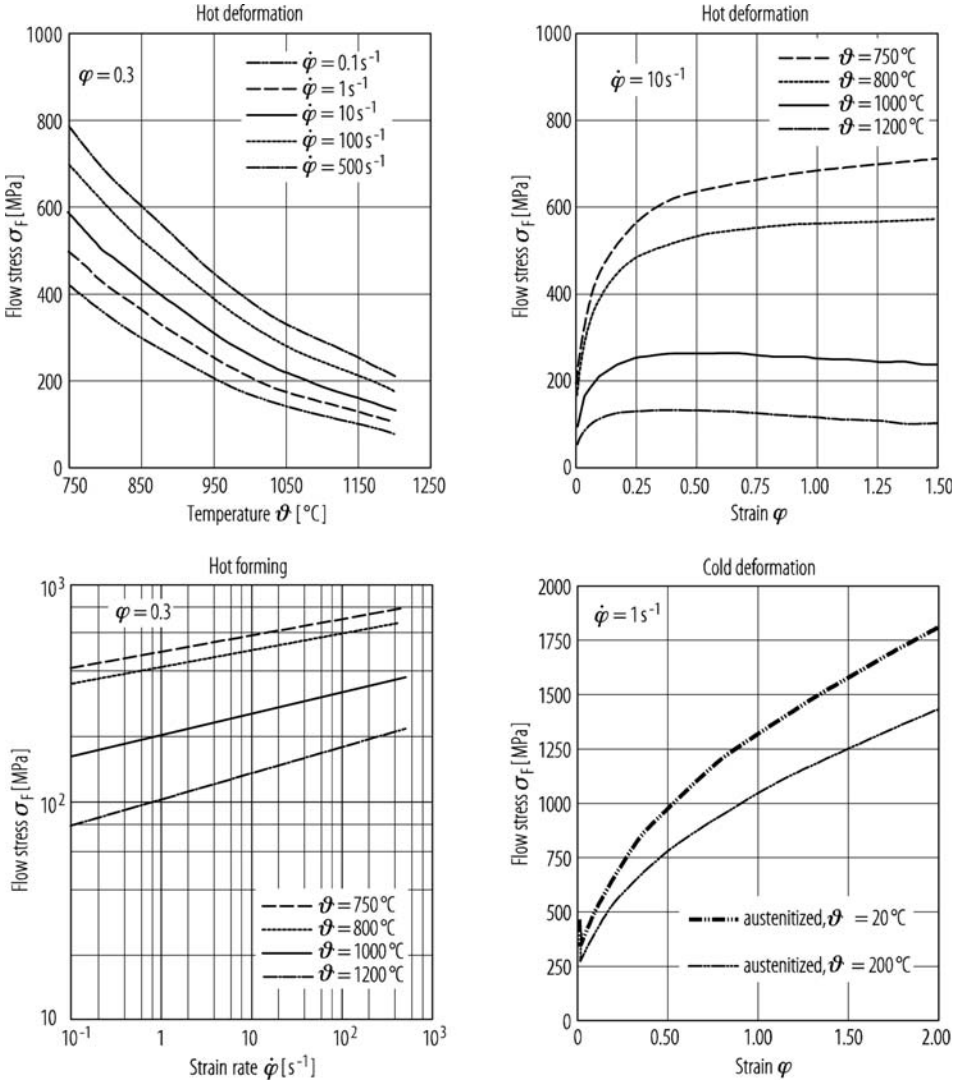
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation austenitized
σ_{F0} [MPa]	217.06	513.3
A	9681.576	1347.65
effect of temperature K_ϑ		
m_1	−0.00307	−0.00130
effect of strain K_φ		
m_2	0.37677	0.44649
m_4	0.00099	0.00764
m_5	−0.00160	
m_7	0.30801	
effect of strain rate $K_{\dot\varphi}$		
m_3		0.00544
m_8	0.000098	
range of validity		
ϑ [°C]	750…1250	20…300
φ	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

DOI: 10.1007/978-3-540-44760-3_101
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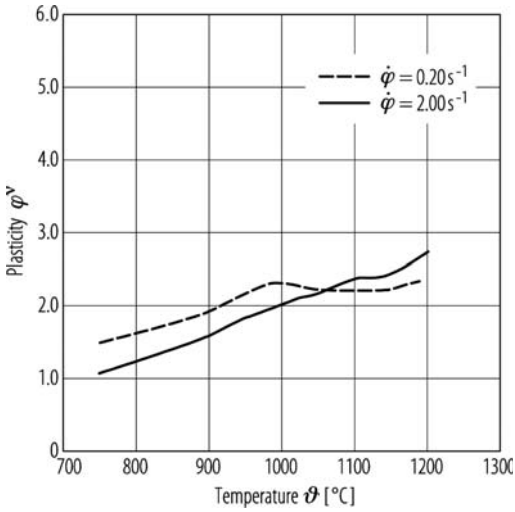
Fig. 5.179.
X2CrNiMoN17–11–2. Flow stress curves by hot and cold forming.



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Fig. 5.180.
X2CrNiMoN17–11–2. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.20…0.60.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	14.73	493.31	16.50	7851.1	197.4
100	16.48	500.10	16.73	7811.7	191.1
200	17.00	508.73	17.31	7769.6	183.4
300	18.36	517.50	17.02	7730.9	176.1
400	19.70	526.43	17.02	7690.8	169.0
500	21.05	535.51	17.92	7640.1	162.0
600	22.44	544.74	18.23	7593.5	154.9
700	23.88	554.14	18.54	7545.4	147.3
800	25.39	563.69	18.87	7495.6	138.8
900	26.96	573.42	19.19	7444.3	129.0
1000	28.61	583.31	19.53	7391.2	117.4
1100	30.35	593.37	19.86	7336.4	103.2
1200	32.17	603.60	20.21	7279.9	85.8

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Steel symbol/number: X4CrNiMo16–5–1/1.4418

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.06	0.00…0.70	0.00…1.50	0.000…0.040	0.000…0.015	15.00…17.00
Mo	Ni	N			
0.80…1.50	4.00…6.00	>0.020			

International comparison of standards

ISO		Euronorm		
		X4CrNiMo16–5–1	10028–7 (2000)	
		X4CrNiMo16–5–1	10088–3 (04/1995)	
United Kingdom		Russia		
X4CrNiMo16–5–1	EN 10272 (10/2000)			
X4CrNiMo16–5–1	EN 10088–3 (04/1995)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

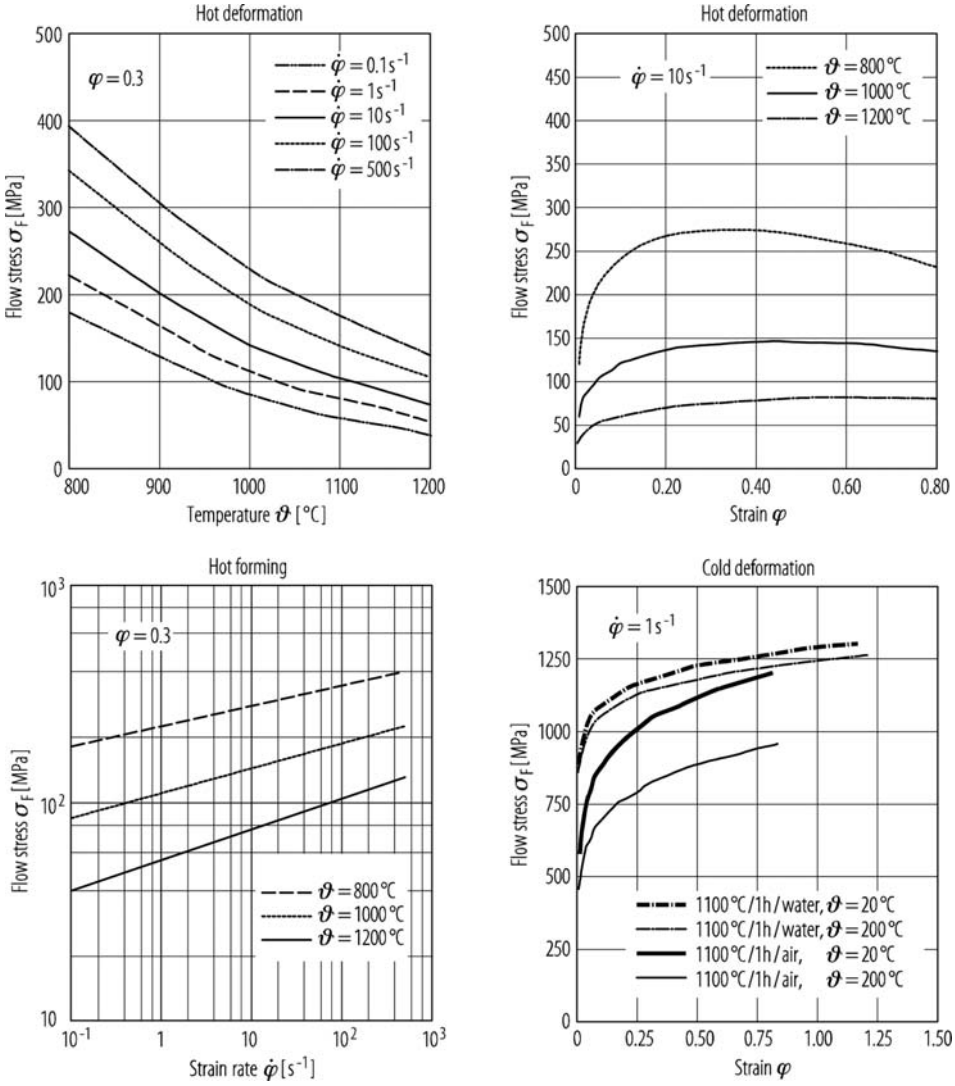
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	1100°C/1h/water	1100°C/1h/air
	austenite		
σ_{F0} [MPa]	119.7	1107.6	889.4
A	7426.50	1290.994	1269.651
Effect of temperature K_ϑ			
m_1	−0.00387	−0.00021	−0.00130
Effect of strain K_φ			
m_2	0.21798	0.07286	0.14874
m_4	−0.00079	0.000000855	0.000001
m_5	0.00143		
m_7	−1.51183		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.00814	0.00544
m_8	0.000116		
Range of validity			
ϑ [°C]	800…1200	20…300	20…300
φ	0.04…0.80	0.04…1.20	0.04…0.80
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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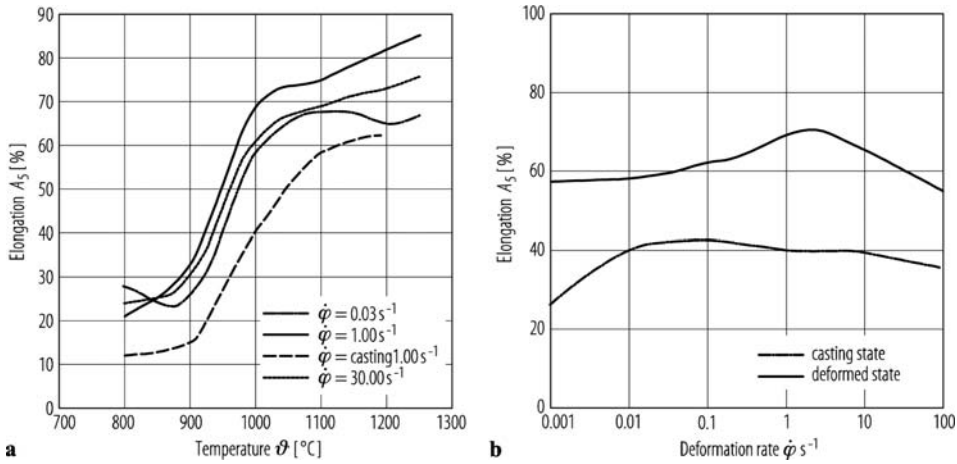
Fig. 5.181.
X4CrNiMo16–5–1. Flow stress curves by hot and cold forming.



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Fig. 5.182.
X4CrNiMo16–5–1. Hot plasticity as a function of the temperature. (a) Deformed and casting state. Direct heating on deformation temperature. (b) Deformation temperature: 1000 °C. Direct heating on deformation temperature.

Plasticity by tensile test



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.24	493.31	16.50	7757.2	
100	15.27	500.10	16.73	7718.2	
200	17.91	508.73	17.31	7676.6	
300	19.23	517.50	17.02	7638.4	
400	20.53	526.43	17.02	7598.8	
500	21.87	535.51	17.92	7548.7	
600	23.25	544.74	18.23	7502.7	
700	24.68	554.14	18.54	7455.1	
800	26.18	563.69	18.87	7405.9	
900	27.75	573.42	19.19	7355.2	
1000	29.40	583.31	19.53	7302.8	
1100	31.14	593.37	19.86	7248.7	
1200	32.97	603.60	20.21	7192.8	

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Steel symbol/number: X2CrNiMoN17–13–3/1.4429

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.03	0.00…1.00	0.00…2.00	0.000…0.045	0.000…0.015	16.50…18.50
Mo	Ni	N			
2.50…3.00	11.00…14.00	0.120…0.220			

International comparison of standards

ISO		Euronorm		
~ X2CrNiMo17–12–3	TR15510 (1997)	X2CrNiMo17–13–3	10088–3 (04/1995)	
~X2CrNiMo17–13–3E	4954 (1993)	X2CrNiMo17–13–3	10272 (10/2000)	
United Kingdom		Russia		
X2CrNiMo17–13–3	EN 10088–3 (04/1995)			
X2CrNiMo17–13–3	EN 10272 (10/2000)			
Japan		China		
~ SUS 316LN	G 4303 (1998)	~ 00Cr17Ni13Mo2N	T 1220 (1992)	
~ SUS 316LN	G 4305 (1999)	~ S31653	T 1220 (1992)	
USA				
ASTM		AISI	SAE	UNS
~ A 182 (F 316 LN)	A 182–02	~ 316 LN	~ S31653	~ S31653
~ A 249 (316 LN)	A 249–02		~ 316 LN	

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

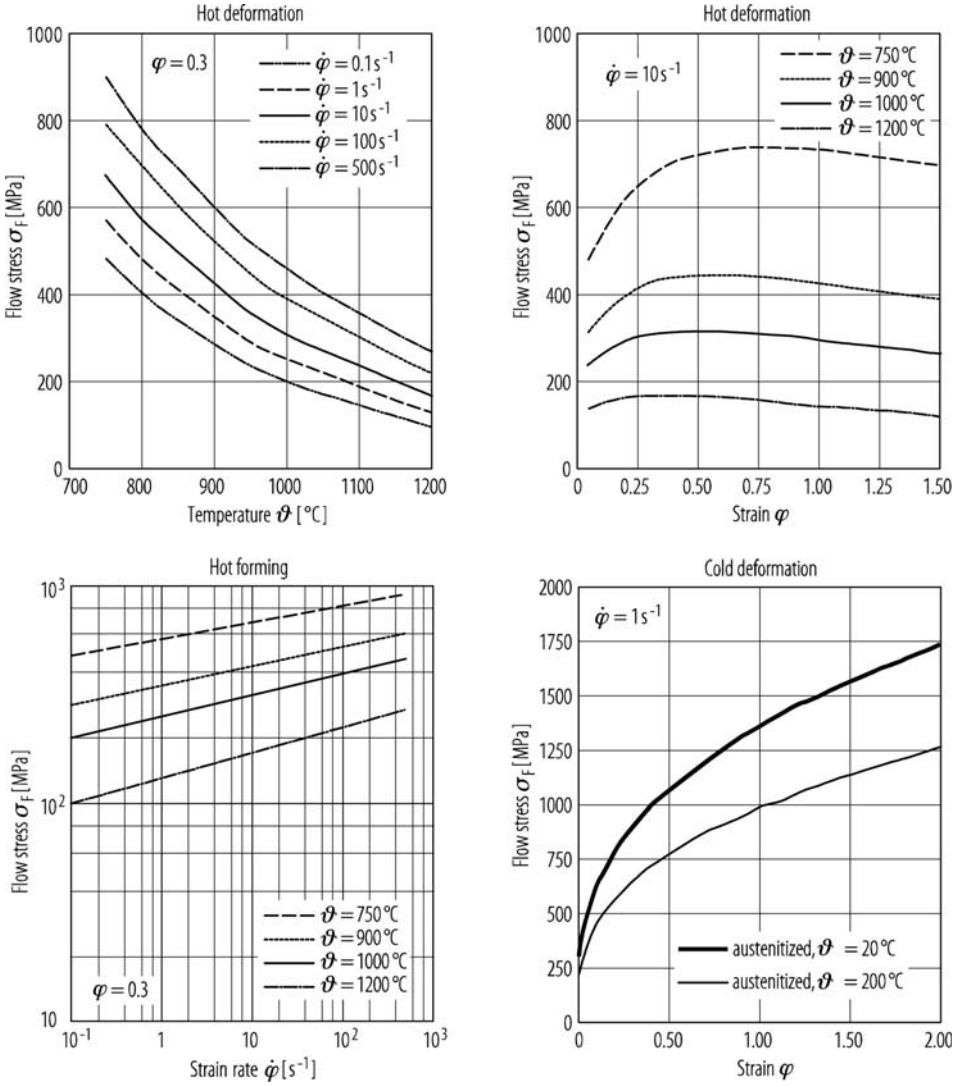
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation austenitized
σ_{F0} [MPa]	260.17	619.7
A	11323.551	1407.617
Effect of temperature K_ϑ		
m_1	−0.00297	−0.00179
Effect of strain K_φ		
m_2	0.47156	0.35021
m_4	0.01803	0.00176
m_5	−0.00125	
m_7	−0.04999	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00125
m_8	0.000098	
Range of validity		
ϑ [°C]	750…1200	20…300
φ	0.04…1.50	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500

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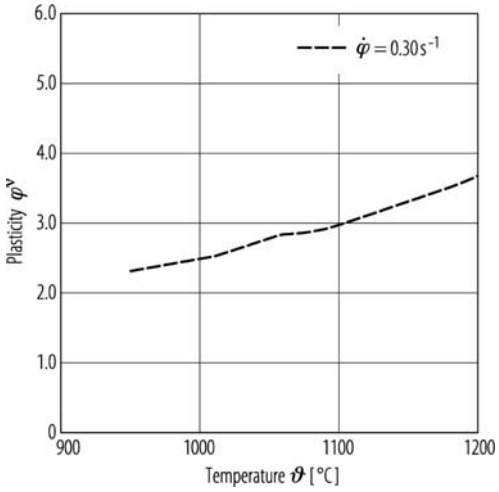
Fig. 5.183.
X2CrNiMoN17–13–3. Flow stress curves by hot and cold forming.



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Fig. 5.184.
X2CrNiMoN17–13–3. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.20…0.60.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.20	493.31	16.50	7883.9	
100	15.24	500.10	16.73	7844.4	
200	16.82	508.73	17.31	7802.1	
300	18.19	517.50	17.02	7763.2	
400	19.53	526.43	17.02	7723.0	
500	20.89	535.51	17.92	7672.1	
600	22.28	544.74	18.23	7625.3	
700	23.72	554.14	18.54	7576.9	
800	25.23	563.69	18.87	7527.0	
900	26.80	573.42	19.19	7475.4	
1000	28.45	583.31	19.53	7422.1	
1100	30.19	593.37	19.86	7367.1	
1200	32.01	603.60	20.21	7310.4	

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Steel symbol/number: X2CrNiMo19–12/1.4430

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
< 0.02	0.00…1.40	0.00…1.90	0.000…0.025	0.000…0.015	17.20…19.80
Mo	Ni				
2.50…3.00	10.70…13.30				

International comparison of standards

ISO		Euronorm	
~ X2CrNi19–11	TR 15510 (1997)	~ X 2 CrNiMo 19 13 03KE	144 (1979)
United Kingdom		Russia	
Japan		China	
		~H00Cr19Ni12Mo2	T 5092 (1996)
		~W43162	T 5092 (1996)
USA			
ASME	Spec	AWS	UNS
~ SFA 5.9 (ER316L)	~ 316 LSi	~ A 5.30 (ERS316L)	~ S31683
~ SFA 5.30 (IN316L)		~ A 5.9 (ERS316L)	~ S31688

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

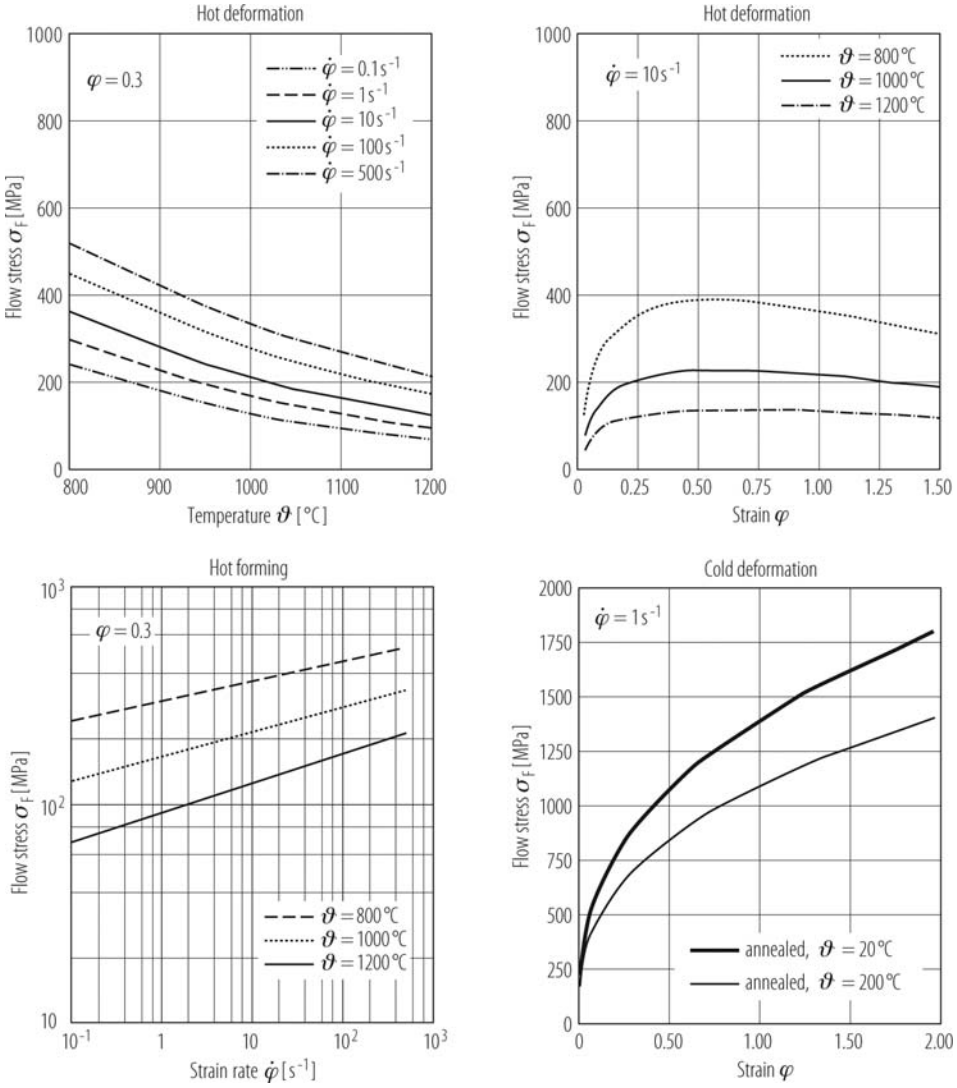
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation austenitized
σ_{F0} [MPa]	154.73	606.3
A	5293.37	1435.546
Effect of temperature K_ϑ		
m_1	−0.00302	−0.00140
Effect of strain K_φ		
m_2	0.22566	0.3729
m_4	−0.02213	0.00040
m_5	0.0003	
m_7	−0.62099	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00984
m_8	0.000113	
Range of validity		
ϑ [°C]	800…1200	20…300
φ	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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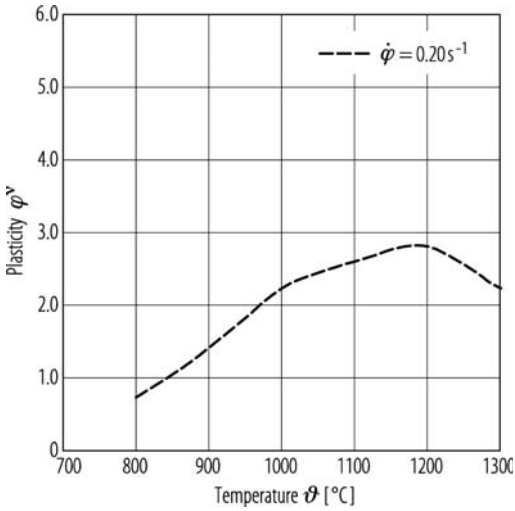
Fig. 5.185.
X2CrNiMo19–12. Flow stress curves by hot and cold forming.



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Fig. 5.186.
X2CrNiMo19–12. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.30…0.60.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.01	493.31	16.50	7847.1	
100	15.08	500.10	16.73	7807.7	
200	16.79	508.73	17.31	7765.6	
300	18.16	517.50	17.02	7726.9	
400	19.51	526.43	17.02	7686.9	
500	20.86	535.51	17.92	7636.2	
600	22.25	544.74	18.23	7589.6	
700	23.70	554.14	18.54	7541.5	
800	25.20	563.69	18.87	7491.8	
900	26.78	573.42	19.19	7440.5	
1000	28.43	583.31	19.53	7387.4	
1100	30.16	593.37	19.86	7332.7	
1200	31.98	603.60	20.21	7276.2	

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Steel symbol/number: X2CrNiMoN17–13–5/1.4439

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.03	0.00…1.00	0.00…2.00	0.000…0.045	0.000…0.015	16.50…18.50
Mo	Ni	N			
4.00…5.00	12.50…14.50	0.120…0.220			

International comparison of standards

ISO		Euronorm		
~ X2CrNiMoN17–13–5	9328–5 (1991)	X2CrNiMoN17–13–5	10272 (10/2000)	
~ X2CrNiMoN18–15–5	TR 15510 (1997)	X2CrNiMoN17–13–5	10088–3 (04/1995)	
United Kingdom		Russia		
X2CrNiMoN17–13–5	EN 10272 (10/2000)			
X2CrNiMoN17–13–5	EN 10088–3 (04/1995)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS
~ A 182 (F 48)	A 182–02	~ 317 LMN	~ 317 LMN	~ S31726
~ A 249 (S 31726)	A 249–02		~ S31726	

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

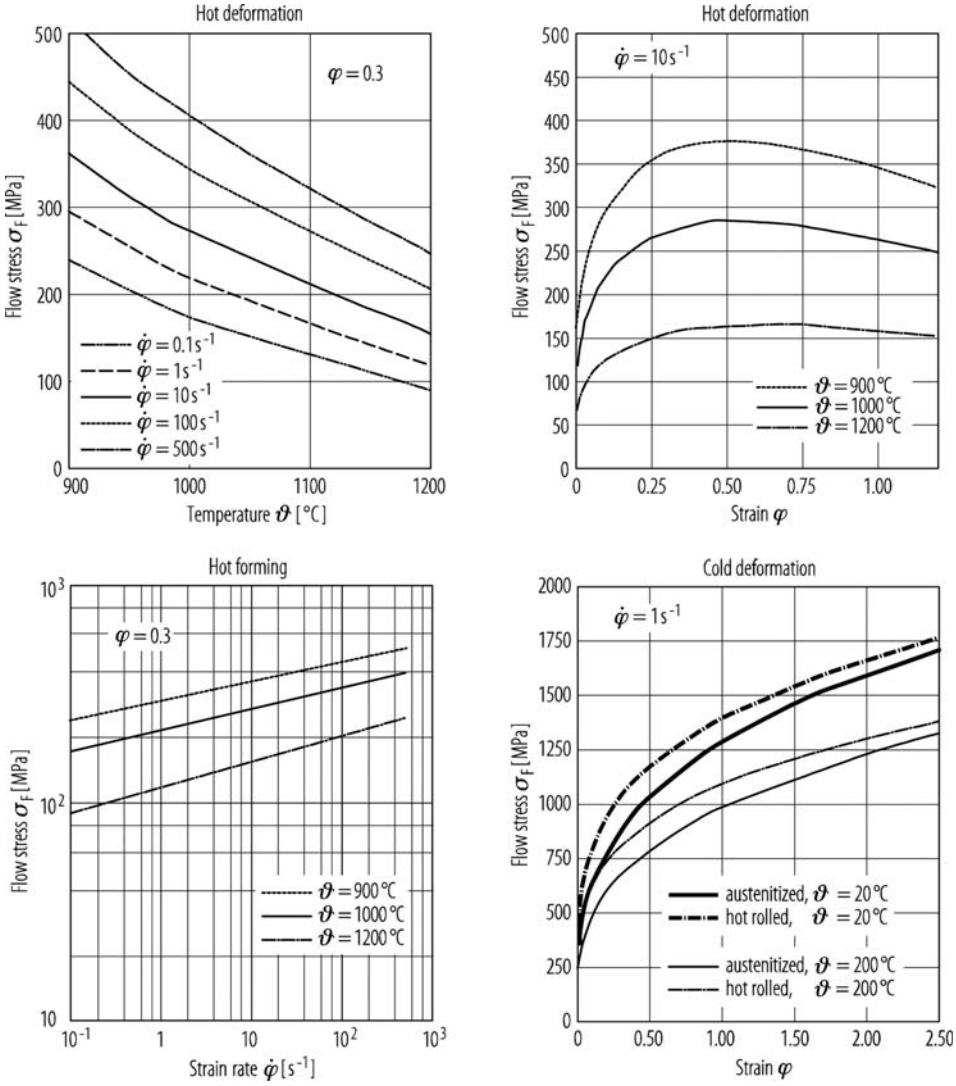
Flow curves

DOI: 10.1007/978-3-540-44760-3_105
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State of material	Hot deformation	Cold deformation	
	deformed state	austenitized	hot rolled
	austenite		
σ_{F0} [MPa]	221.48	625.4	795.2
A	7958.294	1313.925	1429.096
Effect of temperature K_ϑ			
m_1	−0.00319	−0.00147	−0.00137
Effect of strain K_φ			
m_2	0.25804	0.32011	0.25211
m_4	0.00048	0.00022	0.00013
m_5	0.00049		
m_7	−0.77808		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.00951	0.00886
m_8	0.000099		
Range of validity			
ϑ [°C]	900…1200	20…300	20…300
φ	0.04…1.20	0.04…2.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.187.
X2CrNiMoN17–13–5. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	270…290	66.5478	0.67074	570…630	7.5993	1.14548

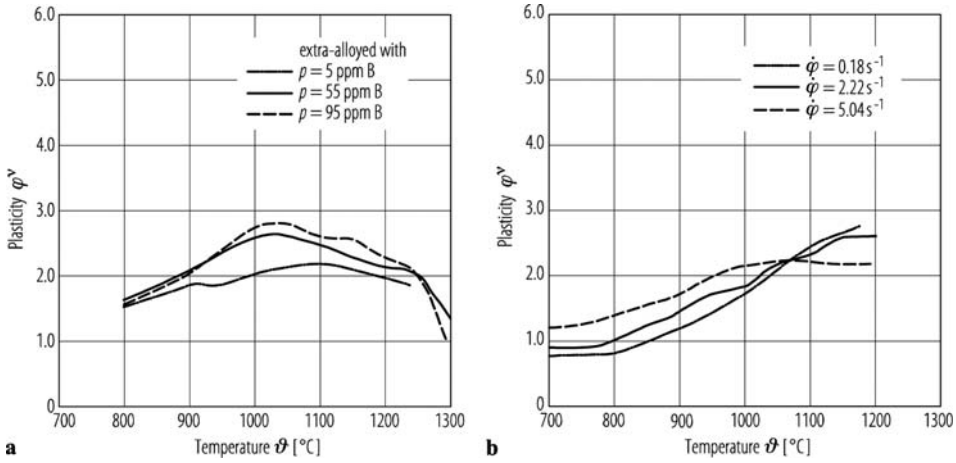
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	55…62	33.04466	0.12497	−7.64121	<80

Fig. 5.188.
X2CrNiMoN17–13–5. Hot plasticity as a function of the temperature. (a) Deformation rate: 0.1 [s^{-1}]. Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	14.73	493.31	16.50	7816.8	
100	16.48	500.10	16.73	7777.6	
200	16.64	508.73	17.31	7735.7	
300	18.02	517.50	17.02	7697.1	
400	19.37	526.43	17.02	7657.2	
500	20.73	535.51	17.92	7606.8	
600	22.12	544.74	18.23	7560.4	
700	23.57	554.14	18.54	7512.4	
800	25.07	563.69	18.87	7462.9	
900	26.65	573.42	19.19	7411.8	
1000	28.30	583.31	19.53	7359.0	
1100	30.03	593.37	19.86	7304.4	
1200	31.85	603.60	20.21	7248.2	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: X2CrNiMoN22–5–3/1.4462

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.03	0.00…1.00	0.00…2.00	0.000…0.035	0.000…0.015	21.00…23.00
Mo	Ni	N			
2.50…3.50	4.50…6.50	0.100…0.220			

International comparison of standards

ISO		Euronorm	
~ X2CrNiMoN22–5–3	TR 15510 (1997)	X2CrNiMoN22–5–3	10272 (10/2000)
		X2CrNiMoN22–5–3	10088–3 (04/1995)
United Kingdom		Russia	
X2CrNiMoN22–5–3	EN 10272 (10/2000)		
X2CrNiMoN22–5–3	EN 10088–3 (04/1995)		
Japan		China	
~ SUS 329J3LTP	G 3459 (1997)		
~ SUS 329J3L	G 4305 (1999)		
USA			
ASTM		SAE	UNS
~ A 182 (F60) (S 32205)	A 182–02	~ S31803	~ S39209
~ A 276 (S 32205)	A 276–02	~ S32205	~ S31803

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

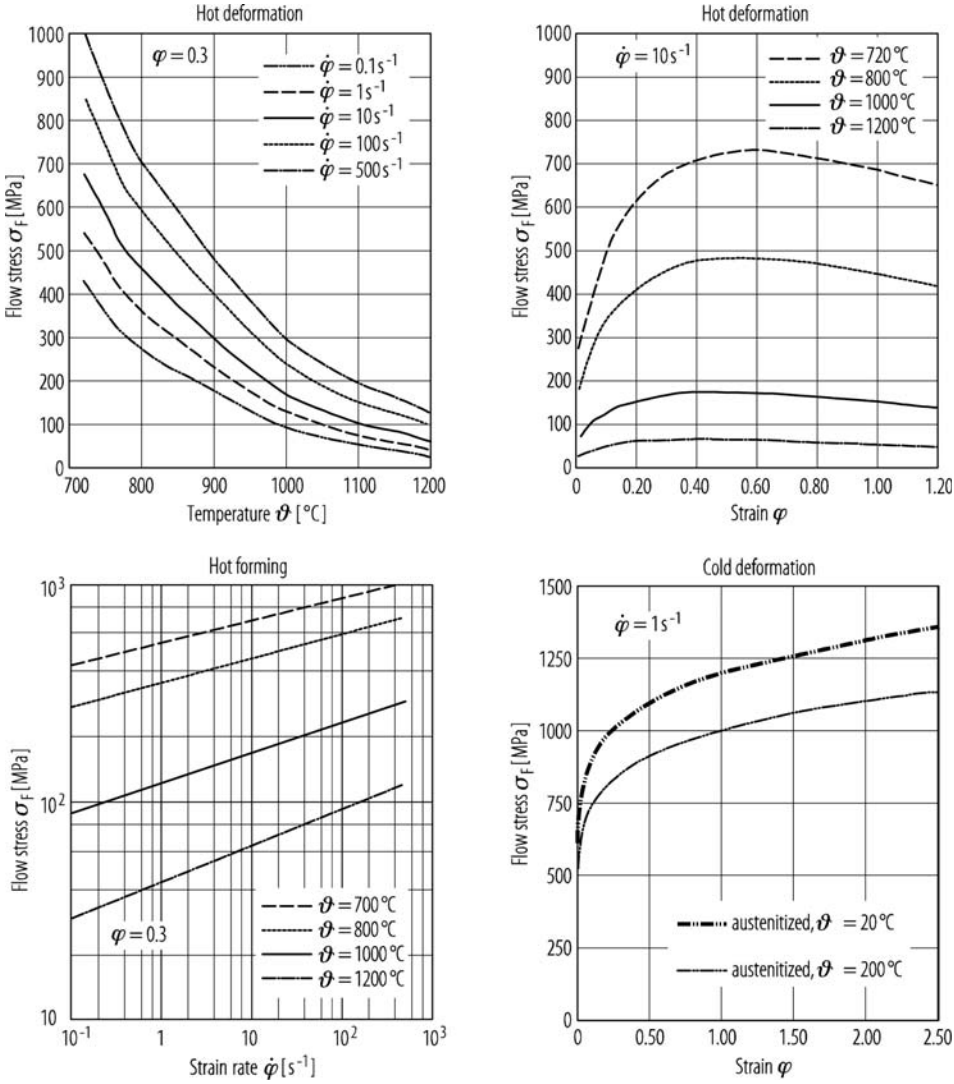
Flow curves

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State of material	Hot deformation deformed state austenite+ferrit	Cold deformation austenitized
σ_{F0} [MPa]	129.9	885.5
A	47099.01	1222.96
Effect of temperature K_ϑ		
m_1	−0.00501	−0.00103
Effect of strain K_φ		
m_2	0.48337	0.13437
m_4	0.00421	0.000008
m_5	−0.00097	
m_7	−0.37454	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00302
m_8	0.000138	
Range of validity		
ϑ [°C]	720…1200	20…300
φ	0.04…1.20	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500

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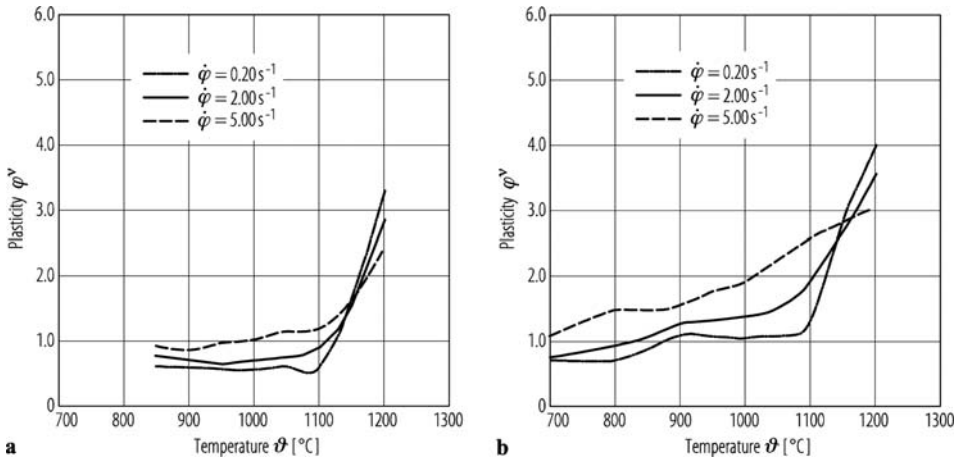
Fig. 5.189.
X2CrNiMoN22–5–3. Flow stress curves by hot and cold forming.



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Fig. 5.190.
X2CrNiMoN22–5–3. Hot plasticity as a function of the temperature. (a) Casting state. Austenitised at 1150 [°C]. (b) Deformaed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	12.29	454.83	12.09	7785.8	191.0
100	14.48	494.60	12.29	7757.0	184.4
200	17.91	530.65	12.55	7727.1	177.2
300	19.23	556.13	12.80	7696.0	170.2
400	20.53	576.51	13.07	7663.7	162.9
500	21.87	593.90	13.34	7630.0	154.6
600	23.25	609.32	13.61	7595.0	145.0
700	24.68	623.36	13.89	7558.6	133.7
800	26.18	636.36	14.18	7520.8	120.5
900	27.75	648.58	14.47	7481.6	105.4
1000	29.40	660.17	14.77	7440.8	88.4
1100	31.14	671.26	15.07	7398.5	69.6
1200	32.97	681.94	15.38	7354.6	49.3

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Steel symbol/number: X5CrNiMoCuTi20–18/1.4506

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.07	0.00…1.00	0.00…2.00	0.000…0.045	0.000…0.030	16.50…18.50
Cu	Mo	Ni	Ti		
1.80…2.20	2.00…2.50	19.00…21.00	> 0.50		

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

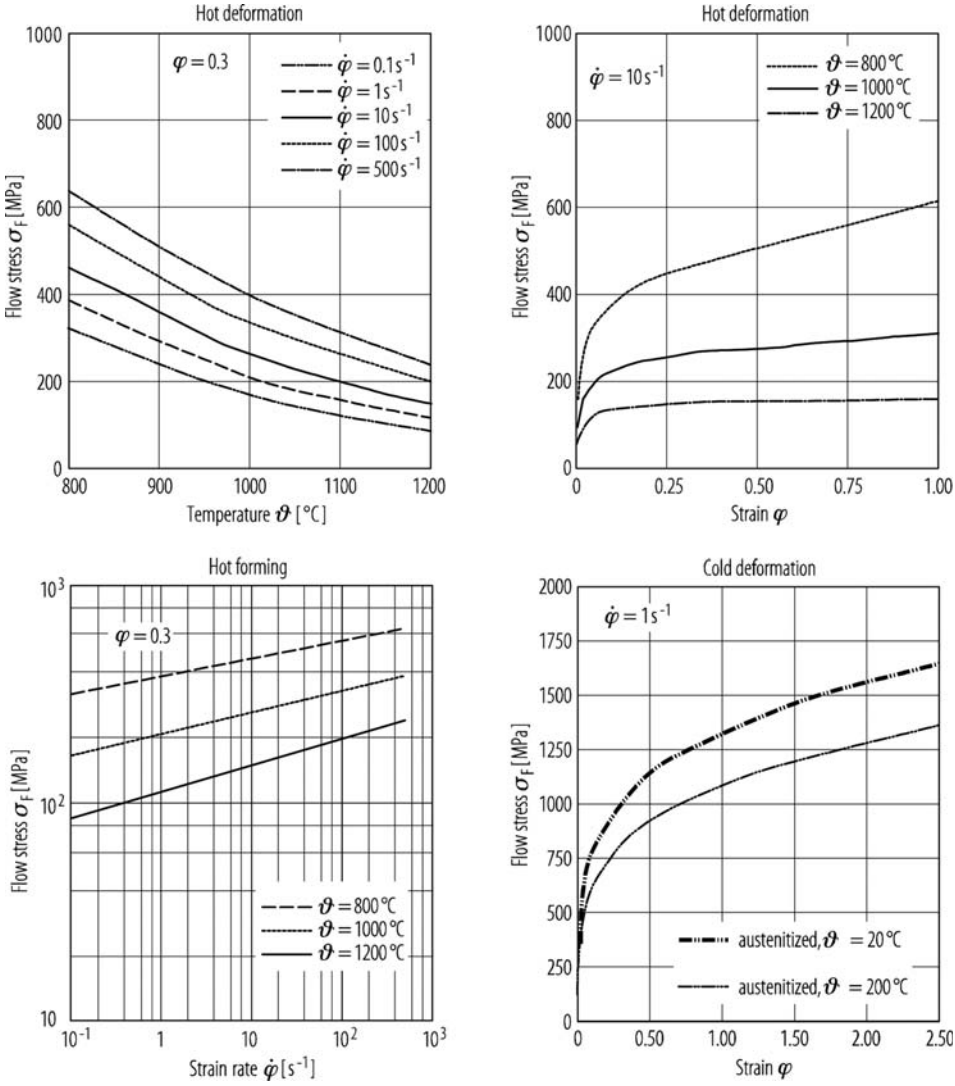
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation austenitized
σ_{F0} [MPa]	226.77	746.1
A	4502.329	1371.05
Effect of temperature K_ϑ		
m_1	−0.00272	−0.00109
Effect of strain K_φ		
m_2	0.18351	0.22623
m_4	−0.00267	−0.00761
m_5	−0.00131	
m_7	0.42452	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00443
m_8	0.000101	
Range of validity		
ϑ [°C]	800…1200	20…300
φ	0.04…1.00	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.191.
X5CrNiMoCuTi20–18. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	225…260	42.5253	0.70619	550…650	7.3292	1.04657

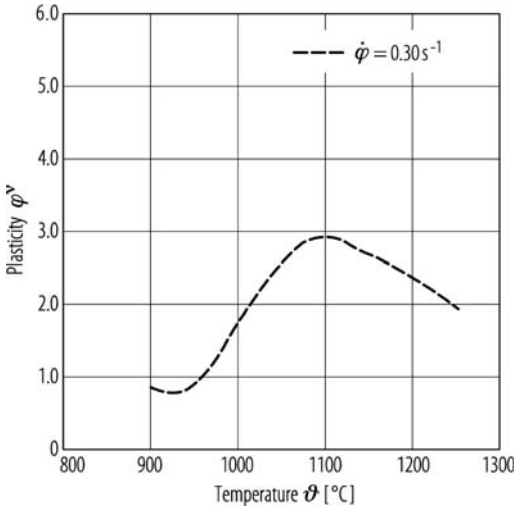
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	38…45	52.44946	−0.06581	−15.707	<80

Fig. 5.192.
X5CrNiMoCuTi20–18. Hot plasticity as a fuction of the temperature; deformed state and austenitized at 1150 [°C]. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.30…0.60.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	26.04	493.31	16.50	7965.0	196.0
100	26.25	500.10	16.73	7925.0	189.9
200	16.08	508.73	17.31	7882.2	182.0
300	17.49	517.50	17.02	7843.0	174.0
400	18.85	526.43	17.02	7802.3	166.0
500	20.22	535.51	17.92	7750.9	158.0

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Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
600	21.62	544.74	18.23	7703.6	150.0
700	23.07	554.14	18.54	7654.8	142.0
800	24.57	563.69	18.87	7604.3	134.0
900	26.15	573.42	19.19	7552.2	125.7
1000	27.80	583.31	19.53	7498.4	117.1
1100	29.53	593.37	19.86	7442.8	107.8
1200	31.35	603.60	20.21	7385.5	97.7

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Steel symbol/number: X3CrTi17/1.4510

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.05	0.00…1.00	0.00…1.00	0.000…0.040	0.000…0.015	16.00…18.00
Ti					
0.35…0.80					

International comparison of standards

ISO		Euronorm		
~ X3CrTi17	TR 15510 (1997)	X3CrTi17	10028–7 (2000)	
		X3CrTi17	10088–2 (04/1995)	
United Kingdom		Russia		
X3CrTi17	EN 10028–7 (2000)	~ 08Ch17T	5632 (1972)	
X3CrTi17	EN 10088–2 (04/1995)			
Japan		China		
~ SUS 430LX	G 4304 (1999)			
~ SUS 430LX	G 4305 (1999)			
USA				
ASTM		AISI	SAE	UNS
~ A 240 (439)	A 240–02	~ 439	~ S43035	~ S43035
~ A 268 (439)	A 268–01	~ 430 Ti	~ 439	~ S43036

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

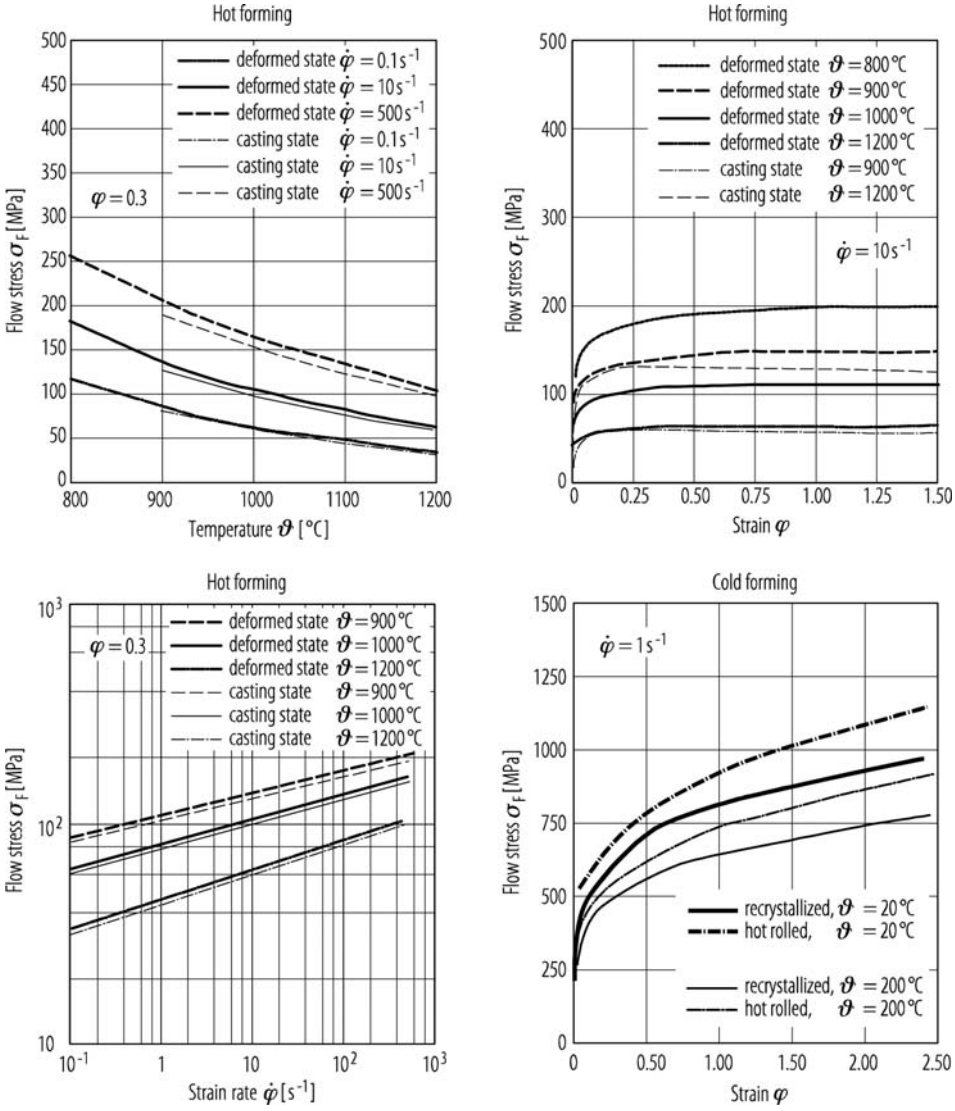
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Flow curves

	Hot deformation		Cold deformation	
	deformed state	casting state	recrystallized	hot rolled
State of material	austenite+ferrite	austenite+ferrite		
σ_{F0} [MPa]	94.7	93.9	512.4	583.1
A	1882.43	1451.16	835.721	931.600
Effect of temperature K_ϑ				
m_1	−0.00291	−0.00284	−0.00130	−0.00127
Effect of strain K_φ				
m_2	0.13787	0.0261	0.19829	0.24657
m_4	0.00021	−0.00802	−0.00528	0.00984
m_5	−0.00027	−0.00017		
m_7	0.00818	0.00822		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.02006	0.01138
m_8	0.000113	0.000112		
Range of validity				
ϑ [°C]	800…1200	900…1200	20…350	20…350
φ	0.04…1.50	0.04…1.50	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.193.
X3CrTi17. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_P [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
hot rolled	350…450	104.32802	0.3158	550…650	20.41888	0.59445

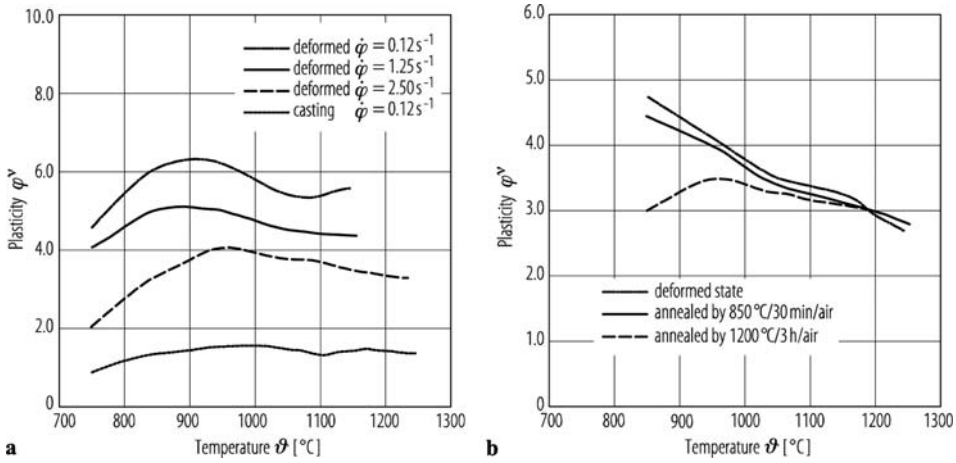
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
hot rolled	30…35	18.78803	0.0673	−1.18395	<70

Fig. 5.194.
X3CrTi17. Hot plasticity as a function of the temperature. (a) Direct heating on deformation temperature. (b) Deformation rate: 0.2 [s^{-1}]. Direct heating on deformation temperature.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.71	439.16	10.01	7673.4	
100	15.66	485.71	10.18	7665.2	
200	26.51	508.06	10.43	7623.9	
300	26.77	528.26	10.76	7596.7	
400	27.03	548.45	11.10	7568.0	
500	27.30	569.06	11.45	7537.4	
600	27.57	590.28	11.82	7505.1	
700	27.84	612.17	12.19	7470.8	
800	28.11	634.82	12.57	7434.5	
900	28.39	658.25	12.97	7396.2	
1000	28.67	682.52	13.38	7355.6	
1100	28.95	707.65	13.80	7312.8	
1200	29.23	733.69	14.24	7267.6	

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Steel symbol/number: X2CrTi12/1.4512

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.030	0.00…1.00	0.00…1.00	0.00…0.040	0.00…0.015	10.50…12.50
Ti					
0.15…0.65					

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

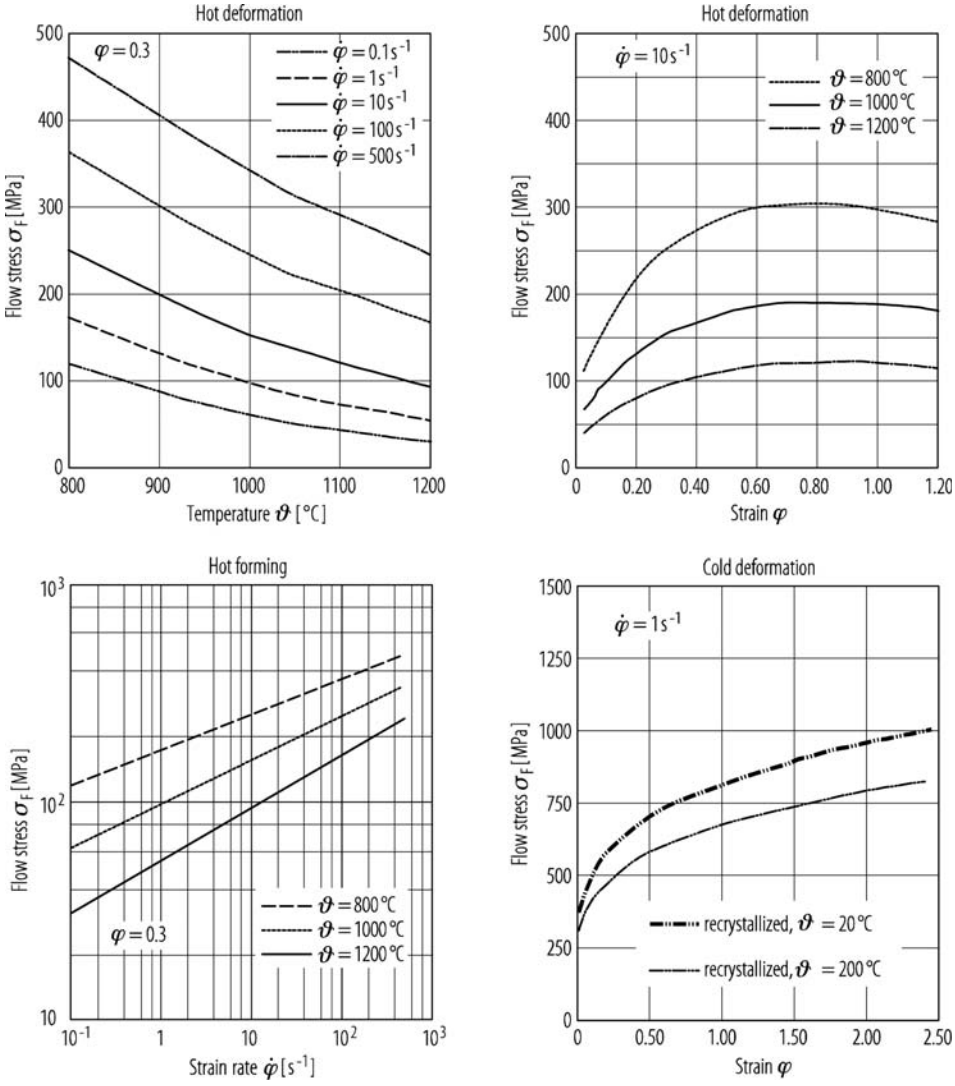
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation recrystallized
σ_{F0} [MPa]	99.13	507.4
A	4422.71	833.672
Effect of temperature K_ϑ		
m_1	−0.00299	−0.00110
Effect of strain K_φ		
m_2	0.48151	0.22854
m_4	0.01191	0.00277
m_5	0.00036	
m_7	−0.89231	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01042
m_8	0.000202	
Range of validity		
ϑ [°C]	800…1200	20…300
φ	0.04…1.20	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.195.
X2CrTi12. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_P [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
hot rolled	280…350	180.36093	0.1734	450…600	56.12829	0.37426

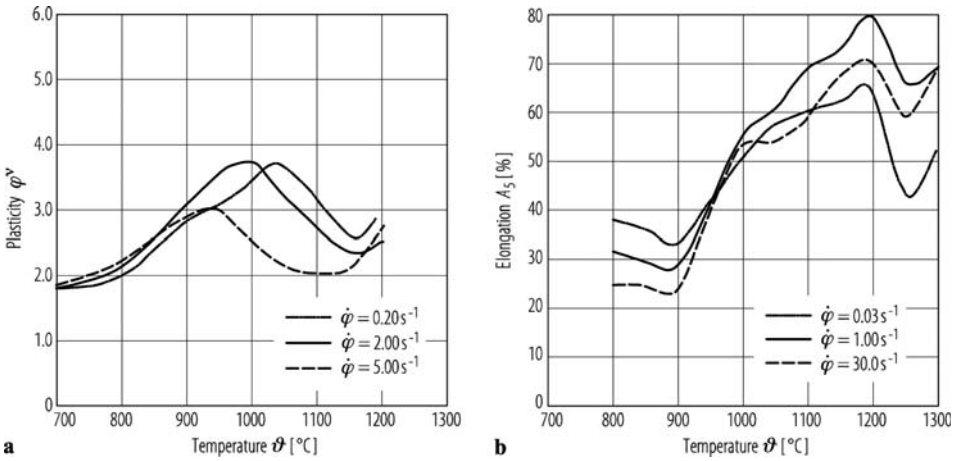
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
hot rolled	33…40	15.76228	0.12997	−0.6614	<70

Fig. 5.196.
X2CrTi12. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1180 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.71	439.16	10.01	7673.4	
100	15.66	485.71	10.18	7665.2	
200	26.51	508.06	10.43	7623.9	
300	26.77	528.26	10.76	7596.7	
400	27.03	548.45	11.10	7568.0	
500	27.30	569.06	11.45	7537.4	
600	27.57	590.28	11.82	7505.1	
700	27.84	612.17	12.19	7470.8	
800	28.11	634.82	12.57	7434.5	
900	28.39	658.25	12.97	7396.2	
1000	28.67	682.52	13.38	7355.6	
1100	28.95	707.65	13.80	7312.8	
1200	29.23	733.69	14.24	7267.6	

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Steel symbol/number: X6CrNiTi18–10/1.4541

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.08	0.00…1.00	0.00…2.00	0.000…0.045	0.000…0.015	17.00…19.00
Ni	Ti				
9.00…12.00	0.20…0.70				

International comparison of standards

ISO		Euronorm		
~ X6CrNiTi18–10	9329–6 (1997)	X6CrNiTi18–10	10272 (10/2000)	
~ X6CrNiTi18–10	TR 15510 (1997)	X6CrNiTi18–10	10088–3 (04/1995)	
United Kingdom		Russia		
X6CrNiTi18–10	EN 10272 (10/2000)	~ 08Ch18N10T	5632 (1972)	
~ 321 S 31	3605 Part 2 (1992)	~ 09Ch18N10T	10498 (1982)	
Japan		China		
~ SUS 321TP	G 3459 (1997)	~ 0Cr18Ni10Ti	T 3090 (12000)	
~ SUS 321	G 4309 (1999)	~ H0Cr20Ni10Ti	T 5092 (1996)	
USA				
ASTM		AISI	SAE	UNS
~ A 182 (F 321)	A 182–02	~ 321	~ S32100	~ S32100
~ A 249 (321)	A 249–02		~ 321	

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

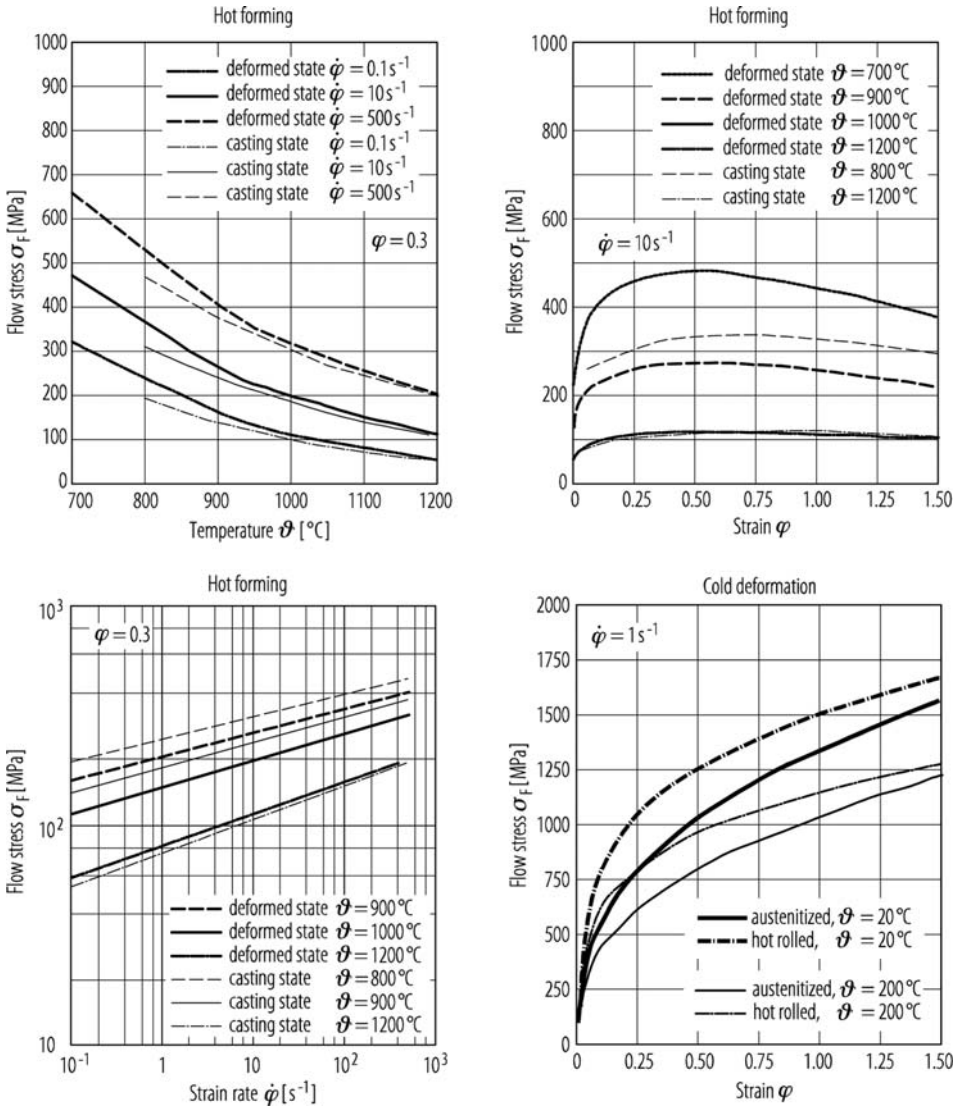
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Flow curves

	Hot deformation		Cold deformation	
	deformed state	casting state	austenitized	hot rolled
State of material	austenite	austenite		
σ_{F0} [MPa]	167.1	154.8	567.9	814.0
A	5392.64	4528.60	1384.39	1569.139
Effect of temperature K_ϑ				
m_1	−0.00321	−0.00306	−0.00143	−0.00152
Effect of strain K_φ				
m_2	0.22312	0.33963	0.37722	0.24011
m_4	0.00003	0.02026	−0.00231	−0.01034
m_5	0.00028	0.00028		
m_7	−0.58508	−0.58516		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.01269	0.01158
m_8	0.000122	0.000128		
Range of validity				
ϑ [°C]	700…1200	800…1200	20…300	20…300
φ	0.04…1.50	0.04…1.50	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<150	<500	<500

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Fig. 5.197.
X6CrNiTi18–10. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	260…300	73.5562	0.60721	550…650	7.7797	1.17565
hot rolled	370…420	22.9843	0.91566	650…700	124.0618	0.55112

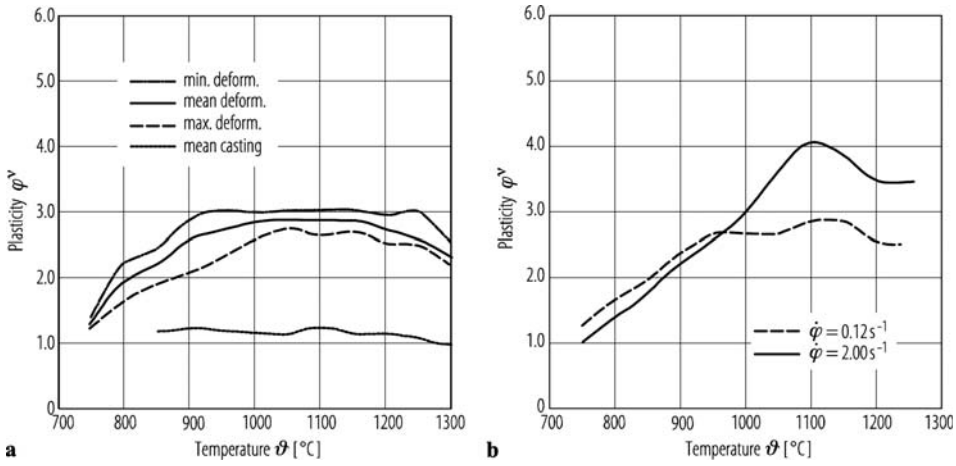
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	50…65	1.89548	0.97393	−1.35026	<80
hot rolled					<75

Fig. 5.198.
X6CrNiTi18–10. Hot plasticity as a function of the temperature. (a) Deformed and casting state. Deformation rate: 0.2 [s^{-1}]. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	14.21	493.31	16.50	7785.0	198.6
100	16.06	500.10	16.73	7746.0	192.8
200	17.17	508.73	17.31	7704.2	184.1
300	18.52	517.50	17.02	7665.8	175.0
400	19.85	526.43	17.02	7626.1	166.0
500	21.20	535.51	17.92	7575.8	157.5
600	22.59	544.74	18.23	7529.6	149.7
700	24.03	554.14	18.54	7481.9	142.2
800	25.54	563.69	18.87	7432.5	134.3
900	27.11	573.42	19.19	7381.6	125.2
1000	28.76	583.31	19.53	7329.0	113.5
1100	30.49	593.37	19.86	7274.7	97.7
1200	32.32	603.60	20.21	7218.6	75.6

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Steel symbol/number: X5CrNiCuNb17–4–4/1.4548

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.07	0.00…1.00	0.00…1.00	0.000…0.025	0.000…0.025	15.00…17.50
Ni	Cu	Nb			
3.00…5.00	3.00…5.00	0.15…0.45			

International comparison of standards

ISO		Euronorm		
		FE–PM 61 (AECMA)		
United Kingdom		Russia		
Japan		China		
~ SUS 630	G 4303 (1998)			
~ SUS 630	G 4305 (1999)			
USA				
ASTM		AISI	AMS	UNS
~ A 564 (630)	A 564–02	~ 630	~ 5604E	~ S17400
~ A 693 (630)	A 693–02	~ S17400	~ 5622D	

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

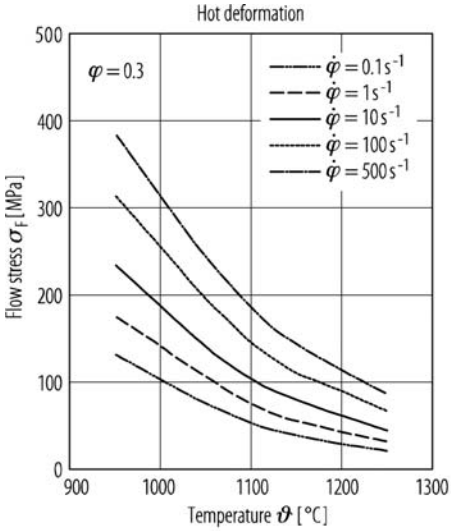
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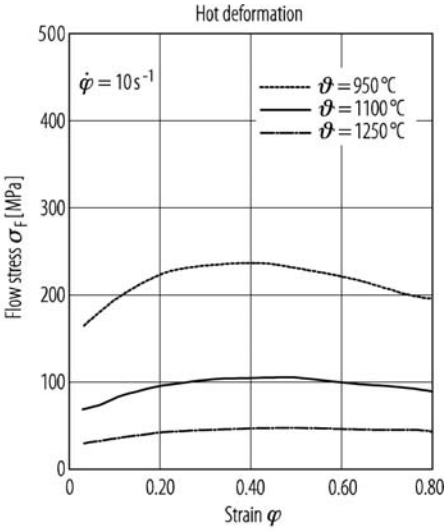
Flow curves

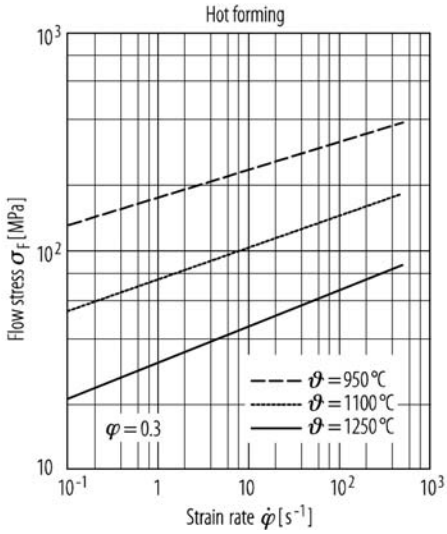
State of material	Hot deformation deformed state austenite	Cold deformation
σ_{F0} [MPa]	145.3	
A	122076.11	
Effect of temperature K_ϑ		
m_1	−0.00616	
Effect of strain K_φ		
m_2	0.40296	
m_4	0.01149	
m_5	0.00135	
m_7	−1.95586	
Effect of strain rate $K_{\dot\varphi}$		
m_3		
m_8	0.000133	
Range of validity		
ϑ [°C]	950…1250	
φ	0.04…0.80	
$\dot\varphi$ [s^{-1}]	<500	

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Fig. 5.199.
X5CrNiCuNb17–4–4. Flow stress curves by hot forming.



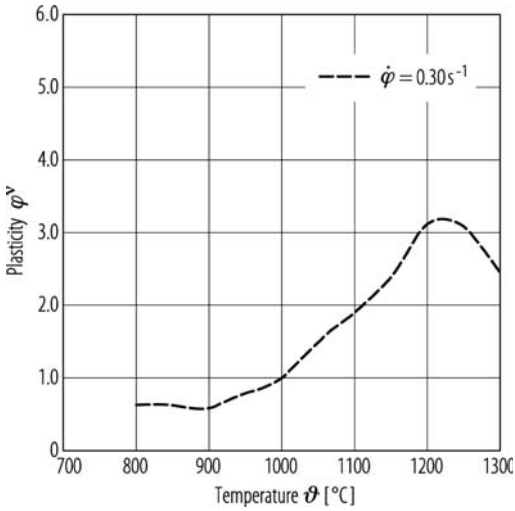




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Fig. 5.200.
X5CrNiCuNb17–4–4. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.80.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	14.49	454.8	11.09	7791.32	196.1
100	16.29	494.6	11.29	7764.9	190.5
200	17.74	530.6	11.55	7738.5	185.7
300	19.07	556.1	11.81	7708.6	178.5
400	20.38	576.5	12.07	7678.5	165.2
500	21.72	593.9	12.34	7647.1	143.2
600	23.10	609.3	12.61	7614.5	111.8
700	24.53	623.4	12.89	7580.4	
800	26.04	636.4	13.18	7544.9	
900	27.61	648.6	13.47	7508.0	
1000	29.26	660.2	13.77	7469.5	
1100	30.99	671.3	14.07	7429.6	
1200	32.82	681.9	14.38	7388.0	

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Steel symbol/number: X2CrNiNb24–12/1.4556

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.07	0.00…1.00	0.00…1.00	0.000…0.025	0.000…0.025	15.00…17.50
Ni	Cu	Nb			
3.00…5.00	3.00…5.00	0.15…0.45			

International comparison of standards

ISO		Euronorm		
		FE-PM 61 (AECMA)		
United Kingdom		Russia		
Japan		China		
∼ SUS 630	G 4303 (1998)			
∼ SUS 630	G 4305 (1999)			
USA				
ASTM		AISI	AMS	UNS
∼ A 564 (630)	A 564–02	∼ 630	∼ 5604E	∼ S17400
∼ A 693 (630)	A 693–02	∼ S17400	∼ 5622D	

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

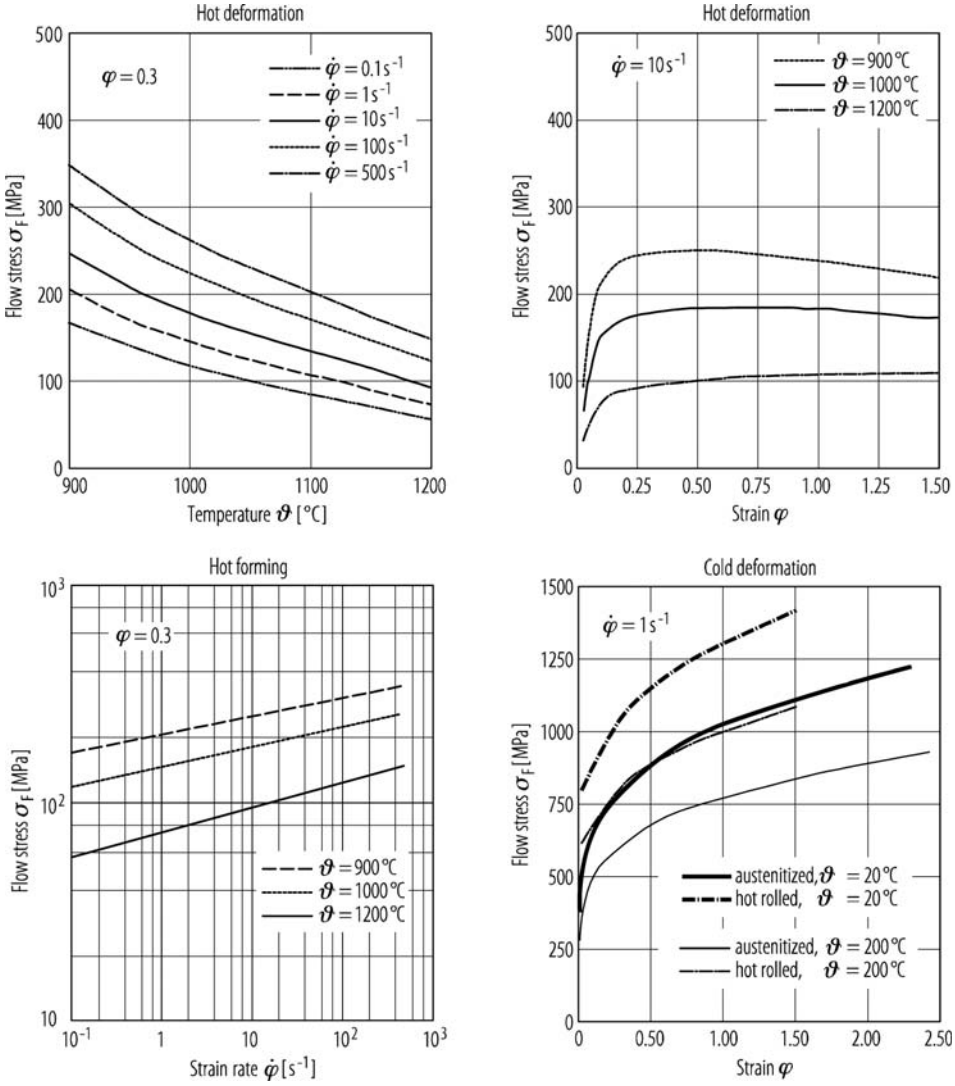
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	hot rolled	austenitized
	austenite		
σ_{F0} [MPa]	151.60	905.00	660.54
A	4677.74	1335.953	1060.108
Effect of temperature K_ϑ			
m_1	−0.00378	−0.00148	−0.00159
Effect of strain K_φ			
m_2	−0.22441	0.19299	0.20251
m_4	−0.04561	0.00581	0.0001
m_5	0.0013		
m_7	−0.53824		
Effect of strain rate $K_{\dot\varphi}$			
m_3			
m_8	0.000095	0.01123	0.01008
Range of validity			
ϑ [°C]	900…1200	20…300	20…300
φ	0.04…1.50	0.04…2.0	0.04…2.5
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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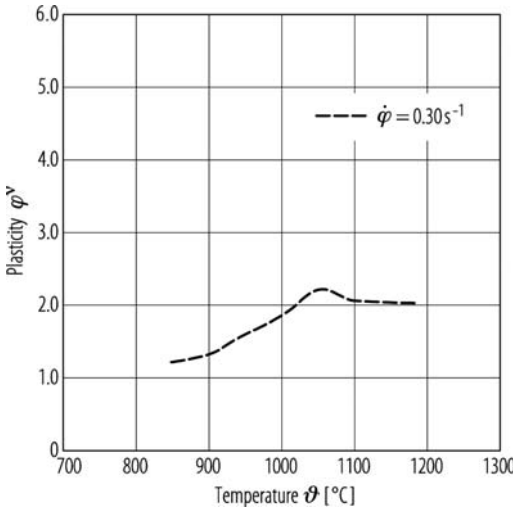
Fig. 5.201.
X2CrNiNb24–12. Flow stress curves by hot and cold forming.



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Fig. 5.202.
X2CrNiNb24–12. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.45…0.80.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	12.83	493.31	16.50	7723.9	
100	14.93	500.10	16.73	7685.2	
200	16.50	508.73	17.31	7646.4	
300	17.89	517.50	17.02	7605.6	
400	19.24	526.43	17.02	7566.2	
500	20.60	535.51	17.92	7516.3	
600	22.00	544.74	18.23	7470.5	
700	23.44	554.14	18.54	7423.1	
800	24.95	563.69	18.87	7374.2	
900	26.53	573.42	19.19	7323.7	
1000	28.18	583.31	19.53	7271.5	
1100	29.91	593.37	19.86	7217.6	
1200	31.73	603.60	20.21	7162.0	

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Steel symbol/number: X3CrNiCu18–9/1.4567

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.04	0.00…1.00	0.00…2.00	0.000…0.045	0.000…0.015	17.00…19.00
Ni	Cu	N			
8.50…10.50	3.00…4.00	0.000…0.110			

International comparison of standards

ISO		Euronorm		
~ X3CrNiCu18–9–3E	4954 (1993)	X3CrNiCu18–9–4	10263–5 (06/2001)	
~ X3CrNiCu18–9–4	TR 15510 (1997)	X3CrNiCu18–9–4	10088–3 (04/1995)	
United Kingdom		Russia		
X3CrNiCu18–9–4	EN 10263–5 (06/2001)			
X3CrNiCu18–9–4	EN 10088–3 (04/1995)			
Japan		China		
~ SUS XM7	G 4303 (1998)	~ 0Cr18Ni9Cu3	T 1220 (1992)	
~ SUS XM7	G 4315 (2000)	~ ML0Cr18Ni9Cu3	T 4232 (1993)	
USA				
ASTM		AISI	SAE	UNS
~ A 493 (S 30430)	A 182–02	~ XM-7	~ EV 17	~ S30430
		~ S30430		

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

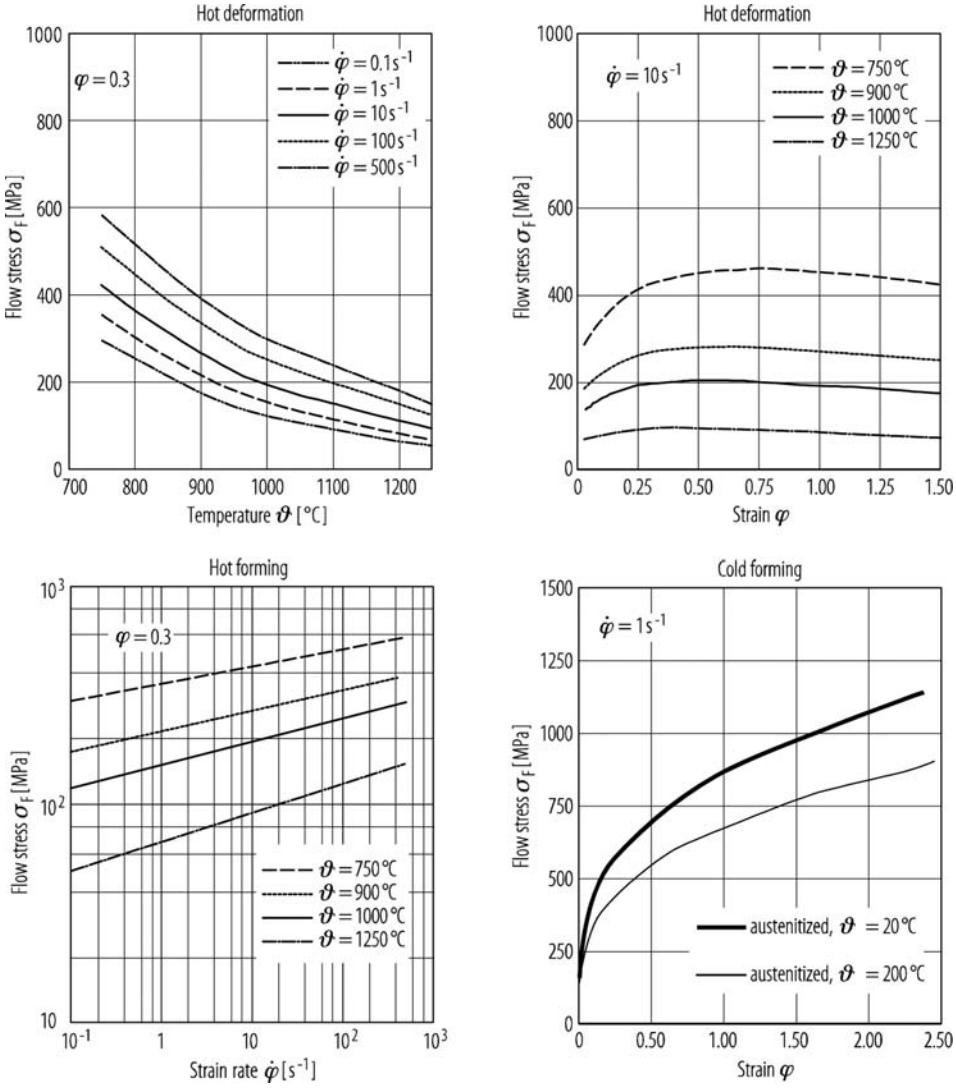
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation austenitized
σ_{F0} [MPa]	162.6	436.1
A	6724.43	894.386
Effect of temperature K_ϑ		
m_1	−0.00314	−0.00141
Effect of strain K_φ		
m_2	0.35898	0.30711
m_4	0.00856	−0.00087
m_5	−0.00072	
m_7	−0.16732	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01116
m_8	0.000106	
Range of validity		
ϑ [°C]	750…1250	20…300
φ	0.04…1.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.203.
X3CrNiCu18–9. Flow stress curves by hot and cold forming.



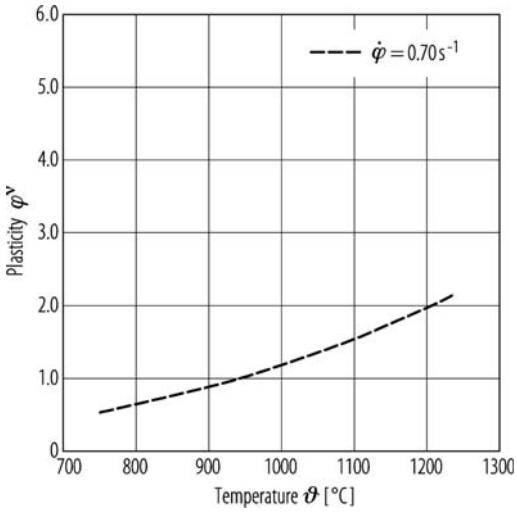
Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
chilled				600…650	7.5436	1.06313	<80

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Fig. 5.204.
X3CrNiCu18–9. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as–cast and as-deformed state is: 0.45…0.85.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	14.11	493.31	16.50	7703.6	
100	15.99	500.10	16.73	7664.9	
200	17.90	508.73	17.31	7623.6	
300	19.22	517.50	17.02	7585.6	
400	20.52	526.43	17.02	7546.3	
500	21.86	535.51	17.92	7496.5	
600	23.24	544.74	18.23	7450.8	
700	24.67	554.14	18.54	7403.6	
800	26.17	563.69	18.87	7354.8	
900	27.74	573.42	19.19	7304.4	
1000	29.39	583.31	19.53	7252.3	
1100	31.13	593.37	19.86	7198.6	
1200	32.96	603.60	20.21	7143.1	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: X7CrNiAl17–7/1.4568

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.09	0.00…0.70	0.00…1.00	0.000…0.040	0.000…0.015	16.00…18.00
Ni	Al				
6.5…7.8	0.70…1.50				

International comparison of standards

ISO		Euronorm		
~ X7CrNiAl17–7	6931–1 (1994)	X7CrNiAl17–7	10151 (06/2002)	
~ X7CrNiAl17–7	TR 15510 (1997)	X7CrNiAl17–7	10088–3 (04/1995)	
United Kingdom		Russia		
X7CrNiAl17–7	EN 10151 (06/2002)	~ 09Ch17N7Ju1	5632 (1972)	
X7CrNiAl17–7	EN 10088–3 (04/1995)			
Japan		China		
~ SUS 631	G 4305 (1999)	~ 0Cr17Ni7Al	T 1220 (1992)	
~ SUS 631–CSP	G 4313 (1996)	~ S51778	T 4231 (1993)	
USA				
ASTM		AISI	SAE	UNS
~ A 313 (631)	A 313–98	~ 631	~ J217	~ S17700
~ A 564 (631)	A 564–02	~ S17700		

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

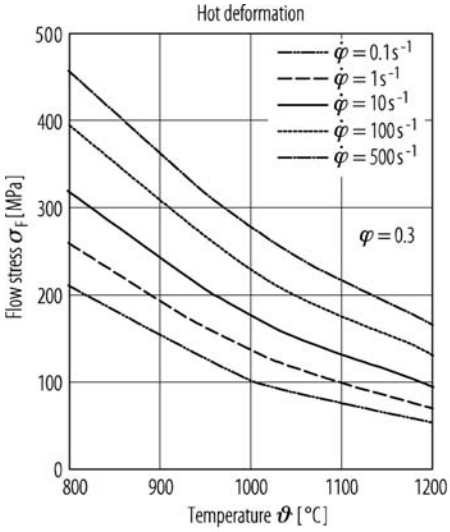
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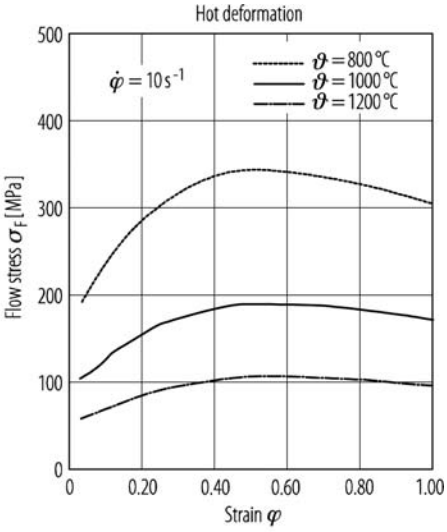
Flow curves

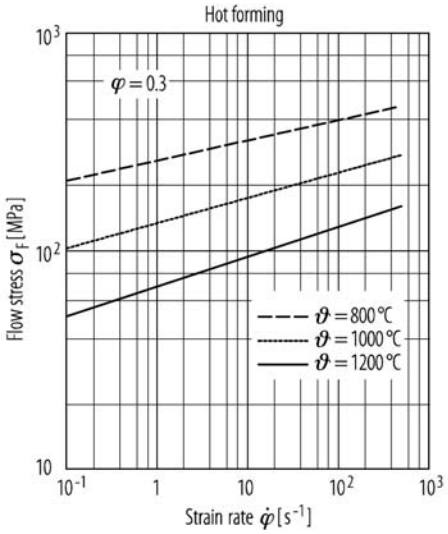
State of material	Hot deformation deformed state austenite	Cold deformation
σ_{F0} [MPa]	126.34	
A	9252.323	
Effect of temperature K_ϑ		
m_1	−0.00336	
Effect of strain K_φ		
m_2	0.56283	
m_4	0.01806	
m_5	0.0003	
m_7	−1.12901	
Effect of strain rate $K_{\dot\varphi}$		
m_3		
m_8	0.000115	
Range of validity		
ϑ [°C]	800…1200	
φ	0.04…1.00	
$\dot\varphi$ [s^{-1}]	<500	

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Fig. 5.205.
X7CrNiAl17–7. Flow stress curves by hot forming.



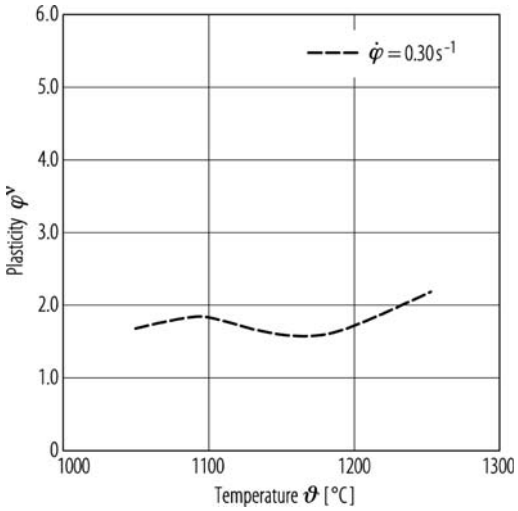




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Fig. 5.206.
X7CrNiAl17–7. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.35…0.65.

Plasticity in torsion



DOI: 10.1007/978-3-540-44760-3_114
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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.42	493.31	16.50	7691.9	
100	15.42	500.10	16.73	7653.3	
200	17.47	508.73	17.31	7612.0	
300	18.81	517.50	17.02	7574.1	
400	20.13	526.43	17.02	7534.8	
500	21.47	535.51	17.92	7485.2	
600	22.85	544.74	18.23	7439.5	
700	24.29	554.14	18.54	7392.3	
800	25.79	563.69	18.87	7343.6	
900	27.37	573.42	19.19	7293.3	
1000	29.02	583.31	19.53	7241.3	
1100	30.75	593.37	19.86	7187.7	
1200	32.58	603.60	20.21	7132.3	

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Steel symbol/number: X6CrNiMoTi17–12–2/1.4571

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.08	0.00…1.00	0.00…2.00	0.000…0.045	0.000…0.015	16.50…18.50
Mo	Ni	Ti			
2.00…2.50	10.50…13.50	0.20…0.70			

International comparison of standards

ISO		Euronorm		
~ X6CrNiMoTi17–12	9330–6 (1997)	X6CrNiMoTi17–12–2	10263–5 (06/2001)	
~ X6CrNiMoTi17–12–2	TR 15510 (1997))	X6CrNiMoTi17–12–2	10088–3 (04/1995)	
United Kingdom		Russia		
X6CrNiMoTi17–12–2	EN 10263–5 (06/2001)	~ 10Ch17N13M2T	5632 (1972)	
~ 320 S 31	970 Part 1 (1996)	~ 08Ch16N11M3T	Not standardized	
Japan		China		
~ SUS 316Ti	G 4303 (1998)	~ 0Cr18Ni12Mo2Ti	T 1220 (1992)	
~ SUS 316Ti	G 4305 (1999)	~ S31668	T 14976 (1994)	
USA				
ASTM		AISI	SAE	UNS
~ A 240 (316 Ti)	A 240–02	~ 316Ti	~ 316Ti	~ S31635
~ A 314 (316 Ti)	A 314–02		~ S31635	

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

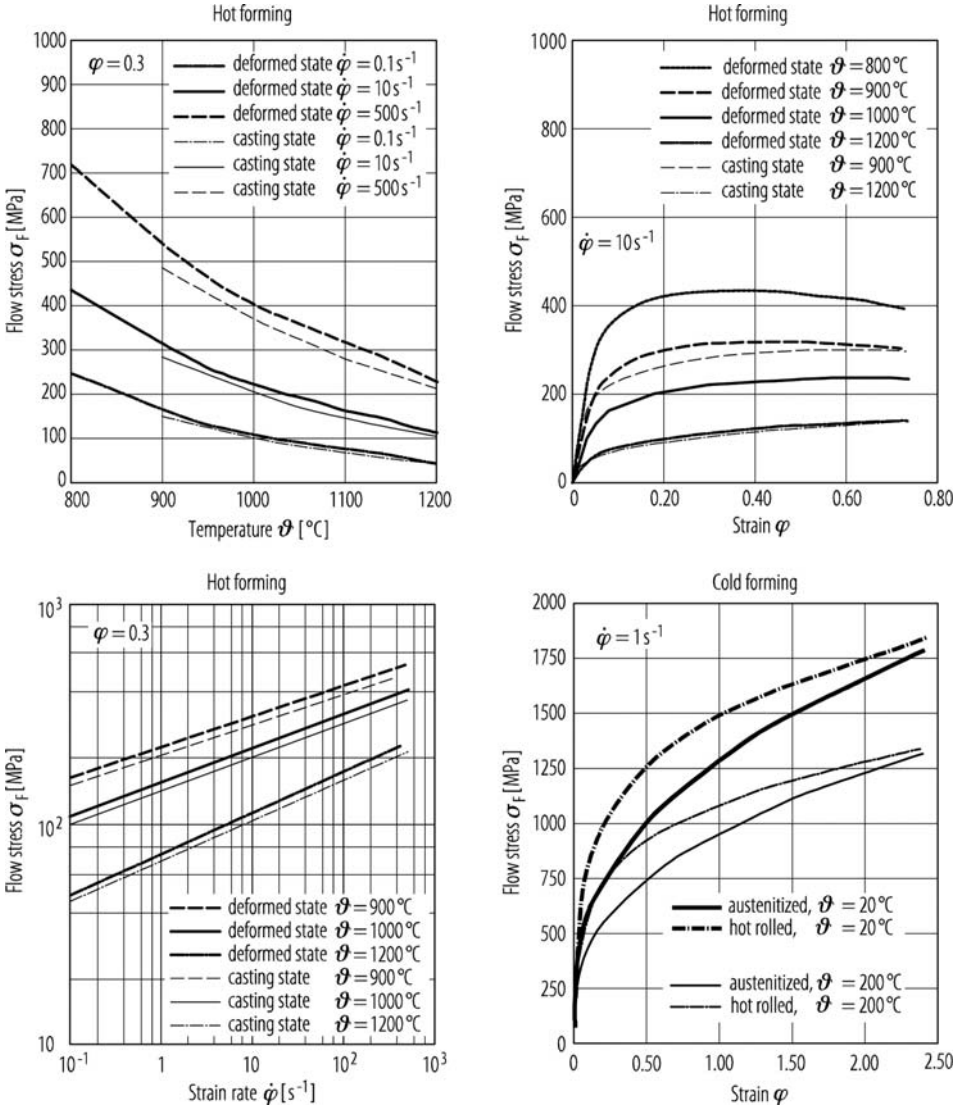
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Flow curves

	Hot deformation		Cold deformation	
	deformed state	casting state	austenitized	hot rolled
State of material	austenite	austenite		
σ_{F0} [MPa]	173.42	158.06	582.2	823.4
A	12034.707	10075.29	1326.651	1551.016
Effect of temperature K_ϑ				
m_1	−0.00449	−0.00442	−0.00168	−0.00175
Effect of strain K_φ				
m_2	−0.02334	0.02600	0.37034	0.22961
m_4	−0.0246	−0.01284	0.00323	−0.01045
m_5	0.00272	0.00286		
m_7	−1.7494	−1.70165		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.01322	0.01286
m_8	0.000155	0.000152		
Range of validity				
ϑ [°C]	800…1200	900…1200	20…300	20…300
φ	0.04…1.50	0.04…0.75	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<150	<500	<500

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Fig. 5.207.
X6CrNiMoTi17–12–2. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	220..240	64.1472	0.66487	550…600	0.7832	1.64308
hot rolled	260…300	30.4483	0.84802	575…650	9.6934	1.04216

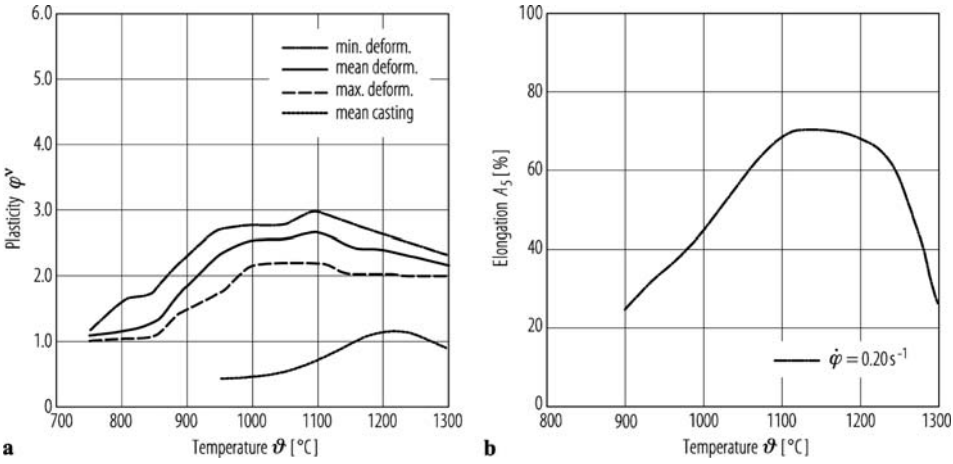
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	50…58	16.87174	0.26133	−3.71005	<80
hot rolled	45…52	5.62359	0.46382	−0.95173	<80

Fig. 5.208.
X6CrNiMoTi17–12–2. Hot plasticity as a function of the temperature. (a) Deformation rate: 0.2 [s^{-1}]. Deformed and casting state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.20	493.31	16.50	7864.5	200.0
100	15.24	500.10	16.73	7825.1	193.9
200	16.95	508.73	17.31	7782.8	186.2
300	18.32	517.50	17.02	7744.1	178.9
400	19.65	526.43	17.02	7703.9	172.0
500	21.01	535.51	17.92	7653.2	165.7
600	22.40	544.74	18.23	7606.5	159.7
700	23.84	554.14	18.54	7558.3	153.7
800	25.34	563.69	18.87	7508.4	147.3
900	26.92	573.42	19.19	7457.0	139.7
1000	28.57	583.31	19.53	7403.8	130.2
1100	30.30	593.37	19.86	7349.0	117.9
1200	32.13	603.60	20.21	7292.4	101.6

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Steel symbol/number: X5CrNiMoNb19–12/1.4576

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.06	0.00…1.40	0.00…1.90	0.000…0.025	0.000…0.015	18.20…19.80
Mo	Ni	Nb			
2.50…3.00	10.20…12.80	0.70…1.15			

International comparison of standards

ISO		Euronorm	
		~ X5CrNiMoNb19–12–03KE	144 (1979)
United Kingdom		Russia	
Japan		China	
USA			
ASME		AWS	SAE	UNS
~ SFA 5.9 (ER318)		~ A 5.9 (ER318)		~ S31980

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

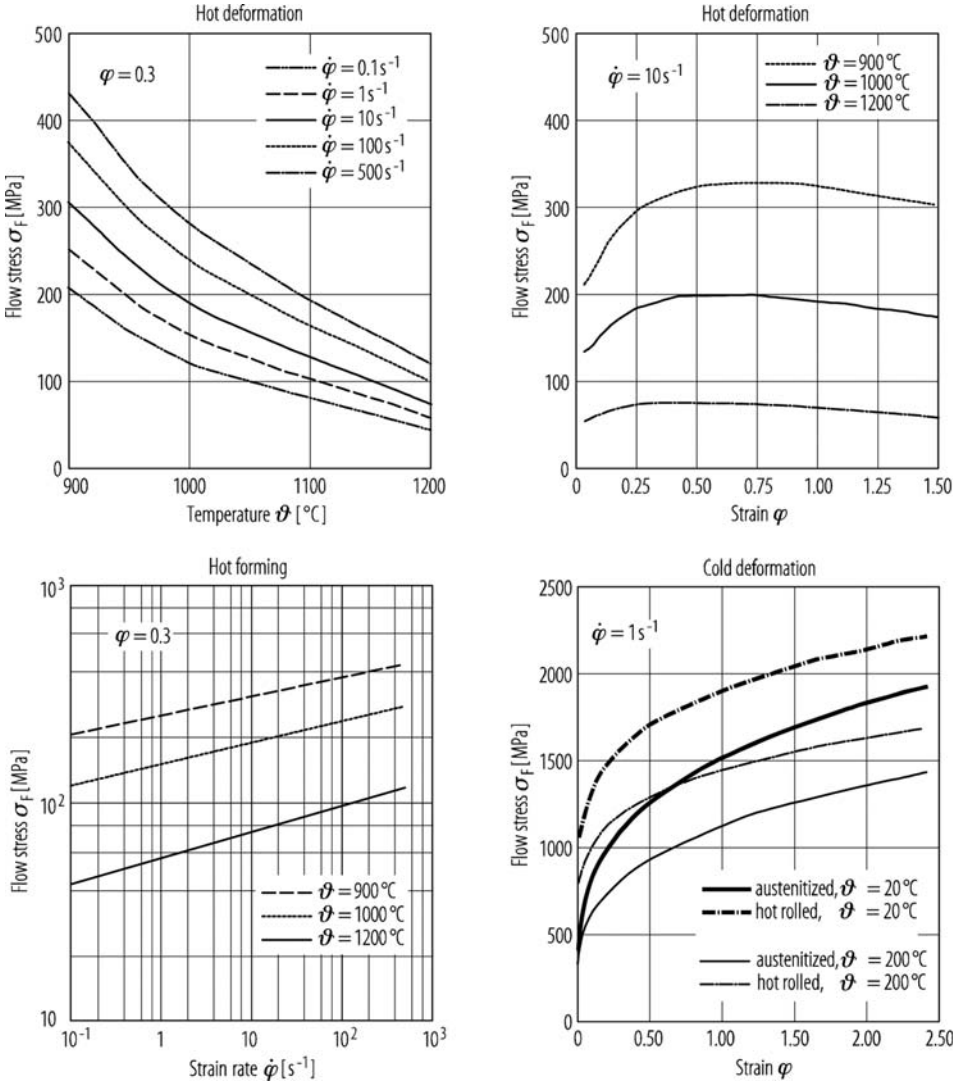
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	austenitized	hot rolled
	austenite		
σ_{F0} [MPa]	153.22	834.1	1339.7
A	36620.00	1570.530	1961.426
Effect of temperature K_ϑ			
m_1	−0.00468	−0.00168	−0.00154
Effect of strain K_φ			
m_2	0.46253	0.27110	0.16950
m_4	0.0151	0.00010	0.00123
m_5	−0.00107		
m_7	−0.06984		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01043	0.01197
m_8	0.000125		
Range of validity			
ϑ [°C]	900…1200	20…300	20…300
φ	0.04…1.50	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.209.
X5CrNiMoNb19–12. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	360…390	35.7886	0.80184	570…640	6.5727	1.17248

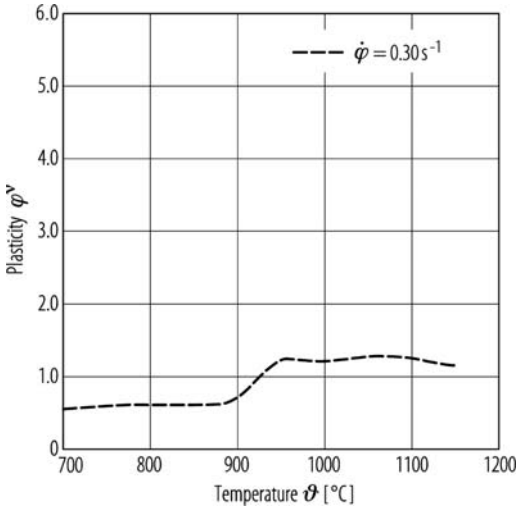
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Mechanical properties after cold deformation

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	45…50	16.68650	0.21131	−4.72685	<80

Fig. 5.210.
X5CrNiMoNb19–12. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.70.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	11.96	493.31	16.50	7840.2	
100	14.20	500.10	16.73	7800.8	
200	16.79	508.73	17.31	7758.7	
300	18.16	517.50	17.02	7720.1	
400	19.50	526.43	17.02	7680.1	
500	20.86	535.51	17.92	7629.4	

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Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
600	22.25	544.74	18.23	7582.9	
700	23.70	554.14	18.54	7534.8	
800	25.20	563.69	18.87	7485.2	
900	26.78	573.42	19.19	7433.9	
1000	28.43	583.31	19.53	7380.9	
1100	30.16	593.37	19.86	7326.2	
1200	31.98	603.60	20.21	7269.8	

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Steel symbol/number: X10CrAlSi7/1.4713

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.12	0.50…1.00	0.00…1.00	0.000…0.040	0.000…0.015	6.00…8.00
Al					
0.50…1.00					

International comparison of standards

ISO		Euronorm	
		X10CrAlSi7	10095 (03/1999)
United Kingdom		Russia	
X10CrAlSi7	EN 10095 (03/1999)		
Japan		China	
USA			
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

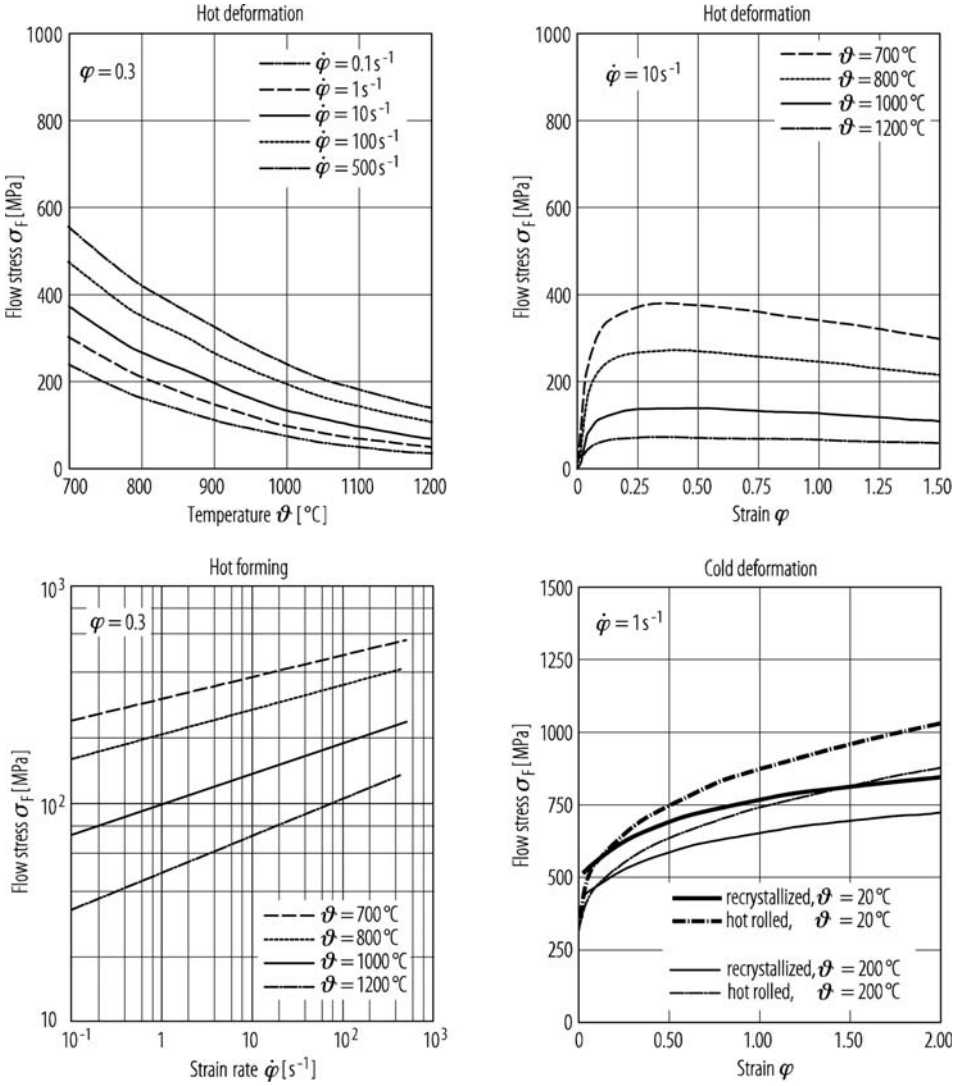
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	recrystallized	hot rolled
	austenite		
σ_{F0} [MPa]	116.98	558.6	567.5
A	4919.342	778.759	876.779
Effect of temperature K_ϑ			
m_1	−0.00368	−0.00092	−0.00092
Effect of strain K_φ			
m_2	0.04126	0.14976	0.24360
m_4	−0.02627	0.00001	0.01145
m_5	0.00006		
m_7	−0.32701		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01341	0.01294
m_8	0.000141		
Range of validity			
ϑ [°C]	700…1200	20…350	20…350
φ	0.04…1.50	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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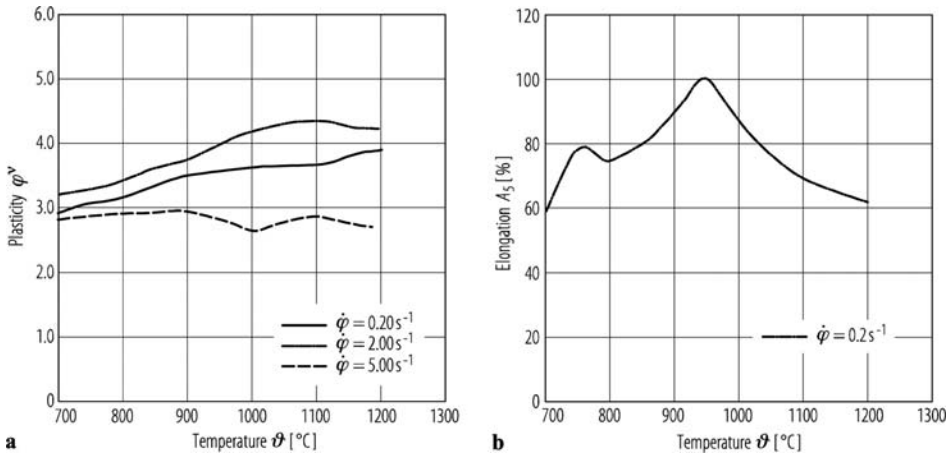
Fig. 5.211.
X10CrAlSi7. Flow stress curves by hot and cold forming.



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Fig. 5.212.
X10CrAlSi7. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity in torsion (left) and tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	21.09	458.84	10.12	7691.7	189.1
100	22.62	471.06	10.30	7667.9	183.7
200	23.82	493.20	10.54	7643.0	178.3
300	24.90	513.66	10.84	7616.6	172.7
400	25.95	534.26	11.15	7588.8	165.9
500	26.99	555.40	11.47	7559.3	156.9
600	28.04	577.21	11.80	7528.3	145.5
700	29.11	599.79	12.14	7495.6	131.6
800	30.21	623.20	12.49	7461.2	115.7
900	31.34	647.48	12.85	7424.9	98.6
1000	32.49	672.68	13.21	7386.8	81.7
1100	33.68	698.83	13.59	7346.6	66.6
1200	34.91	725.99	13.98	7304.5	55.4

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: X45CrSi9–3/1.4718

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.40…0.50	2.70…3.30	0.00…0.60	0.000…0.040	0.000…0.030	8.00…10.00
Ni					
0.00…0.50					

International comparison of standards

ISO		Euronorm	
~ X45CrSi9-3	683–15 (1992)	X45CrSi9–3	10090 (02/1998)
United Kingdom		Russia	
X45CrSi9–3	EN 10090 (02/1998)	~ 40Ch9S2	5632 (1972)
Japan		China	
~ SUH 1	G 4311 (1991)	~ 4Cr9Si2	T 1221 (1992)
		~ ZG 40Cr9Si2	T 6403 (1992)
USA			
Spec	AISI	SAE	UNS
~ Silchrome 1		~ HNV 3	~ S65007
~ Sil 1			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

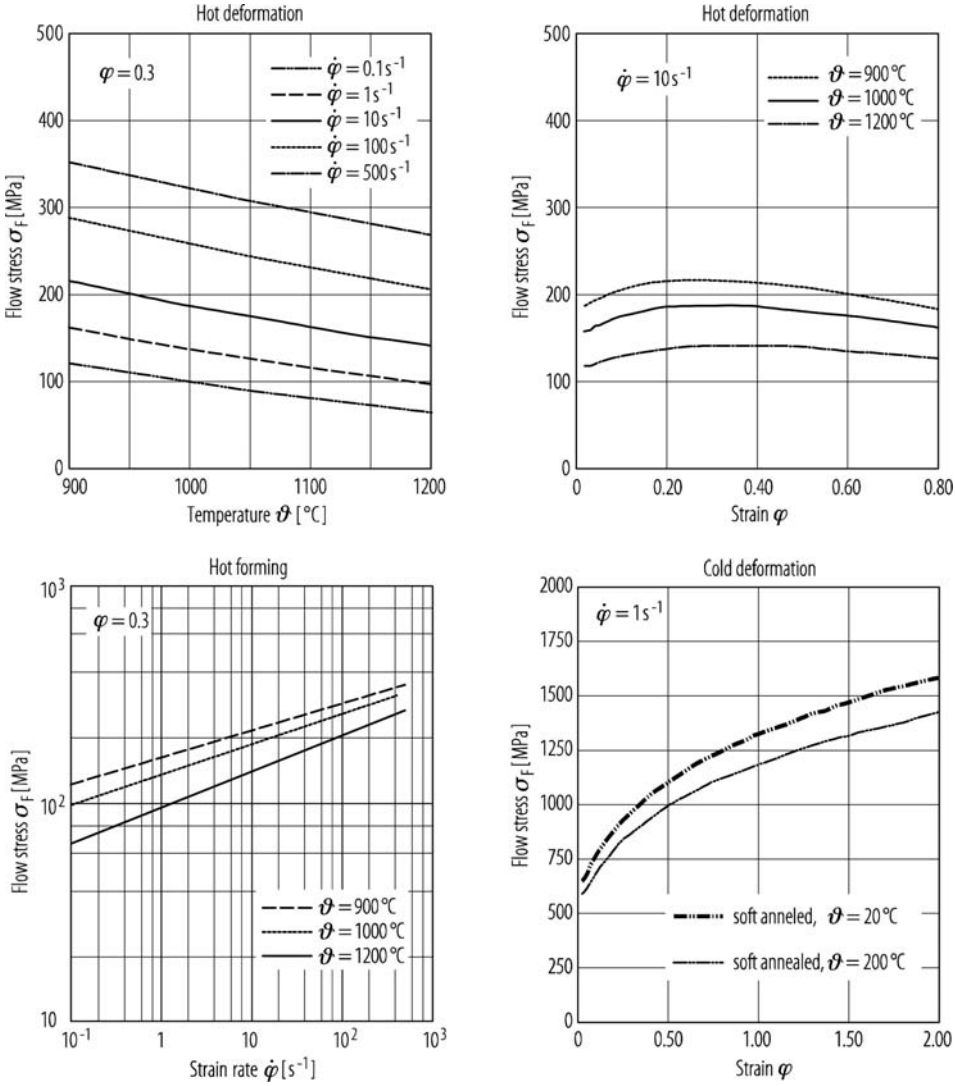
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	175.7	775.7
A	1263.233	1326.651
Effect of temperature K_ϑ		
m_1	−0.00189	−0.00061
Effect of strain K_φ		
m_2	0.16937	0.27017
m_4	0.00339	0.00740
m_5	0.00055	
m_7	−0.96588	
Effect of strain rate K_φ		
m_3		0.01026
m_8	0.000138	
Range of validity		
ϑ [°C]	900…1200	20…400
φ	0.04…0.80	0.04…2,00
$\dot{\varphi}$ [s^{-1}]	<500	<500

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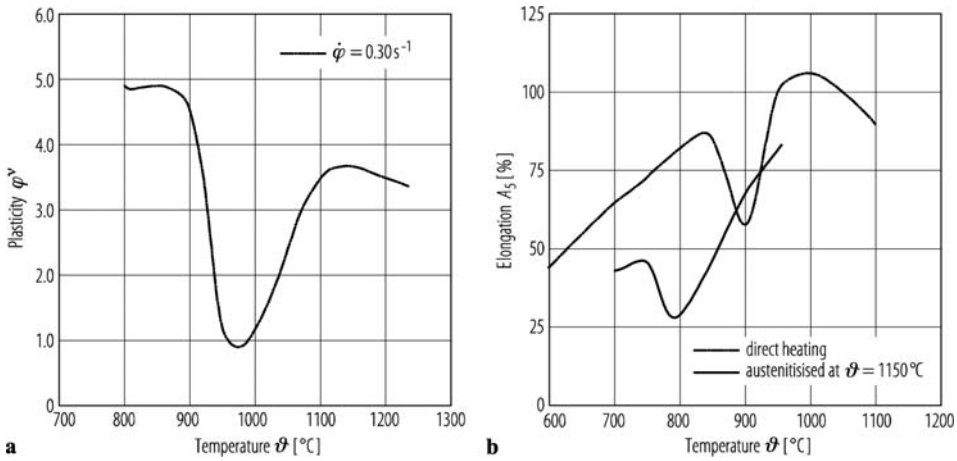
Fig. 5.213.
X45CrSi9–3. Flow stress curves by hot and cold forming.



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Fig. 5.214.
X45CrSi9–3. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity in torsion (left) and tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	18.07	467.49	10.12	7590.8	211.5
100	19.93	483.86	10.30	7567.4	208.0
200	26.00	506.13	10.54	7542.8	202.7
300	26.25	526.25	10.84	7516.8	195.7
400	26.51	546.36	11.15	7489.3	186.3
500	26.77	566.90	11.47	7460.2	174.4
600	27.04	588.03	11.80	7429.6	160.0
700	27.30	609.85	12.14	7397.3	143.6
800	27.57	632.40	12.49	7363.4	125.8
900	27.84	655.75	12.85	7327.6	107.7
1000	28.12	679.92	13.21	7289.9	90.4
1100	28.39	704.96	13.59	7250.3	75.7
1200	28.67	730.90	13.98	7208.7	65.3

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Steel symbol/number: X10CrAlSi13/1.4724

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.12	0.70…1.40	0.00…1.00	0.000…0.040	0.000…0.015	12.00…14.00
Al					
0.70…1.20					

International comparison of standards

ISO		Euronorm		
~ X10CrAlSi13	4955 (1994)	~ X10CrAlSi13	10095 (03/1999)	
United Kingdom		Russia		
~ X10CrAlSi13	EN 10095 (03/1999)	~ 10Ch13SJu	5632 (1972)	
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

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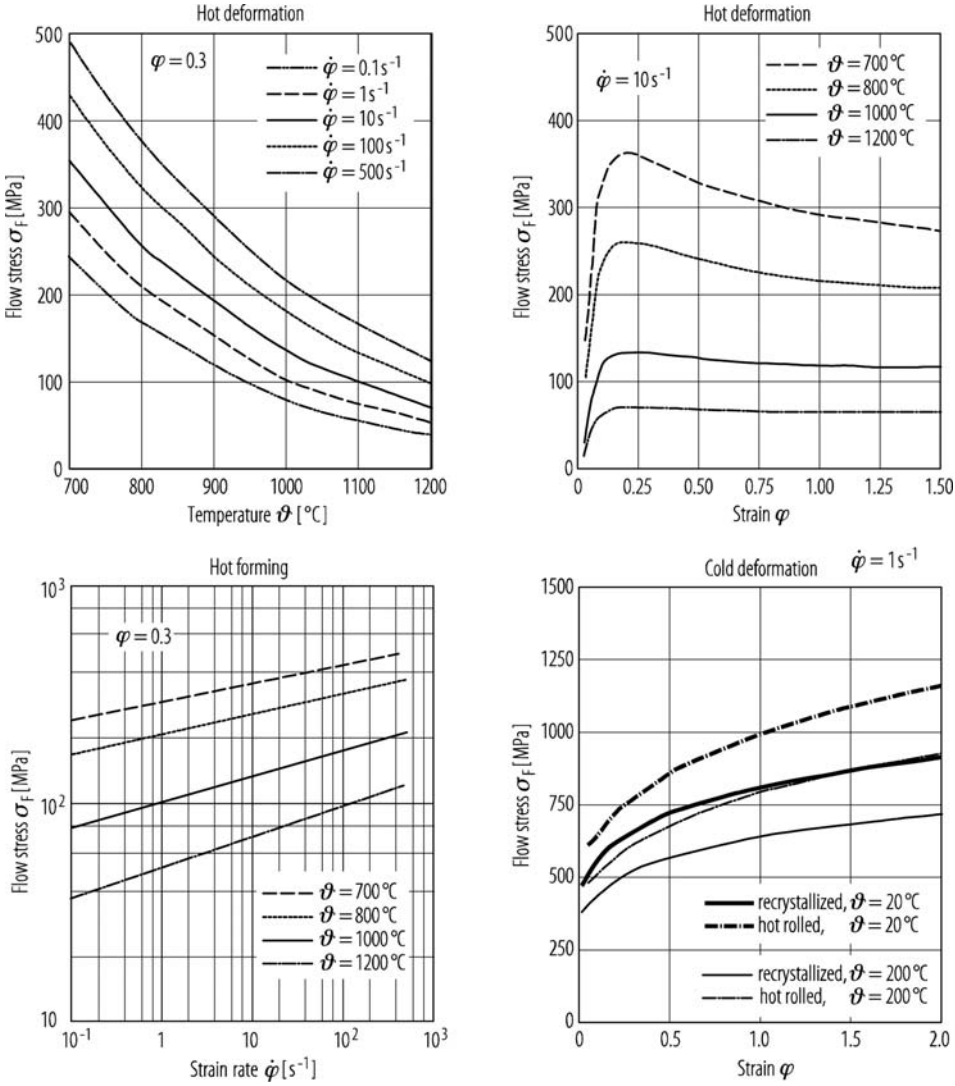
DOI: 10.1007/978-3-540-44760-3_119
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	recrystallized	hot rolled
	austenite		
σ_{F0} [MPa]	119.3	568.2	656.4
A	2460.99	828.732	1007.919
Effect of temperature K_ϑ			
m_1	−0.00365	−0.00135	−0.00128
Effect of strain K_φ			
m_2	−0.48068	0.17528	0.23427
m_4	−0.08124	0.00307	0.01120
m_5	0.00056		
m_7	0.04181		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.00976	0.01049
m_8	0.000118		
Range of validity			
ϑ [°C]	700…1200	20…350	20…350
φ	0.04…1.50	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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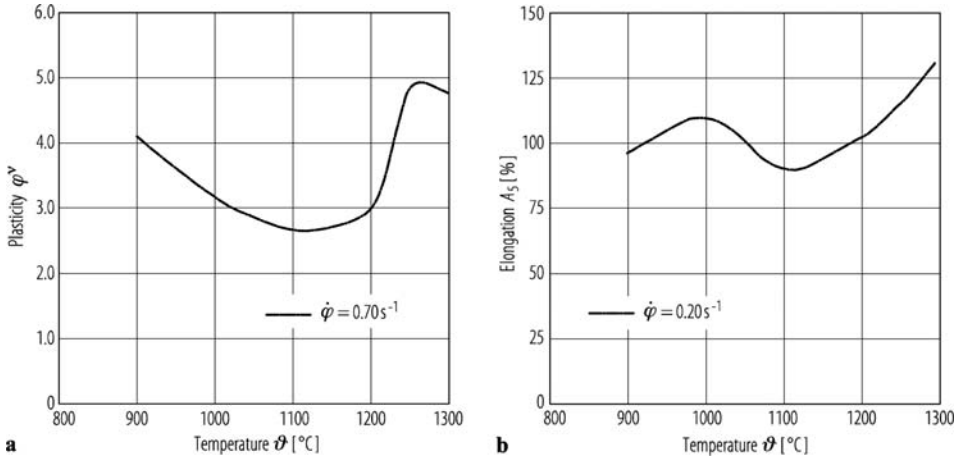
Fig. 5.215.
X10CrAlSi13. Flow stress curves by hot and cold forming.



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Fig. 5.216.
X10CrAlSi13. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	16.26	468.25	10.12	7615.4	
100	18.28	486.89	10.30	7591.8	
200	21.25	509.78	10.54	7567.2	
300	22.37	530.92	10.84	7541.1	
400	23.43	552.22	11.15	7513.5	
500	24.46	574.06	11.47	7484.3	
600	25.50	596.61	11.80	7453.6	
700	26.55	619.95	12.14	7421.3	
800	27.61	644.15	12.49	7387.2	
900	28.70	669.24	12.85	7351.3	
1000	29.81	695.29	13.21	7313.5	
1100	30.96	722.32	13.59	7273.8	
1200	32.13	750.39	13.98	7232.0	

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Steel symbol/number: X10CrAlSi18/1.4742

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.12	0.70…1.40	0.00…1.00	0.000…0.040	0.000…0.015	17.00…19.00
Al					
0.70…1.20					

International comparison of standards

ISO		Euronorm		
~ X10CrAlSi18	4955 (1994)	X10CrAlSi18	10095 (03/1999)	
United Kingdom		Russia		
X10CrAlSi18	EN 10095 (03/1999)	~ 15Ch18SJu	5632 (1972)	
Japan		China		
~ SUH 21	G 4312 (1991)	~ 1Cr19Al3	T 4238 (1992)	
		~ S11940	T 4238 (1992)	
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

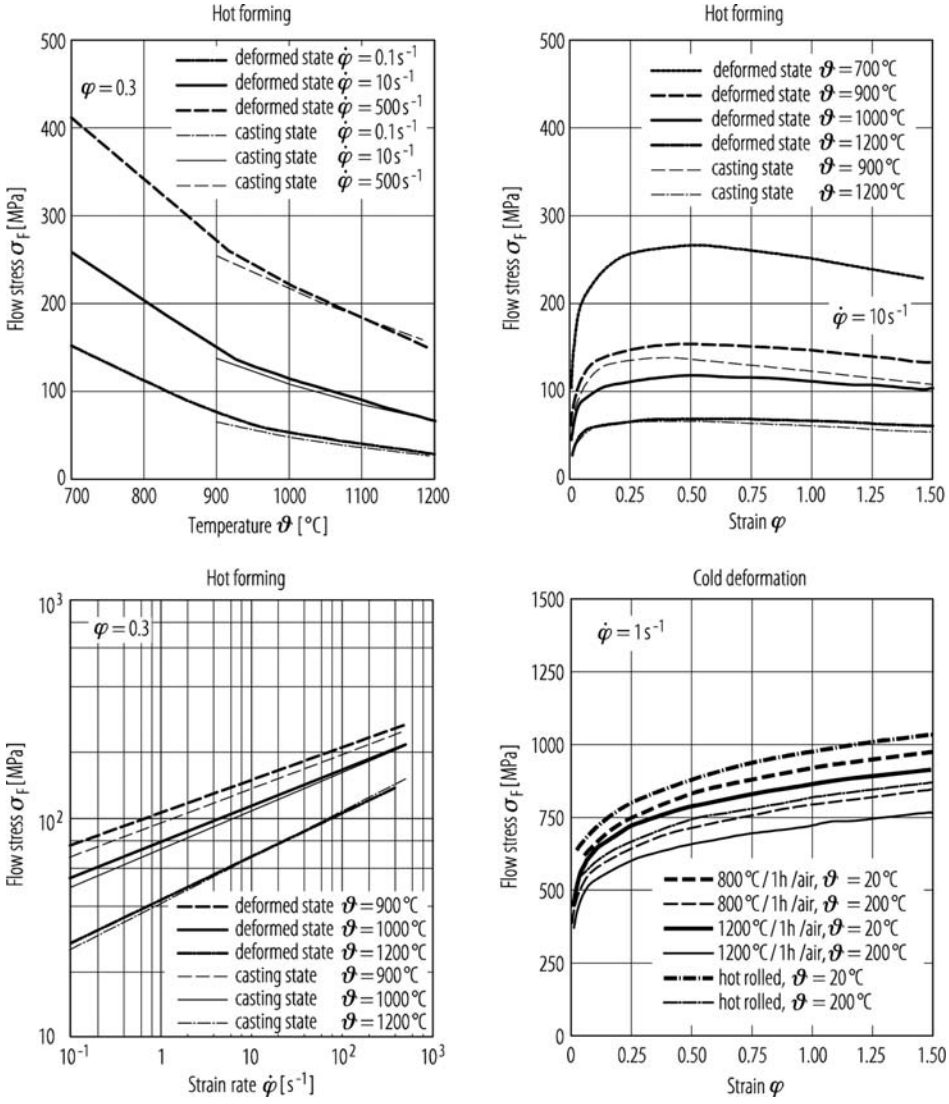
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Flow curves

State of material	Hot deformation		Cold deformation		
	deformed state	casting state	800°C/1h/air	1200°C/1h/air	hot rolled
	austenite +ferrite	austenite +ferrite			
σ_{F0} [MPa]	100.3	94.8	661.0	651.5	720.7
A	2356.51	1473.65	937.569	881.804	994.074
Effect of temperature K_ϑ					
m_1	−0.00311	−0.00279	−0.00083	−0.00097	−0.00102
Effect of strain K_φ					
m_2	0.16246	0.05073	0.14564	0.13186	0.15088
m_4	−0.00245	−0.02108	0.00008	0.00008	0.00313
m_5	0.00005	0.00005			
m_7	−0.35081	−0.35098			
Effect of strain rate $K_{\dot\varphi}$					
m_3			0.00070	0.00848	0.00648
m_8	0.000166	0.000175			
Range of validity					
ϑ [°C]	700…1200	900…1200	20…300	20…300	20…300
φ	0.04…1.50	0.04…1.50	0.04…1.50	0.04…1.50	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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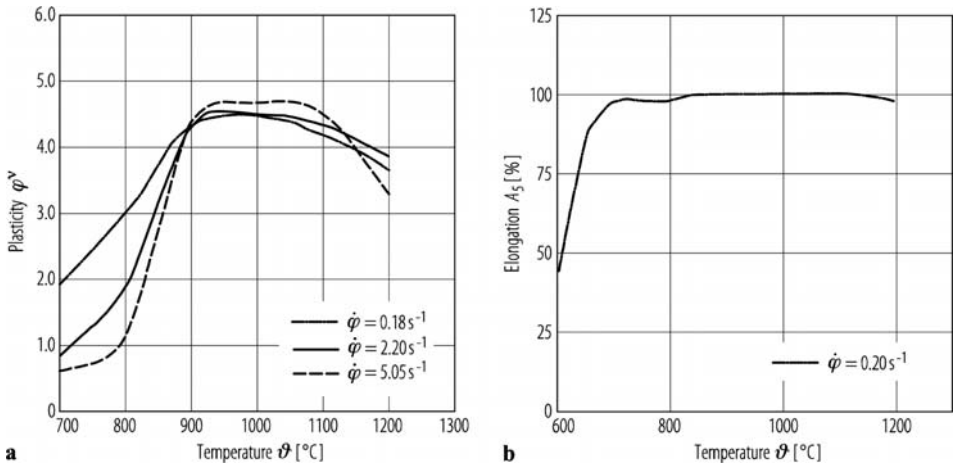
Fig. 5.217.
X10CrAlSi18. Flow stress curves by hot and cold forming.



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Fig. 5.218.
X10CrAlSi18. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.84	475.26	10.12	7578.9	191.0
100	16.03	494.59	10.30	7555.5	187.5
200	19.66	517.84	10.54	7531.0	182.4
300	20.79	539.33	10.84	7504.9	175.9
400	21.85	560.96	11.15	7477.5	167.5
500	22.88	583.15	11.47	7448.5	157.2
600	23.90	606.05	11.80	7417.9	145.0
700	24.93	629.76	12.14	7385.7	131.4
800	25.97	654.34	12.49	7351.7	116.9
900	27.03	679.83	12.85	7316.0	102.4
1000	28.11	706.29	13.21	7278.4	89.0
1100	29.23	733.75	13.59	7238.9	78.1
1200	30.37	762.26	13.98	7197.4	71.3

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Steel symbol/number: X10CrAlSi24/1.4762

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.12	0.70…1.40	0.00…1.00	0.000…0.040	0.000…0.015	23.00…26.00
Al					
1.20…1.70					

International comparison of standards

ISO		Euronorm		
~ X10CrAlSi25	4955 (1994)	X10CrAlSi25	10095 (03/1999)	
United Kingdom		Russia		
X10CrAlSi25	EN 10095 (03/1999)			
Japan		China		
~ SUH 446	G 4321 (1991)			
USA				
ASTM		AISI	ASME	UNS
~ A 176 (446)	A 176–99	~ 446	~ SA 268 (446)	~S44600
~ A 511 (MT446–1,–2)	A 511–96	~S44600		

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

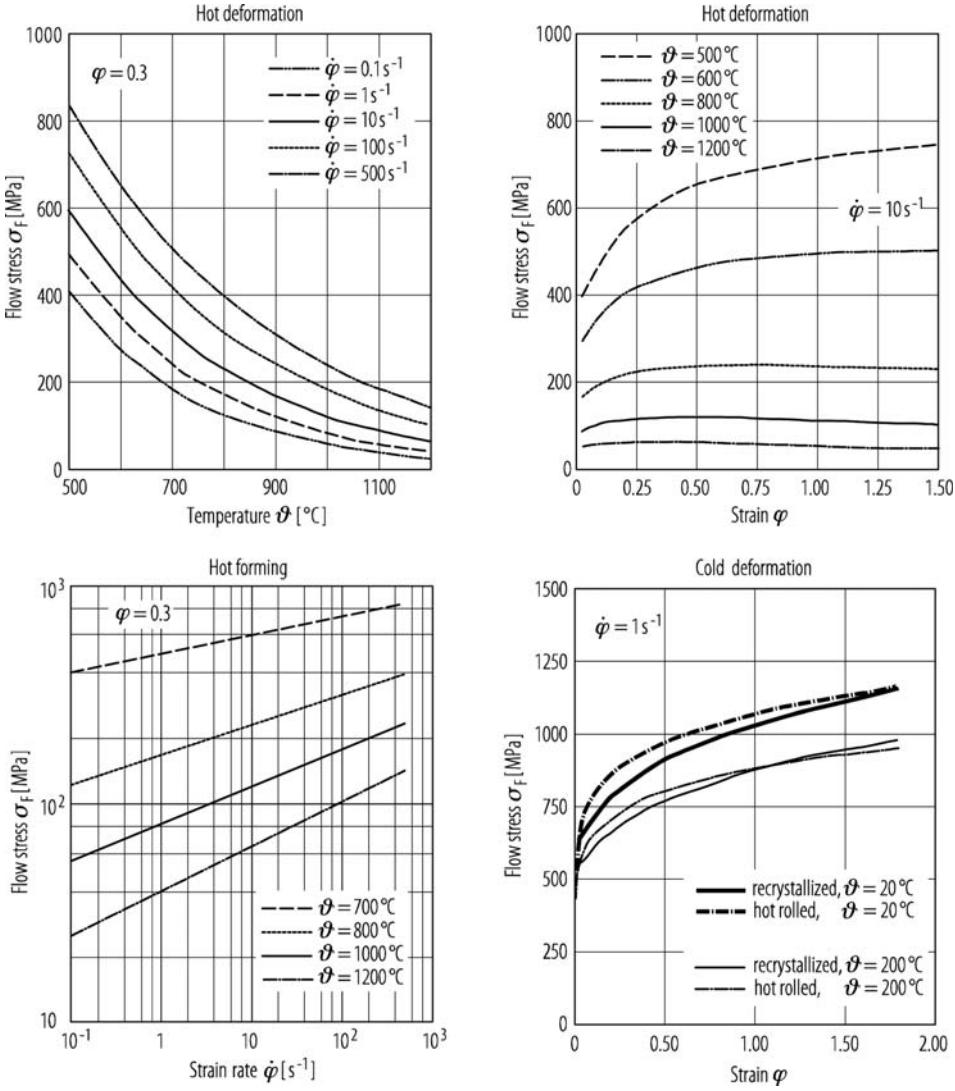
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	recrystallized	hot rolled
	ferrite+carb.		
σ_{F0} [MPa]	105.2	723.8	798.4
A	4184.11	1041.982	1087.690
Effect of temperature K_ϑ			
m_1	−0.00330	−0.00094	−0.00108
Effect of strain K_φ			
m_2	0.32668	0.19548	0.13579
m_4	0.00775	0.00794	−0.00004
m_5	−0.00112		
m_7	0.06566		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01092	0.01106
m_8	0.000170		
Range of validity			
ϑ [°C]	500…1200	20…350	20…350
φ	0.04…1.50	0.04…1.80	0.04…1.80
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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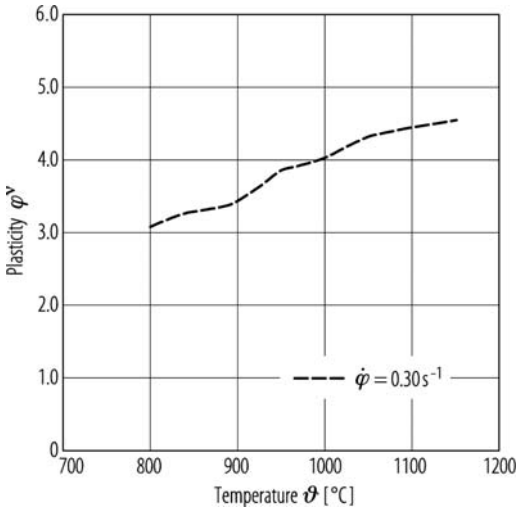
Fig. 5.219.
X10CrAlSi24. Flow stress curves by hot and cold forming.



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Fig. 5.220.
X10CrAlSi24. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.25…0.70.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	7.12	483.65	10.12	7501.9	
100	9.31	503.81	10.30	7478.7	
200	17.45	527.49	10.54	7454.5	
300	18.60	549.37	10.84	7428.7	
400	19.65	571.41	11.15	7401.5	
500	20.65	594.01	11.47	7372.9	
600	21.65	617.34	11.80	7342.6	
700	22.64	641.49	12.14	7310.7	
800	23.65	666.53	12.49	7277.1	
900	24.67	692.50	12.85	7241.7	
1000	25.70	719.45	13.21	7204.5	
1100	26.77	747.42	13.59	7165.4	
1200	27.86	776.46	13.98	7124.3	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: CrAl20–5/1.4767

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.10	0.00…1.00	0.00…1.00	0.000…0.045	0.000…0.030	19.00…22.00
Al					
4.00…5.50					

International comparison of standards

ISO		Euronorm	
United Kingdom		Russia	
		Ch23Ju5T	10994 (1974)
Japan		China	
USA			
ASTM	AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

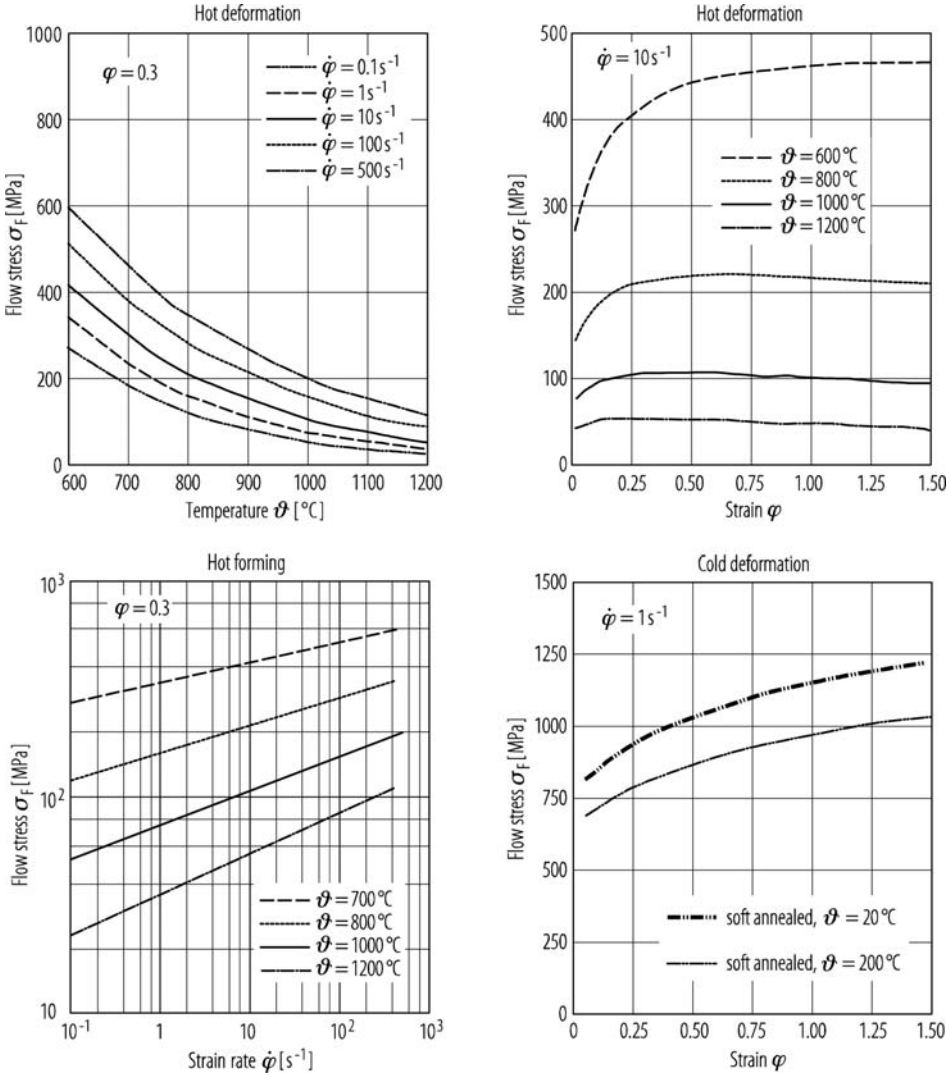
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Flow curves

State of material	Hot deformation deformed state ferrite	Cold deformation soft annealed
σ_{F0} [MPa]	95.1	864.72
A	4192.31	1163.025
Effect of temperature K_ϑ		
m_1	−0.00349	−0.00096
Effect of strain K_φ		
m_2	0.26316	0.16446
m_4	0.00347	0.00776
m_5	−0.00095	
m_7	0.06325	
Effect of strain rate $K_{\dot\varphi}$		
m_3		
m_8	0.000156	0.01023
Range of validity		
ϑ [°C]	600…1200	20…200
φ	0.04…1.50	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500

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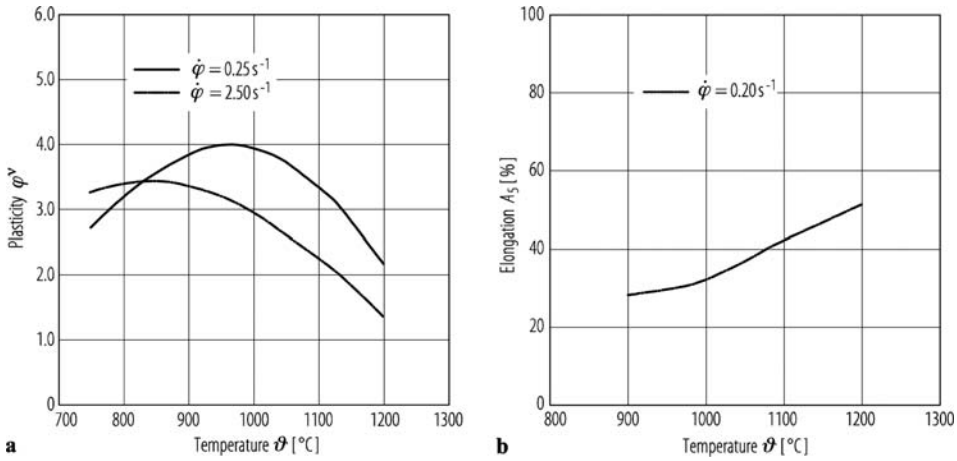
Fig. 5.221.
CrAl20–5. Flow stress curves by hot and cold forming.



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Fig. 5.222.
CrAl20–5. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.48	502.17	10.12	7330.9	
100	15.47	527.44	10.30	7308.3	
200	10.69	552.23	10.54	7284.6	
300	11.74	575.14	10.84	7259.4	
400	12.67	598.21	11.15	7232.8	
500	13.55	621.87	11.47	7204.8	
600	14.40	646.30	11.80	7175.2	
700	15.24	671.59	12.14	7144.1	
800	16.07	697.80	12.49	7111.2	
900	16.91	724.98	12.85	7076.7	
1000	17.77	753.19	13.21	7040.3	
1100	18.64	782.48	13.59	7002.1	
1200	19.52	812.88	13.98	6961.9	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: X12CrNi26–5/1.4820

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.14	0.00…1.40	0.00…1.40	0.000…0.030	0.000…0.025	24.80…27.20
Ni					
4.10…5.90					

International comparison of standards

ISO		Euronorm	
United Kingdom		Russia	
Japan		China	
USA			
ASTM	AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

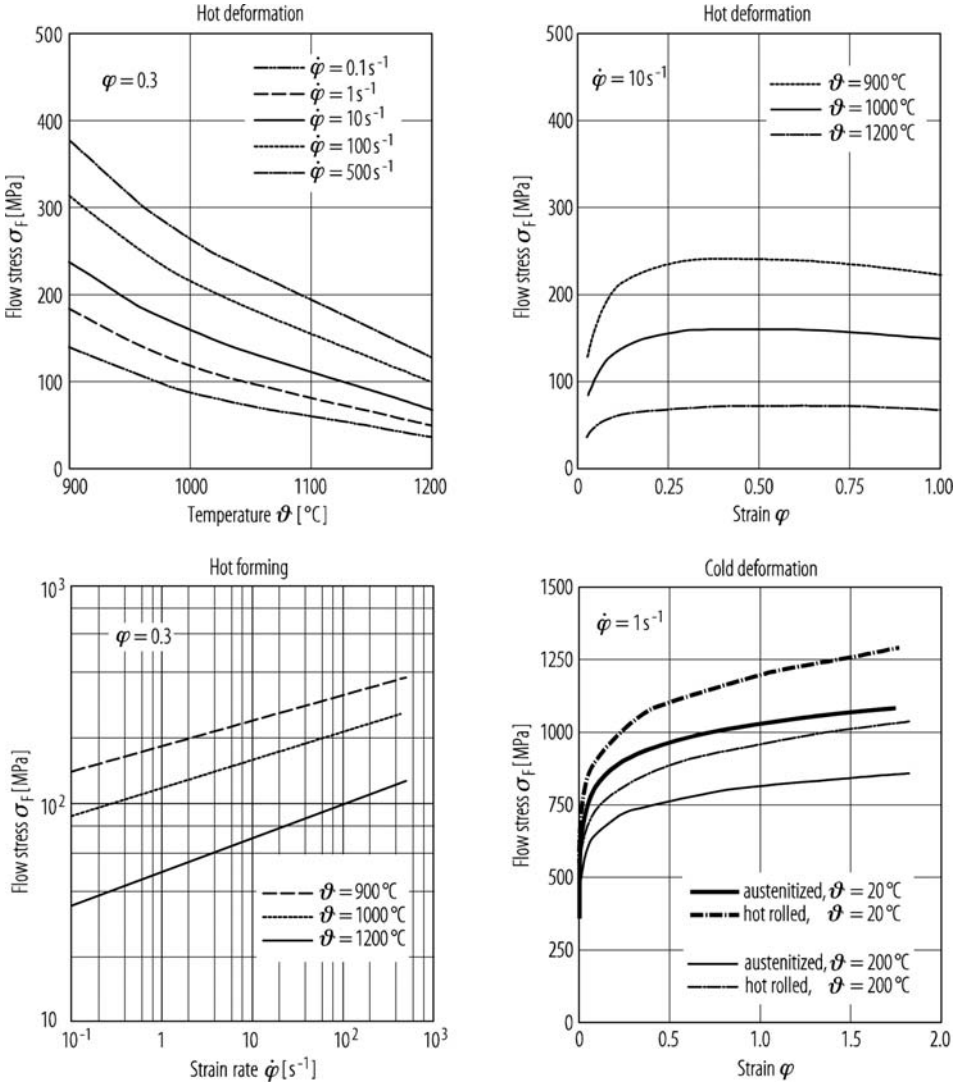
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	austenitized	hot rolled
	austenite		
σ_{F0} [MPa]	134.16	835.0	922.1
A	13236.27	1059.775	1228.614
Effect of temperature K_ϑ			
m_1	−0.00447	−0.00132	−0.00123
Effect of strain K_φ			
m_2	0.10524	0.08504	0.12061
m_4	−0.01548	−0.00393	−0.00074
m_5	0.000288		
m_7	−0.500002		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01004	0.00987
m_8	0.000129		
Range of validity			
ϑ [°C]	900…1200	20…280	20…280
φ	0.04…1.00	0.04…1.80	0.04…1.80
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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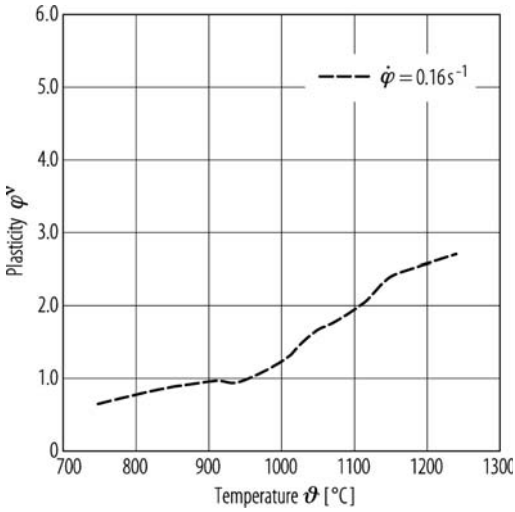
Fig. 5.223.
X12CrNi26–5Flow stress curves by hot and cold forming.



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Fig. 5.224.
X12CrNi26–5. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.30…0.60.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.25	454.83	12.09	7639.8	
100	15.28	494.60	12.29	7611.7	
200	16.99	530.65	12.55	7582.3	
300	18.36	556.13	12.80	7551.8	
400	19.69	576.51	13.07	7520.0	
500	21.05	593.90	13.34	7487.0	
600	22.44	609.32	13.61	7452.7	
700	23.88	623.36	13.89	7417.0	
800	25.38	636.36	14.18	7379.9	
900	26.96	648.58	14.47	7341.4	
1000	28.61	660.17	14.77	7301.4	
1100	30.34	671.26	15.07	7259.8	
1200	32.17	681.94	15.38	7216.7	

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Steel symbol/number: X15CrNiSi25–4/1.4821

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.10…0.20	0.80…1.50	0.00…2.00	0.000…0.040	0.000…0.015	24.50…26.50
Ni	N				
3.50…5.50	0.000…0.110				

International comparison of standards

ISO		Euronorm		
		X15CrNiSi25–4	10095 (03/1999)	
United Kingdom		Russia		
X15CrNiSi25–	EN 10095 (03/1999)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

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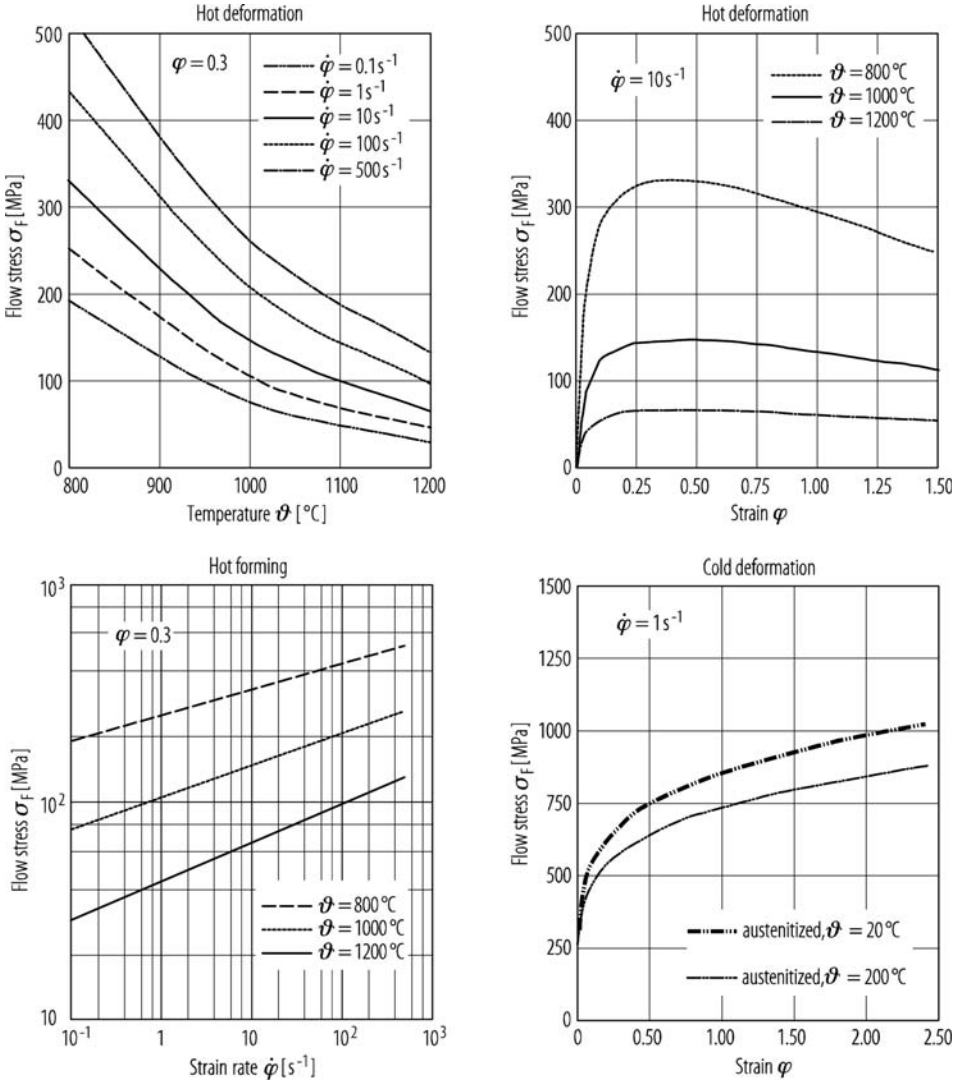
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation austenitized
σ_{F0} [MPa]	123.3	556.7
A	11821.68	871.469
Effect of temperature K_ϑ		
m_1	−0.00445	−0.00086
Effect of strain K_φ		
m_2	0.10776	0.19695
m_4	−0.01751	−0.00005
m_5	0.00027	
m_7	−0.53834	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01003
m_8	0.000147	
Range of validity		
ϑ [°C]	800…1250	20…300
φ	0.04…1.60	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500

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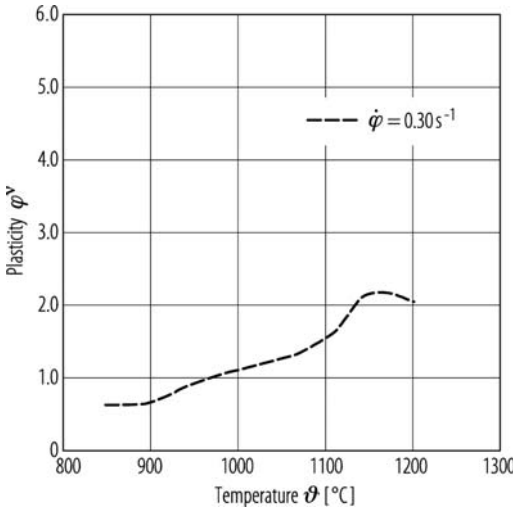
Fig. 5.225.
X15CrNiSi25–4. Flow stress curves by hot and cold forming.



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Fig. 5.226.
X15CrNiSi25–4. Hot plasticity as a fuction of the temperature; deformed state and austenitized at 1200 [°C]. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.30…0.60.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	12.80	454.83	12.09	7572.8	201.5
100	14.91	494.60	12.29	7544.9	199.1
200	16.82	530.65	12.55	7515.8	191.1
300	18.20	556.13	12.80	7485.6	180.2
400	19.54	576.51	13.07	7454.1	168.6
500	20.89	593.90	13.34	7421.3	157.7
600	22.29	609.32	13.61	7387.3	148.5
700	23.73	623.36	13.89	7351.9	141.2
800	25.23	636.36	14.18	7315.1	135.6
900	26.81	648.58	14.47	7277.0	130.6
1000	28.46	660.17	14.77	7237.3	124.6
1100	30.19	671.26	15.07	7196.2	115.6
1200	32.02	681.94	15.38	7153.4	100.7

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Steel symbol/number: X15CrNiSi20–12/1.4828

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.20	1.50…2.50	0.00…2.00	0.000…0.045	0.000…0.015	19.00…21.00
Ni	N				
11.00…13.00	0.00…0.110				

International comparison of standards

ISO		Euronorm		
~ X15CrNiSi20–12	4955 (1994)	X15CrNiSi20–12	10095 (03/1999)	
United Kingdom		Russia		
X15CrNiSi20–12	EN 10095 (03/1999)	~ 20Ch20N14S2	5632 (1972)	
Japan		China		
~ SUH 309	G 4311 (1991)	~ S 38210	T 1221 (1992)	
~ SUH 309	G 4312 (1991)	~ 1Cr20Ni14Si2	T 1221 (1992)	
USA				
ASTM		AISI	ASME	UNS
~ A 314 (309)	A 314–02	~ S30900	~ SA 358 (309)	~ S30900
~ A 167 (309)	A 167–99	~ 309		

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

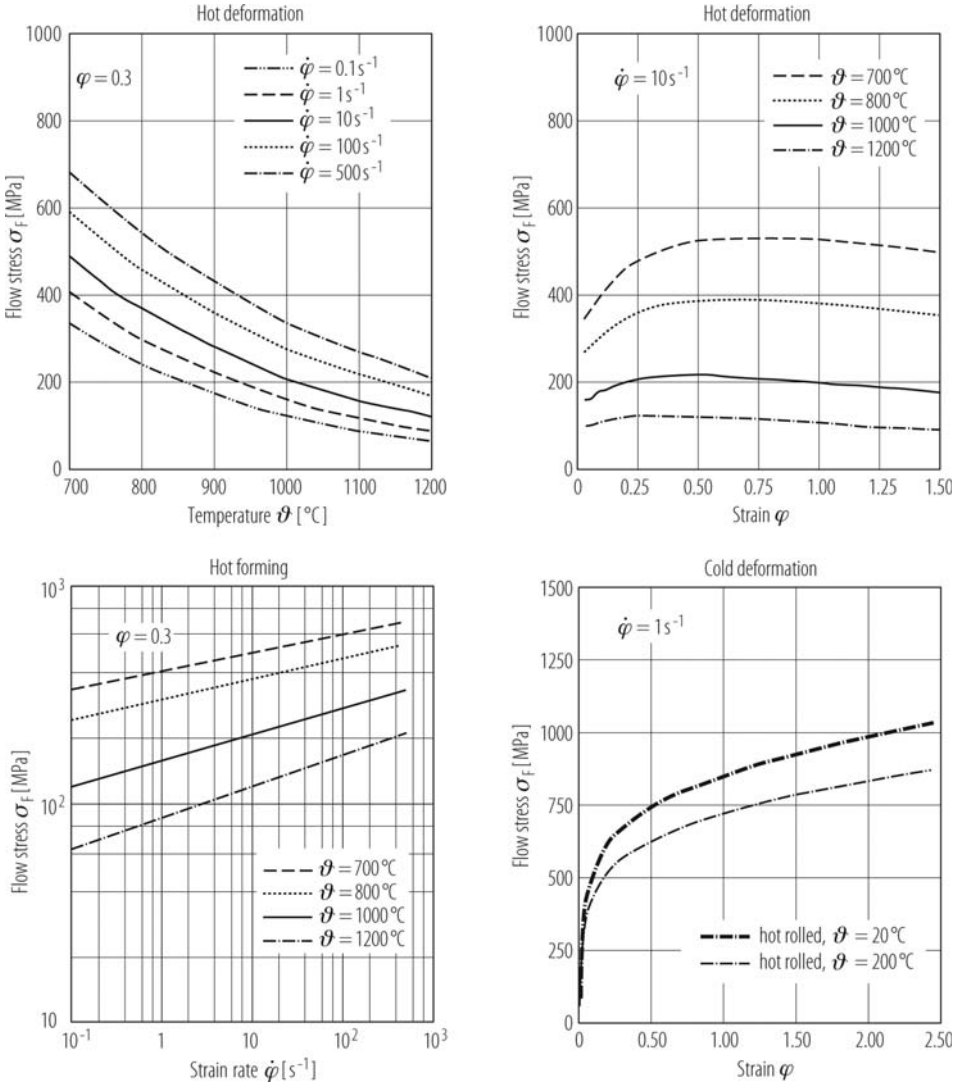
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation hot rolled
σ_{F0} [MPa]	178.84	514.2
A	5577.411	878.193
Effect of temperature K_ϑ		
m_1	−0.00285	−0.00093
Effect of strain K_φ		
m_2	0.38006	0.19554
m_4	0.01129	−0.00891
m_5	−0.00096	
m_7	−0.10956	
Effect of strain rate $K_{\dot\varphi}$		
m_3		
m_8	0.000119	0.00986
Range of validity		
ϑ [°C]	700…1250	20…300
φ	0.04…1.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.227.
X15CrNiSi20–12. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	280…320	87.0289	0.6044	650…700	6.3944	1.179
hot rolled				450…500	139.9059	0.50693

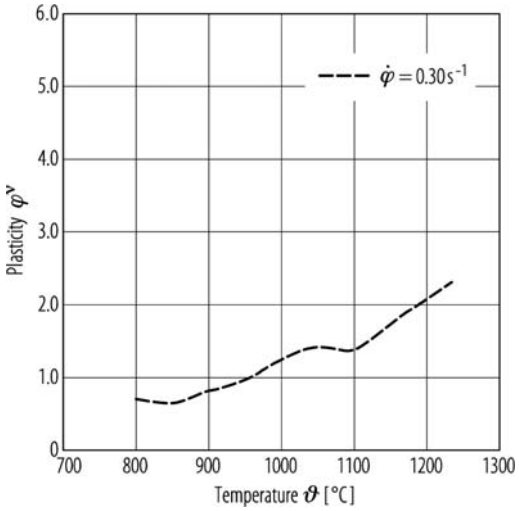
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	50…55	21.09867	0.21664	−7.43757	<80
hot rolled					<75

Fig. 5.228.
X15CrNiSi20–12. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.75.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	12.97	493.31	16.50	7683.1	
100	15.05	500.10	16.73	7644.6	
200	16.61	508.73	17.31	7606.0	
300	18.00	517.50	17.02	7565.5	
400	19.34	526.43	17.02	7526.2	
500	20.70	535.51	17.92	7476.6	
600	22.10	544.74	18.23	7431.0	
700	23.54	554.14	18.54	7383.9	
800	25.05	563.69	18.87	7335.3	
900	26.62	573.42	19.19	7285.0	
1000	28.27	583.31	19.53	7233.1	
1100	30.01	593.37	19.86	7179.5	
1200	31.83	603.60	20.21	7124.2	

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Steel symbol/number: X12CrNi22–12/1.4829

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.14	0.90…1.90	0.00…1.90	0.000…0.025	0.000…0.015	20.80…23.20
Ni					
10.20…12.80					

International comparison of standards

ISO		Euronorm	
		~ X 12 CrNiSi 22 12 KE	144 (1979)
United Kingdom		Russia	
Japan		China	
~ SUS Y 309	G 4316 (1991)	~ H1Cr24Ni13	T 5092 (1996)
		~ W43091	T 5092 (1996)
USA			
ASME	Spec	AWS	UNS
~ SFA 5.9 (ER 309)	~ 309 Si	~ A 5.9 (ER309)	~ S30980
~ SFA 5.9 (ER 309Si)		~ A 5.9 (ER309Si)	~ S30981

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

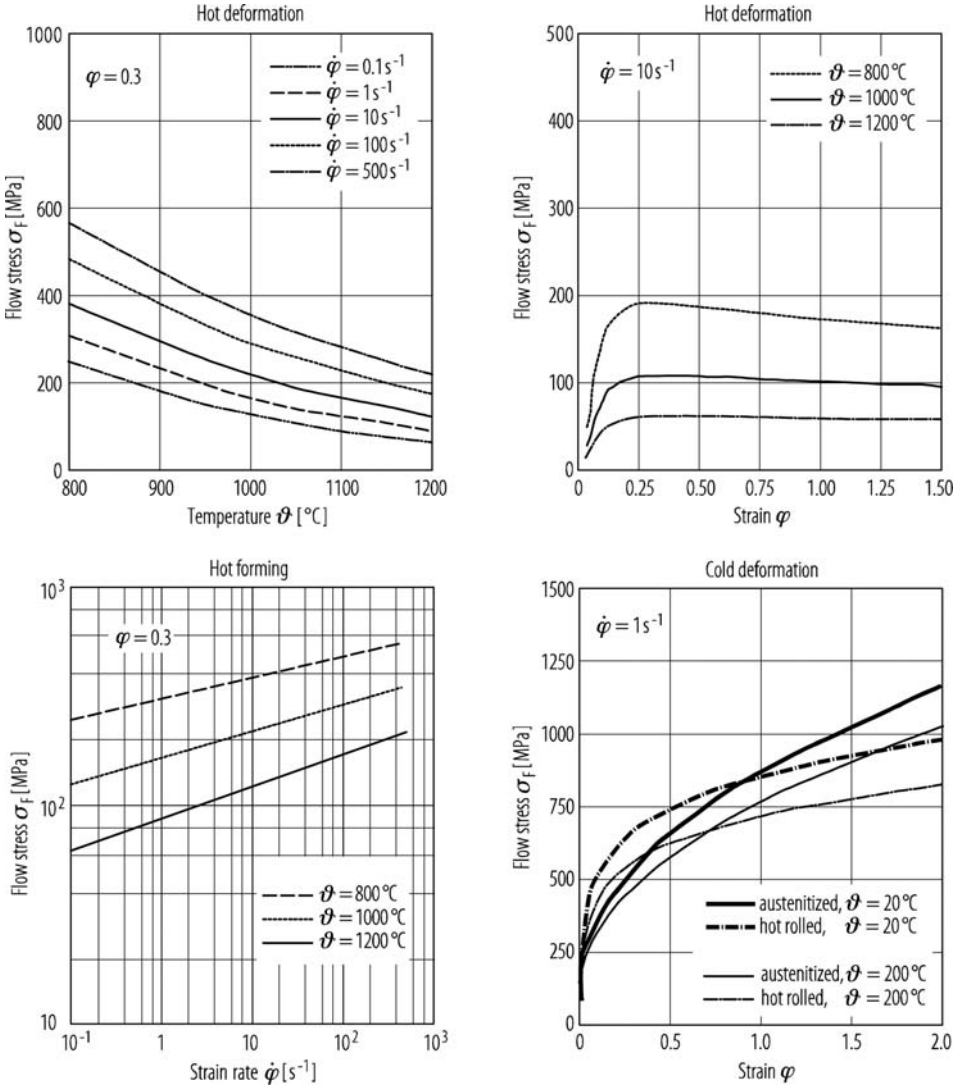
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	austenitized	hot rolled
	austenite		
σ_{F0} [MPa]	162.1	361.8	519.2
A	3395.96	873.522	879.289
Effect of temperature K_ϑ			
m_1	−0.00324	−0.00073	−0.00102
Effect of strain K_φ			
m_2	−0.35731	0.41999	0.19154
m_4	−0.09402	0.00808	−0.00872
m_5	0.00042		
m_7	−0.05510		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.00839	0.00948
m_8	0.000122		
Range of validity			
ϑ [°C]	800…1200	20…300	20…300
φ	0.04…1.50	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.229.
X12CrNi22–12. Flow stress curves by hot and cold forming.



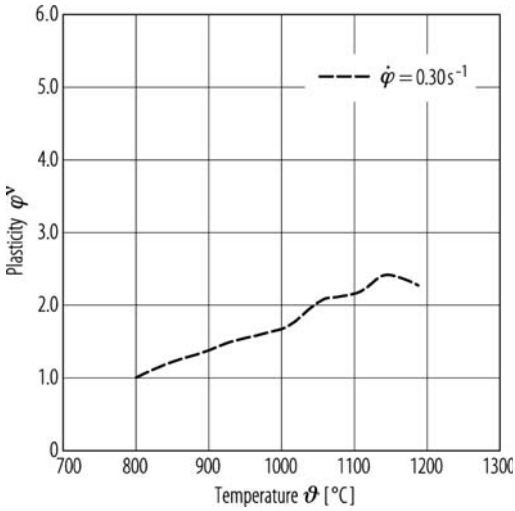
Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
hot rolled				400….450	126.4997	0.50301	<75

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Fig. 5.230.
X12CrNi22–12. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.45…0.70.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.62	493.31	16.50	7711.8	196.1
100	15.58	500.10	16.73	7673.1	189.9
200	16.48	508.73	17.31	7631.7	182.0
300	17.87	517.50	17.02	7593.7	174.1
400	19.22	526.43	17.02	7554.4	166.0
500	20.58	535.51	17.92	7504.6	158.0
600	21.98	544.74	18.23	7458.8	149.9
700	23.43	554.14	18.54	7411.5	142.0
800	24.93	563.69	18.87	7362.7	134.3
900	26.51	573.42	19.19	7312.2	126.9
1000	28.16	583.31	19.53	7260.1	120.1
1100	29.89	593.37	19.86	7206.3	114.0
1200	31.71	603.60	20.21	7150.8	108.8

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

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Steel symbol/number: X15CrNiSi25–21/1.4841

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.20	1.50…2.50	0.00…2.00	0.000…0.045	0.000…0.015	24.00…26.00
Ni	N				
19.00…22.00	0.000…0.110				

International comparison of standards

ISO		Euronorm		
		X15CrNiSi25–21	10095 (03/1999)	
United Kingdom		Russia		
X15CrNiSi25–21	EN 10095 (03/1999)	~ 20Ch25N20S2	5632 (1972)	
~ 314 S 25	1554 (1990)			
Japan		China		
~ SUH 310	G 4311 (1991)	~ 1Cr25Ni20Si2	T 1221 (1992)	
~ SUS Y 310	G 4316 (1991)	~ S38310	T 1221 (1992)	
USA				
ASTM		AISI	AMS	UNS
~ A 314 (314)	A 314–02	~ 314	~ 7490N	~S31400
~ A 789 (S 31500)	A 789–01	~S31000		~ S31500

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

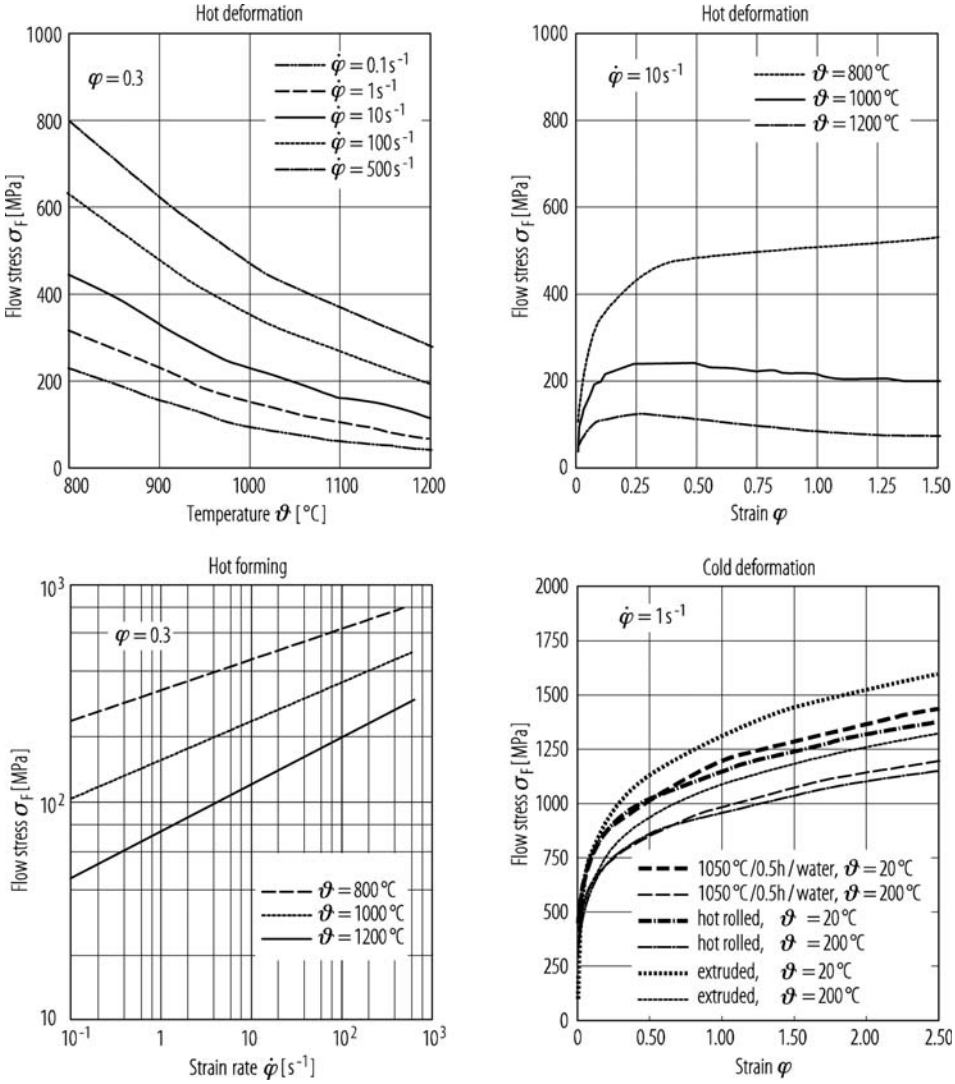
DOI: 10.1007/978-3-540-44760-3_127
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Flow curves

State of material	Hot deformation	Cold deformation			
	deformed state	1050°C/0.5h/ water	1100°C/1h/ water	hot rolled	extruded
	austenite				
σ_{F0} [MPa]	164.02	740.6	705.2	740.4	756.9
A	10992.02	1203.294	1286.650	1172.509	1362.159
Effect of temperature K_ϑ					
m_1	−0.00329	−0.00104	−0.00107	−0.00104	−0.00112
Effect of strain K_φ					
m_2	0.44545	0.21089	−0.00079	0.19973	0.20363
m_4	0.00075	0.000015	−0.06078	0.00001	−0.0112
m_5	−0.00303				
m_7	0.68719				
Effect of strain rate $K_{\dot\varphi}$					
m_3		0.00907	0.01132	0.00907	0.00681
m_8	0.000140				
Range of validity					
ϑ [°C]	800…1250	20…300	20…300	20…400	20…400
φ	0.04…1.50	0.04…2.50	0.04…2.50	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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Fig. 5.231.
X15CrNiSi25–21. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	300…360	48.1249	0.76882	670…730	7.6368	1.17075

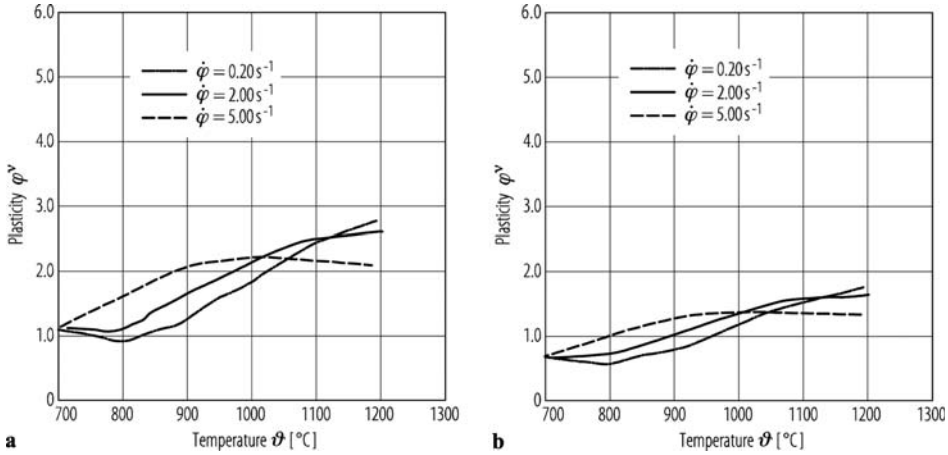
DOI: 10.1007/978-3-540-44760-3_127
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	40…45	39.15625	0.00974	−10.485	<80

Fig. 5.232.
X15CrNiSi25–21. Hot plasticity as a function of the temperature. (a) Casting state. Austenitised at 1200 [°C]. (b) Deformed state. Austenitised at 1200 [°C].

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	11.53	493.31	16.50	7520.8	182.5
100	13.83	500.10	16.73	7483.0	177.8
200	17.10	508.73	17.31	7442.7	171.9
300	18.46	517.50	17.02	7405.6	165.9
400	19.79	526.43	17.02	7367.2	159.9
500	21.14	535.51	17.92	7318.7	153.7
600	22.53	544.74	18.23	7274.0	147.3
700	23.97	554.14	18.54	7227.9	140.7
800	25.48	563.69	18.87	7180.3	133.5
900	27.05	573.42	19.19	7131.1	125.7
1000	28.70	583.31	19.53	7080.2	116.8
1100	30.43	593.37	19.86	7027.8	106.6
1200	32.26	603.60	20.21	6973.6	94.7

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Steel symbol/number: X8CrNi25–21/1.4845

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.10	0.00…1.50	0.00…2.00	0.000…0.045	0.000…0.015	24.00…26.00
Ni	N				
19.00…22.00	0.000…0.110				

International comparison of standards

ISO		Euronorm		
~ X6CrNi25–21	4955 (1994)	X8CrNi25–21	10095 (03/1999)	
United Kingdom		Russia		
X8CrNi25–21	EN 10095 (03/1999)	~ 20Ch23N18	5632 (1972)	
~ 310 S 25	1554 (1990)			
Japan		China		
~ SUS 310STP	G 3459 (1997)			
~ SUS 310S	G 4309 (1999)			
USA				
ASTM		AISI	SAE	UNS
~ A 213 (310 S)	A 213–01	~ 310S	~S31008	~S31008
~ A 314 (314 S)	A 314–02		~310 S	

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

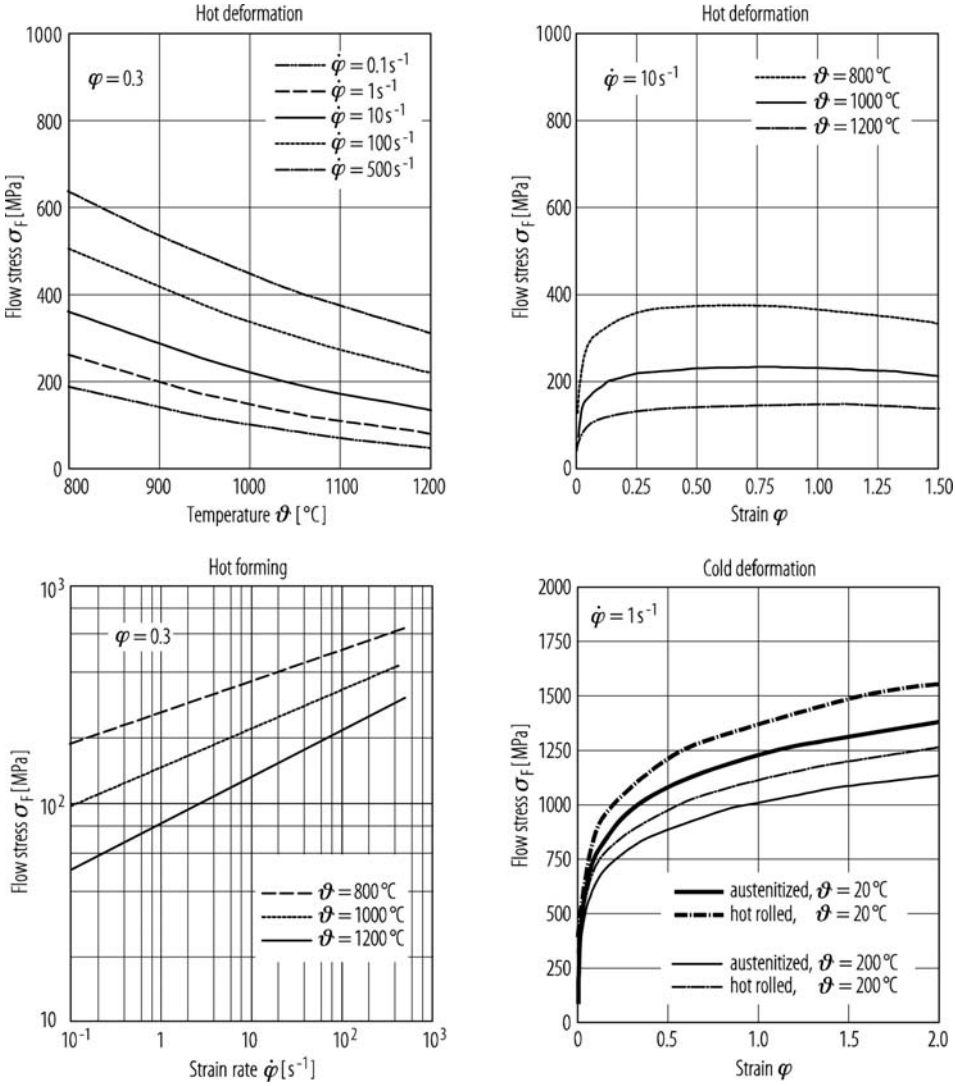
DOI: 10.1007/978-3-540-44760-3_128
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	austenitized	hot rolled
	austenite		
σ_{F0} [MPa]	191.0	776.9	874.1
A	3536.79	1266.197	1421.494
Effect of temperature K_ϑ			
m_1	−0.00299	−0.00110	−0.00121
Effect of strain K_φ			
m_2	0.12948	0.16382	0.17640
m_4	−0.00363	−0.01126	−0.00803
m_5	0.00040		
m_7	−0.42426		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01014	0.01060
m_8	0.000178		
Range of validity			
ϑ [°C]	800…1200	20…300	20…300
φ	0.04…1.50	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.233.
X8CrNi25–21. Flow stress curves by hot and cold forming.



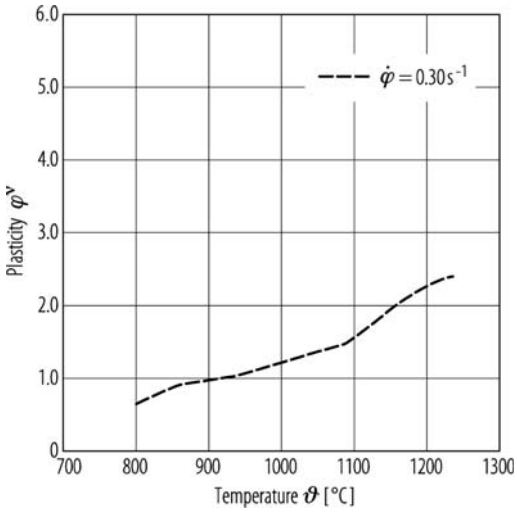
Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
hot rolled				450…500	126.5136	0.48849	<75

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Fig. 5.234.
X8CrNi25–21. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.80.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	10.91	493.31	16.50	7809.3	
100	13.30	500.10	16.73	7770.2	
200	15.49	508.73	17.31	7728.2	
300	16.92	517.50	17.02	7689.8	
400	18.30	526.43	17.02	7649.9	
500	19.68	535.51	17.92	7599.5	
600	21.08	544.74	18.23	7553.1	
700	22.53	554.14	18.54	7505.2	
800	24.04	563.69	18.87	7455.8	
900	25.62	573.42	19.19	7404.7	
1000	27.26	583.31	19.53	7351.9	
1100	28.99	593.37	19.86	7297.4	
1200	30.81	603.60	20.21	7241.2	

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Steel symbol/number: X12NiCrSi35–16/1.4864

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.15	1.00…2.00	0.00…2.00	0.000…0.045	0.000…0.015	15.00…17.00
Ni	N				
33.00…37.00	0.00…0.110				

International comparison of standards

ISO		Euronorm		
~ X12NiCrSi35–16	4955 (1994)	X12NiCrSi35–16	10095 (03/1999)	
United Kingdom		Russia		
X12NiCrSi35–16	EN 10095 (03/1999)			
~ NA 17	3076 (1989)			
Japan		China		
~ SUH 330	G 4309 (1999)	~ 1Cr16Ni35	T 1221 (1992)	
~ SUH 330	G 4312 (1991)	~S33010	T 1221 (1992)	
USA				
ASTM		AISI	AMS	UNS
~ B 512 (N 08330)	B 512–99	~ 330	~ 5716G	~ N08330
~ B 366 (N 08330)	B 366–99		~ 5592E	

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

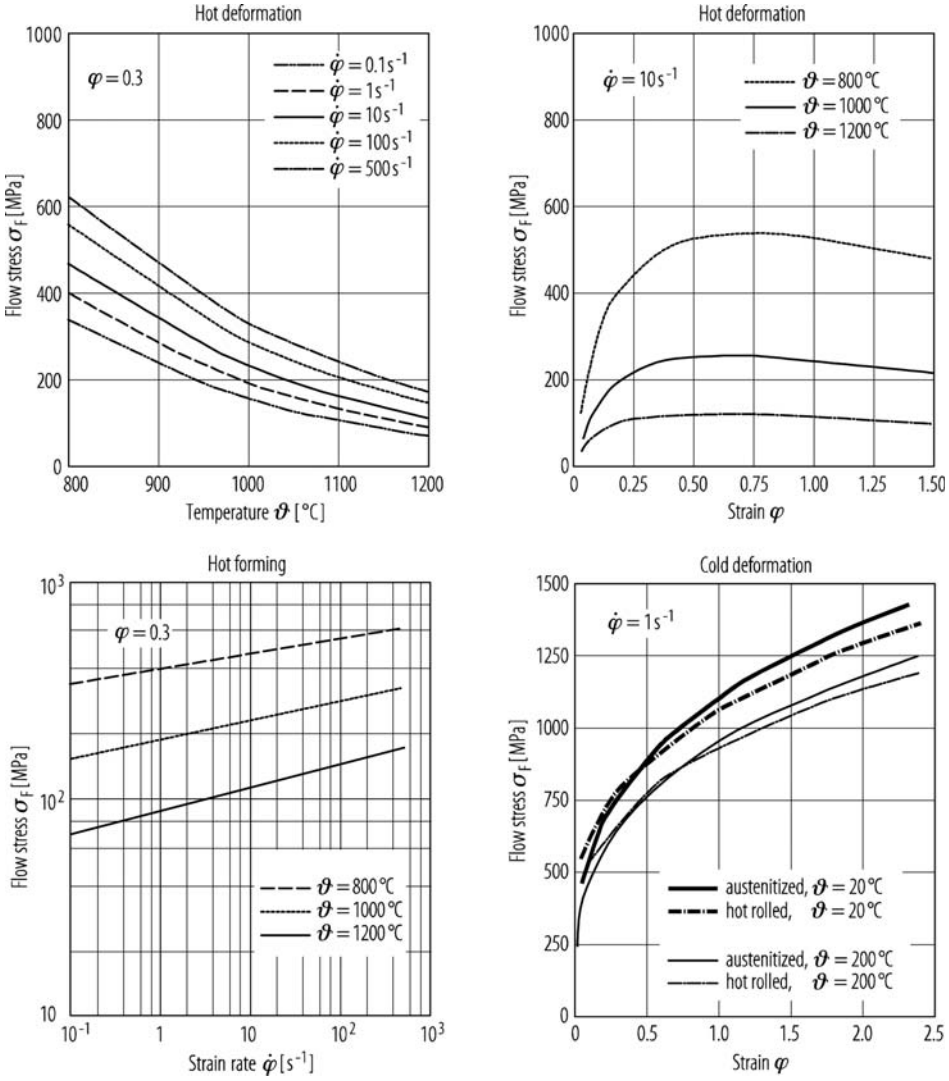
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	austenitized	hot rolled
	austenite		
σ_{F0} [MPa]	142.33	548.6	609.5
A	15358.13	1114.758	1073.417
Effect of temperature K_ϑ			
m_1	−0.00356	−0.00083	−0.00074
Effect of strain K_φ			
m_2	0.38169	0.31409	0.28110
m_4	−0.03562	0.00013	0.00686
m_5	−0.00070		
m_7	−0.27007		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01281	0.01194
m_8	0.000089		
Range of validity			
ϑ [°C]	800…1200	20…300	20…300
φ	0.04…1.50	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.235.
X12NiCrSi35–16. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	240…270	44.2768	0.73219	575…630	7.4489	1.0722

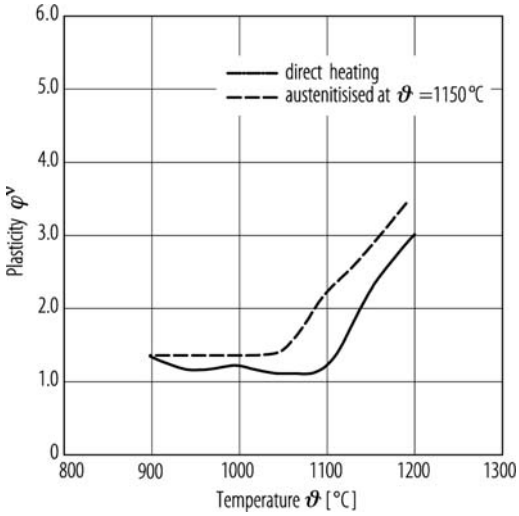
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	45…52	7.53147	0.40891	−2.44615	<80

Fig. 5.236.
X12NiCrSi35–16. Hot plasticity as a function of the temperature. Deformation rate: 0.2 [s^{-1}]. Deformed state. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.70.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	12.48	493.31	16.50	8001.2	193.9
100	14.64	500.10	16.73	7961.0	189.1
200	14.99	508.73	17.31	7918.1	183.0
300	16.44	517.50	17.02	7878.6	176.5
400	17.83	526.43	17.02	7837.8	169.6
500	19.21	535.51	17.92	7786.1	161.9
600	20.62	544.74	18.23	7738.7	153.4
700	22.08	554.14	18.54	7689.6	143.8
800	23.58	563.69	18.87	7638.9	132.9
900	25.16	573.42	19.19	7586.5	120.6
1000	26.80	583.31	19.53	7532.5	106.7
1100	28.53	593.37	19.86	7476.7	91.0
1200	30.34	603.60	20.21	7419.1	73.3

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Steel symbol/number: X53CrMnNiN21–9/1.4871

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.48…0.58	0.00…0.25	8.00…10.00	0.000…0.045	0.000…0.030	20.00…22.00
Ni	N				
3.25…4.50	0.350…0.500				

International comparison of standards

ISO		Euronorm	
		X53CrMnNiN21–9	
United Kingdom		Russia	
X53CrMnNiN21–9			
Japan		China	
USA			
ASTM	AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

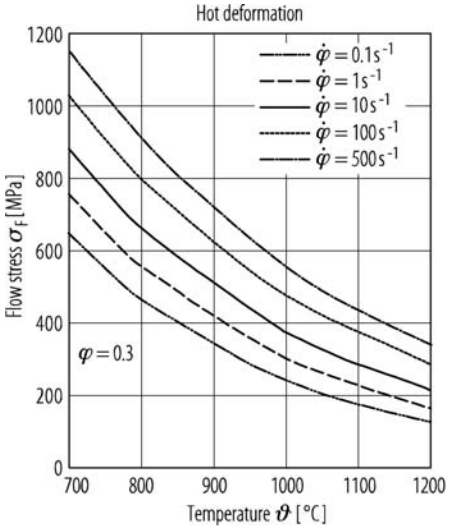
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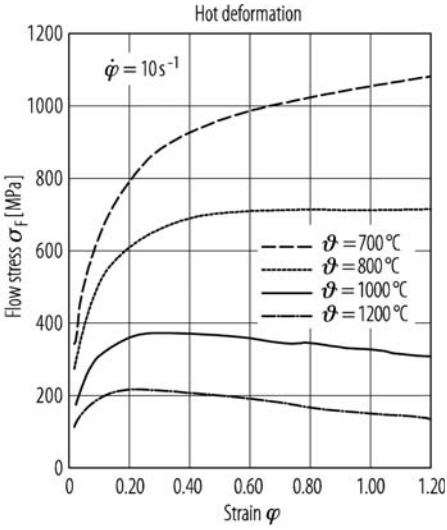
Flow curves

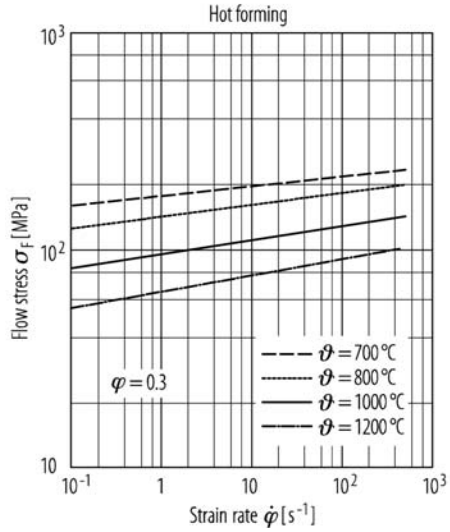
State of material	Hot deformation deformed state austenite	Cold deformation austenitized
σ_{F0} [MPa]	311.30	1520.4
A	9251.121	2047.936
Effect of temperature K_ϑ		
m_1	−0.00238	−0.00095
Effect of strain K_φ		
m_2	0.45790	0.14274
m_4	0.00011	0.00292
m_5	−0.00254	
m_7	0.56803	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00896
m_8	0.000098	
Range of validity		
ϑ [°C]	700…1200	20…400
φ	0.04…1.20	0.04…0.40
$\dot\varphi$ [s^{-1}]	<500	<500

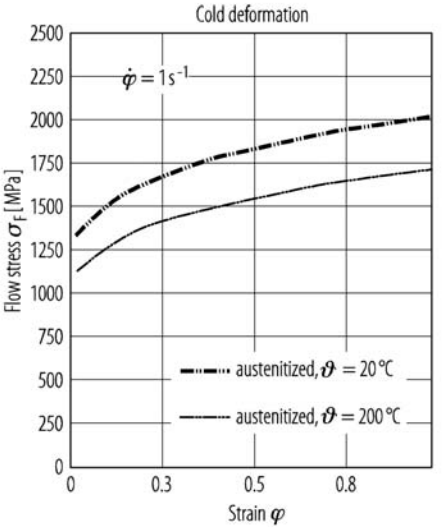
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Fig. 5.237.
X53CrMnNiN21–9. Flow stress curves by hot and cold forming.





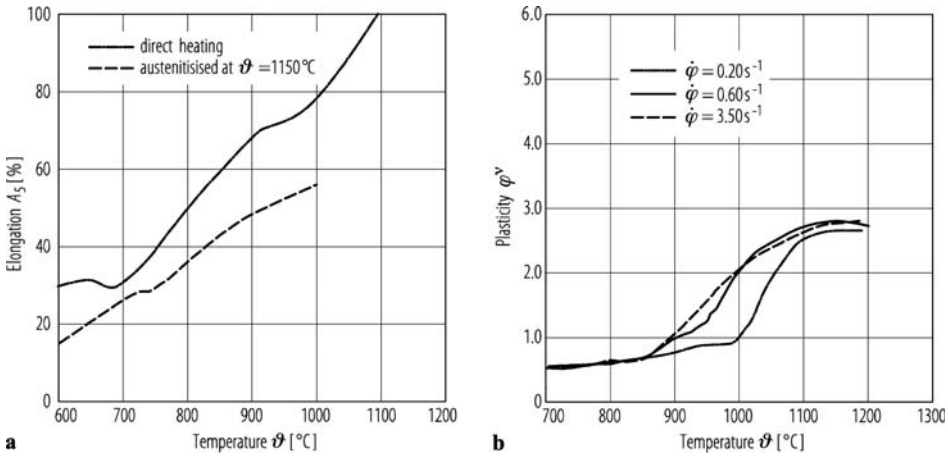




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Fig. 5.238.
X53CrMnNiN21–9. Hot plasticity a function of the temperature. (a) Deformation rate: 0.2 [s^{-1}]. Casting state. (b) Deformed state. Austenitised at 1200 [°C].

Plasticity in tensile test (left) and torsion (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.06	493.31	16.50	7934.2	
100	15.13	500.10	16.73	7894.4	
200	16.69	508.73	17.31	7854.6	
300	18.06	517.50	17.02	7812.7	
400	19.41	526.43	17.02	7772.2	
500	20.77	535.51	17.92	7721.0	
600	22.16	544.74	18.23	7673.9	
700	23.61	554.14	18.54	7625.3	
800	25.11	563.69	18.87	7575.0	
900	26.69	573.42	19.19	7523.1	
1000	28.34	583.31	19.53	7469.5	
1100	30.07	593.37	19.86	7414.1	
1200	31.89	603.60	20.21	7357.0	

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Steel symbol/number: X45CrNiW18–9/1.4873

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.40…0.50	2.00…3.00	0.80…1.50	0.000…0.045	0.000…0.030	17.00…19.00
Ni	W				
8.00…10.00	0.80…1.20				

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
Japan		China		
~ SUH 31	D 3731 (1993)			
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

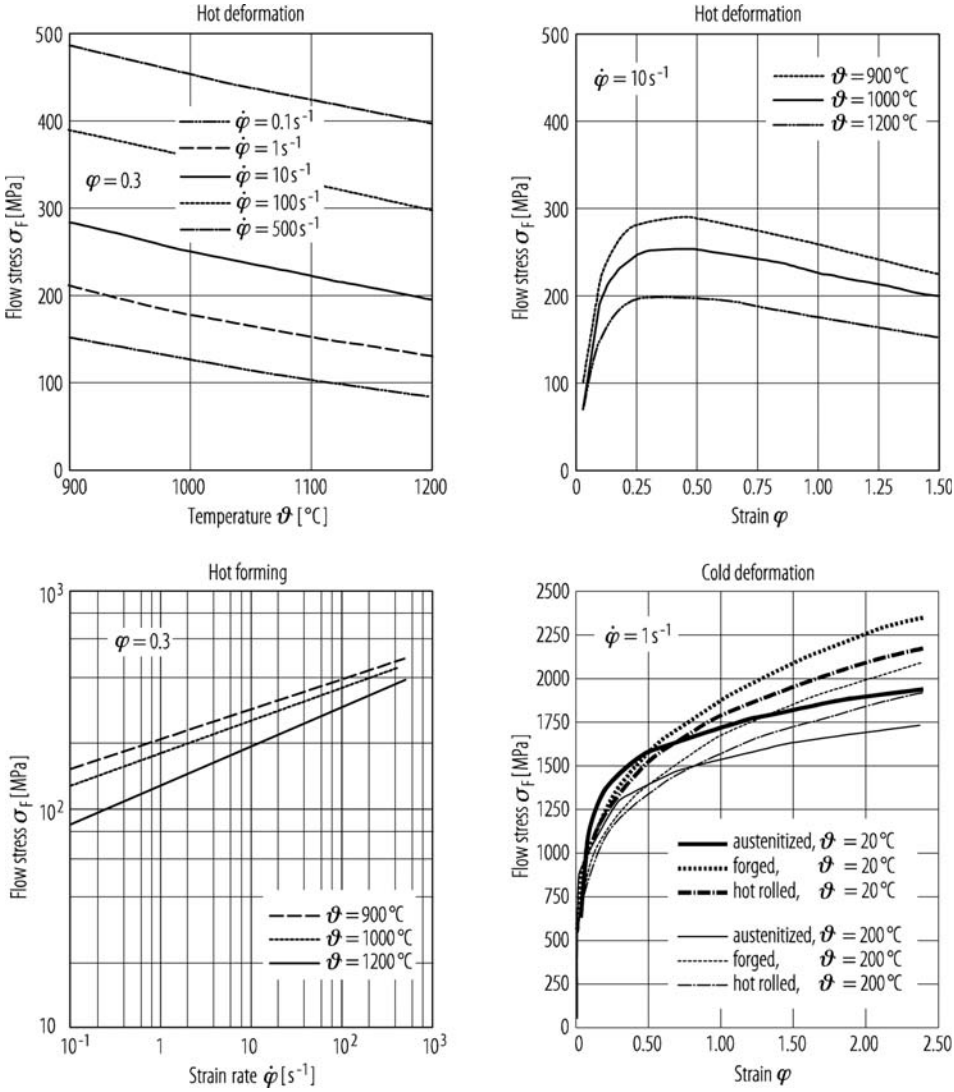
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Flow curves

State of material	Hot deformation	Cold deformation		
	deformed state	austenitized	forged	hot rolled
	austenite			
σ_{F0} [MPa]	189.25	1136.1	992.6	1048.0
A	1156.299	1781.619	1916.843	1807.043
Effect of temperature K_ϑ				
m_1	−0.00160	−0.00064	−0.00068	−0.00073
Effect of strain K_φ				
m_2	−0.00224	0.11489	0.25366	0.23130
m_4	−0.05314	−0.01936	−0.00824	0.00001
m_5	−0.00004			
m_7	−0.29578			
Effect of strain rate $K_{\dot\varphi}$				
m_3		0.00913	0.00954	0.00099
m_8	0.000098			
Range of validity				
ϑ [°C]	900…1200	20…300	20…300	20…300
φ	0.04…1.50	0.04…2.50	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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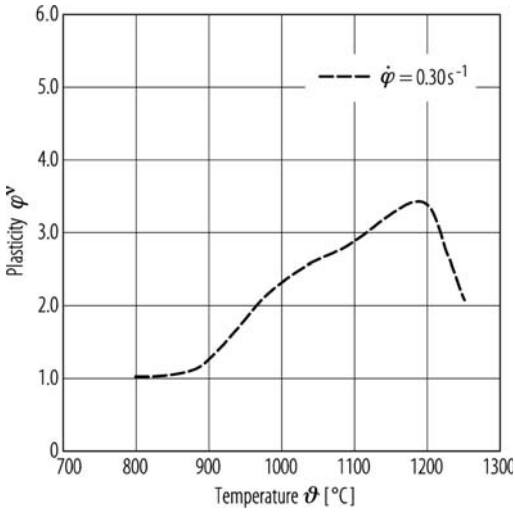
Fig. 5.239.
X45CrNiW18–9. Flow stress curves by hot and cold forming.



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Fig. 5.240.
X45CrNiW18–9. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.35…0.70.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	10.77	493.31	16.50	7773.1	206.7
100	13.18	500.10	16.73	7734.1	200.6
200	16.73	508.73	17.31	7692.3	193.3
300	18.10	517.50	17.02	7654.0	186.1
400	19.45	526.43	17.02	7614.4	179.0
500	20.80	535.51	17.92	7564.2	171.8
600	22.20	544.74	18.23	7518.0	164.4
700	23.64	554.14	18.54	7470.4	156.3
800	25.15	563.69	18.87	7421.1	147.3
900	26.72	573.42	19.19	7370.3	136.9
1000	28.37	583.31	19.53	7317.7	124.7
1100	30.11	593.37	19.86	7263.5	110.0
1200	31.93	603.60	20.21	7207.6	92.4

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DOI: 10.1007/978-3-540-44760-3_131
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Steel symbol/number: X10NiCrAlTi32–21/1.4876

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.12	0.00…1.00	0.00…2.00	0.000…0.030	0.000…0.015	19.00…23.00
Ni	Al	Ti			
30.00…34.00	0.1500…0.6000	0.15…0.60			

International comparison of standards

ISO		Euronorm		
~ X8NiCrAlTi32–21	4955 (1994)	X10NiCrAlTi32–21	10095 –(03/1999)	
United Kingdom		Russia		
X10NiCrAlTi32–21	EN 10095 – (03/1999)			
~ NA 15 H	3074 (1989)			
Japan		China		
~ NCF 800 TP	G 4903 (1991)	~ NS 111	T 15007 (1994)	
~ NCF 800 TB	G 4904 (1991)	~ H01120	T 15007 (1994)	
USA				
ASTM		AMS	SAE	UNS
~ A 240 (N08800)	A 240–02	~ 5766C	~ N08800	~ N08332
~ A 240 (N08810)	A 240–02	~ 5871D	~ N08810	~ N08800

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

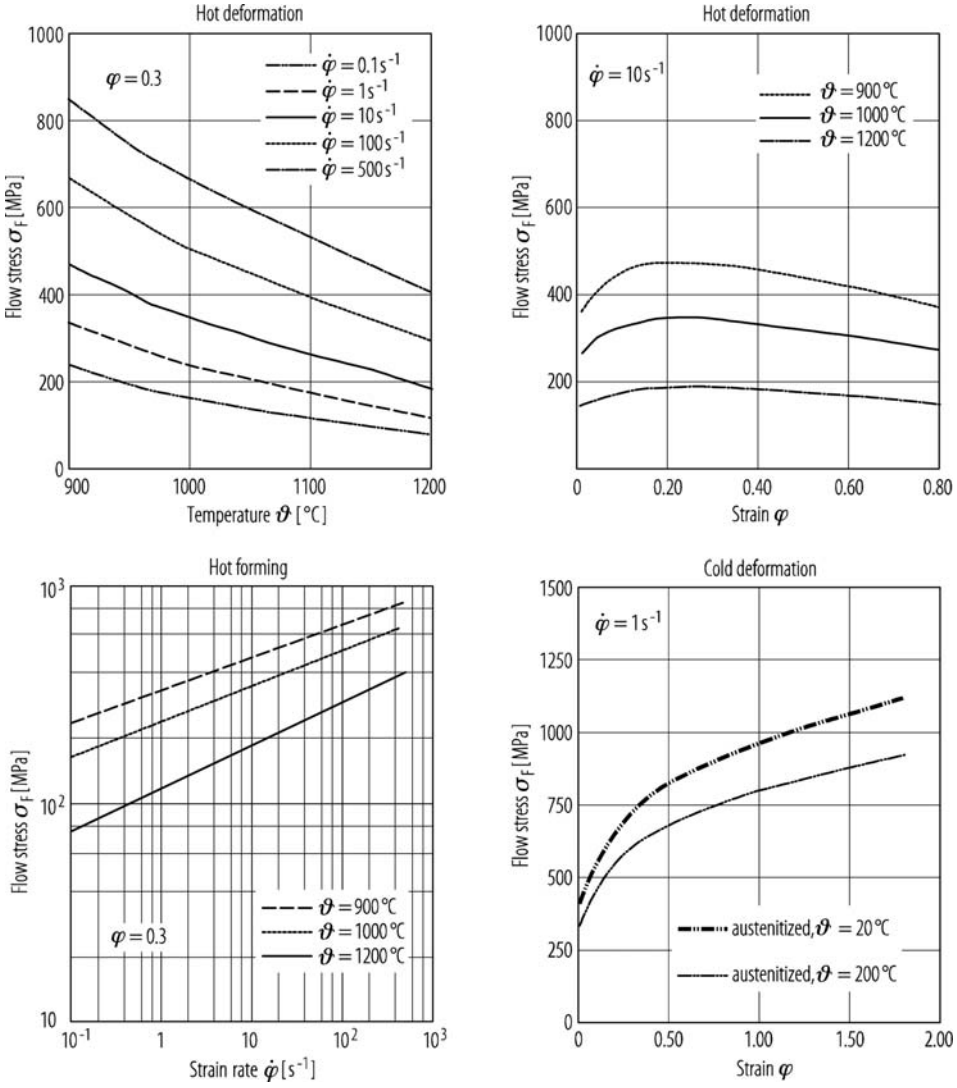
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation austenitized
σ_{F0} [MPa]	328.96	581.0
A	12877.8	979.584
Effect of temperature K_ϑ		
m_1	−0.00349	−0.00105
Effect of strain K_φ		
m_2	0.21613	0.23830
m_4	0.00235	0.00223
m_5	0.00015	
m_7	−0.97823	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01087
m_8	0.000165	
Range of validity		
ϑ [°C]	900…1200	20…300
φ	0.04…0.80	0.04…1.80
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.241.
X10NiCrAlTi32–21. Flow stress curves by hot and cold forming.



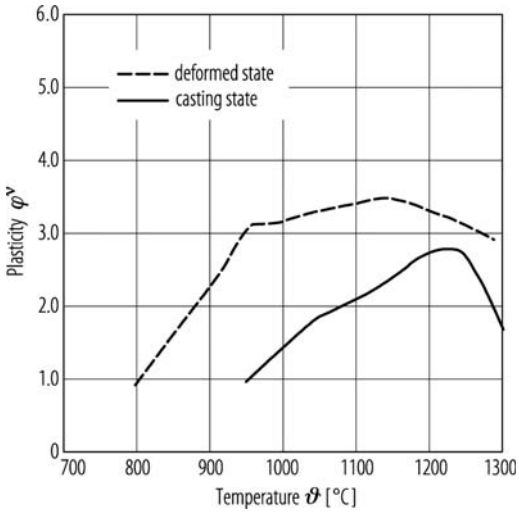
Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]			Validity ε [%]
	A_0	A	n_1	B_0	B	n_2	
chilled	350…420	59.7076	0.58451				<75

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Fig. 5.242.
X10NiCrAlTi32–21. Hot plasticity as a function of the temperature. Deformation rate: 0.3 [s^{-1}]. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.35…0.80.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.70	493.31	16.50	7952.8	
100	15.65	500.10	16.73	7912.9	
200	14.88	508.73	17.31	7870.2	
300	16.34	517.50	17.02	7831.0	
400	17.72	526.43	17.02	7790.4	
500	19.11	535.51	17.92	7739.0	
600	20.52	544.74	18.23	7691.8	
700	21.97	554.14	18.54	7643.1	
800	23.48	563.69	18.87	7592.7	
900	25.05	573.42	19.19	7540.7	
1000	26.70	583.31	19.53	7486.9	
1100	28.42	593.37	19.86	7431.4	
1200	30.24	603.60	20.21	7374.2	

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Steel symbol/number: X10CrMoVNb9–1/1.4903

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.08…0.12	0.00…0.50	0.30…0.60	0.000…0.020	0.000…0.005	8.00…9.50
Mo	Ni	V	Al	Cu	Nb
0.85…1.05	0.00…0.30	0.18…0.25	0.000…0.040	0.00…0.30	0.060…0.100
N					
0.030…0.070					

International comparison of standards

ISO		Euronorm		
		X10CrMoVNb9–1	10028–2 (06/2003)	
		X10CrMoVNb9–1	10302 (05/2002)	
United Kingdom		Russia		
X10CrMoVNb9–1	EN 10028–2 (2003)			
Japan		China		
USA				
ASTM		ASME	Spec	UNS
∼ A 213 (T91)	A 213–01	∼ SA 335 (P91)	∼ 9Cr-1Mo-V-Cb-N	∼ K90901
∼ A 234 (WP91)	A 234–02	∼ SA 336 (F91)		∼ S59180

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

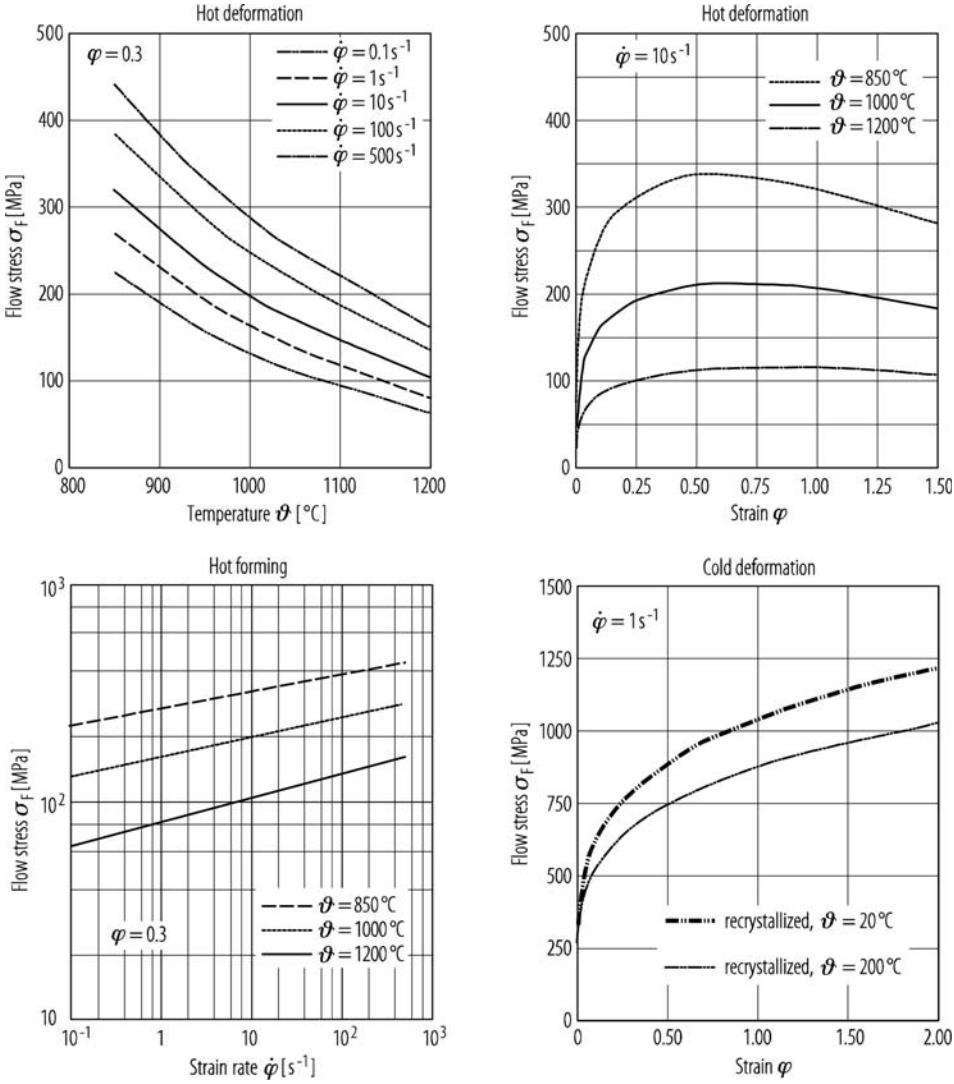
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation recrystallized
σ_{F0} [MPa]	161.46	624.7
A	7477.19	1057.831
Effect of temperature K_ϑ		
m_1	−0.00356	−0.00098
Effect of strain K_φ		
m_2	0.18760	0.23165
m_4	−0.00477	0.00008
m_5	0.00059	
m_7	−0.64687	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01107
m_8	0.000092	
Range of validity		
ϑ [°C]	850…1280	20…300
φ	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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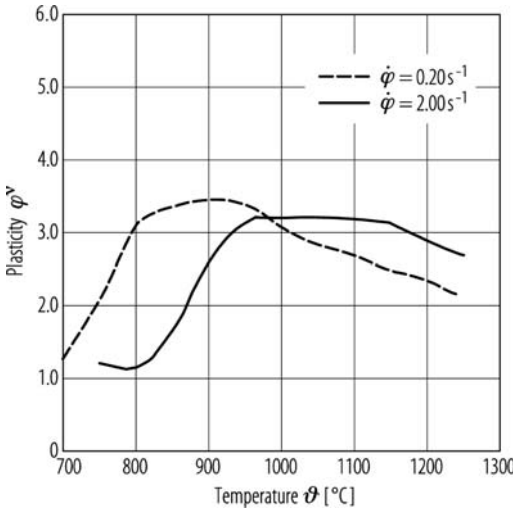
Fig. 5.243.
X10CrMoVNb9–1. Flow stress curves by hot and cold forming.



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Fig. 5.244.
X10CrMoVNb9–1. Hot plasticity as a fuction of the temperature (and deformation rate); deformed state and austenitized at 1200 [°C]. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.30…0.75.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	23.28	459.61	10.12	7789.4	213.0
100	23.47	475.14	10.18	7649.4	206.5
200	23.70	497.01	10.43	7739.1	200.0
300	23.93	516.78	10.76	7711.5	193.6
400	24.17	536.52	11.10	7682.3	185.8
500	24.40	556.69	11.45	7651.3	175.6
600	24.65	577.44	11.82	7618.5	162.2
700	24.89	598.86	12.19	7583.7	145.6
800	25.13	621.01	12.57	7546.9	125.9
900	25.38	643.94	12.97	7507.9	103.7
1000	25.63	667.68	13.38	7466.8	82.7
1100	25.88	692.26	13.80	7423.3	60.5
1200	26.14	717.74	14.24	7377.4	43.6

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Steel symbol/number: X22CrMoV12–1/1.4923

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.18…0.24	0.00…0.50	0.40…0.90	0.000…0.025	0.000…0.015	11.00…12.50
Mo	Ni	V			
0.80…1.20	0.30…0.80	0.25…0.35			

International comparison of standards

ISO		Euronorm		
		X22CrMoV12–1	10302–2 (05/2002)	
		X22CrMoV12–1	10269 (08/1999)	
United Kingdom		Russia		
X22CrMoV12–1	EN 10302–2 (05/2002)			
X22CrMoV12–1	EN 10269 (08/1999)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

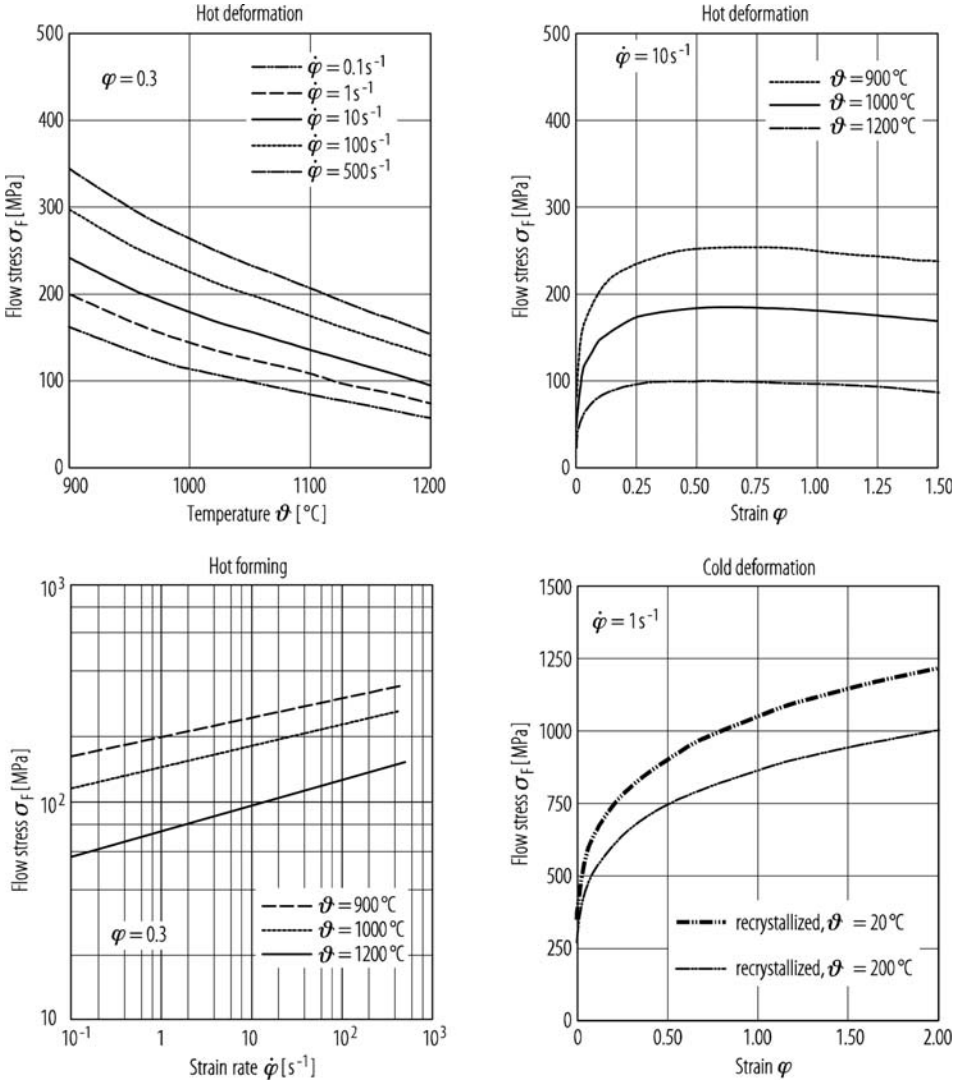
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation recrystallized
σ_{F0} [MPa]	151.57	672.8
A	5286.1	1070.875
Effect of temperature K_ϑ		
m_1	−0.00321	−0.00110
Effect of strain K_φ		
m_2	0.22691	0.21960
m_4	0.00014	0.00190
m_5	−0.00032	
m_7	−0.16619	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01905
m_8	0.000098	
Range of validity		
ϑ [°C]	900…1200	20…300
φ	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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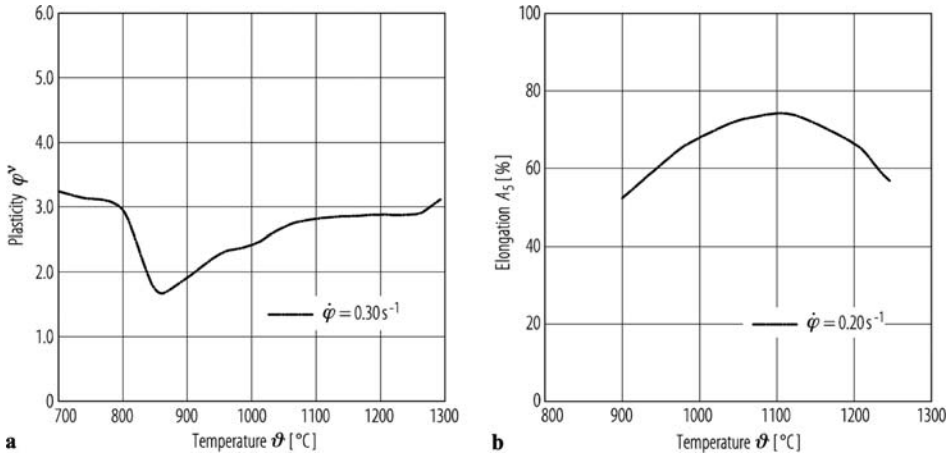
Fig. 5.245.
X22CrMoV12–1. Flow stress curves by hot and cold forming.



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Fig. 5.246.
X22CrMoV12–1. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	24.82	465.04	10.01	7765.3	211.6
100	25.02	481.15	10.18	7765.0	202.9
200	25.26	503.29	10.43	7715.2	195.7
300	25.51	523.31	10.76	7687.7	190.0
400	25.76	543.31	11.10	7658.6	183.6
500	26.02	563.73	11.45	7627.7	174.7
600	26.27	584.74	11.82	7595.0	162.4
700	26.53	606.44	12.19	7560.3	146.3
800	26.79	628.87	12.57	7523.6	121.6
900	27.06	652.08	12.97	7484.8	97.2
1000	27.32	676.12	13.38	7443.7	77.7
1100	27.59	701.02	13.80	7400.4	62.2
1200	27.87	726.81	14.24	7354.7	49.7

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Steel symbol/number: X6CrNiTiB18–10/1.4941

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.04…0.08	0.00…1.00	0.00…2.00	0.000…0.035	0.000…0.015	17.00…19.00
Ni	Ti	B			
9.00…12.00	0.20…0.80	0.0015…0.0050			

International comparison of standards

ISO		Euronorm		
~ X7CrNiTi18–10	9329–4 (1997)	X6CrNiTiB18–10	10302 (05/2002)	
~ X7CrNiTi18–10	TR 15510 (1997)	X6CrNiTiB18–10	10222–5 (02/2000)	
United Kingdom		Russia		
X6CrNiTiB18–10	EN 10302 (05/2002)			
X6CrNiTiB18–10	EN 10222–5 (02/2000)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

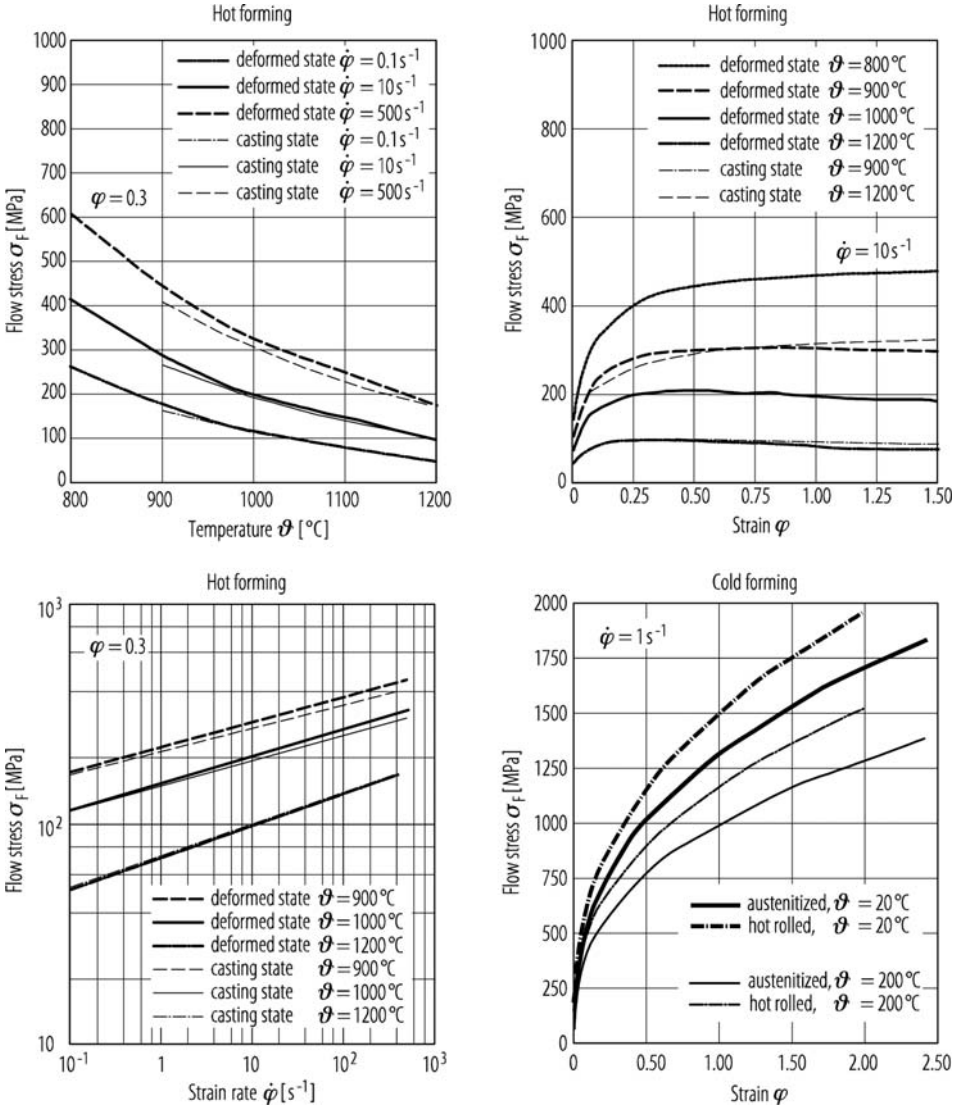
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Flow curves

	Hot deformation		Cold deformation	
	deformed state	casting state	austenitized	hot rolled
State of material	austenite	austenite		
σ_{F0} [MPa]	164.9	157.4	539.3	634.9
A	10446.17	8379.23	1362.369	1548.026
Effect of temperature K_ϑ				
m_1	−0.00345	−0.00320	−0.00156	−0.00143
Effect of strain K_φ				
m_2	0.37677	0.49328	0.36728	0.37726
m_4	0.00099	0.02123	−0.00738	−0.00231
m_5	−0.00160	−0.00157		
m_7	0.30801	0.30846		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.01042	0.01264
m_8	0.000122	0.000116		
Range of validity				
ϑ [°C]	800…1200	900…1200	20…300	20…300
φ	0.04…1.50	0.04…1.50	0.04…2.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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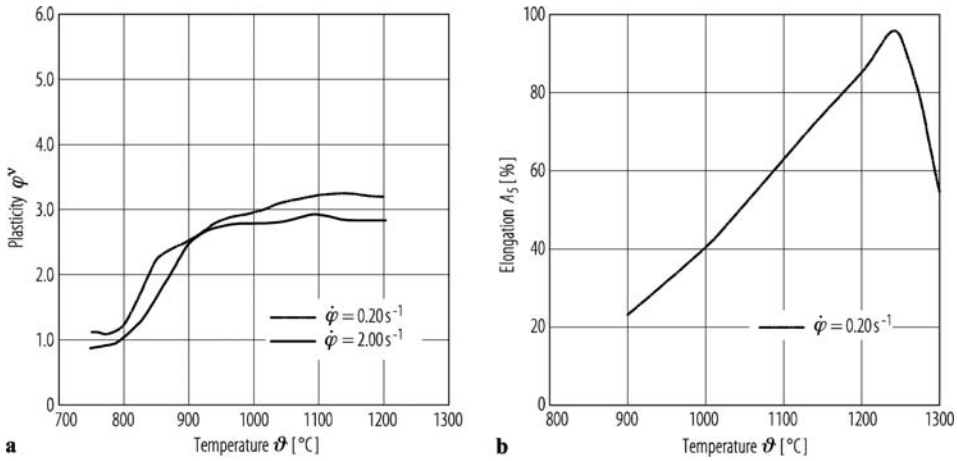
Fig. 5.247.
X6CrNiTiB18–10 Flow stress curves by hot and cold forming.



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Fig. 5.248.
X6CrNiTiB18–10. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Austenitised at 1200 [°C].

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	10.77	493.31	16.50	7785.6	
100	13.17	500.10	16.73	7746.6	
200	17.16	508.73	17.31	7704.8	
300	18.52	517.50	17.02	7666.4	
400	19.85	526.43	17.02	7626.7	
500	21.20	535.51	17.92	7576.4	
600	22.59	544.74	18.23	7530.2	
700	24.03	554.14	18.54	7482.4	
800	25.53	563.69	18.87	7433.1	
900	27.11	573.42	19.19	7382.2	
1000	28.76	583.31	19.53	7329.6	
1100	30.49	593.37	19.86	7275.3	
1200	32.31	603.60	20.21	7219.2	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: X7CrNiMoBNb16–16/1.4986

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.04…0.10	0.30…0.60	0.00…1.50	0.000…0.045	0.000…0.030	15.50…17.50
Ni	Mo	Nb	B		
15.50…17.50	1.60…2.00	0.60…1.20	0..05…0.10		

International comparison of standards

ISO		Euronorm		
		X7CrNiMoBNb16–16	10269 (08/1999)	
United Kingdom		Russia		
X7CrNiMoBNb16–16	EN 10369 (08/1999)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

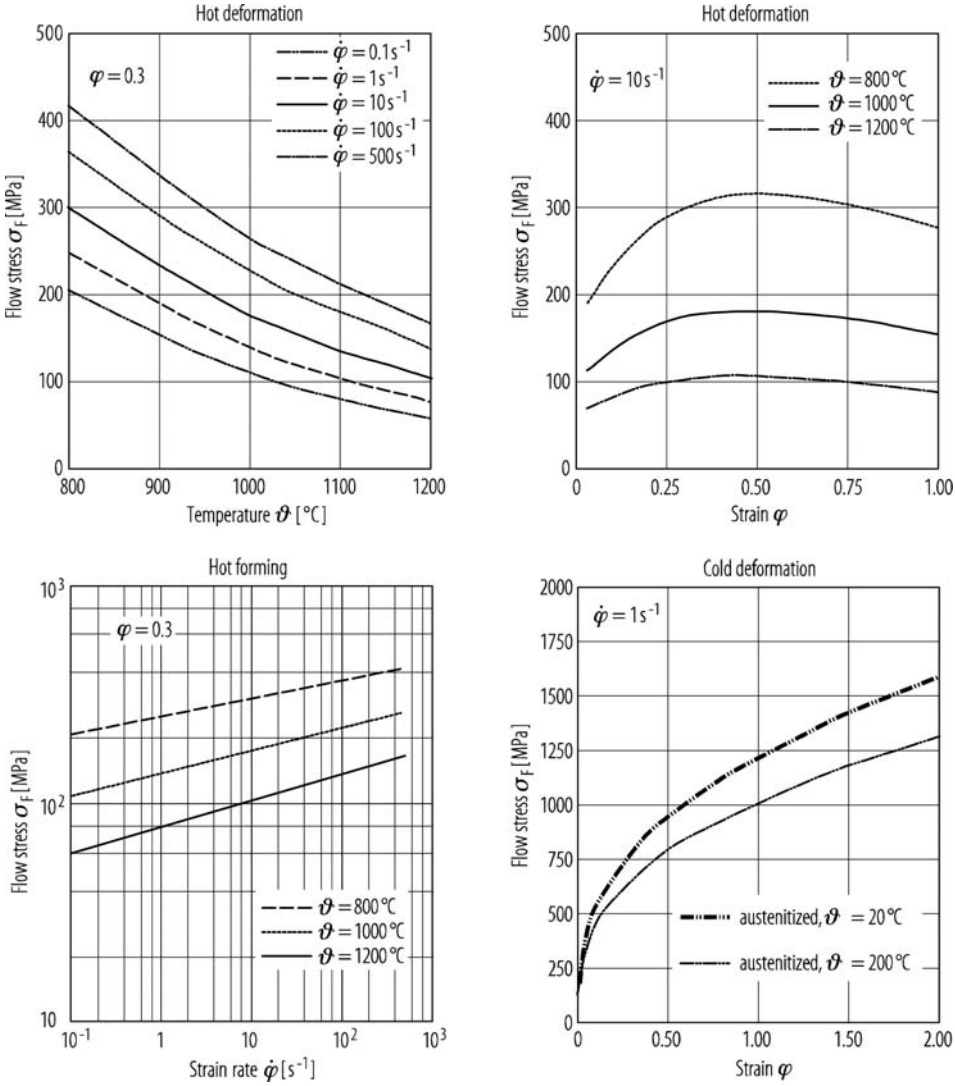
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation austenitized
σ_{F0} [MPa]	137.14	528.9
A	5717.974	1249.570
Effect of temperature K_ϑ		
m_1	−0.00281	−0.00107
Effect of strain K_φ		
m_2	0.52032	0.36935
m_4	0.01539	−0.00103
m_5	−0.00045	
m_7	−0.73813	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00973
m_8	0.000104	
Range of validity		
ϑ [°C]	800…1200	20…300
φ	0.04…1.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.249.
X7CrNiMoBNb16–16. Flow stress curves by hot and cold forming.



Mechanical properties after cold deformation

State of material	Yield stress ΔR_p [MPa]			Tensile strength ΔR_m [MPa]		
	A_0	A	n_1	B_0	B	n_2
chilled	460…520	51.9478	0.7446	650…700	36.5171	0.78485

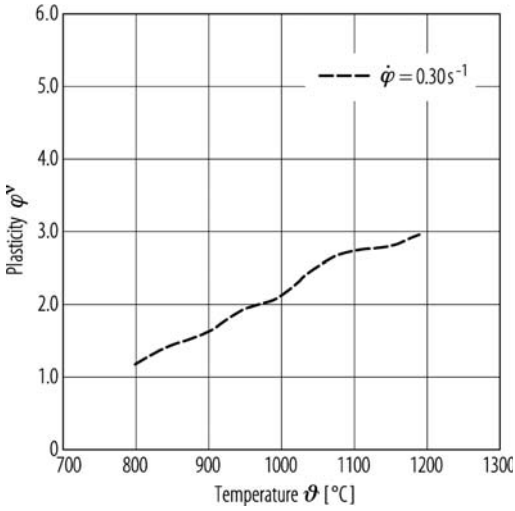
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Mechanical properties after cold deformation (2nd part)

State of material	Elongation to fracture ΔA_5 [%]				Validity ε [%]
	C_0	C	n_3	n_4	
chilled	20…25	51.5	−0.15315	−8.80054	<60

Fig. 5.250.
X7CrNiMoBNb16–16. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.85.

Plasticity in torsion



DOI: 10.1007/978-3-540-44760-3_136
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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	13.19	493.31	16.50	7798.7	
100	15.23	500.10	16.73	7759.5	
200	16.78	508.73	17.31	7720.4	
300	18.15	517.50	17.02	7679.2	
400	19.49	526.43	17.02	7639.4	
500	20.85	535.51	17.92	7589.1	
600	22.24	544.74	18.23	7542.8	
700	23.69	554.14	18.54	7495.0	
800	25.19	563.69	18.87	7445.6	
900	26.77	573.42	19.19	7394.5	
1000	28.42	583.31	19.53	7341.8	
1100	30.15	593.37	19.86	7287.4	
1200	31.97	603.60	20.21	7231.3	

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: 48Si7/1.5021

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.45…0.52	1.60…2.00	0.50…0.80	0.000…0.025	0.000…0.025	0.00…0.40
Mo	Ni				
0.00…0.10	0.00…0.40				

International comparison of standards

ISO		Euronorm		
		48Si7	10132–4 (02/2000)	
United Kingdom		Russia		
48Si7	EN 10132–4 (02/2000)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

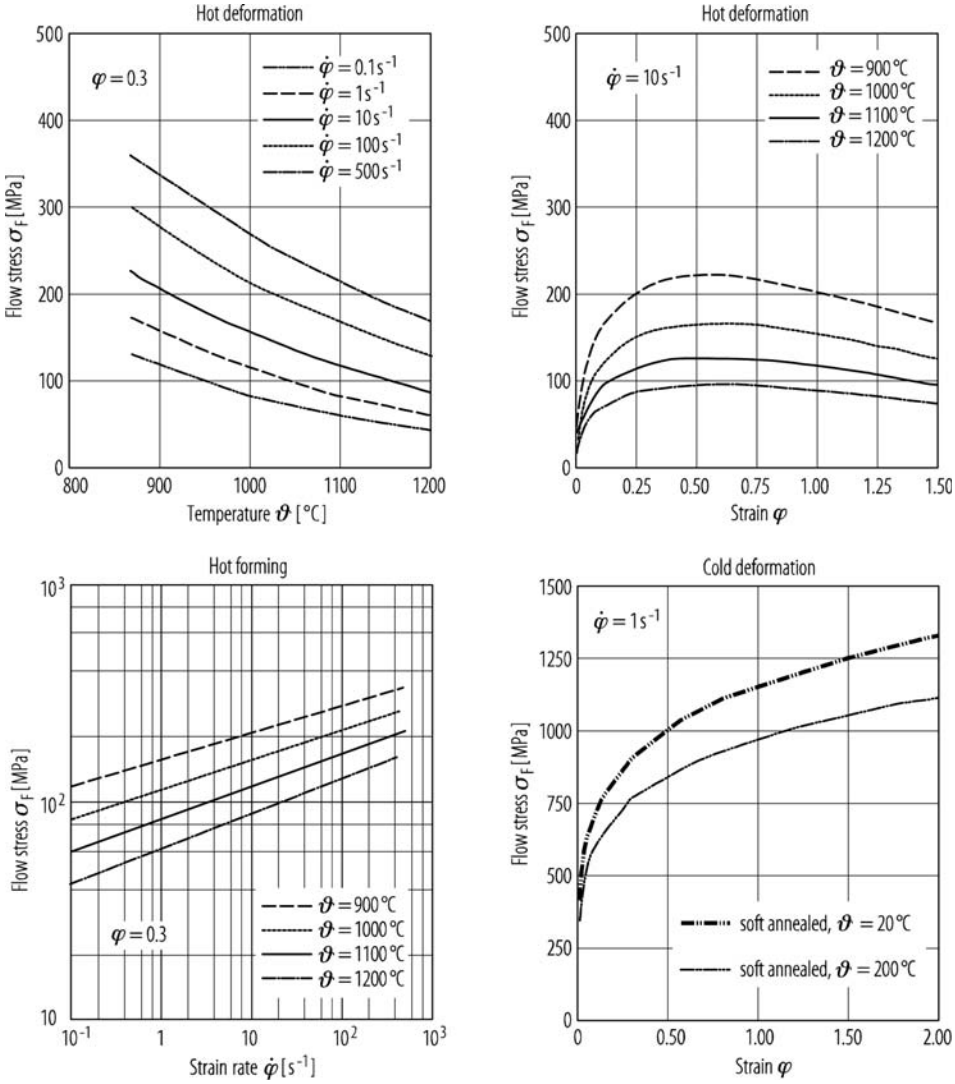
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	117.43	750.2
A	5274.32	1181.072
Effect of temperature K_ϑ		
m_1	−0.00319	−0.00096
Effect of strain K_φ		
m_2	0.36951	0.19958
m_4	−0.00151	−0.00009
m_5	0.00015	
m_7	−0.76312	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01121
m_8	0.000136	
Range of validity		
ϑ [°C]	870…1200	20…200
φ	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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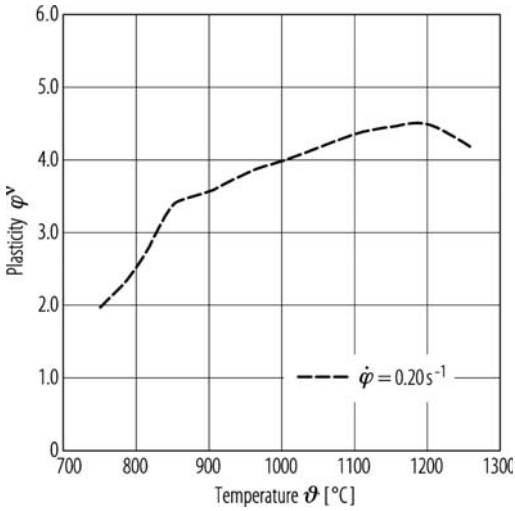
Fig. 5.251.
48Si7. Flow stress curves by hot and cold forming.



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Fig. 5.252.
48Si7. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.90.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	35.87	477.43	10.27	7733.8	209.0
100	39.24	491.02	10.76	7708.8	198.3
200	39.53	504.89	11.57	7680.1	192.1
300	37.91	525.22	12.15	7649.2	188.9
400	35.6	549.88	12.67	7616.1	184.7
500	33.01	577.2	13.2	7580.7	176.6
600	30.37	606.55	13.71	7542.9	163.1
700	27.80	637.91	14.24	7502.4	143.9
800	23.28	699.82	15.21	7451.4	116.1
900	26.24	697.31	16.52	7388.8	90.5
1000	28.22	694.80	17.70	7323.1	70.6
1100	29.79	692.30	18.78	7254.6	55.0
1200	31.40	689.82	19.77	7183.4	42.9

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Steel symbol/number: 46Si7/1.5024

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	N
0.42…0.50	1.50…1.80	0.50…0.80	0.000…0.025	0.000…0.025	0.000…0.007

International comparison of standards

ISO		Euronorm		
		46Si7	10089–2 (12/2002)	
		~ 45 Si 7	89 (1971)	
United Kingdom		Russia		
46Si7	EN 10089–2 (12/2002)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

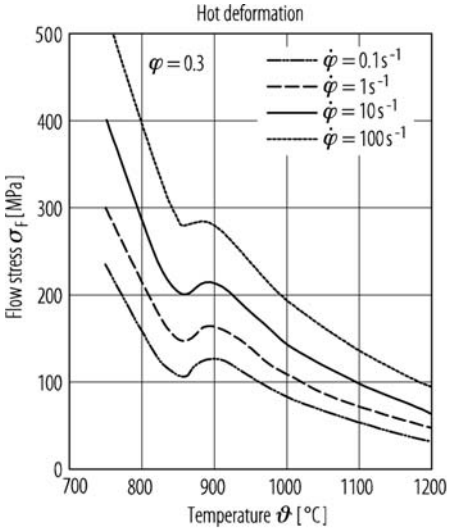
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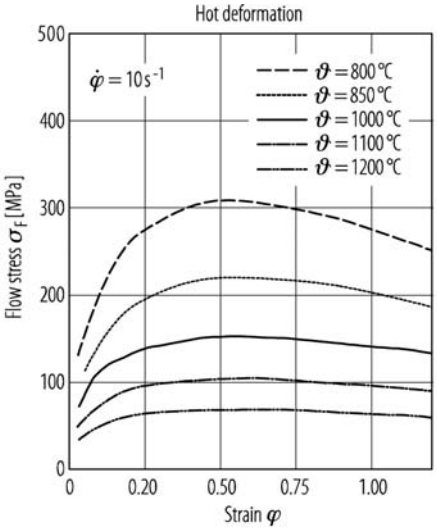
Flow curves

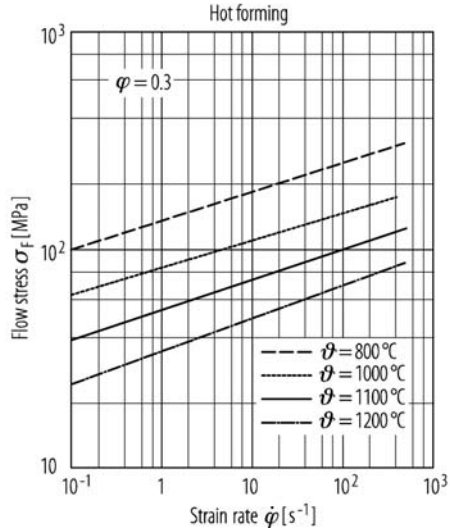
State of material	Hot deformation		Cold deformation
	deformed state		soft annealed
	austenite	ferrite+Fe_3C	
σ_{F0} [MPa]	110.00	(52.35)	743.4
A	13715.97	148394.00	1130.874
Effect of temperature K_ϑ			
m_1	−0.00419	−0.00726	−0.00101
Effect of strain K_φ			
m_2	0.36393	0.44544	0.18486
m_4	−0.00156	0.00158	0.00012
m_5	−0.00013	0.00053	
m_7	−0.57660	−1.08007	
Effect of strain rate $K_{\dot\varphi}$			
m_3			0.01092
m_8	0.000125	0.000164	
Range of validity			
ϑ [°C]	900…1200	750…850	20…200
φ	0.04…1.20	0.04…1.20	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

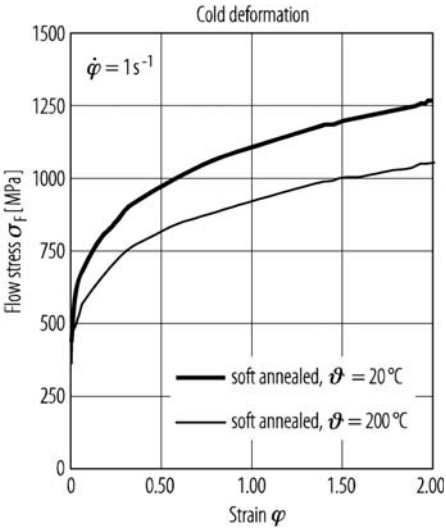
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Fig. 5.253.
46Si7. Flow stress curves by hot and cold forming.





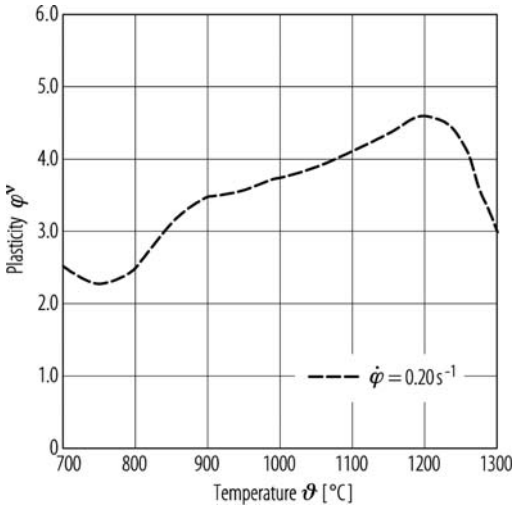




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Fig. 5.254.
46Si7. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.90.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	36.92	476.85	10.19	7742.1	
100	40.01	490.25	10.90	7716.8	
200	40.22	504.06	11.70	7687.7	
300	38.55	524.34	12.27	7656.6	
400	36.2	548.93	12.79	7623.2	
500	33.55	576.2	13.3	7587.5	
600	30.87	605.49	13.84	7549.3	
700	28.25	636.77	14.37	7508.4	
800	23.30	699.09	14.51	7472.4	
900	26.20	696.58	15.74	7413.1	
1000	28.11	694.08	16.84	7351.0	
1100	29.63	691.58	17.84	7286.4	
1200	31.18	689.10	18.76	7219.2	

DOI: 10.1007/978-3-540-44760-3_138
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Steel symbol/number: 56Si7/1.5026

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.52…0.60	1.60…2.00	0.60…0.90	0.000…0.025	0.000…0.025	0.00…0.40
Mo	Ni				
0.00…0.10	0.00…0.40				

International comparison of standards

ISO		Euronorm		
~ 59Si7	683–14 (1992)	56Si7	10089 (12/2000)	
		56Si7	10132–4 (02/2000)	
United Kingdom		Russia		
56Si7	EN 10089 (12/2000)	~ 55S2	14959 (1979)	
~251 A 58	970 Part 2 (1988)			
Japan		China		
		~ 55Si2Mn	T 1222 (1984)	
		~ A11552	T 1222 (1984)	
USA				
ASTM		AISI	SAE	UNS
~ A 711 (9255)	A 711–01	~ 9255	~ 9255	~ G92550

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

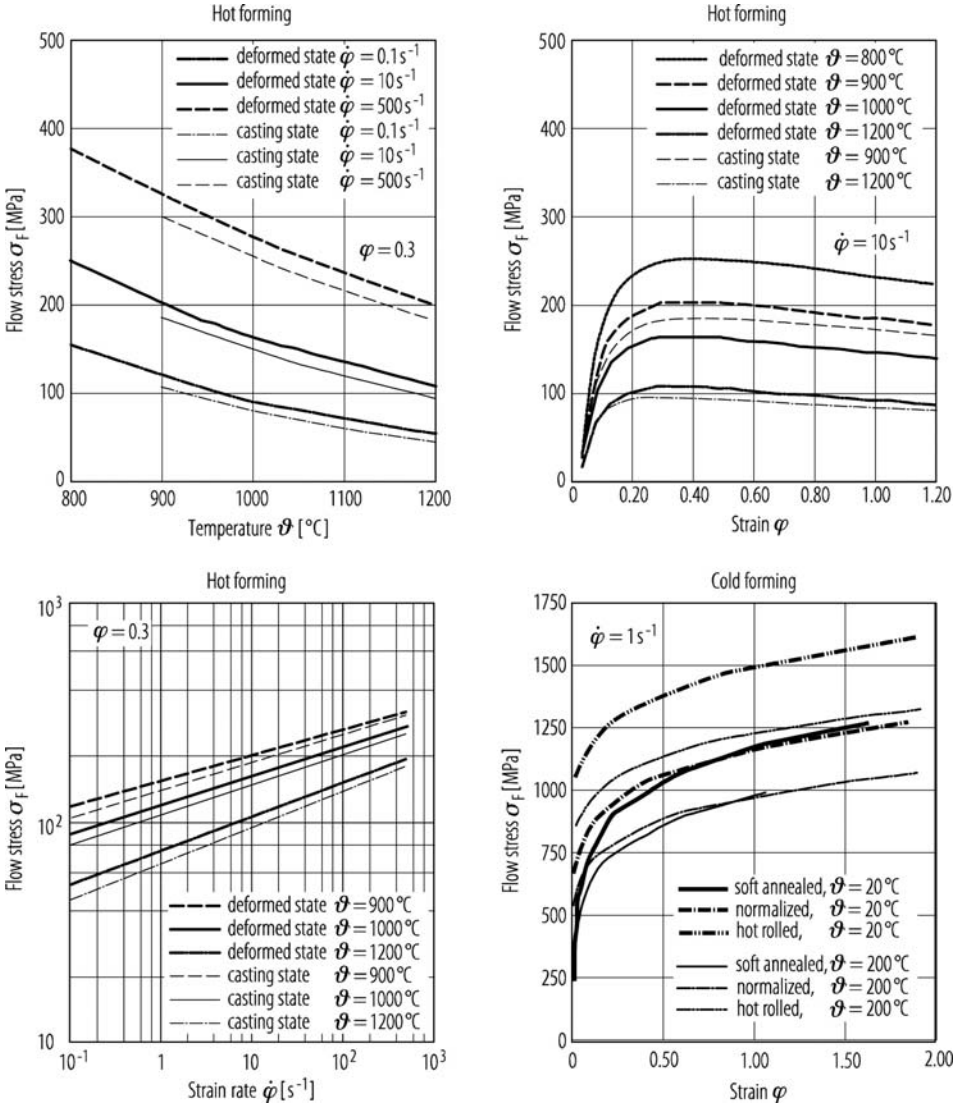
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Flow curves

State of material	Hot deformation		Cold deformation		
	deformed state	casting state	soft annealed	normalized	hot rolled
	austenite	austenite			
σ_{F0} [MPa]	117.87	105.6	772.6	870.5	1201.5
A	1540.20	1508.20	1200.444	1189.923	1525.979
Effect of temperature K_ϑ					
m_1	−0.00229	−0.00243	−0.00098	−0.00100	−0.00109
Effect of strain K_φ					
m_2	−0.08786	−0.10243	0.17521	0.14282	0.11207
m_4	−0.07419	−0.07496	−0.00398	0.00095	0.00167
m_5	−0.00048	−0.00033			
m_7	0.03627	0.00633			
Effect of strain rate $K_{\dot\varphi}$					
m_3			0.00962	0.01163	0.01046
m_8	0.000131	0.000137			
Range of validity					
ϑ [°C]	800…1200	900…1200	20…140	20…140	20…140
φ	0.04…1.20	0.04…1.20	0.04…1.60	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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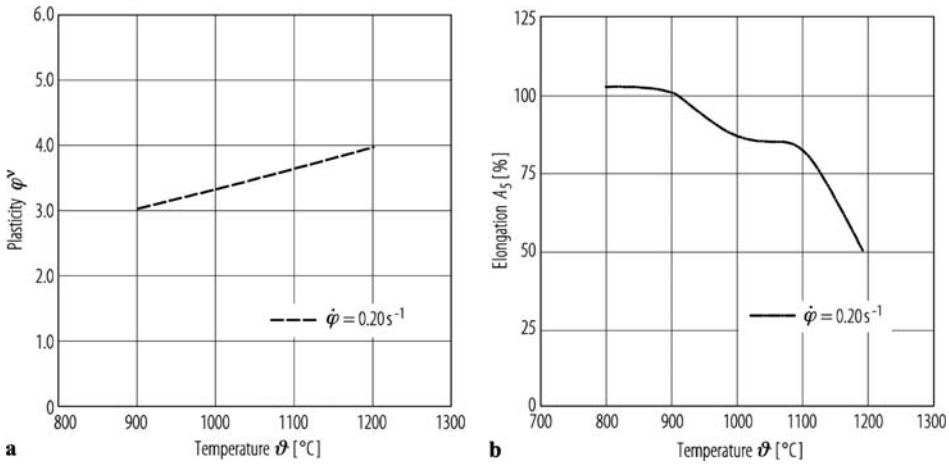
Fig. 5.255.
56Si7. Flow stress curves by hot and cold forming.



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Fig. 5.256.
56Si7. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	35.40	477.72	10.19	7729.9	208.8
100	38.90	491.43	10.69	7705.1	204.3
200	39.21	505.32	11.51	7676.5	199.0
300	37.62	525.68	12.08	7645.8	192.6
400	35.3	550.37	12.61	7612.9	183.9
500	32.76	577.7	13.1	7577.7	172.0
600	30.15	607.11	13.65	7540.0	156.7
700	27.60	638.50	14.18	7499.8	137.9
800	23.27	700.19	15.62	7440.1	112.6
900	26.27	697.67	16.98	7375.4	88.3
1000	28.27	695.17	18.21	7307.6	69.3
1100	29.87	692.67	19.33	7236.9	54.4
1200	31.50	690.18	20.36	7163.4	42.6

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.
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Steel symbol/number: 10MnSi5/1.5112

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.07…0.11	0.55…0.75	1.03…1.27	0.000…0.020	0.000…0.020	0.00…0.12
Mo	Ni	Al	Cu	Ti + Zr	
0.00…0.12	0.00…0.12	0.000…0.020	0.00…0.17	< 0.13	

International comparison of standards

ISO		Euronorm	
		~ 9 MnSi 5 3 KE	133 (1979)
United Kingdom		Russia	
Japan		China	
USA			
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

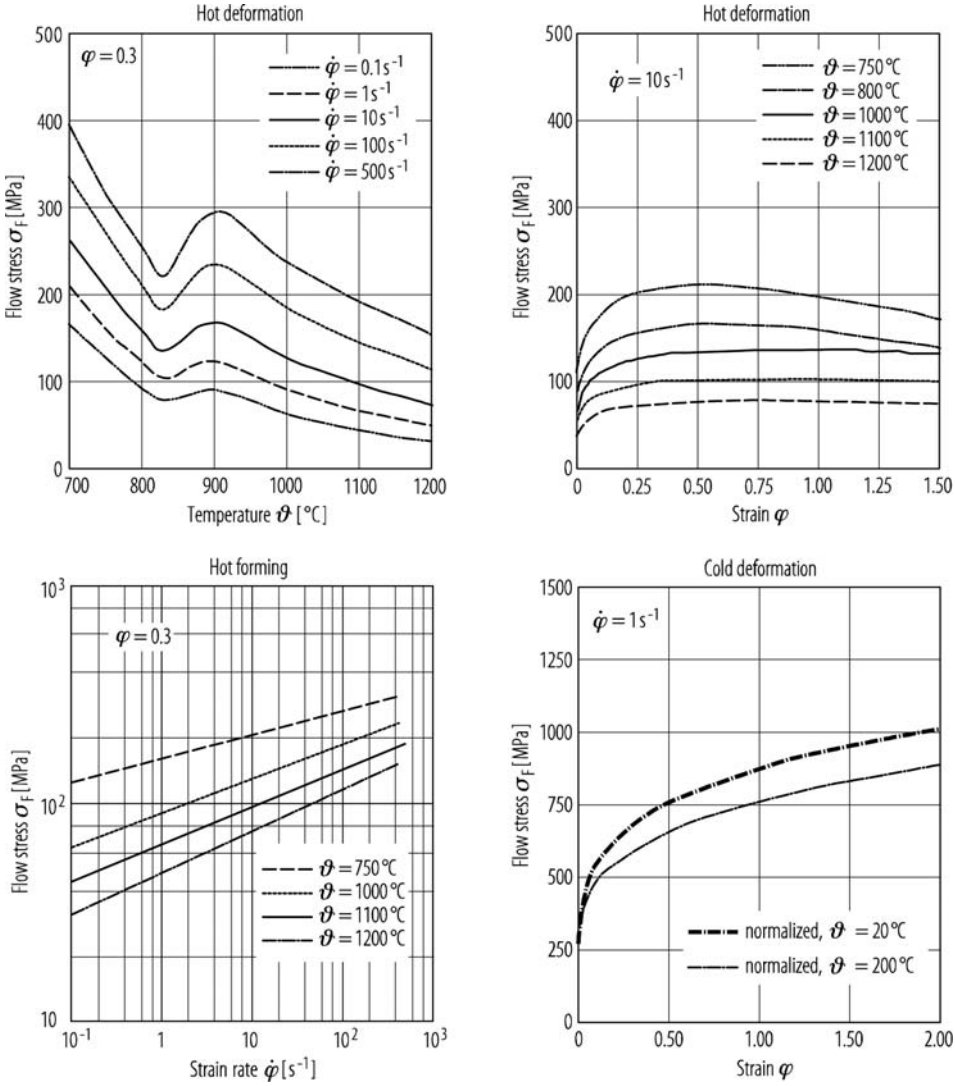
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Flow curves

	Hot deformation			Cold deformation
	deformed state		casting state	normalized
State of material	austenite	ferrite+Fe_3C	austenite	
σ_{F0} [MPa]	110.2	(55.0)	94.2	560.4
A	2658.13	13857.73	2209.92	890.18
Effect of temperature K_ϑ				
m_1	−0.00308	−0.00561	−0.00291	−0.00078
Effect of strain K_φ				
m_2	0.18481	0.13386	0.27292	0.20416
m_4	−0.00077	0.00029	0.00533	0.00011
m_5	−0.00017	0.00135	−0.00017	
m_7	−0.12814	−0.82961	−0.12805	
Effect of strain rate $K_{\dot\varphi}$				
m_3				0.00947
m_8	0.000156	0.000148	0.000156	
Range of validity				
ϑ [°C]	900…1200	700…830	900…1200	20…300
φ	0.04…1.50	0.04…1.50	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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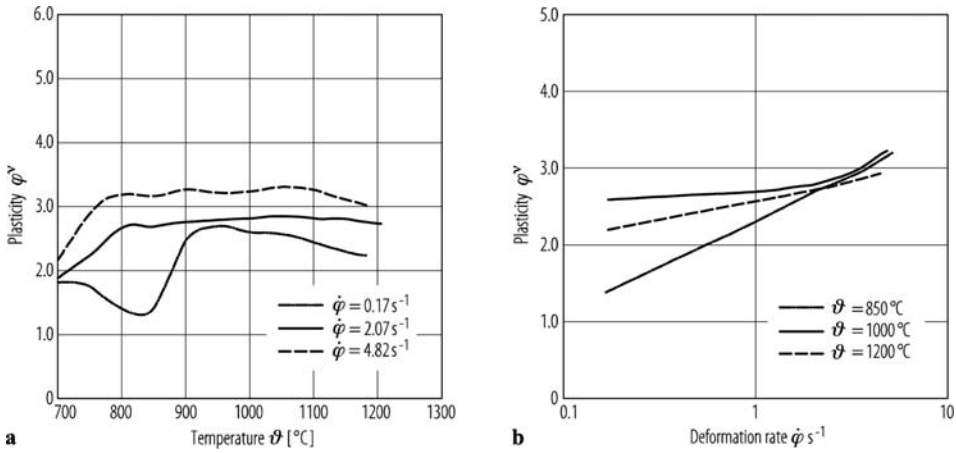
Fig. 5.257.
10MnSi5. Flow stress curves by hot and cold forming.



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Fig. 5.258.
10MnSi5. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Austenitised at 1200 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	44.52	474.68	11.12	7819.8	
100	44.87	486.93	11.53	7792.8	
200	44.55	500.11	12.22	7762.5	
300	42.52	520.13	12.76	7730.0	
400	39.8	544.46	13.28	7695.2	
500	36.88	571.4	13.8	7658.0	
600	33.91	600.45	14.33	7618.2	
700	31.01	631.43	14.87	7575.6	
800	23.73	695.12	12.50	7585.2	
900	26.22	692.62	13.42	7536.4	
1000	27.75	690.13	14.25	7485.6	
1100	28.92	687.65	15.00	7432.8	
1200	30.15	685.18	15.69	7378.2	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: 37MnSi5/1.5122

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S
0.33…0.41	1.10…1.40	1.10…1.40	0.000…0.035	0.000…0.035

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
Japan		China		
		~ 35SiMn	T 3077 (1999)	
		~ A10352	T 3077 (1999)	
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

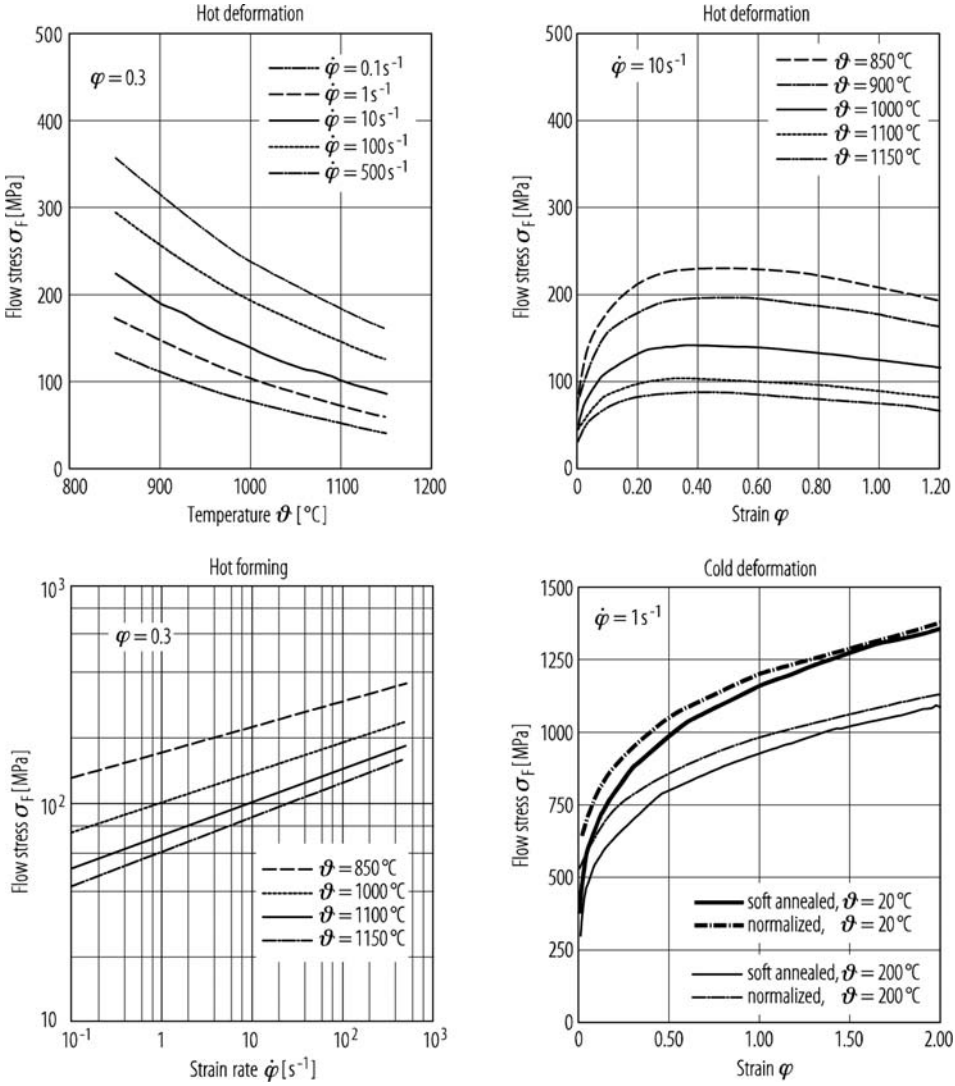
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	normalized
	austenite		
σ_{F0} [MPa]	112.10	713.8	804.4
A	5965.48	1189.170	1219.044
Effect of temperature K_ϑ			
m_1	−0.00337	−0.00123	−0.00109
Effect of strain K_φ			
m_2	0.36089	0.22485	0.19547
m_4	0.00048	0.00011	0.00296
m_5	−0.00048		
m_7	−0.47863		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01216	0.01153
m_8	0.000137		
Range of validity			
ϑ [°C]	850…1150	20…300	20…300
φ	0.04…1.20	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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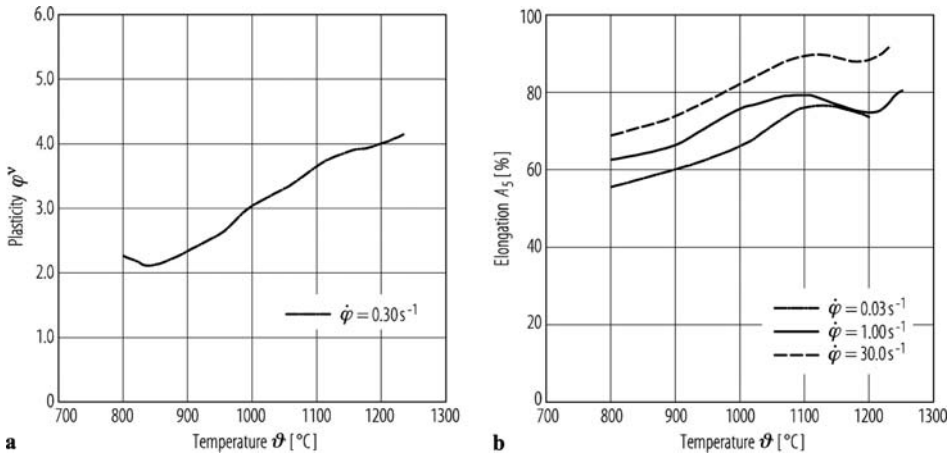
Fig. 5.259.
37MnSi5. Flow stress curves by hot and cold forming.



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Fig. 5.260.
37MnSi5 . Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	38.17	476.21	10.57	7764.4	
100	40.88	489.48	11.04	7738.7	
200	41.01	503.25	11.81	7709.4	
300	39.28	523.46	12.38	7677.9	
400	36.8	548.00	12.91	7644.2	
500	34.16	575.2	13.4	7608.0	
600	31.43	604.43	13.95	7569.4	
700	28.76	635.65	14.49	7528.2	
800	23.34	698.33	13.93	7504.8	
900	26.16	695.82	15.07	7448.4	
1000	28.01	693.32	16.10	7389.3	
1100	29.46	690.83	17.04	7327.8	
1200	30.95	688.35	17.90	7264.0	

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Steel symbol/number: 20MnV6/1.5217

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	V
0.16…0.22	0.10…0.50	1.30…1.70	0.000…0.035	0.000…0.035	0.10…0.20

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
Japan		China		
		~ 20MnV	T 3077 (1999)	
		~ A01202	T 3077 (1999)	
USA				
ASTM		AISI	SAE	UNS
~ A 381	A 381–01			~K03013

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

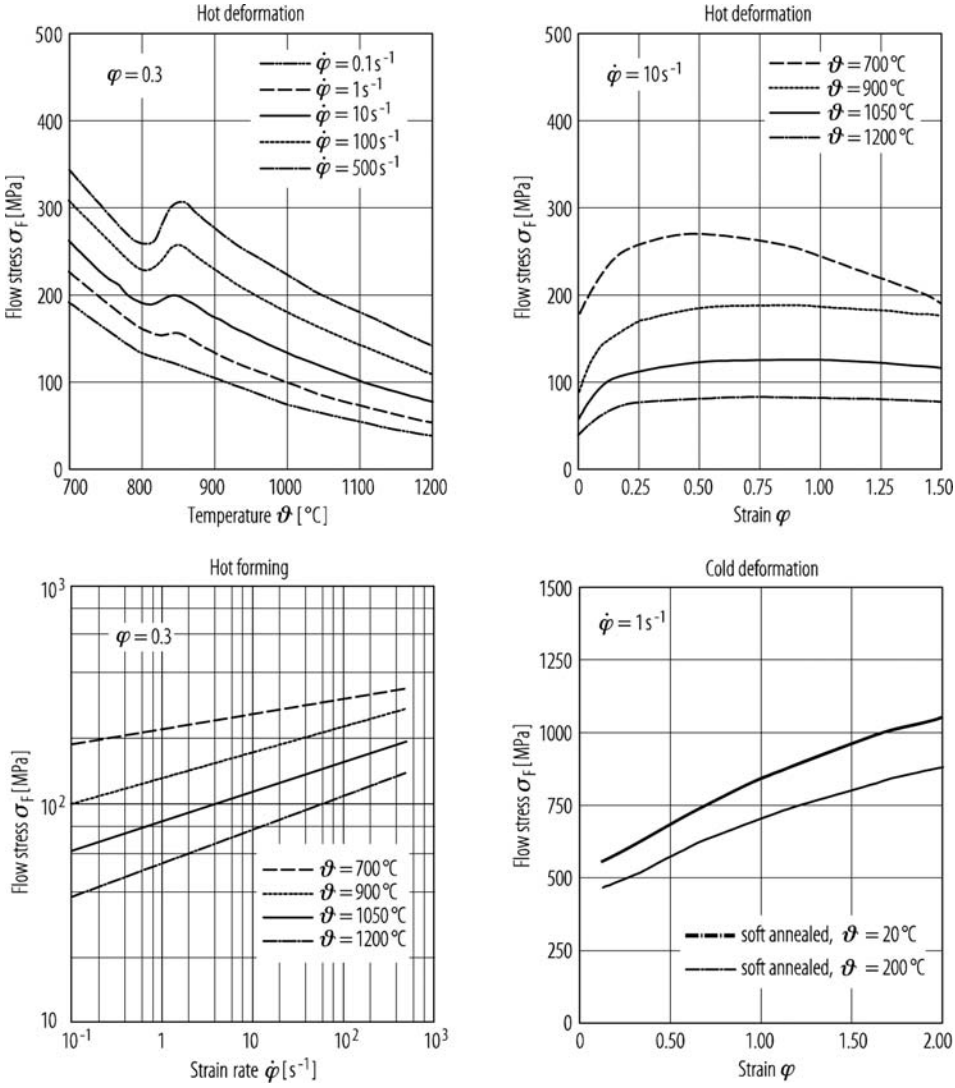
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Flow curves

State of material	Hot deformation		Cold deformation
	deformed state		soft annealed
	austenite	ferrite+Fe_3C	
σ_{F0} [MPa]	80.75	(66.1)	578.2
A	3028.04	4900.82	818.428
Effect of temperature K_ϑ			
m_1	−0.00300	−0.00450	−0.00099
Effect of strain K_φ			
m_2	0.26088	0.07784	0.35976
m_4	0.00146	0.00042	0.04752
m_5	−0.00011	0.00311	
m_7	−0.28600	−1.48800	
Effect of strain rate $K_{\dot\varphi}$			
m_3			0.01108
m_8	0.000129	0.000096	
Range of validity			
ϑ [°C]	850…1200	700…800	20…300
φ	0.04…1.50	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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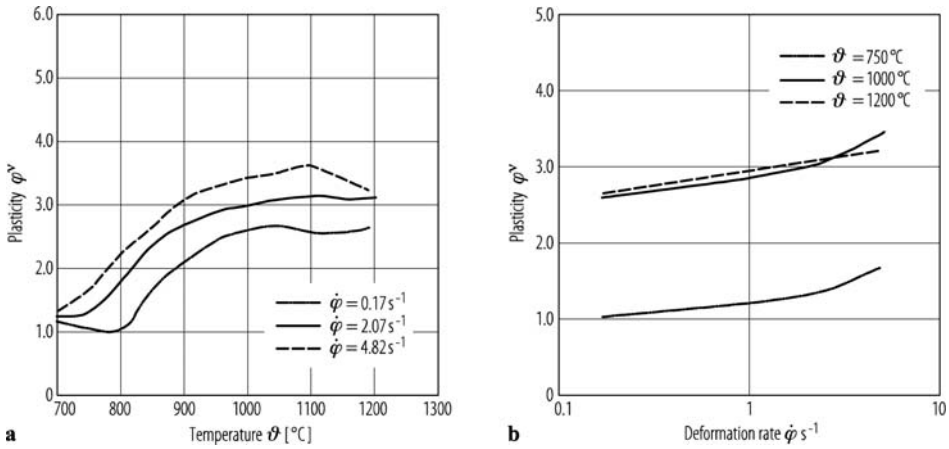
Fig. 5.261.
20MnV6. Flow stress curves by hot and cold forming.



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Fig. 5.262.
20MnV6. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	44.08	473.86	11.09	7817.7	
100	44.62	487.09	11.50	7790.7	
200	44.33	500.30	12.19	7760.5	
300	42.33	520.33	12.74	7728.1	
400	39.6	544.67	13.26	7693.3	
500	36.72	571.6	13.8	7656.1	
600	33.76	600.68	14.31	7616.3	
700	30.88	631.67	14.85	7573.9	
800	23.69	695.32	12.56	7582.1	
900	26.21	692.82	13.49	7533.0	
1000	27.75	690.33	14.32	7481.8	
1100	28.94	687.85	15.08	7428.6	
1200	30.19	685.38	15.78	7373.6	

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Steel symbol/number: 42MnV7/1.5223

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	V
0.38…0.45	0.15…0.35	1.60…1.90	0.000…0.035	0.000…0.035	0.07…0.12

International comparison of standards

ISO		Euronorm		
~ 42Mn6	683–18 (1996)			
United Kingdom		Russia		
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

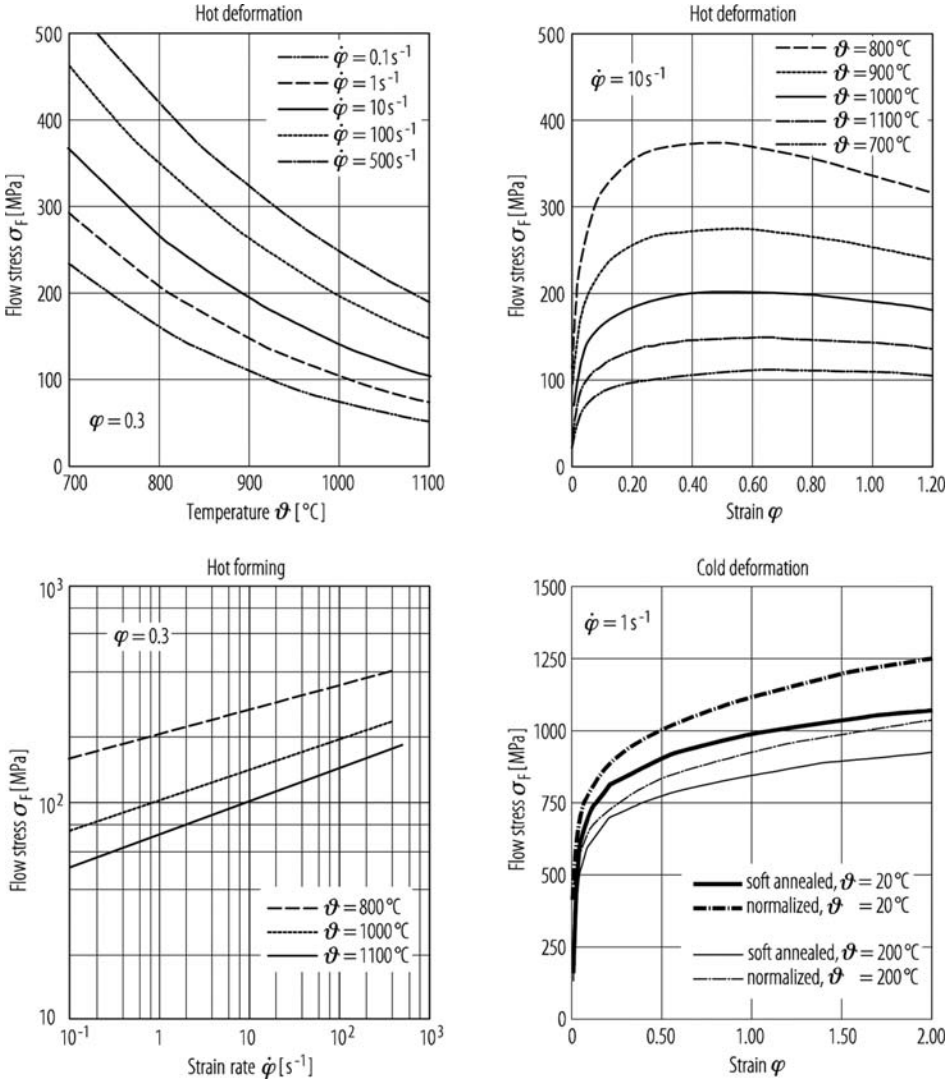
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	normalized
	austenite		
σ_{F0} [MPa]	117.05	742.6	816.1
A	5192.80	1013.19	1146.598
Effect of temperature K_ϑ			
m_1	−0.00371	−0.00084	−0.00106
Effect of strain K_φ			
m_2	0.15043	0.11145	0.15454
m_4	−0.00601	−0.00778	0.00001
m_5	0.00076		
m_7	−0.73021		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01757	0.01604
m_8	0.000141		
Range of validity			
ϑ [°C]	700…1100	20…300	20…250
φ	0.04…1.20	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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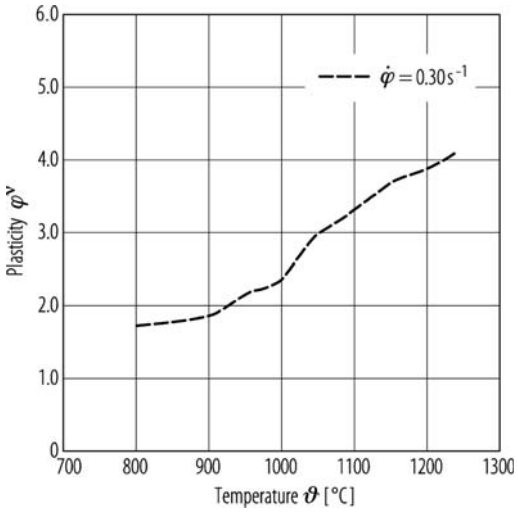
Fig. 5.263.
42MnV7. Flow stress curves by hot and cold forming.



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Fig. 5.264.
42MnV7. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as–cast and as-deformed state is: 0.50…0.90.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	40.80	475.04	10.76	7816.5	
100	42.63	488.72	11.27	7790.1	
200	42.57	501.81	12.01	7760.2	
300	40.72	521.93	12.56	7728.1	
400	38.2	546.37	13.09	7693.8	
500	35.37	573.4	13.6	7657.0	
600	32.53	602.59	14.14	7617.6	
700	29.76	633.70	14.68	7575.6	
800	23.47	696.92	13.13	7570.3	
900	26.14	694.41	14.16	7517.8	
1000	27.85	691.92	15.08	7462.9	
1100	29.17	689.43	15.92	7405.9	
1200	30.55	686.95	16.69	7346.8	

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Steel symbol/number: 38MnSiVS5/1.5231

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	V
0.35…0.40	0.50…0.80	1.20…1.50	0.000…0.035	0.030…0.065	0.08…0.13

International comparison of standards

ISO		Euronorm		
~ 38MnVS6	11692 (1994)			
United Kingdom		Russia		
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

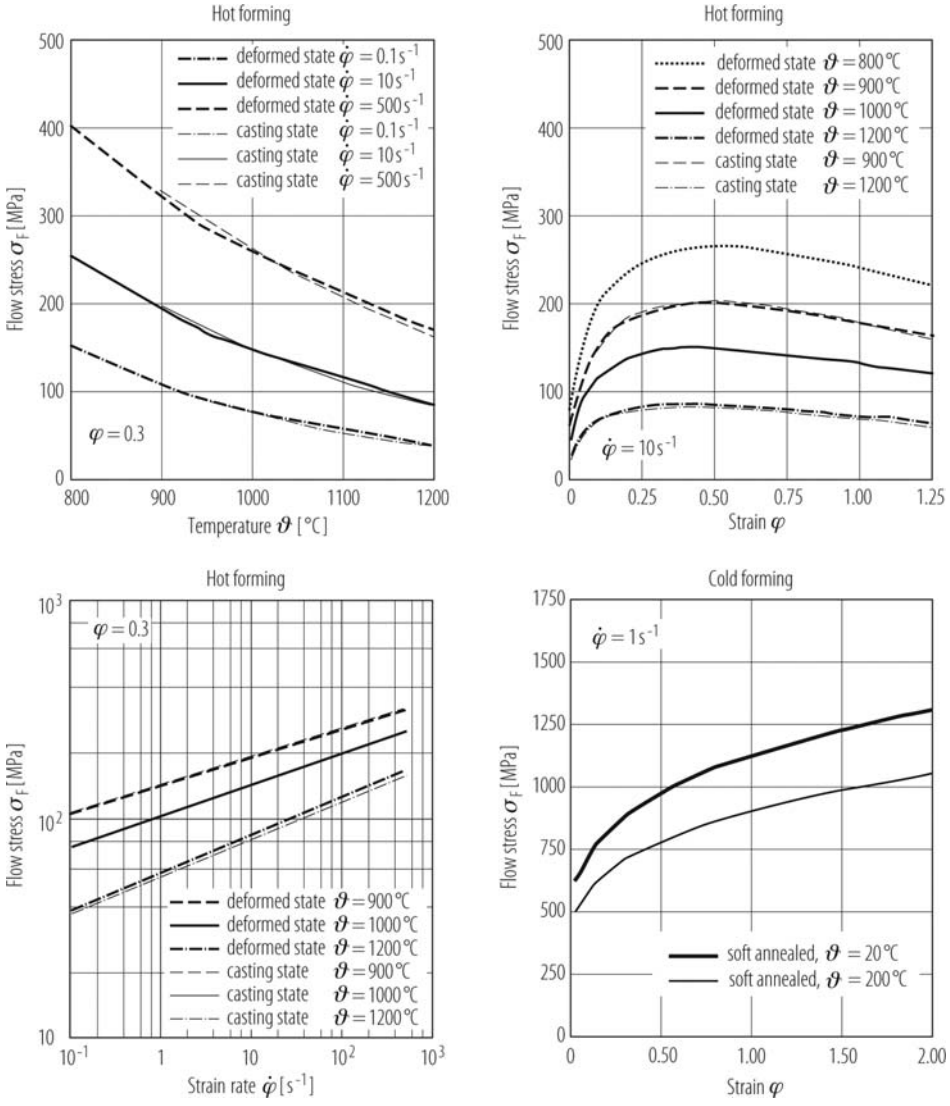
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Flow curves

State of material	Hot deformation		Cold deformation
	deformed state	casting state	soft annealed
	austenite	austenite	
σ_{F0} [MPa]	116.00	114.1	748.5
A	4241.14	5209.87	1150.783
Effect of temperature K_ϑ			
m_1	−0.00295	−0.00307	−0.00121
Effect of strain K_φ			
m_2	0.38339	0.42365	0.21296
m_4	0.00027	0.00043	0.00504
m_5	−0.00052	−0.00061	
m_7	−0.48576	−0.53164	
Effect of strain rate $K_{\dot\varphi}$			
m_3			0.01478
m_8	0.000143	0.000144	
Range of validity			
ϑ [°C]	800…1300	900…1200	20…250
φ	0.04…1.25	0.04…1.25	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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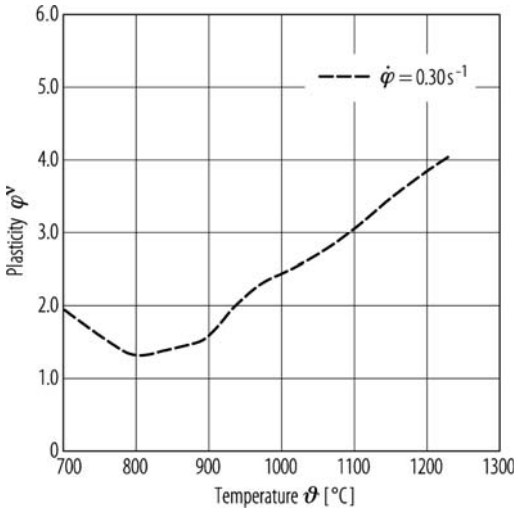
Fig. 5.265.
38MnSiVS5. Flow stress curves by hot and cold forming.



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Fig. 5.266.
38MnSiVS5. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.90.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	40.09	475.34	10.76	7793.6	
100	42.17	489.56	11.21	7767.4	
200	42.17	502.17	11.96	7737.7	
300	40.34	522.31	12.52	7705.8	
400	37.8	546.78	13.04	7671.6	
500	35.05	573.9	13.6	7635.0	
600	32.24	603.05	14.09	7595.9	
700	29.50	634.19	14.63	7554.1	
800	23.43	697.28	13.30	7544.8	
900	26.14	694.78	14.36	7491.4	
1000	27.88	692.28	15.31	7435.7	
1100	29.24	689.79	16.17	7377.7	
1200	30.65	687.31	16.96	7317.6	

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Steel symbol/number: 16Mo3/1.5415

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.12…0.20	0.00…0.35	0.40…0.90	0.000…0.025	0.000…0.010	0.00…0.30
Mo	Ni	V	Cu	Nb	N
0.25…0.35	0.00…0.30	0.00…0.02	0.00…0.30	0.000…0.020	0.000…0.012

International comparison of standards

ISO		Euronorm		
~ 16Mo3	9330–4 (2000)	16Mo3	10217–5 (05/2002)	
United Kingdom		Russia		
16Mo3	EN 10217–5 (05/2002)	~ 55S2	14959 (1979)	
16Mo3	EN 10028–2 (06/2003)			
Japan		China		
~ STPA 12	G 3458 (1988)	~ 15MoG	5310 (1995)	
~ STBA 12	G 3462 (1988)	~ A65158	5310 (1995)	
USA				
ASTM		AISI	SAE	UNS
~ A 204 (A)	A 204 (99)			~ K11820
~ A 204 (B)	A 204 (99)			~ K12020

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

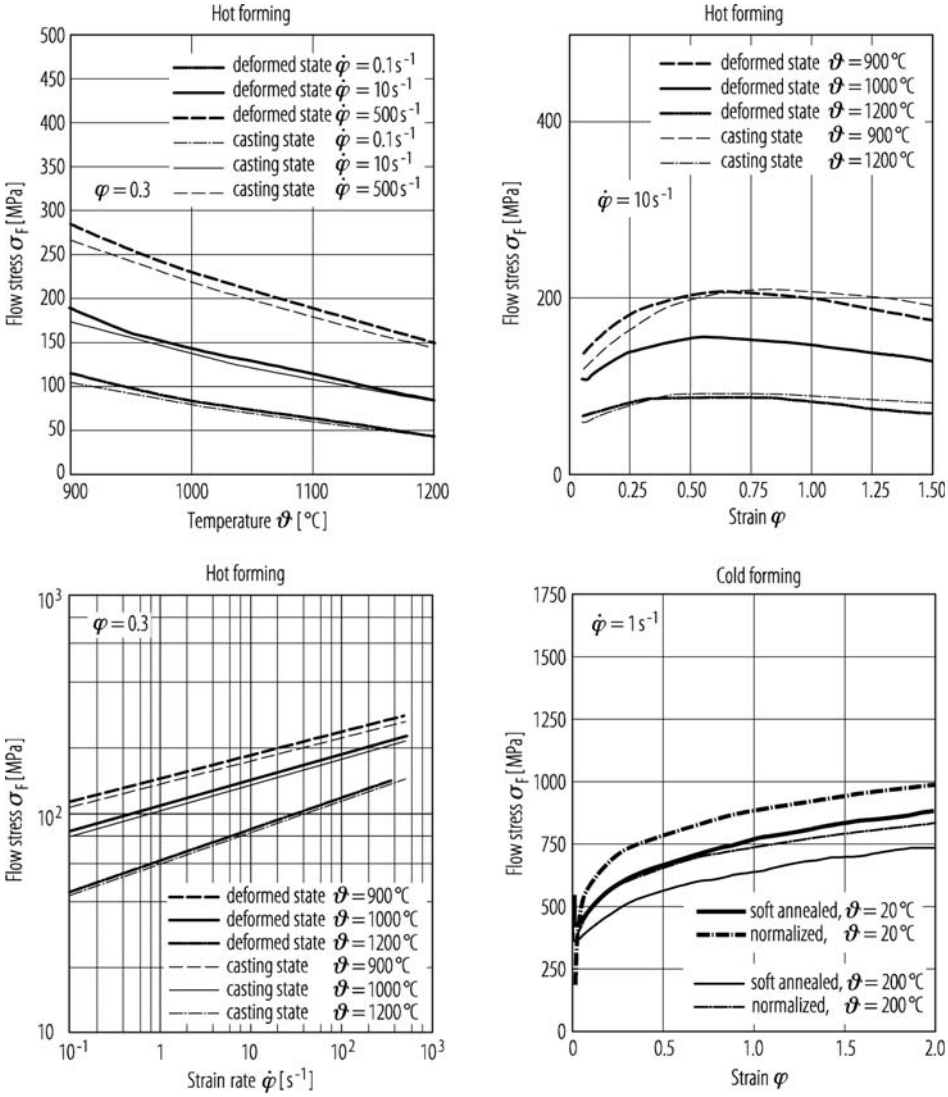
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Flow curves

	Hot deformation		Cold deformation	
	deformed state	casting state	soft annealed	normalized
State of material	austenite	austenite		
σ_{F0} [MPa]	114.76	102.4	505.3	589.9
A	4035.52	3555.08	776.364	905.82
Effect of temperature K_ϑ				
m_1	−0.00272	−0.00257	−0.00097	−0.00102
Effect of strain K_φ				
m_2	0.55288	0.64102	0.20717	0.15922
m_4	0.02688	0.03303	0.00440	−0.00478
m_5	−0.00074	−0.00070		
m_7	−0.36975	−0.36980		
Effect of strain rate K_φ				
m_3			0.00997	0.01109
m_8	0.000118	0.000118		
Range of validity				
ϑ [°C]	900…1200	900…1200	20…300	20…300
φ	0.04…1.50	0.04…1.50	0.04…2.00	0.04…2.00
$\dot{\varphi}$ [s^{-1}]	<500	<500	<500	<500

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Fig. 5.267.
16Mo3. Flow stress curves by hot and cold forming.

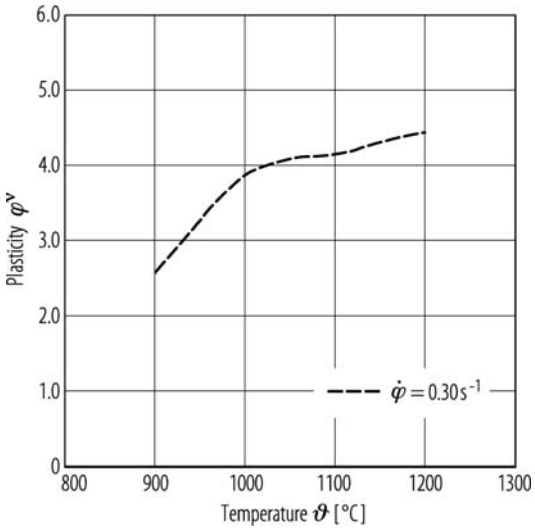


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Fig. 5.268.

16Mo3. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.60…0.95.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	46.71	472.91	11.28	7848.2	211.6
100	46.06	486.33	11.67	7820.7	203.1
200	45.59	499.21	12.32	7790.2	197.5
300	43.47	519.18	12.85	7757.4	193.7
400	40.7	543.45	13.37	7722.3	188.6
500	37.67	570.3	13.9	7684.7	180.2
600	34.63	599.31	14.42	7644.5	167.0
700	31.66	630.23	14.96	7601.6	148.4
800	23.92	694.10	12.29	7616.7	124.9
900	26.32	691.61	13.16	7569.3	107.2
1000	27.76	689.12	13.94	7519.9	83.4
1100	28.84	686.65	14.65	7468.7	63.9
1200	30.00	684.18	15.31	7415.7	54.2

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Steel symbol/number: 22MnB5/1.5528

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.19…0.25	0.00…0.40	1.10…1.40	0.000…0.025	0.000…0.015	0.15…0.35
Al	B	Ti			
0.020…0.060	0.0008… 0.0050	0.02…0.05			

International comparison of standards

ISO		Euronorm	
United Kingdom		Russia	
Japan		China	
		~ A 70204	T 6478 (2001)
		~ ML20B	T 6478 (2001)
USA			
ASTM	AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

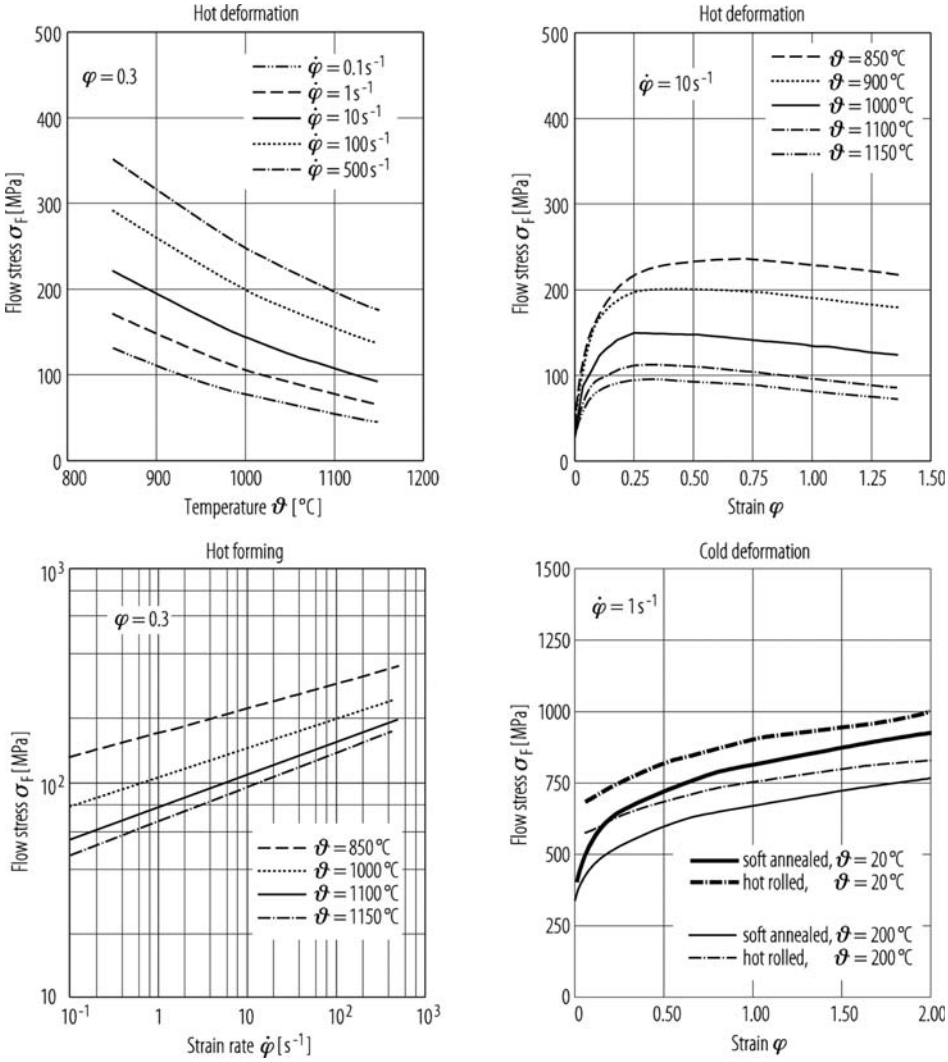
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformde state	soft annealed	hot rolled
	austenite		
σ_{F0} [MPa]	114.21	572.2	716.3
A	3899.05	841.168	909.450
Effect of temperature K_ϑ			
m_1	−0.00287	−0.00112	−0.00101
Effect of strain K_φ			
m_2	0.34485	0.17546	0.14536
m_4	−0.00723	0.00116	0.00889
m_5	−0.00119		
m_7	0.03845		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01271	0.01184
m_8	0.000137		
Range of validity			
ϑ [°C]	850…1150	20…300	20…250
φ	0.04…1.40	0.04…2.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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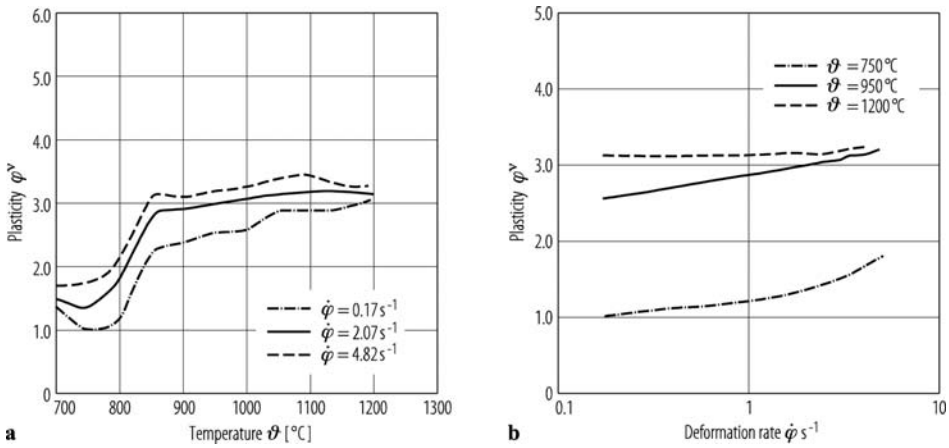
Fig. 5.269.
22MnB5. Flow stress curves by hot and cold forming.



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Fig. 5.270.
22MnB5. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	46.71	475.63	11.14	7848.2	211.6
100	46.06	487.67	11.67	7820.7	203.1
200	45.59	499.21	12.32	7790.2	197.5
300	43.47	519.18	12.85	7757.4	193.7
400	40.7	543.45	13.37	7722.3	188.6
500	37.67	570.3	13.9	7684.7	180.2
600	34.63	599.31	14.42	7644.5	167.0
700	31.66	630.23	14.96	7601.6	148.4
800	23.92	694.10	12.29	7616.7	124.9
900	26.32	691.61	13.16	7569.3	107.2
1000	27.76	689.12	13.94	7519.9	83.4
1100	28.84	686.65	14.65	7468.7	63.9
1200	30.00	684.18	15.31	7415.7	54.2

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Steel symbol/number: X8Ni9/1.5662

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Mo
0.00…0.10	0.00…0.35	0.30…0.80	0.000…0.020	0.000…0.010	0.00…0.10
Ni	V	Cr+Cu+Mo			
8.50…10.00	0.00…0.05	< 0.50			

International comparison of standards

ISO		Euronorm		
~ X8Ni9	9328–3 (1991)	X8Ni9	10028-4 (06/2003)	
~ X10Ni9	9329–3 (1997)	X8Ni9	10269 (08/1999)	
United Kingdom		Russia		
X8Ni9	EN 10028–4 (06/2003)	~ 55S2	14959 (1979)	
X8Ni9	EN 10269 (08/1999)			
Japan		China		
~ SL9N520	G 3127 (2000)			
~ SL9N590	G 3127 (2000)			
USA				
ASTM		AISI	SAE	UNS
~ A 333 (8)	A 333 (99)			~ K71340
~ A 353	A 353 (99)			~ K81340

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

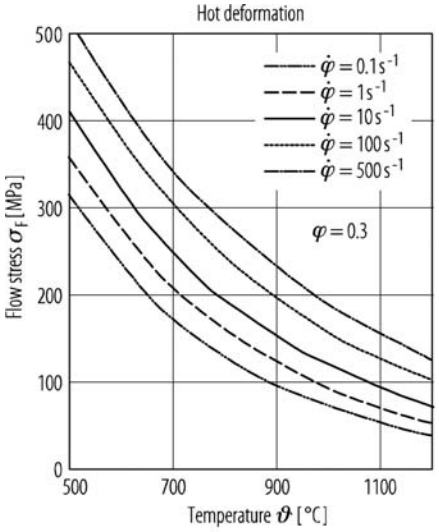
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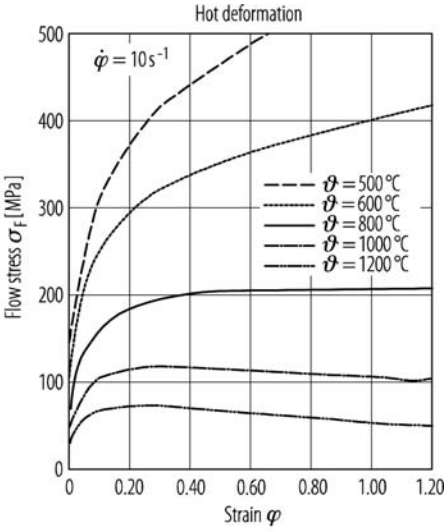
Flow curves

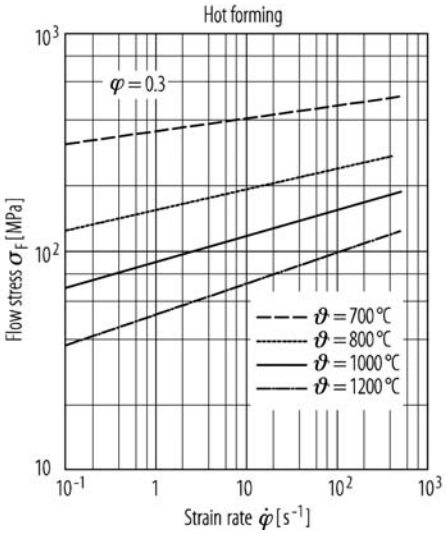
State of material	Hot deformation deformed state austenite	Cold deformation
σ_{F0} [MPa]	108.49	
A	1858.305	
Effect of temperature K_ϑ		
m_1	−0.00224	
Effect of strain K_φ		
m_2	0.33786	
m_4	0.00012	
m_5	−0.00198	
m_7	0.46653	
Effect of strain rate $K_{\dot\varphi}$		
m_3		
m_8	0.000117	
Range of validity		
ϑ [°C]	500…1200	
φ	0.04…1.20	
$\dot\varphi$ [s^{-1}]	<500	

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Fig. 5.271.
X8Ni9. Flow stress curves by hot forming.



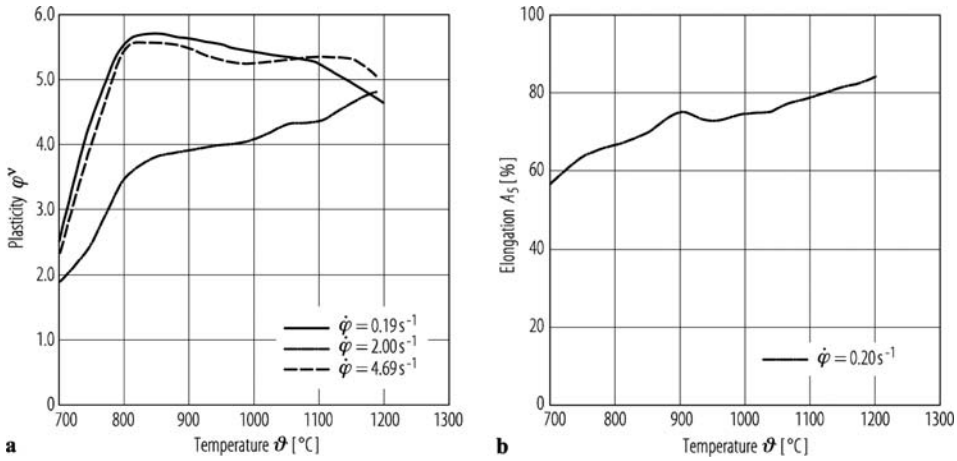




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Fig. 5.272.
X8Ni9. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	33.89	493.31	11.04	7946.5	196.9
100	34.80	500.10	11.19	7919.9	190.2
200	36.21	508.73	11.38	7892.3	184.9
300	36.27	517.50	11.58	7863.7	180.5
400	35.7	526.43	11.78	7834.2	174.8
500	34.69	535.51	11.99	7803.6	166.4
600	33.49	544.74	12.20	7772.1	154.5
700	32.17	554.14	12.41	7739.5	138.9
800	26.22	563.69	12.62	7705.8	119.8
900	27.38	573.42	12.84	7671.0	98.3
1000	28.19	583.31	13.06	7635.1	76.1
1100	29.02	593.37	13.29	7598.0	61.4
1200	30.07	603.60	13.52	7559.7	49.5

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Steel symbol/number: 16NiCr4/1.5714

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.13…0.19	0.00…0.40	0.70…1.00	0.000…0.035	0.000…0.035	0.60…1.00
Ni					
0.80…1.10					

International comparison of standards

ISO		Euronorm		
		16NiCr4	10084 (04/1998)	
United Kingdom		Russia		
16NiCr4	EN 10084 (04/1998)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

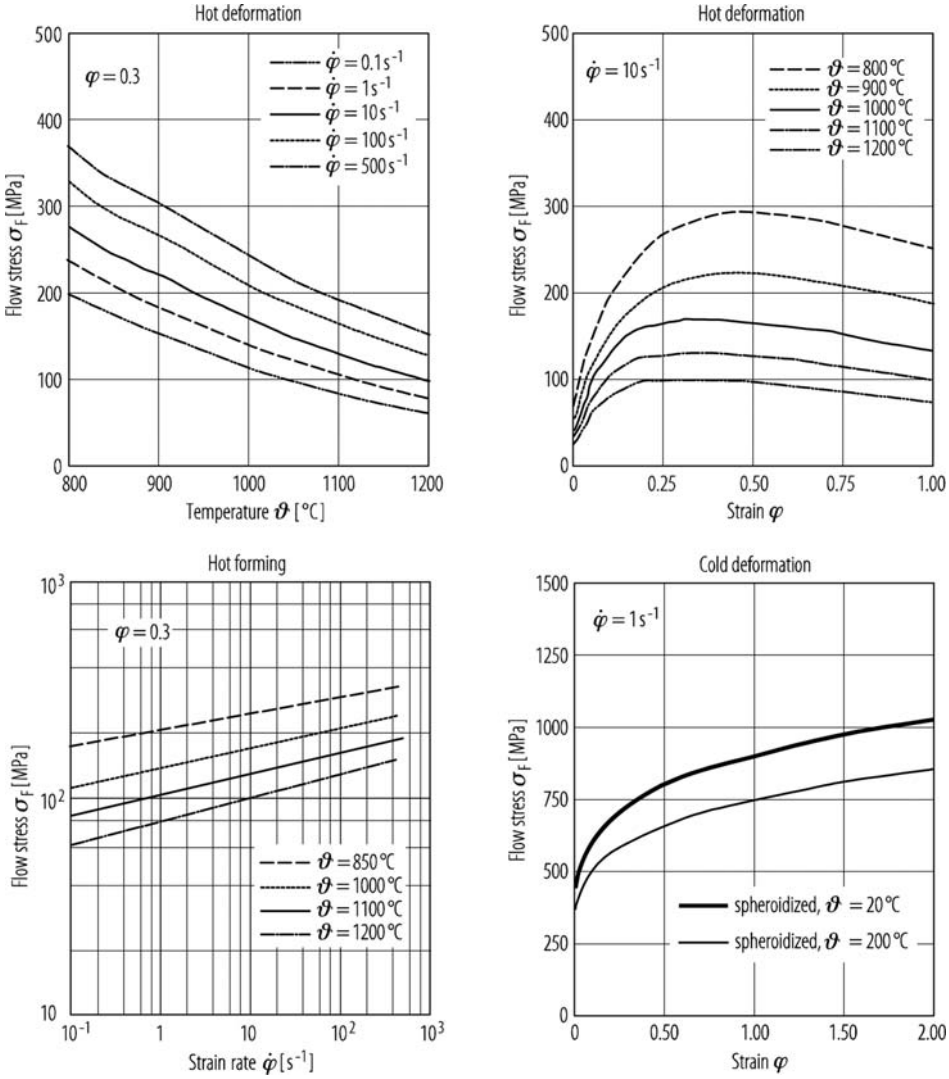
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation spheroidized
σ_{F0} [MPa]	118.14	620.1
A	5454.64	923.884
Effect of temperature K_ϑ		
m_1	−0.00262	−0.00107
Effect of strain K_φ		
m_2	0.56466	0.17923
m_4	0.00271	0.00122
m_5	−0.00078	
m_7	−0.72153	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01007
m_8	0.000090	
Range of validity		
ϑ [°C]	800…1200	20…300
φ	0.04…1.0	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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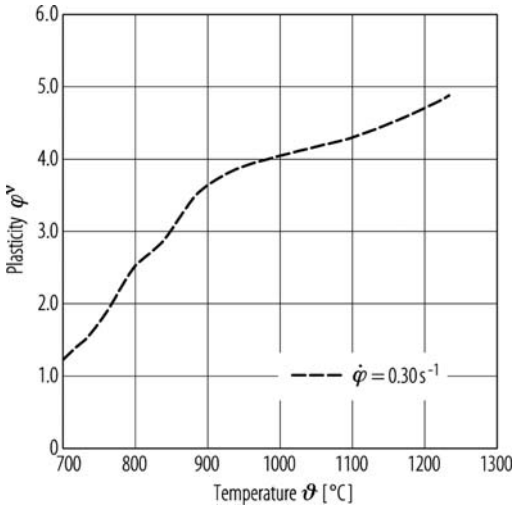
Fig. 5.273.
16NiCr4. Flow stress curves by hot and cold forming.



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Fig. 5.274.
16NiCr4. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.55…0.90.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	41.84	474.61	10.91	7835.2	
100	43.28	489.04	11.35	7808.6	
200	43.15	501.31	12.07	7778.5	
300	41.25	521.40	12.62	7746.2	
400	38.7	545.81	13.15	7711.6	
500	35.81	572.8	13.7	7674.6	
600	32.93	601.95	14.20	7635.0	
700	30.13	633.02	14.74	7592.7	
800	23.53	696.40	12.91	7592.5	
900	26.15	693.90	13.90	7541.1	
1000	27.81	691.40	14.79	7487.5	
1100	29.09	688.92	15.61	7431.7	
1200	30.42	686.44	16.35	7374.0	

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Steel symbol/number: 15NiCr13/1.5752

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.14…0.20	0.00…0.40	0.40…0.70	0.000…0.035	0.000…0.035	0.60…0.90
Ni					
3.00…3.50					

International comparison of standards

ISO		Euronorm		
~ 15NiCr13	683–11 (1987)	15NiCr13	10277–4 (07/1999)	
		15NiCr13	10084 (04/1998)	
United Kingdom		Russia		
15NiCr13	EN 10277–4 (07/1999)			
15NiCr13	EN 10084 (04/1998)			
Japan		China		
~ SNC 815 H	G 4052 (1979)			
USA				
ASTM		AISI	SAE	UNS
~ A 506 (E3310)	A 506–00	~ E 9315	~ 9315	~ G93150
~ A 507 (E 3310)	A 507–00	~ E 3316	~ 3310	~ G33106

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

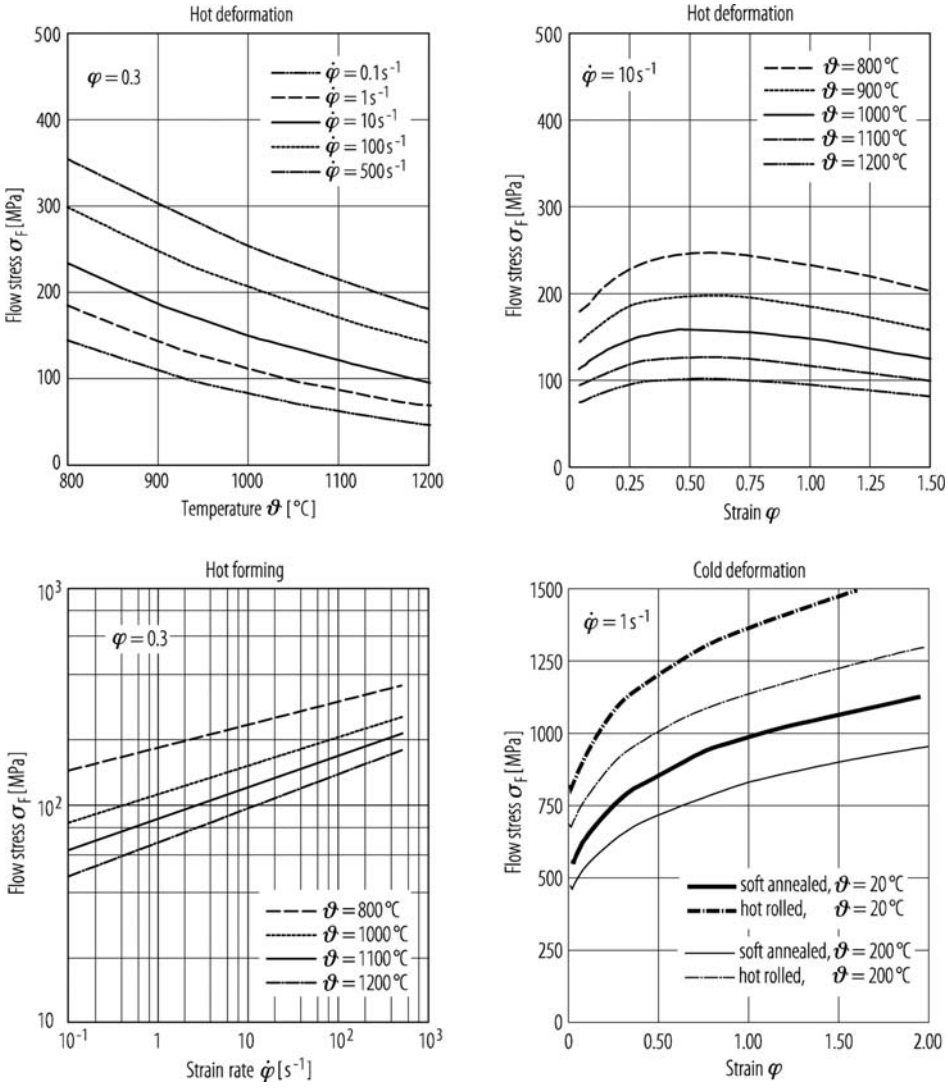
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	hot rolled
	austenite		
σ_{F0} [MPa]	125.99	648.2	948.5
A	2380.95	997.415	1390.697
Effect of temperature K_ϑ			
m_1	−0.00245	−0.00098	−0.00102
Effect of strain K_φ			
m_2	0.37389	0.21042	0.18618
m_4	0.01385	0.00471	0.00392
m_5	−0.0002		
m_7	−0.51485		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01131	0.01182
m_8	0.000132		
Range of validity			
ϑ [°C]	800…1200	20…300	20…160
φ	0.04…1.50	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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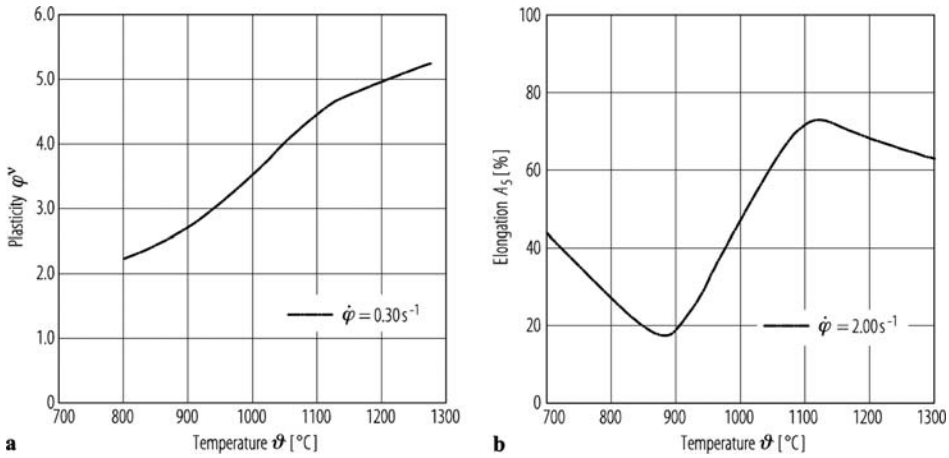
Fig. 5.275.
15NiCr13. Flow stress curves by hot and cold forming.



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Fig. 5.276.
15NiCr13. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	35.54	476.42	10.51	7861.8	
100	35.88	489.81	10.98	7835.9	
200	37.23	503.59	11.76	7806.3	
300	37.27	523.83	12.33	7774.5	
400	36.6	548.40	12.86	7740.5	
500	35.62	575.6	13.4	7704.0	
600	34.39	604.88	13.90	7665.1	
700	33.03	636.13	14.44	7623.4	
800	25.16	698.66	14.17	7594.5	
900	26.61	696.15	15.34	7536.1	
1000	27.68	693.65	16.40	7475.0	
1100	28.72	691.15	17.36	7411.3	
1200	29.96	688.67	18.25	7345.3	

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Steel symbol/number: 17NiCr6–6/1.5918

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.14…0.20	0.00…0.40	0.50…0.90	0.000…0.035	0.000…0.035	1.40…1.70
Ni					
1.40…1.70					

International comparison of standards

ISO		Euronorm		
		17NiCr6–6	10263–3 (06/2001)	
		17NiCr6–6	10084 (04/1998)	
United Kingdom		Russia		
17NiCr6–6	EN 10263–3 (06/2001)			
17NiCr6–6	EN 10084 (04/1998)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

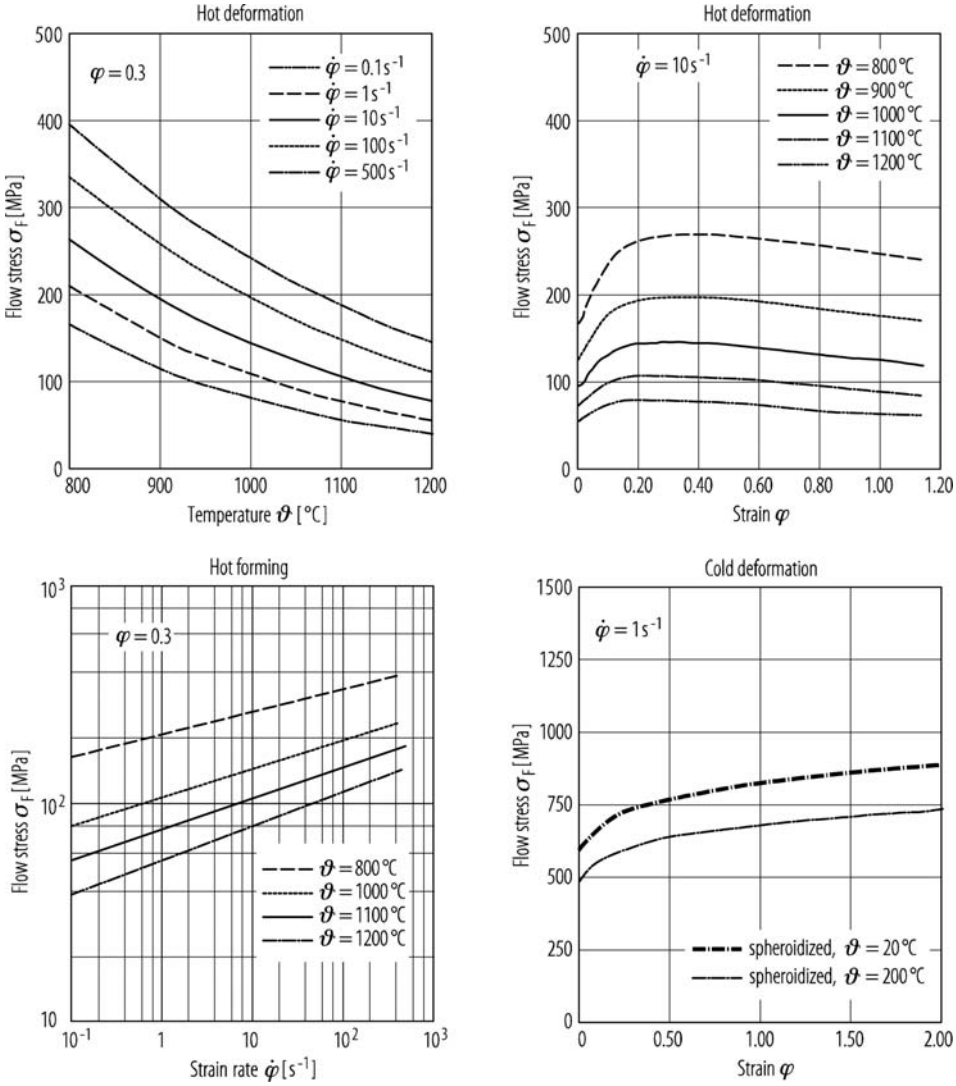
DOI: 10.1007/978-3-540-44760-3_150
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Flow curves

State of material	Hot deformation	Cold deformation
	deformed state	spheroidized
	austenite	
σ_{F0} [MPa]	125.71	680.1
A	4421.89	843.077
Effect of temperature K_ϑ		
m_1	−0.00308	−0.00109
Effect of strain K_φ		
m_2	0.31330	0.09923
m_4	0.00427	0.00122
m_5	−0.00085	
m_7	−0.17674	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01007
m_8	0.000129	
Range of validity		
ϑ [°C]	800…1200	20…300
φ	0.04…1.20	0.04…2.0
$\dot\varphi$ [s^{-1}]	<500	<500

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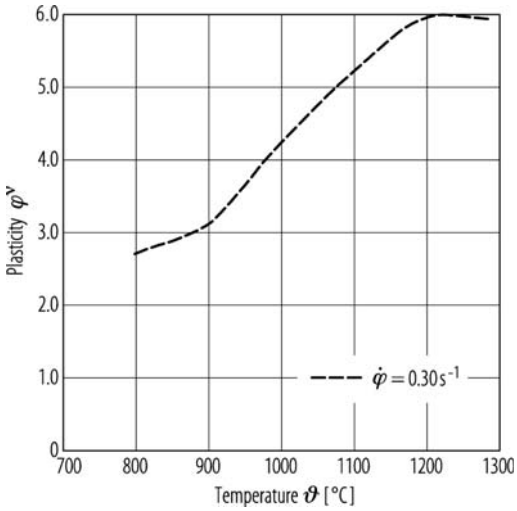
Fig. 5.277.
17NiCr6–6. Flow stress curves by hot and cold forming.



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Fig. 5.278.
17NiCr6–6. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.85.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	37.06	475.93	10.63	7836.4	
100	36.84	489.61	11.09	7810.3	
200	38.16	502.90	11.86	7780.6	
300	38.17	523.10	12.42	7748.7	
400	37.5	547.61	12.95	7714.6	
500	36.46	574.7	13.5	7678.0	
600	35.19	603.99	14.00	7638.9	
700	33.79	635.18	14.54	7597.2	
800	24.70	698.00	13.71	7578.5	
900	26.41	695.50	14.83	7522.6	
1000	27.71	693.00	15.83	7464.2	
1100	28.97	690.51	16.74	7403.4	
1200	30.40	688.03	17.58	7340.4	

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Steel symbol/number: X2NiCoMo18–9–5/1.6358

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Mo
0.00…0.03	0.00…0.10	0.00…0.10	0.000…0.010	0.000…0.010	4.50…5.50
Ni	Al	Co	Ti		
17.00…19.00	0.0500… 0.1500	8.00…10.00	0.50…0.80		

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
Japan		China		
USA				
ASTM		AMS	Spec	UNS
∼ A 579 (73)	A 579–01	∼ 6501C	∼ Marage 250	∼ K92890
∼ A 646 (19) (Marage 250)	A 646–99	∼ 6514D	∼ Marage 300	∼ K93120

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

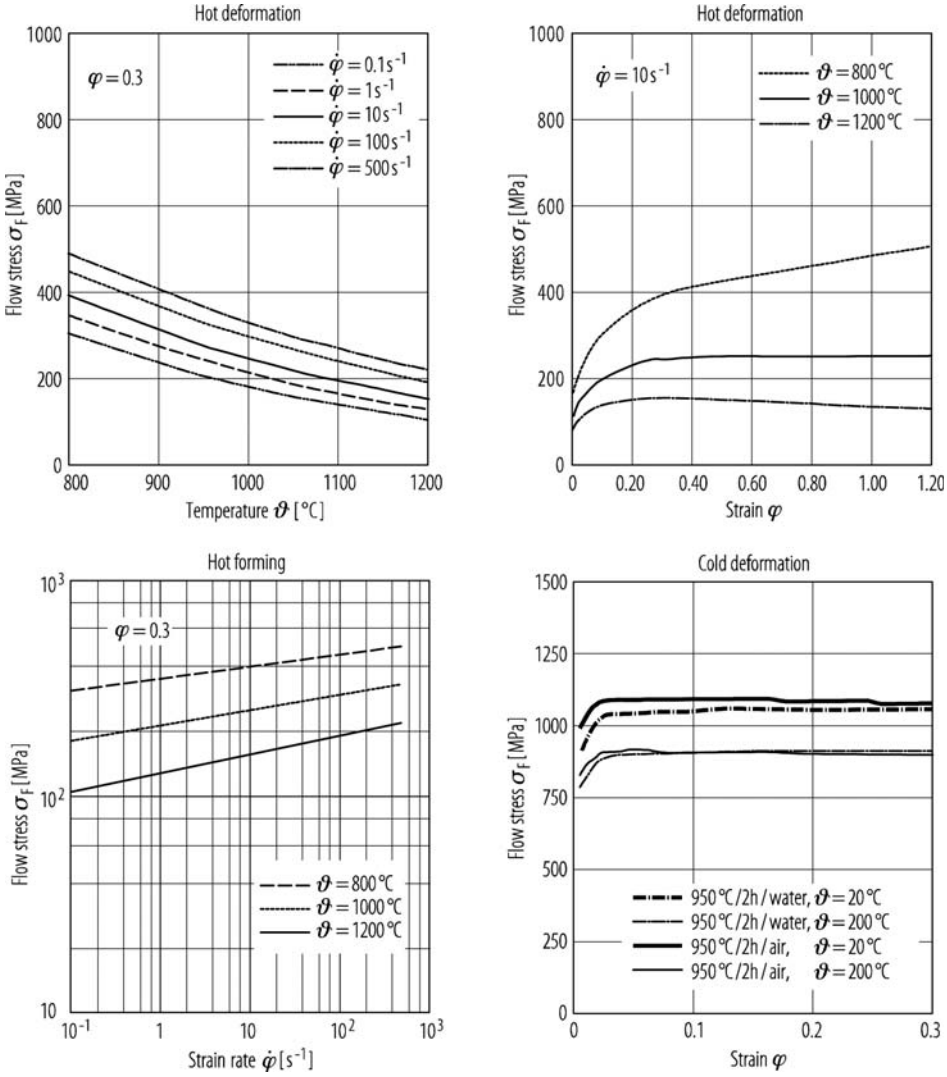
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	950°C/water	950°C/air
	austenite		
σ_{F0} [MPa]	214.73	1062.0	1108.4
A	3492.9	1065.33	1081.47
Effect of temperature K_ϑ			
m_1	−0.00193	−0.00084	−0.00102
Effect of strain K_φ			
m_2	0.38164	−0.00555	−0.01641
m_4	0.00263	−0.00106	−0.00092
m_5	−0.00251		
m_7	0.68227		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.00496	0.00707
m_8	0.000071		
Range of validity			
ϑ [°C]	800…1200	20…200	20…210
φ	0.04…1.20	0.03…0.30	0.03…0.25
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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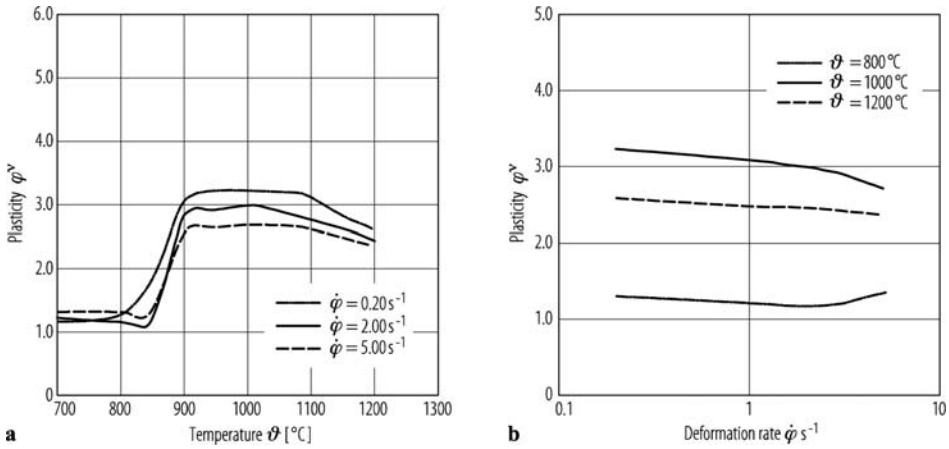
Fig. 5.279.
X2NiCoMo18–9–5. Flow stress curves by hot and cold forming.



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Fig. 5.280.
X2NiCoMo18–9–5. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Austenitised at 1200 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	14.04	493.31	16.50	8259.1	
100	18.28	500.10	16.73	8217.6	
200	19.52	508.73	17.31	8173.3	
300	20.74	517.50	17.02	8132.6	
400	21.98	526.43	17.02	8090.4	
500	23.28	535.51	17.92	8037.1	
600	24.63	544.74	18.23	7988.1	
700	26.05	554.14	18.54	7937.4	
800	27.54	563.69	18.87	7885.1	
900	29.10	573.42	19.19	7831.1	
1000	30.75	583.31	19.53	7775.3	
1100	32.49	593.37	19.86	7717.7	
1200	34.31	603.60	20.21	7658.2	

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Steel symbol/number: 15NiCuMoNb5/1.6368

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.17	0.25…0.50	0.80…1.20	0.000…0.025	0.000…0.010	0.00…0.30
Mo	Ni	Al	Cu	Nb	
0.25…0.50	1.00…1.30	> 0.0150	0.50…0.80	0.015…0.045	

International comparison of standards

ISO		Euronorm		
		15NiCuMoNb5–6–4	10028–2 (06/2003)	
		15NiCuMoNb5–6–4	10216–2 (05/2002)	
United Kingdom		Russia		
15NiCuMoNb5–6–4	EN 10028–2 (06/2003)			
15NiCuMoNb5–6–4	EN 10216–2 (05/2002)			
Japan		China		
~ SBV 2	G 3119 (1987)			
~ SBV 3	G 3119 (1987)			
USA				
ASTM		AISI	SAE	UNS
~ A 302 (C)	A 302–97			~ K12039
~ A 508 (3)	A 508–99			~ K12042

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

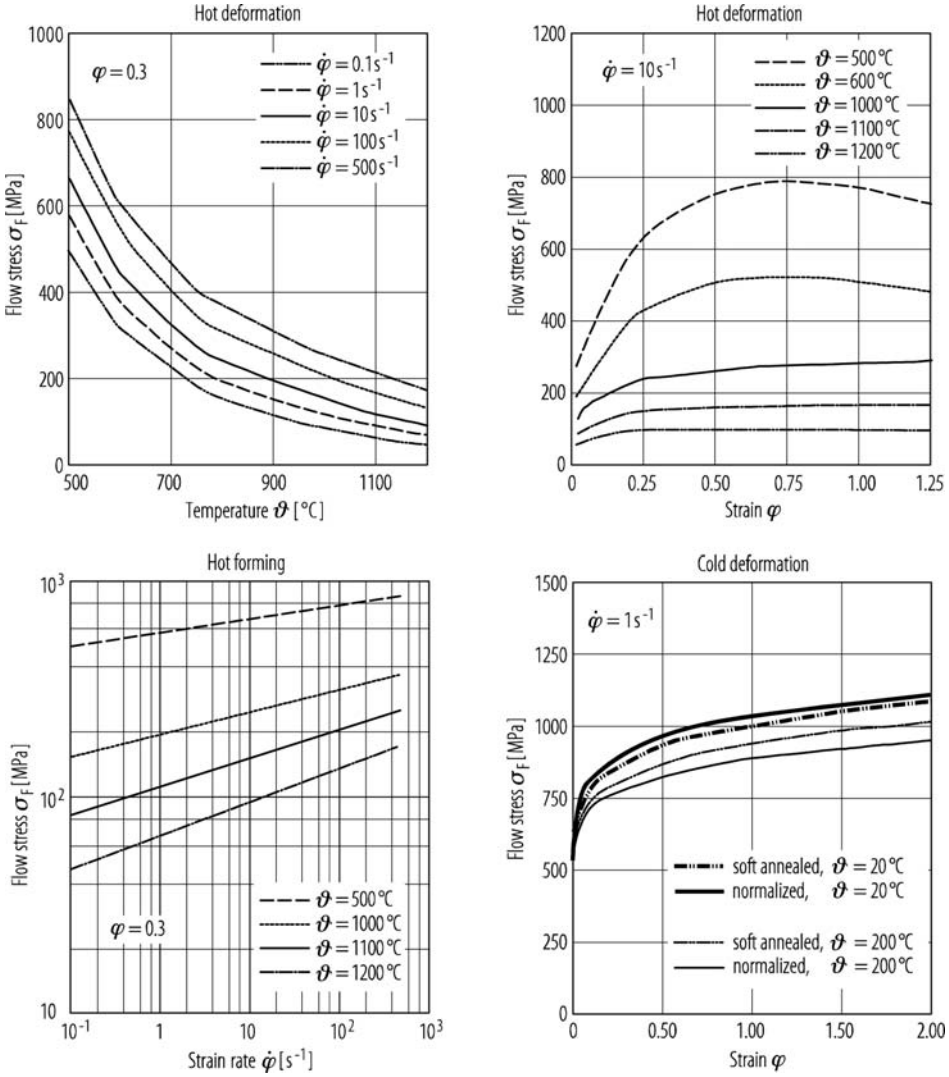
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Flow curves

	Hot deformation		Cold deformation	
	deformed state		soft annealed	normalized
State of material	austenite	ferrite+Fe_3C		
σ_{F0} [MPa]	122.49	(80.51)	786.9	834.5
A	2364.99	11372.92	1013.275	1047.62
Effect of temperature K_ϑ				
m_1	−0.00245	−0.00410	−0.00042	−0.00084
Effect of strain K_φ				
m_2	0.32659	0.49128	0.11154	0.09723
m_4	0.00176	0.01039	0.00003	0.00003
m_5	−0.00088	−0.00051		
m_7	0.08462	−0.62465		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.00525	0.00564
m_8	0.000130	0.000125		
Range of validity				
ϑ [°C]	750…1200	500…700	20…320	20…320
φ	0.04…1.25	0.04…1.25	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<70	<70

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Fig. 5.281.
15NiCuMoNb5. Flow stress curves by hot and cold forming.

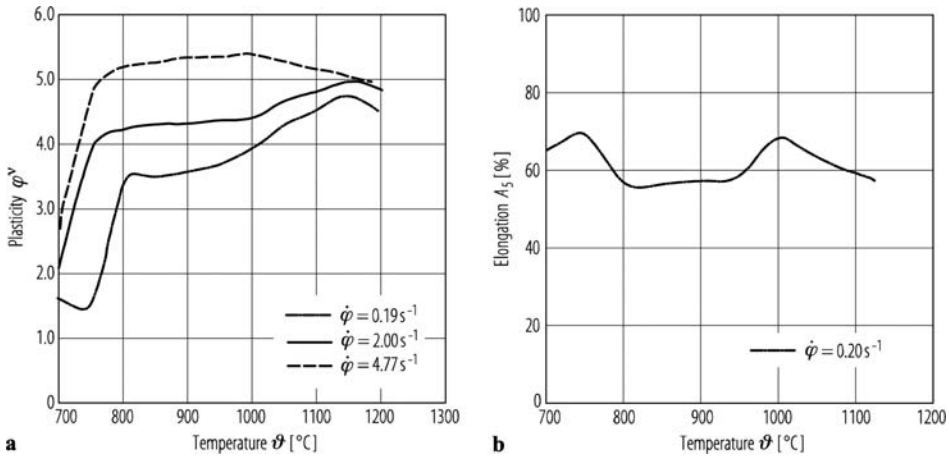


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Fig. 5.282.

15NiCuMoNb5. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	38.70	475.33	10.76	7856.6	212.5
100	37.86	488.95	11.21	7830.1	201.8
200	39.13	502.16	11.96	7800.2	195.6
300	39.11	522.31	12.52	7768.0	192.4
400	38.4	546.77	13.04	7733.6	188.2
500	37.34	573.9	13.6	7696.7	180.1
600	36.03	603.04	14.09	7657.3	166.6
700	34.60	634.18	14.63	7615.1	147.4
800	24.67	697.28	13.30	7605.8	123.5
900	26.68	694.77	14.36	7552.0	97.1
1000	28.26	692.27	15.30	7495.9	71.7
1100	29.76	689.79	16.16	7437.5	52.1
1200	31.43	687.31	16.96	7376.9	44.2

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: 30NiCrMo2–2/1.6545

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.27…0.34	0.15…0.40	0.70…1.00	0.000…0.035	0.000…0.035	0.40…0.60
Mo	Ni				
0.15…0.30	0.40…0.70				

International comparison of standards

ISO		Euronorm		
		~ 30 NiCrMo2 KD	119–3 (1974)	
United Kingdom		Russia		
Japan		China		
USA				
ASTM		AISI	SAE	UNS
~ A 304 (8630H)	A 304–02	~ 8632	~ 8630	~ H86300
~ A 322 (8630)	A 322–01	~ 8785	~ 8632	~ J13049

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

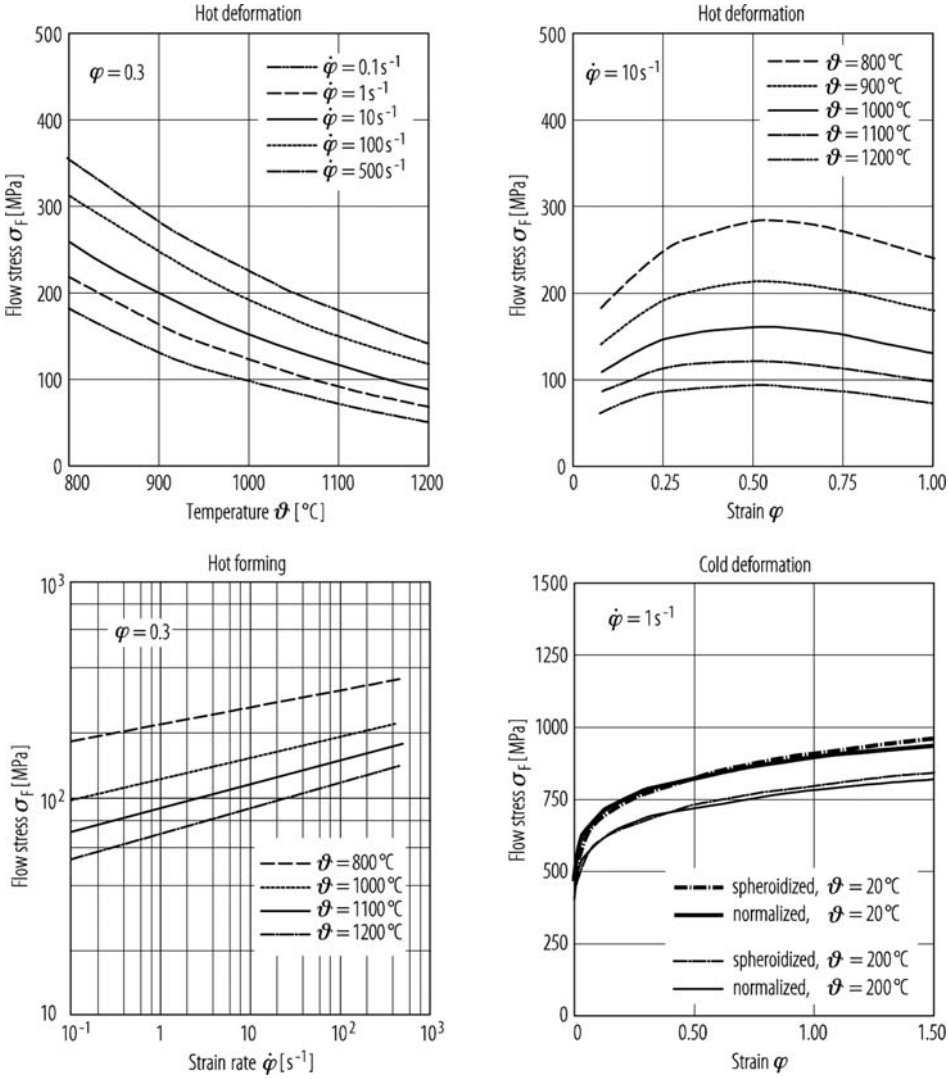
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	spherodized	normalized
	austenite		
σ_{F0} [MPa]	116.90	673.2	681.0
A	8506.11	922.51	910.77
Effect of temperature K_ϑ			
m_1	−0.00272	−0.00074	−0.00074
m_2	0.99557	0.12731	0.11296
m_4	0.06916	0.00001	−0.00003
m_5	−0.00075		
m_7	−1.22868		
Effect of strain rate K_φ			
m_3		−0.00318	−0.00681
m_8	0.000099		
Range of validity			
ϑ [°C]	800…1200	20…320	20…320
φ	0.04…1.0	0.04…1.50	0.04…1.50
$\dot{\varphi}$ [s^{-1}]	<500	<500	<500

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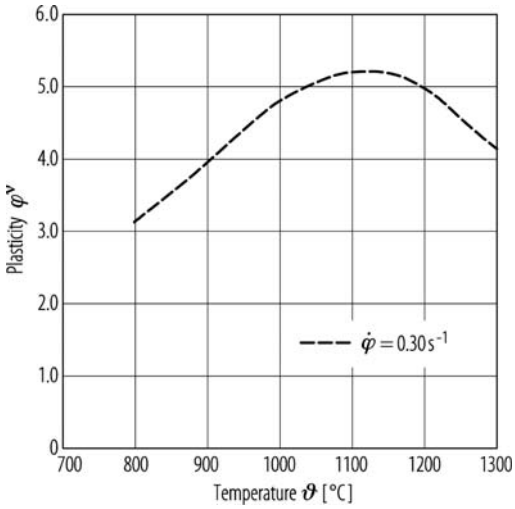
Fig. 5.283.
30NiCrMo2–2. Flow stress curves by hot and cold forming.



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Fig. 5.284.
30NiCrMo2–2. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.80.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	53.05	474.9	10.93	7842.8	
100	47.23	487.4	11.37	7816.1	
200	45.83	501.2	12.09	7789.4	
300	42.75	521.3	12.64	7753.6	
400	39.10	545.7	13.16	7719.0	
500	35.36	572.7	13.68	7681.9	
600	31.73	601.8	14.21	7642.2	
700	28.33	632.9	14.75	7599.9	
800	23.52	696.3	12.86	7600.7	
900	25.25	693.8	13.85	7549.6	
1000	26.61	691.3	14.73	7496.2	
1100	27.90	688.8	15.54	7440.7	
1200	29.34	686.3	16.28	7383.2	

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: GS–34CrNiMo6/1.6582

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.30…0.37	0.00…0.60	0.60…1.00	0.000…0.020	0.000…0.015	1.40…1.70
Mo	Ni				
0.20…0.30	1.40…1.70				

International comparison of standards

ISO		Euronorm		
~ 36 CrNiMo6	683–18 (1996)	34CrNiMo6	10263–4 (06/2001)	
~ 36 CrNiMo6	683–1 (1987)	34CrNiMo6	10277–5 (07/1999)	
United Kingdom		Russia		
34CrNiMo6	EN 10263–4 (06/2001)	~38Ch2N2MA	4543 (1971)	
34CrNiMo6	EN 10277–5 (07/1999)			
Japan		China		
USA				
ASTM		AMS	SAE	UNS
~ A 322 (4340)	A 322–01	~ 6359F	~ 4340	~ G43400
~ A 646 (7) (4340)	A 646–99			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

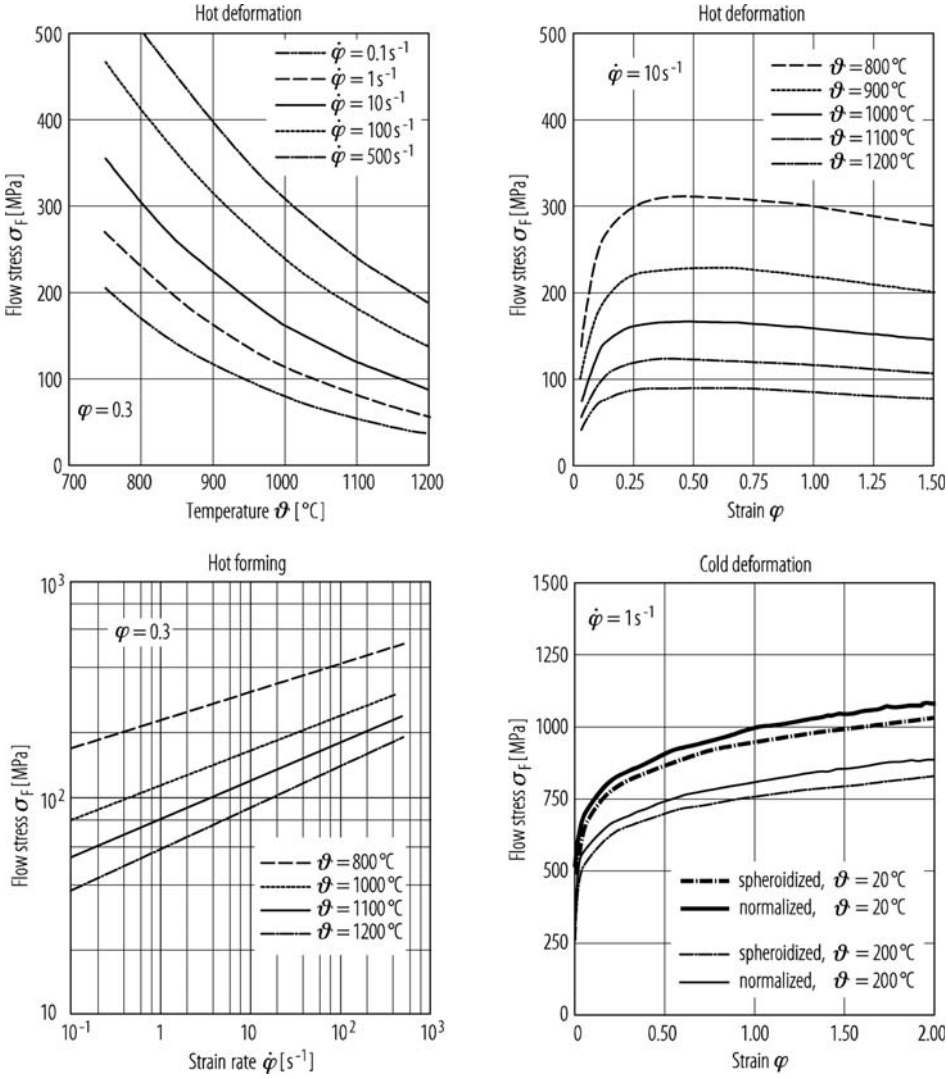
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	spheroidized	normalized
	austenite		
σ_{F0} [MPa]	129.62	719.9	752.60
A	4490.40	974.28	1009.68
Effect of temperature K_ϑ			
m_1	−0.00343	−0.00126	−0.00110
Effect of strain K_φ			
m_2	0.03774	0.11869	0.12815
m_4	−0.03690	−0.00299	−0.00002
m_5	−0.00011		
m_7	−0.17115		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01121	0.01017
m_8	0.000160		
Range of validity			
ϑ [°C]	750…1200	20 … 300°C	20 … 300°C
φ	0.04…1.50	0.03 … 2.00	0.03 … 2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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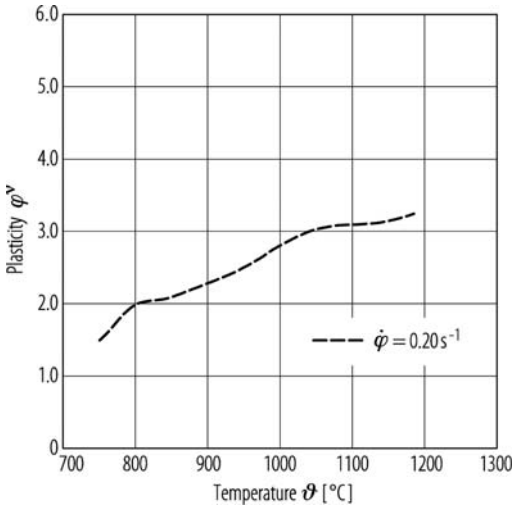
Fig. 5.285.
GS–34CrNiMo6. Flow stress curves by hot and cold forming.



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Fig. 5.286.
GS–34CrNiMo6. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.80.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	34.10	476.91	10.39	7826.7	
100	34.94	490.43	10.87	7801.2	
200	36.34	504.26	11.67	7772.0	
300	36.40	524.54	12.24	7740.5	
400	35.8	549.15	12.77	7706.8	
500	34.80	576.4	13.3	7670.8	
600	33.60	605.73	13.81	7632.2	
700	32.28	637.03	14.34	7591.0	
800	26.05	699.26	14.67	7551.3	
900	27.25	696.75	15.91	7490.6	
1000	28.09	694.25	17.02	7427.0	
1100	28.95	691.75	18.04	7360.7	
1200	30.02	689.27	18.98	7292.0	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

DOI: 10.1007/978-3-540-44760-3_154
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Steel symbol/number: 18CrNiMo7–6/1.6587

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.12…0.18	0.15…0.40	0.40…0.60	0.000…0.035	0.000…0.035	0.000…0.020
Cu	Cr	Ni	Mo		
0.00…0.30	1.50…1.80	1.40…1.70	0.25…0.35		

International comparison of standards

ISO		Euronorm		
		15 Cr 2 KD	119–3 (1974)	
United Kingdom		Russia		
523 M 15	970 Part 1 (1976)			
523 M 15	PD 970 (2001)			
Japan		China		
~ SCr 415 H	G 4052 (1979)			
USA				
ASTM		AISI	SAE	UNS
~ A 331 (5015)	A 331–00	~ 5015	~ 5015	~ G50150
~ A 711 (5015)	A 711–01			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

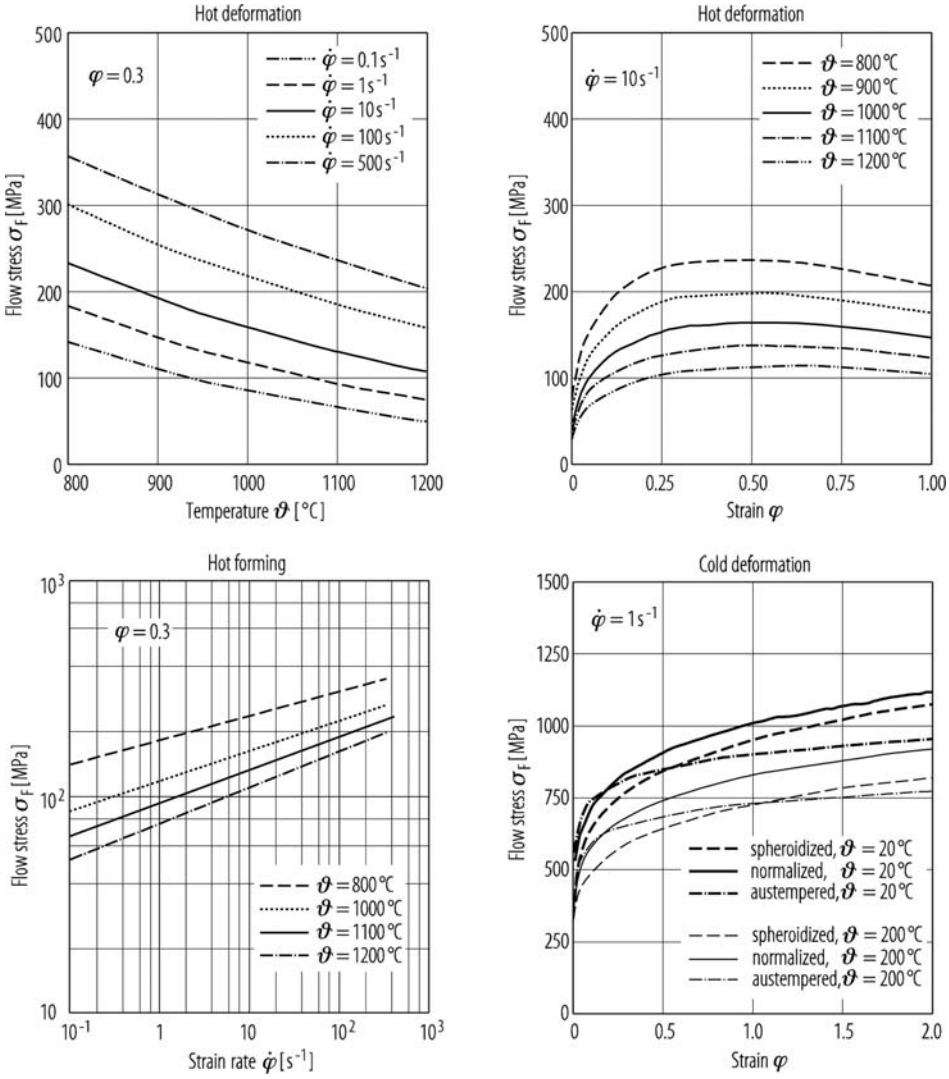
DOI: 10.1007/978-3-540-44760-3_155
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Flow curves

State of material	Hot deformation	Cold deformation		
	deformed state	spheroidized	normalized	austempered
	austenite			
σ_{F0} [MPa]	124.2	668.3	724.9	731.9
A	2142.86	980.64	1033.79	923.593
Effect of temperature K_ϑ				
m_1	−0.00238	−0.00147	−0.00110	−0.00114
Effect of strain K_φ				
m_2	0.31681	0.16809	0.14811	0.07874
m_4	−0.00048	0.00010	−0.00134	−0.00352
m_5	0.00057			
m_7	−1.00839			
Effect of strain rate $K_{\dot\varphi}$				
m_3		0.01407	0.00933	0.00290
m_8	0.000136			
Range of validity				
ϑ [°C]	800…1200	20…210	20…200	20…200
φ	0.04…1.00	0.03…2.00	0.03…2.00	0.03…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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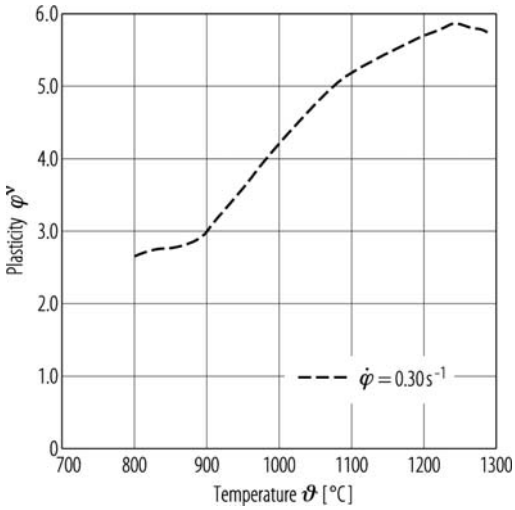
Fig. 5.287.
18CrNiMo7–6. Flow stress curves by hot and cold forming.



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Fig. 5.288.
18CrNiMo7–6. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.85.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	54.05	475.3	10.57	7855.1	
100	46.11	489.6	11.04	7829.1	
200	44.94	503.2	11.81	7803.1	
300	41.97	523.5	12.38	7767.6	
400	38.41	548.0	12.91	7733.4	
500	34.75	575.2	13.43	7696.9	
600	31.20	604.4	13.95	7657.8	
700	27.86	635.6	14.49	7616.1	
800	23.33	698.3	13.93	7592.6	
900	25.10	695.8	15.07	7535.5	
1000	26.49	693.3	16.10	7475.7	
1100	27.81	690.8	17.03	7413.5	
1200	29.28	688.3	17.90	7349.0	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: 17Cr3/1.7016

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.14…0.20	0.00…0.40	0.60…0.90	0.000…0.035	0.000…0.035	0.70…1.00

International comparison of standards

ISO		Euronorm		
~ 16MnCr5	683–11 (1987)	17Cr3	10263–3 (06/2001)	
		17Cr3	10132–2 (02/2000)	
United Kingdom		Russia		
17Cr3	EN 10263–3 (06/2001)	~ 15Ch	4543 (1971)	
17Cr3	EN 10132–2 (02/2000)			
Japan		China		
		~A20152	T 3077 (1999)	
		~ 15Cr	T 3077 (1999)	
USA				
ASTM		AISI	SAE	UNS
~ A 29 (6118)	A 29–99		~ 4615	~ G51170
~ A 322 (5117)	A 322–01		~ 6118	~ G61180

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

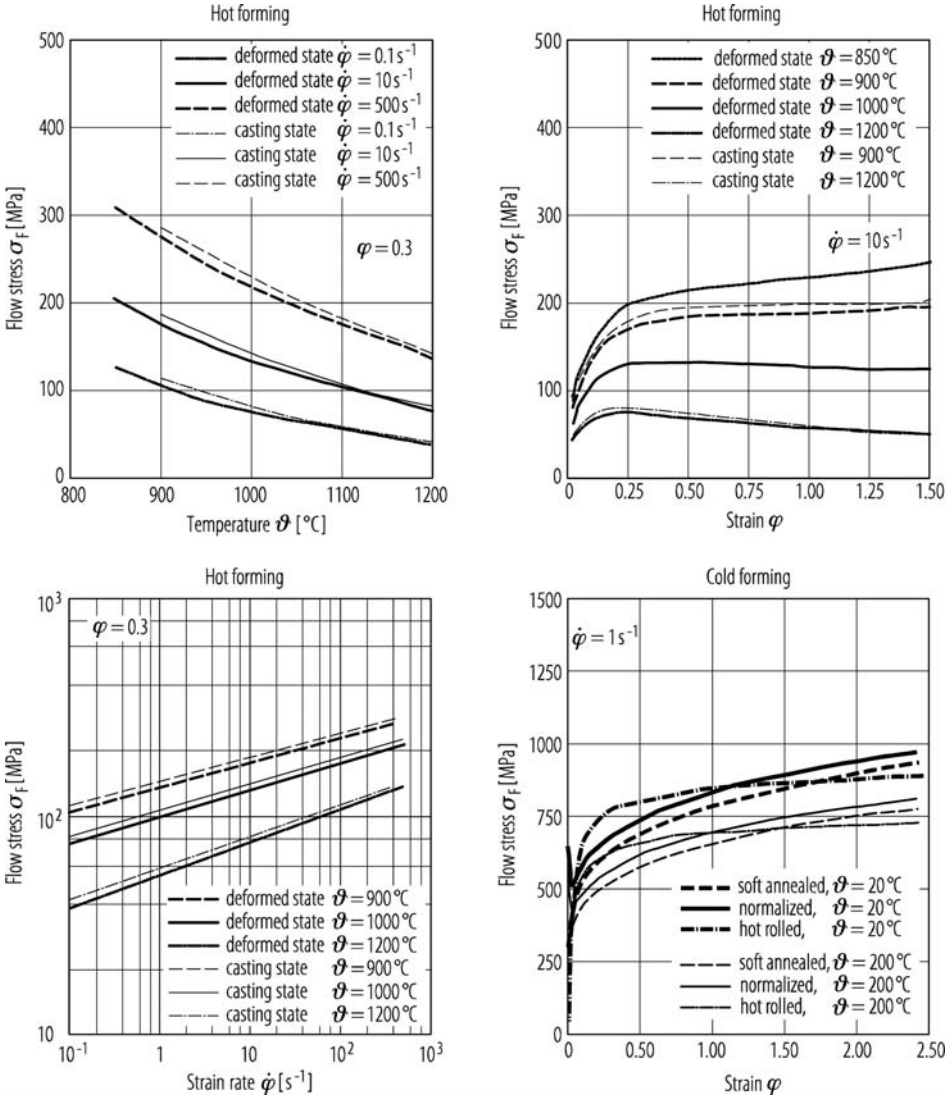
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Flow curves

State of material	Hot deformation		Cold deformation		
	deformed state	casting state	soft annealed	normalized	hot rolled
	austenite	austenite			
σ_{F0} [MPa]	108.74	112.83	527.9	589.7	661.7
A	2961.83	2237.94	804.876	844.381	879.010
Effect of temperature K_ϑ					
m_1	−0.00240	−0.00227	−0.00104	−0.00100	−0.00114
Effect of strain K_φ					
m_2	0.44545	0.39357	0.18604	0.17564	0.04455
m_4	0.00075	0.00688	0.00009	0.00402	−0.01846
m_5	−0.00263	−0.00249			
m_7	0.78719	0.78736			
Effect of strain rate $K_{\dot\varphi}$					
m_3			0.01151	0.01096	0.01129
m_8	0.000124	0.000121			
Range of validity					
ϑ [°C]	850…1250	900…1200	20…300	20…300	20…300
φ	0.04…1.50	0.04…1.50	0.04…2.50	0.04…2.50	0.04…2.50
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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Fig. 5.289.
17Cr3. Flow stress curves by hot and cold forming.

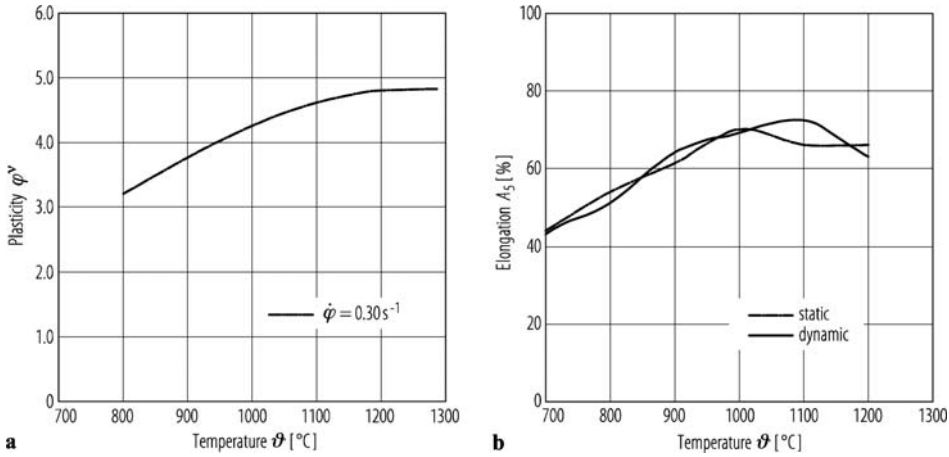


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Fig. 5.290.

17Cr3. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformation rate: 0.2 [s^{-1}]. Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



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Physical properities

Temperature	Thermal conductivity-	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_p [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	45.19	473.46	11.17	7823.8	
100	45.24	486.23	11.58	7796.6	
200	44.88	499.83	12.25	7766.3	
300	42.82	519.83	12.79	7733.8	
400	40.1	544.15	13.31	7698.9	
500	37.13	571.1	13.8	7661.5	
600	34.13	600.09	14.36	7621.6	
700	31.22	631.05	14.90	7579.0	
800	23.78	694.81	12.43	7590.4	
900	26.25	692.31	13.33	7542.1	
1000	27.75	689.82	14.14	7491.8	
1100	28.89	687.34	14.88	7439.6	
1200	30.10	684.87	15.56	7385.6	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

DOI: 10.1007/978-3-540-44760-3_156
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Steel symbol/number: 34Cr4/1.7033

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.30…0.37	0.00…0.40	0.60…0.90	0.000…0.035	0.000…0.035	0.90…1.20

International comparison of standards

ISO		Euronorm		
~ 34Cr4	683–18 (1996)	34Cr4	10263–4 (06/2001)	
~ 34Cr4E	4954 (1993)	34Cr4	10250–3 (10/1999)	
United Kingdom		Russia		
34Cr4	EN 10263–4 (06/2001)	~ 35Ch	GOST 4543 (1971)	
34Cr4	EN 10250–3 (10/1999)			
Japan		China		
~ SCr 430 H	G 4052 (1979)	~A20352	T 3077 (1999)	
		~ 35Cr	T 3077 (1999)	
USA				
ASTM		AISI	SAE	UNS
~ A 29 (5132)	A 29–99		~ 5132	~ G51320
~ A 322 (5132)	A 322–01		~ 5132 H	~ H51320

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

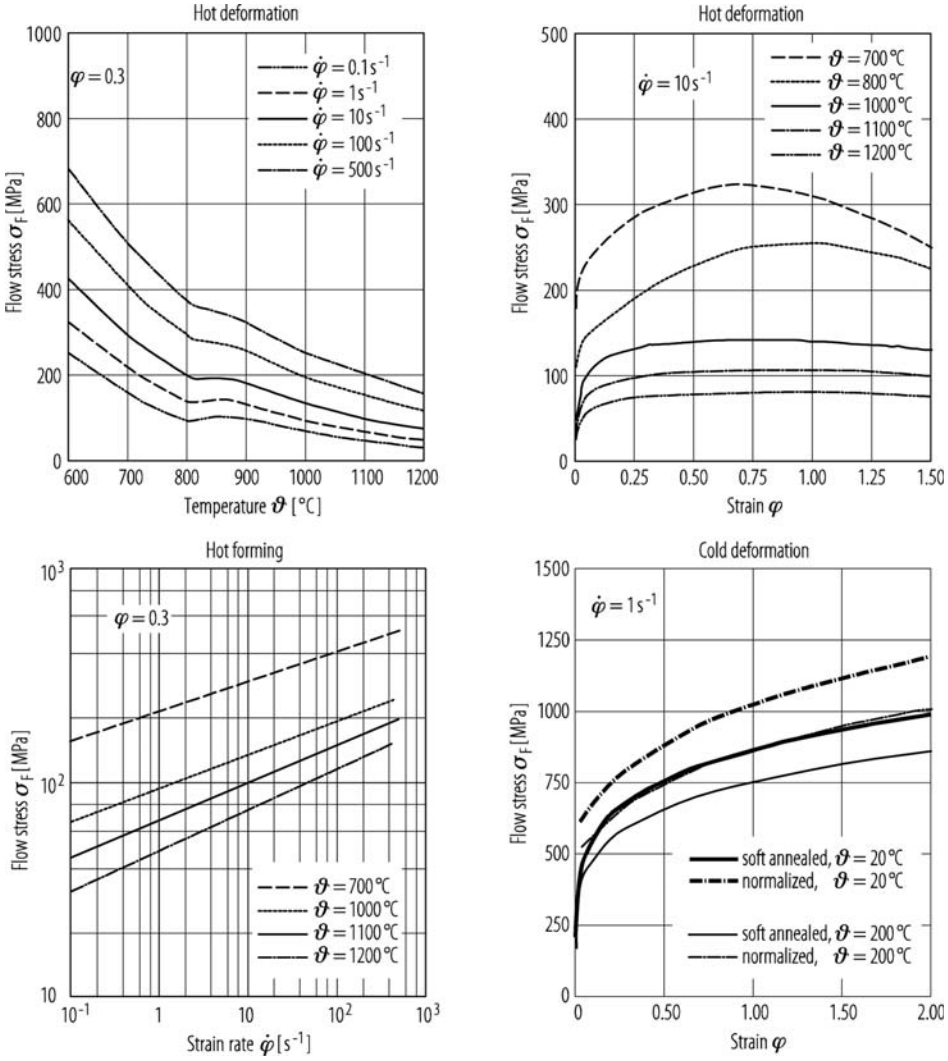
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Flow curves

State of material	Hot deformation			Cold deformation	
	deformed state		casting state	soft annealed	normalized
	austenite	ferrite+Fe_3C	austenite		
σ_{F0} [MPa]	115.96	(68.87)	115.0	558.7	680.3
A	3510.82	6997.24	4312.70	881.91	1032.966
Effect of temperature K_ϑ					
m_1	−0.00344	−0.00534	−0.00356	−0.00078	−0.00095
Effect of strain K_φ					
m_2	0.12948	0.006065	0.16974	0.18693	0.22174
m_4	−0.00363	−0.001413	−0.00347	−0.00294	0.00856
m_5	0.00040	0.00421	0.00032		
m_7	−0.42426	−1.74483	−0.47018		
Effect of strain rate $K_{\dot\varphi}$					
m_3				0.00826	0.01143
m_8	0.00016	0.000199	0.000164		
Range of validity					
ϑ [°C]	880…1200	600…810	900…1200	20…300	20…220
φ	0.04…1.50	0.04…1.50	0.04…1.50	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<100	<500

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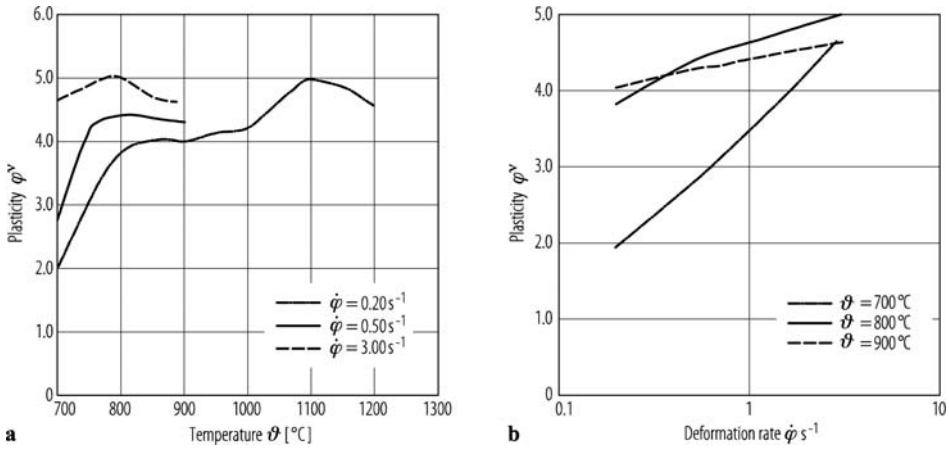
Fig. 5.291.
34Cr4. Flow stress curves by hot and cold forming.



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Fig. 5.292.
34Cr4. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Austenitised at 1200 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	41.78	474.77	10.91	7814.9	
100	43.24	488.67	11.34	7788.3	
200	43.12	501.33	12.07	7758.3	
300	41.22	521.43	12.62	7726.2	
400	38.6	545.84	13.14	7691.7	
500	35.79	572.9	13.7	7654.8	
600	32.91	601.99	14.19	7615.3	
700	30.11	633.06	14.74	7573.1	
800	23.53	696.43	12.92	7572.6	
900	26.15	693.92	13.92	7521.3	
1000	27.81	691.43	14.81	7467.7	
1100	29.09	688.95	15.62	7412.0	
1200	30.42	686.47	16.37	7354.3	

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Steel symbol/number: 41Cr4/1.7035

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.38…0.45	0.00…0.40	0.60…0.90	0.000…0.035	0.000…0.035	0.90…1.20

International comparison of standards

ISO		Euronorm		
~ 41Cr4	683–18 (1996)	41Cr4	20297–1 (06/2003)	
~ 41Cr4E	4954 (1993)	41Cr4	10263–4 (06/2001)	
United Kingdom		Russia		
41Cr4	En 20297–1 (06/2003)	~ 40Ch	4543 (1971)	
41Cr4	EN 10263–4 (06/2001)			
Japan		China		
~ SCr 440 M	G 3311 (1998)	~A20402	T 3077 (1999)	
~ SCr 440 H	G 4052 (1979)	~ 40Cr	T 3077 (1999)	
USA				
ASTM		AISI	SAE	UNS
~ A 29 (5140)	A 29–99		~ 5140	~ G51400
~ A 322 (5140)	A 322–01		~ 5140 H	~ H51400

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

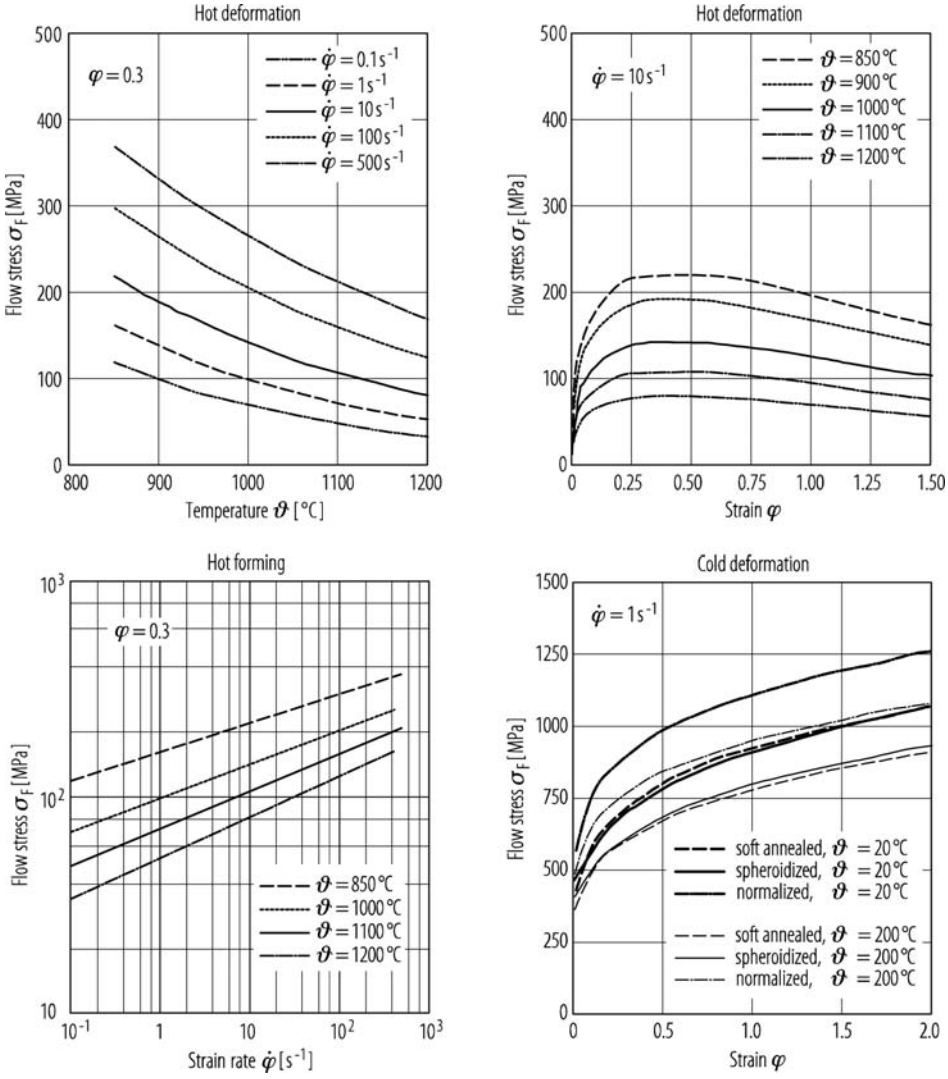
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Flow curves

	Hot deformation	Cold deformation		
	deformed state	soft annealed	spheroidized	normalized
State of material	austenite			
σ_{F0} [MPa]	116.04	572.2	579.5	754.8
A	4199.75	922.140	936.913	1131.541
Effect of temperature K_ϑ				
m_1	−0.00319	−0.00074	−0.00092	−0.00089
Effect of strain K_φ				
m_2	0.27827	0.22359	0.21463	0.17763
m_4	−0.00496	0.00394	0.00124	0.00001
m_5	−0.00018			
m_7	−0.55148			
Effect of strain rate $K_{\dot\varphi}$				
m_3		0.00565	0.00859	0.00947
m_8	0.000158			
Range of validity				
ϑ [°C]	850…1200	20…300	20…300	20…300
φ	0.04…1.5	0.04…2.00	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<100	<100	<100

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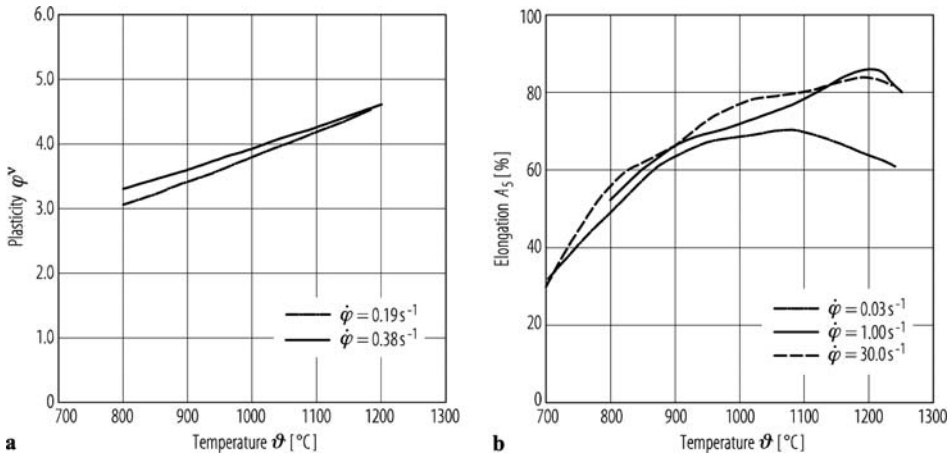
Fig. 5.293.
41Cr4. Flow stress curves by hot and cold forming.



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Fig. 5.294.
41Cr4. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	40.75	475.09	10.82	7811.4	
100	42.60	488.14	11.26	7785.0	
200	42.55	501.83	12.00	7755.2	
300	40.69	521.96	12.56	7723.1	
400	38.1	546.40	13.08	7688.8	
500	35.35	573.5	13.6	7652.0	
600	32.51	602.62	14.13	7612.7	
700	29.74	633.73	14.67	7570.7	
800	23.47	696.94	13.14	7565.1	
900	26.14	694.44	14.17	7512.6	
1000	27.85	691.94	15.09	7457.7	
1100	29.18	689.45	15.94	7400.7	
1200	30.55	686.98	16.71	7341.5	

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Steel symbol/number: 67SiCr5/1.7103

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.62…0.72	1.20…1.40	0.40…0.60	0.000…0.035	0.000…0.035	0.40…0.60

International comparison of standards

ISO		Euronorm		
		67 SiCr 5	∼ 132 (1979)	
United Kingdom		Russia		
Japan		China		
USA				
ASTM		AMS	SAE	UNS
∼ A 29 (9254)	A 29–99	∼ 6451B	∼ 9254	∼ G92540
∼ A 711 /(9254)	A 711–01			∼ K15590

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

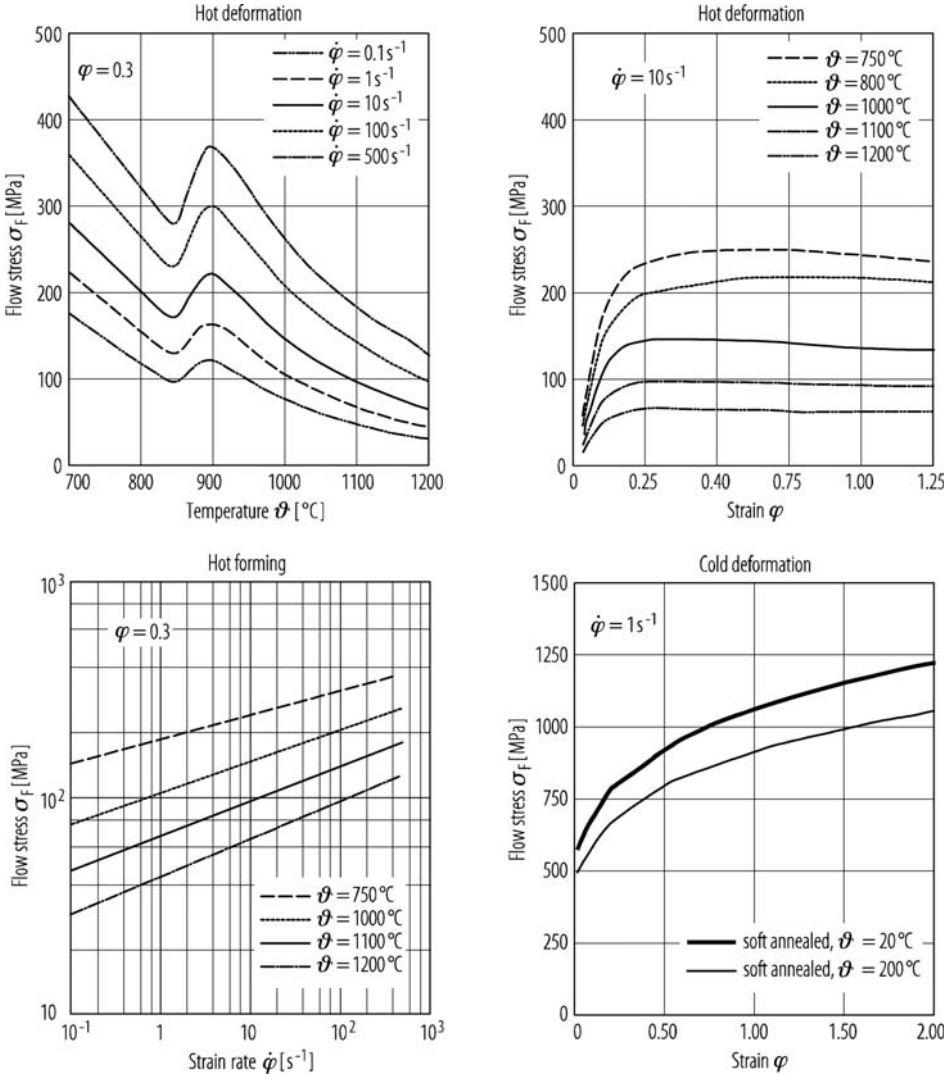
DOI: 10.1007/978-3-540-44760-3_159
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Flow curves

	Hot deformation			Cold deformation
	deformed state		casting state	soft annealed
State of material	austenite	ferrite+Fe_3C	austenite	
σ_{F0} [MPa]	109.02	(66.26)	89.7	702.6
A	7929.45	3171.12	8155.35	1074.844
Effect of temperature K_ϑ				
m_1	−0.00454	−0.00429	−0.00458	−0.00083
Effect of strain K_φ				
m_2	−0.35731	−0.36852	−0.31622	0.20674
m_4	−0.09402	−0.09177	−0.09433	0.00391
m_5	0.00042	0.00229	0.00083	
m_7	−0.0551	−0.7046	−0.37823	
Effect of strain rate $K_{\dot\varphi}$				
m_3				0.01233
m_8	0.000146	0.000149	0.000106	
Range of validity				
ϑ [°C]	900…1200	700…850	900…1200	20…300
φ	0.04…1.25	0.04…1.25	0.04…1.25	0.04..2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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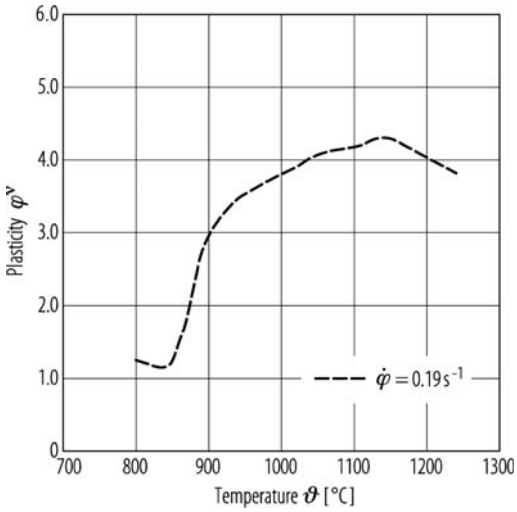
Fig. 5.295.
67SiCr5. Flow stress curves by hot and cold forming.



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Fig. 5.296.
67SiCr5. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.90.

Plasticity in torsion



DOI: 10.1007/978-3-540-44760-3_159
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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	36.72	476.91	10.39	7754.3	38.0
100	39.86	490.39	10.87	7729.0	41.2
200	40.09	504.21	11.67	7700.0	41.4
300	38.43	524.50	12.25	7668.9	39.7
400	36.1	549.10	12.77	7635.5	37.4
500	33.44	576.3	13.3	7599.7	34.7
600	30.77	605.68	13.81	7561.5	32.1
700	28.16	636.97	14.35	7520.7	29.5
800	23.30	699.23	14.63	7482.0	24.6
900	26.21	696.71	15.87	7422.1	27.5
1000	28.13	694.21	16.98	7359.2	29.4
1100	29.66	691.71	18.00	7293.8	31.0
1200	31.22	689.23	18.93	7225.8	32.5

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Steel symbol/number: 56SiCr7/1.7106

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.52…0.60	1.60…2.00	0.70…1.00	0.000…0.025	0.000…0.025	0.20…0.45
N					
0.000…0.007					

International comparison of standards

ISO		Euronorm		
		56 SiCr7	10089 (12/2002)	
United Kingdom		Russia		
56 SiCr7	EN 10089 (12/2002)			
~ 251 H 60	970 Part 2 (1988)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

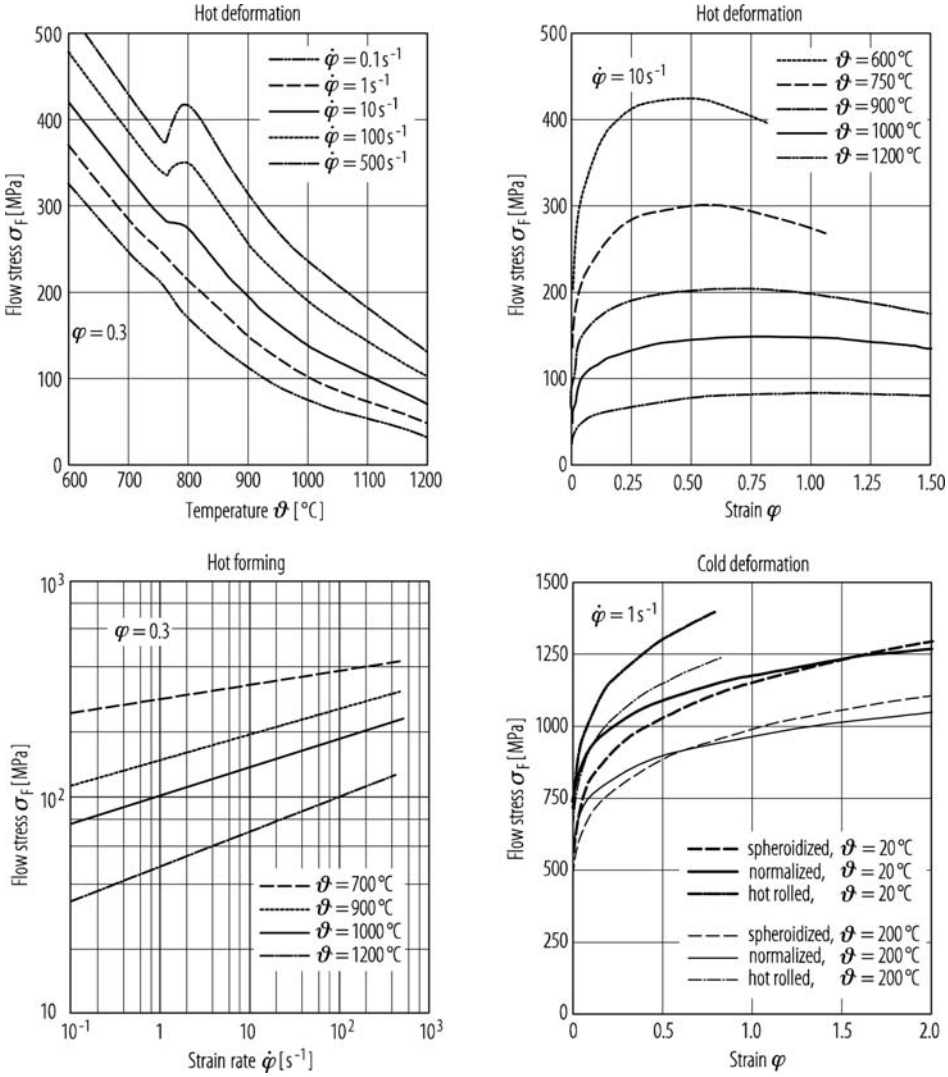
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Flow curves

State of material	Hot deformation		Cold deformation		
	deformed state		spheroidized	normalized	hot rolled
	austenite	ferrite+Fe_3C			
σ_{F0} [MPa]	116.24	124.70	817.4	932.9	1040.7
A	6067.41	3170.9	1172.733	1201.012	1464.950
Effect of temperature K_ϑ					
m_1	−0.00406	−0.00296	−0.00088	−0.00110	−0.00071
Effect of strain K_φ					
m_2	0.08779	0.21703	0.16181	0.11269	0.15439
m_4	−0.00379	0.00007	0.00061	0.00059	0.00059
m_5	0.00124	0.00111			
m_7	−0.8171	−0.96771			
Effect of strain rate $K_{\dot\varphi}$					
m_3			0.01004	0.00997	0.00948
m_8	0.000134	0.000093			
Range of validity					
ϑ [°C]	800…1200	600…760	20…300	20…300	20…400
φ	0.04…1.50	0.04…1.00	0.04…2.00	0.04…2.00	0.04…0.80
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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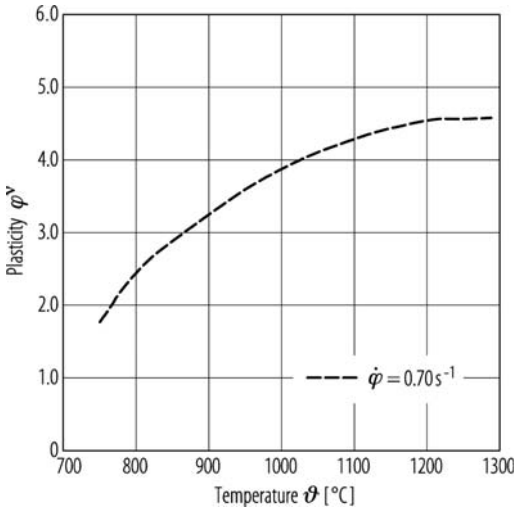
Fig. 5.297.
56SiCr7. Flow stress curves by hot and cold forming.



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Fig. 5.298.
56SiCr7. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.90.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	35.47	477.69	10.21	7722.5	
100	38.94	491.37	10.70	7697.7	
200	39.26	505.26	11.52	7669.1	
300	37.66	525.62	12.09	7638.4	
400	35.4	550.30	12.62	7605.5	
500	32.79	577.6	13.1	7570.3	
600	30.18	607.03	13.65	7532.7	
700	27.62	638.42	14.19	7492.4	
800	23.27	700.14	15.56	7434.1	
900	26.26	697.62	16.92	7369.8	
1000	28.27	695.12	18.14	7302.3	
1100	29.86	692.62	19.25	7232.0	
1200	31.49	690.13	20.27	7158.9	

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Steel symbol/number: 60SiCr5/1.7108

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.57…0.65	1.60…2.00	0.70…1.00	0.000…0.025	0.000…0.025	0.20…0.45

International comparison of standards

ISO		Euronorm		
		61 SiCr7	10089 (12/2002)	
		~ 60 SiCr 8	89 (1971)	
United Kingdom		Russia		
61 SiCr7	EN 10089 (12/2002)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS
~ A 29 (9260)	A 29–99	~ 9261	~ 9260	~ G92600
~ A 322 (9260)	A 32–01	~ 9262	~ 9261	~ G92620

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

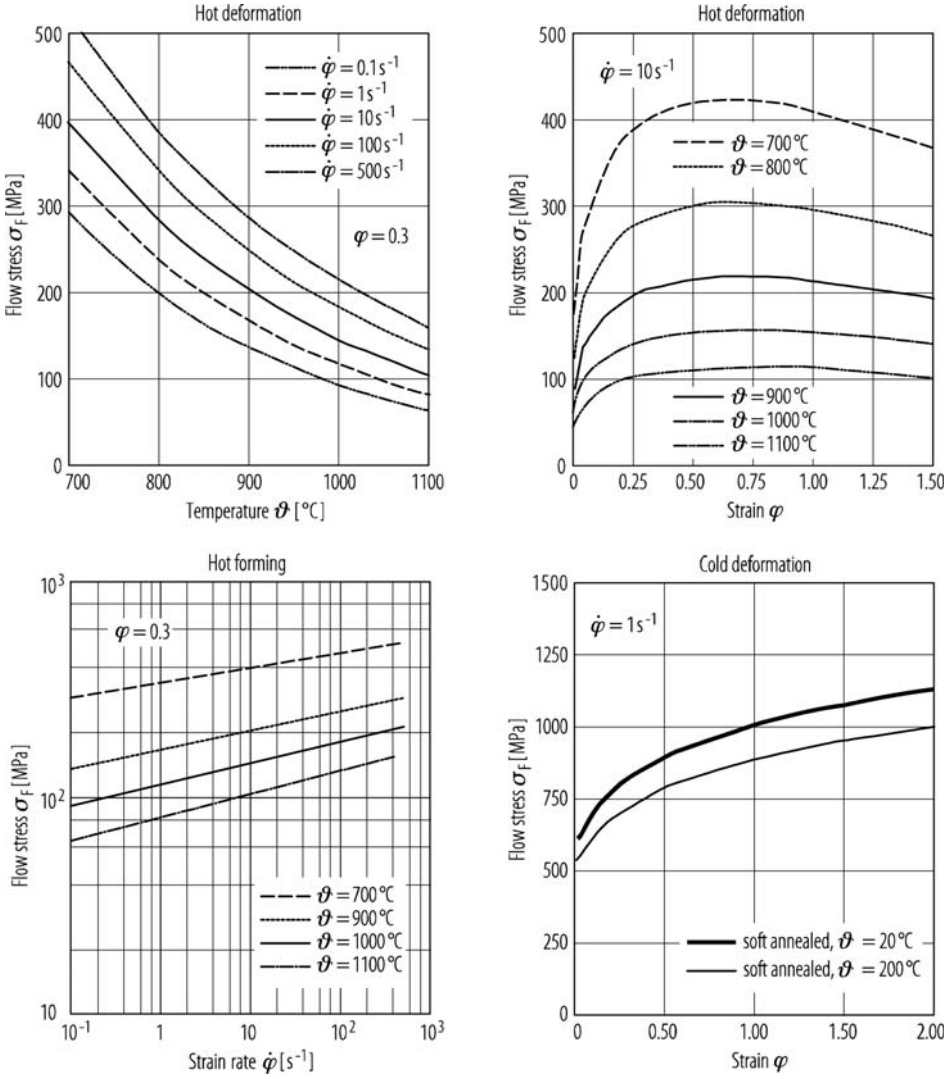
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	116.54	712.9
A	6586.33	1017.316
Effect of temperature K_ϑ		
m_1	−0.00365	−0.00072
Effect of strain K_φ		
m_2	0.25492	0.17564
m_4	0.00039	0.00402
m_5	0.00024	
m_7	−0.50012	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01001
m_8	0.000098	
Range of validity		
ϑ [°C]	700…1100	20…300
φ	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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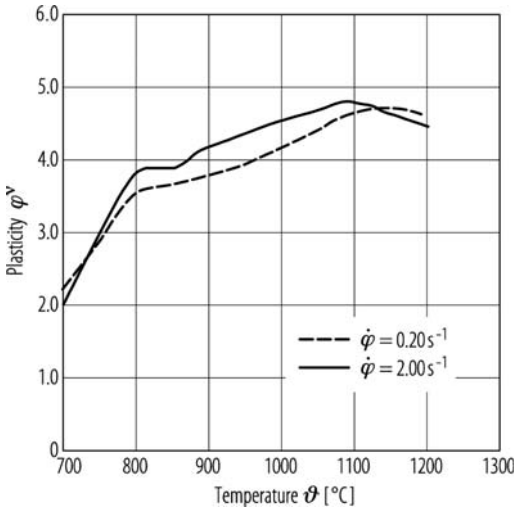
Fig. 5.299.
60SiCr5. Flow stress curves by hot and cold forming.



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Fig. 5.300.
60SiCr5. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.60…0.90.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	35.27	477.83	10.17	7720.3	
100	38.79	491.55	10.66	7695.6	
200	39.12	505.46	11.49	7667.1	
300	37.54	525.83	12.06	7636.5	
400	35.2	550.53	12.59	7603.7	
500	32.69	577.8	13.1	7568.6	
600	30.08	607.29	13.62	7531.0	
700	27.54	638.69	14.15	7490.8	
800	23.27	700.31	15.76	7428.3	
900	26.27	697.79	17.14	7363.1	
1000	28.29	695.28	18.38	7294.7	
1100	29.90	692.78	19.51	7223.3	
1200	31.54	690.29	20.55	7149.1	

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Steel symbol/number: 16MnCr5/1.7131

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.14…0.19	0.00…0.40	1.00…1.30	0.000…0.035	0.000…0.035	0.80…1.10

International comparison of standards

ISO		Euronorm		
~ 16MnCr5	683–18 (1996)	16MnCr5	10297–1 (06/2003)	
~ 16MnCr5E	4954 (1993)	16MnCr5	10263–3 (06/2001)	
United Kingdom		Russia		
16MnCr5	EN 10297–1 (06/2003)	~ 18ChG	4543 (1971)	
16MnCr5	EN 10263–3 (06/2001)			
Japan		China		
		~ A22202	T 3077 (1999)	
		~ 20CrMn	T 3077 (1999)	
USA				
ASTM		AISI	SAE	UNS
~ A 29 (5115)	A 29–99		~ 5115	~ G51150
~ A 322 (5117)	A 322–01		~ 5117	~ G51170

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

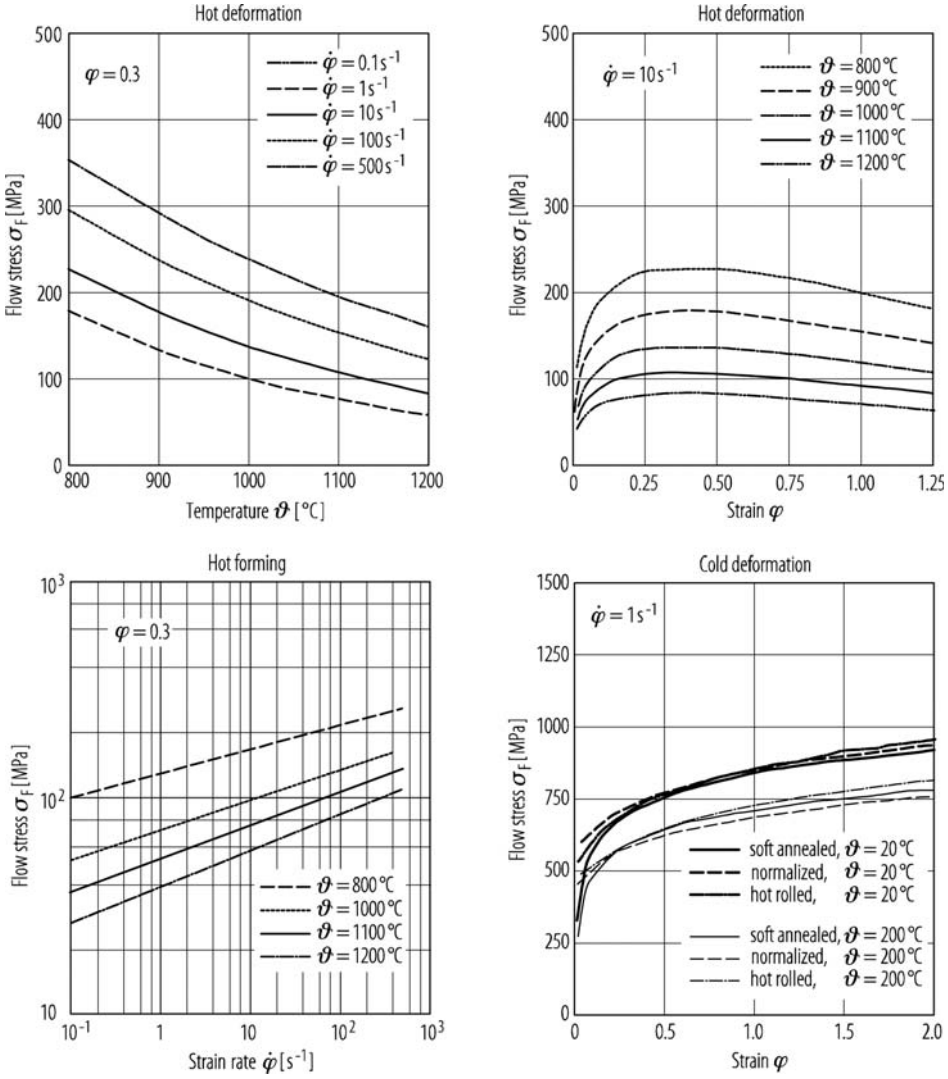
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Flow curves

	Hot deformation	Cold deformation		
	deformed state	soft annealed	normalized	hot rolled
State of material	austenite			
σ_{F0} [MPa]	116.51	587.9	609.2	655.8
A	2693.28	862.909	861.795	866.908
Effect of temperature K_ϑ				
m_1	−0.00277	−0.00092	−0.00090	−0.00120
Effect of strain K_φ				
m_2	0.24436	0.12910	0.17069	0.14432
m_4	−0.00560	−0.00977	0.00401	0.00467
m_5	−0.00021			
m_7	−0.51926			
Effect of strain rate K_φ				
m_3		0.01283	0.01046	0.01326
m_8	0.000139			
Range of validity				
ϑ [°C]	800…1200	20…300	20…300	20…300
φ	0.04…1.25	0.04…2.50	0.04…2.00	0.04…2.00
$\dot{\varphi}$ [s^{-1}]	<500	<100	<500	<500

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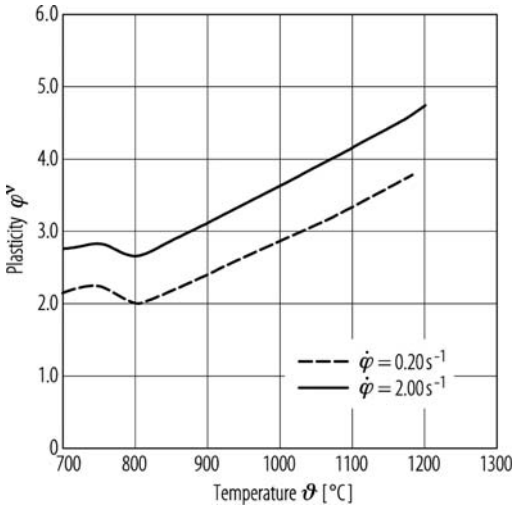
Fig. 5.301.
16MnCr5. Flow stress curves by hot and cold forming.



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Fig. 5.302.
16MnCr5. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.60…0.95.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	43.39	474.14	11.04	7821.8	213.0
100	44.21	487.37	11.46	7794.9	203.6
200	43.98	500.60	12.16	7764.7	195.6
300	42.00	520.65	12.70	7732.3	189.1
400	39.3	545.01	13.22	7697.7	182.0
500	36.44	572.0	13.7	7660.5	172.5
600	33.51	601.06	14.28	7620.8	159.7
700	30.65	632.08	14.82	7578.4	143.2
800	23.64	695.65	12.65	7584.3	123.5
900	26.18	693.15	13.60	7534.6	101.5
1000	27.76	690.66	14.45	7482.7	78.7
1100	28.98	688.18	15.22	7428.8	57.4
1200	30.25	685.71	15.94	7373.0	46.5

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: 20MnCr5/1.7147

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.17…0.22	0.00…0.40	1.10…1.40	0.000…0.035	0.000…0.035	1.00…1.30

International comparison of standards

ISO		Euronorm		
~ 20MnCr5	683–11 (1987)	20MnCr5	10084 (04/1998)	
~ 20MnCr5	683–18 (1996)	~ 16MnCr5 KD	119– (1974)	
United Kingdom		Russia		
20MnCr5	EN 10084 (04/1998)			
Japan		China		
~ SMnC 420 H	G 4052 (1979)	~ A22202	T 3077 (1999)	
		~ 20CrMn	T 3077 (1999)	
USA				
ASTM		AISI	SAE	UNS
~ A 29 (4820)	A 29–99		~ 4820	~ G48200
~ A 322 (5120)	A 322–01		~ 5120 H	~ G51200

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

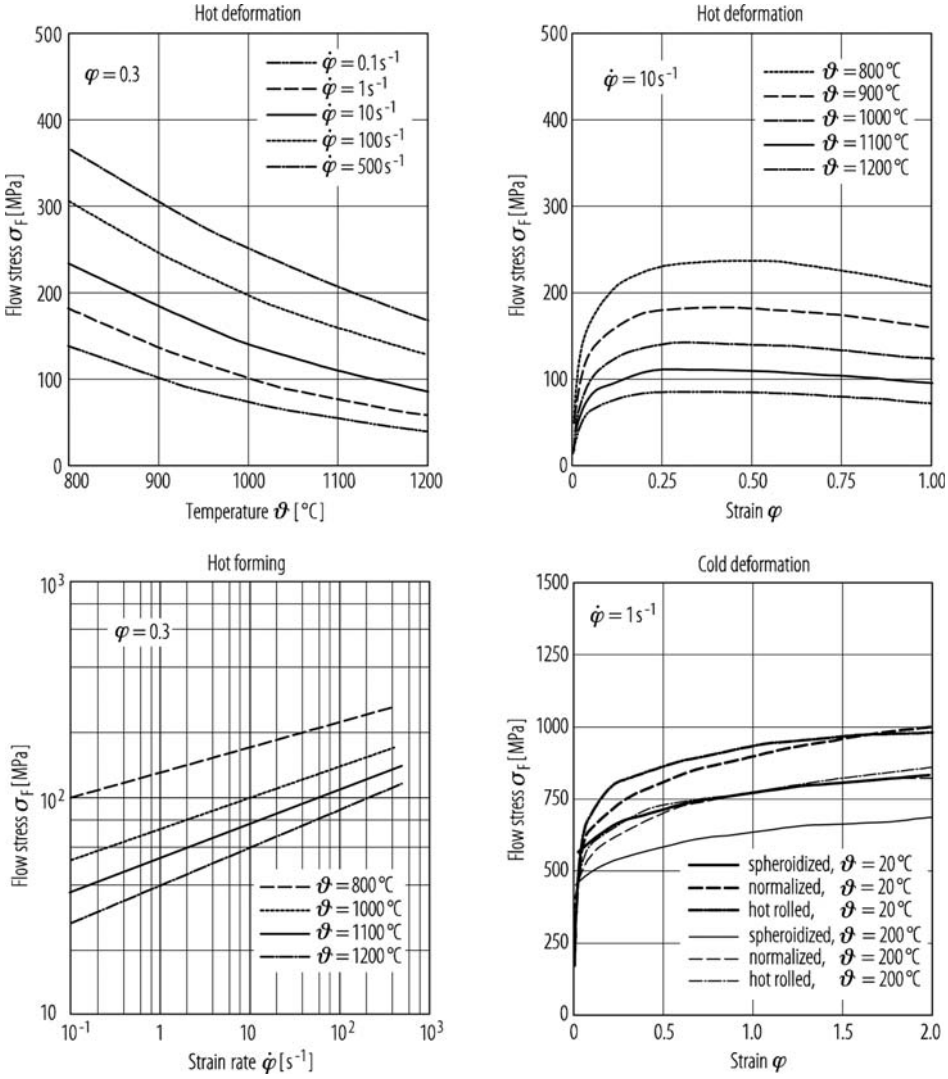
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Flow curves

	Hot deformation	Cold deformation		
	deformed state	spheroidized	normalized	hot rolled
State of material	austenite			
σ_{F0} [MPa]	120.00	621.7	655.3	724.9
A	2800.77	786.130	917.541	955.004
Effect of temperature K_ϑ				
m_1	−0.00279	−0.00112	−0.00088	−0.00102
Effect of strain K_φ				
m_2	0.24424	0.11691	0.14748	0.08775
m_4	−0.00571	0.00290	0.00005	−0.00807
m_5	−0.00021			
m_7	−0.52227			
Effect of strain rate $K_{\dot\varphi}$				
m_3		0.01213	0.00871	0.01193
m_8	0.000144			
Range of validity				
ϑ [°C]	800…1200	20…300	20…300	20…300
φ	0.04…1.00	0.04…2.00	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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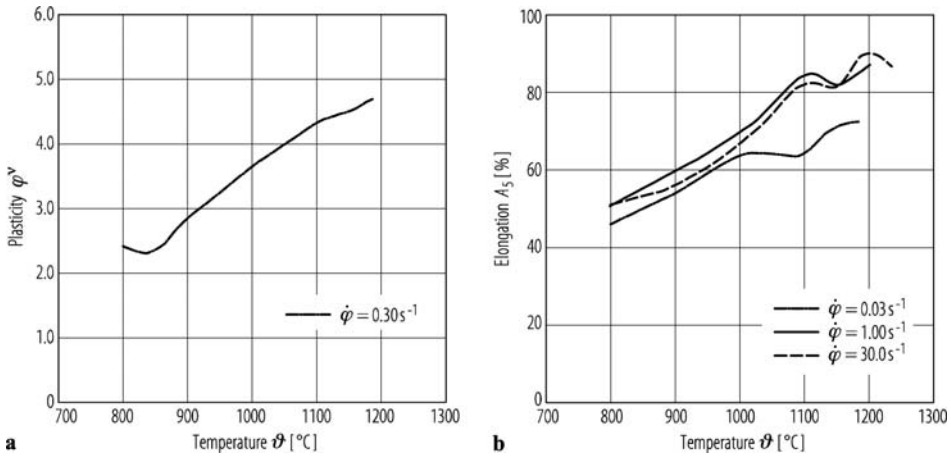
Fig. 5.303.
20MnCr5. Flow stress curves by hot and cold forming.



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Fig. 5.304.
20MnCr5. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	41.93	474.58	10.92	7818.6	
100	43.34	487.90	11.35	7792.0	
200	43.20	501.26	12.08	7761.9	
300	41.29	521.35	12.63	7729.7	
400	38.7	545.76	13.15	7695.2	
500	35.85	572.8	13.7	7658.2	
600	32.97	601.90	14.20	7618.7	
700	30.16	632.97	14.74	7576.5	
800	23.54	696.35	12.89	7576.7	
900	26.15	693.85	13.88	7525.5	
1000	27.80	691.36	14.77	7472.1	
1100	29.08	688.87	15.58	7416.6	
1200	30.41	686.40	16.33	7359.1	

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Steel symbol/number: 25CrMo4/1.7218

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.22…0.29	0.00…0.40	0.60…0.90	0.000…0.035	0.000…0.035	0.90…1.20
Mo					
0.15…0.30					

International comparison of standards

ISO		Euronorm		
~ 25CrMo4	683–18 (1996)	25CrMo4	10216–2 (05/2002)	
~ 25CrMo4	683–1 (1987)	25CrMo4	10263–4 (06/2001)	
United Kingdom		Russia		
25CrMo4	EN 10216– (05/2002)	~ 20ChM	4543 (1971)	
~ CFS 10	6323 Part 4 (1982)	~ 30ChM	4543 (1971)	
Japan		China		
~ SCCrM 1	G 5111 (1991)	~ 30CrMo	T3077 (1999)	
~ SCM 420 TK	G 3441 (1988)	~ A30302	T3077 (1999)	
USA				
ASTM		AMS	SAE	UNS
~ A 29 (4130)	A 29–99	~ 7496J	~ 4130	~ G41300
~ A 322 (4130)	A 322–01	~ 6346	~ 4130 H	~ H41300

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

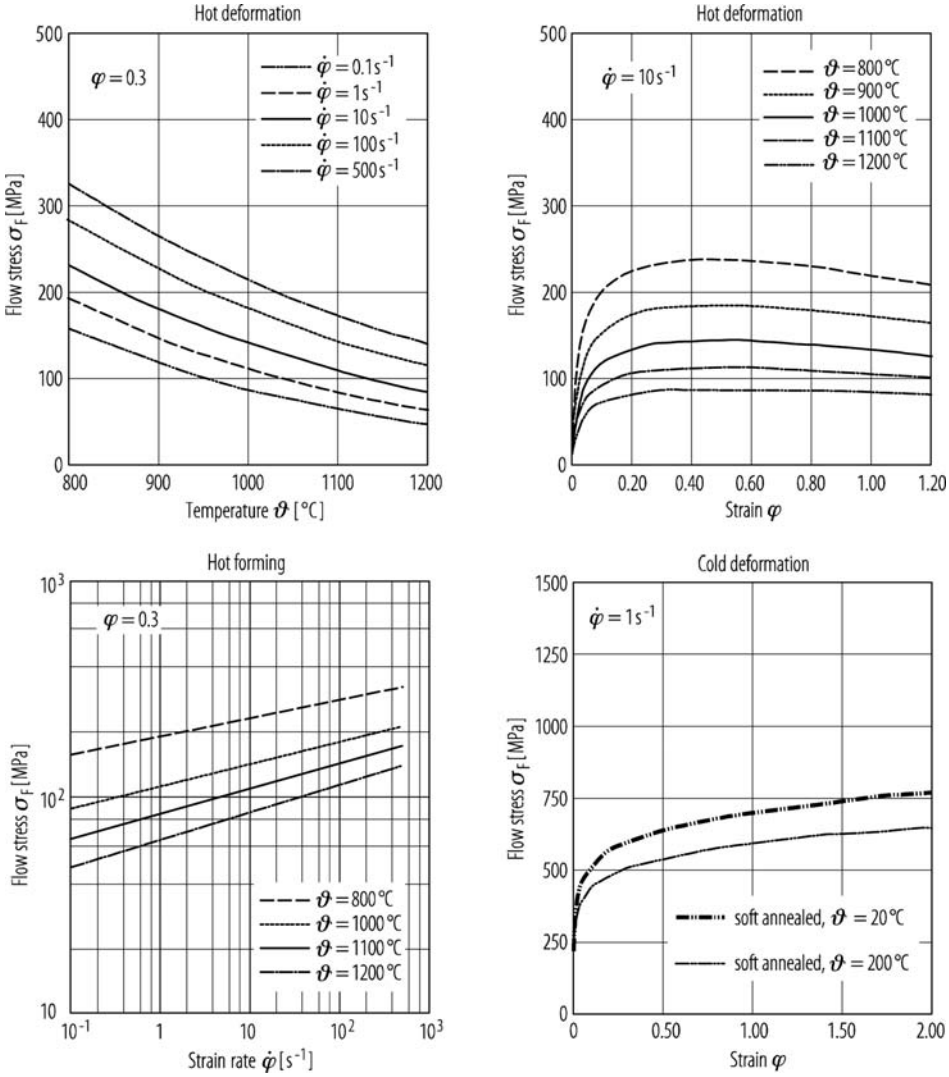
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Flow curves

State of material	Hot deformation defomed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	118.19	526.5
A	2632.18	718.631
Effect of temperature K_ϑ		
m_1	−0.00282	−0.00093
Effect of strain K_φ		
m_2	0.18256	0.12900
m_4	−0.00712	−0.00219
m_5	0.00021	
m_7	−0.53515	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00897
m_8	0.000105	
Range of validity		
ϑ [°C]	800…1200	20…300
φ	0.04…1.20	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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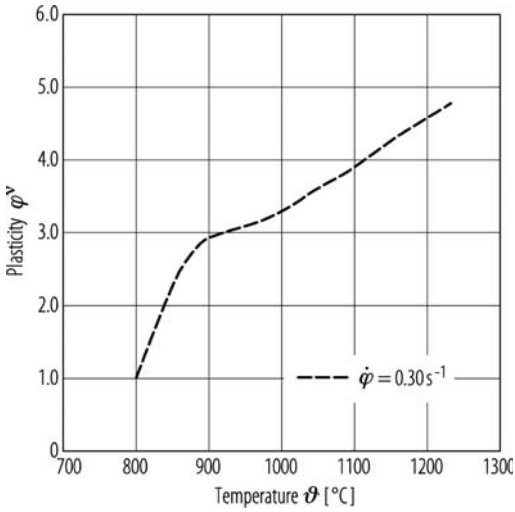
Fig. 5.305.
25CrMo4. Flow stress curves by hot and cold forming.



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Fig. 5.306.
25CrMo4. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.60…0.90.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	42.47	474.13	10.97	7825.6	211.5
100	43.66	487.36	11.39	7798.9	205.7
200	43.49	501.01	12.11	7768.8	199.8
300	41.56	521.09	12.66	7736.5	193.7
400	38.9	545.48	13.18	7701.9	185.7
500	36.07	572.5	13.7	7664.8	175.0
600	33.17	601.58	14.23	7625.2	160.9
700	30.34	632.63	14.77	7582.9	143.5
800	23.57	696.09	12.80	7585.3	123.2
900	26.16	693.59	13.77	7534.7	100.9
1000	27.79	691.10	14.64	7481.8	77.9
1100	29.04	688.62	15.44	7426.9	56.0
1200	30.35	686.14	16.17	7370.0	47.7

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Steel symbol/number: 34CrMo4/1.7220

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.30…0.37	0.00…0.40	0.60…0.90	0.000…0.035	0.000…0.035	0.90…1.20
Mo					
0.15…0.30					

International comparison of standards

ISO		Euronorm		
~ 34CrMo4	683–18 (1996)	34CrMo4	10297– (06/2003)	
~ 34CrMo4E	4954 (1993)	34CrMo4	10263–4 (06/2001)	
United Kingdom		Russia		
34CrMo4	EN 10297–(06/2003)	~ 35ChML	977 (1988)	
34CrMo4	EN 10263–4 (06/2001)	~ AS38ChGM	1414 (1975)	
Japan		China		
~ SCM 435 M	G 3311 (1998)	~ A30352	T3077 (1999)	
~ SCCrM 3	G 5111 (1991)	~ ML35CrMoA	T 5954 (1999)	
USA				
ASTM		AMS	SAE	UNS
~ A 29 (4130)	A 29–99	~ 6346	~ 4130	~ G41300
~ A 322 (4137)	A 322–01	+ 6361D	~ 4135	~ G41350

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

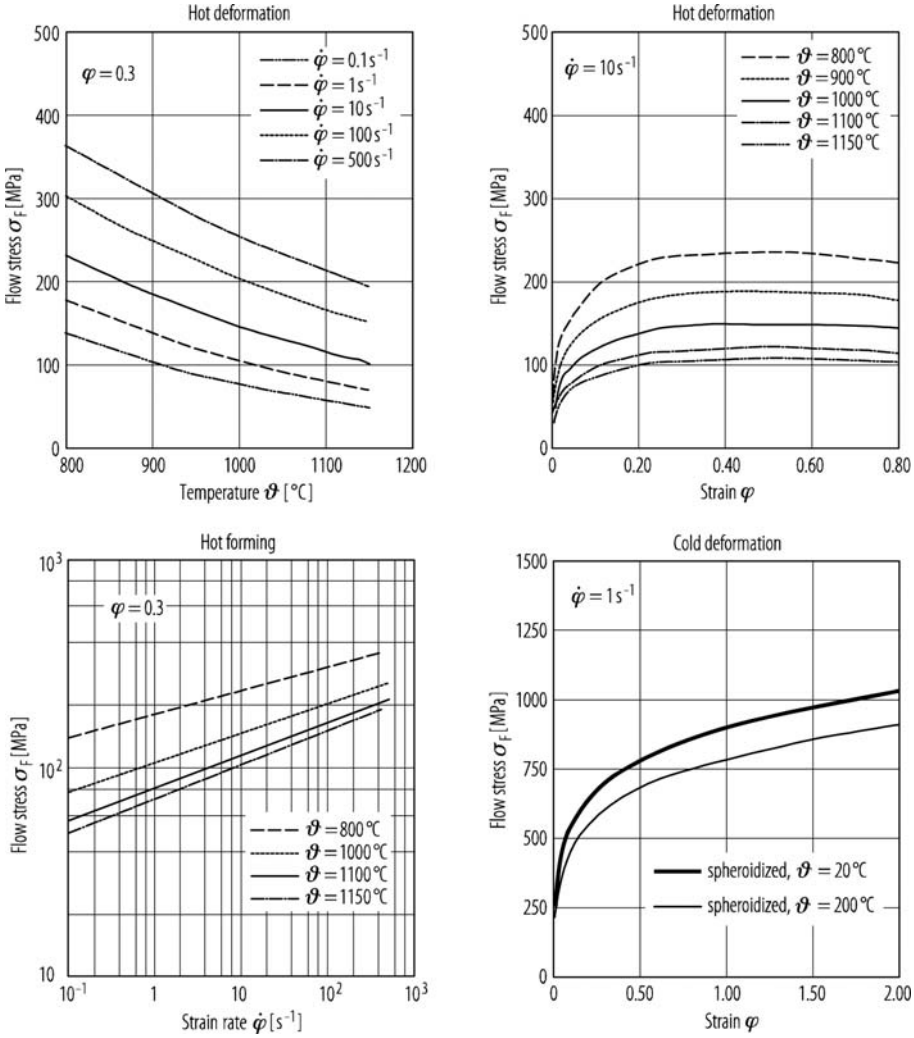
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation spheroidized
σ_{F0} [MPa]	119.29	536.31
A	2595.77	924.39
Effect of temperature K_ϑ		
m_1	−0.00271	−0.00075
Effect of strain K_φ		
m_2	0.27628	0.18682
m_4	−0.00104	−0.01249
m_5	0.00028	
m_7	−0.77201	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01114
m_8	0.000142	
Range of validity		
ϑ [°C]	800…1150	20…300
φ	0.04…0.80	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<100

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Fig. 5.307.
34CrMo4. Flow stress curves by hot and cold forming.

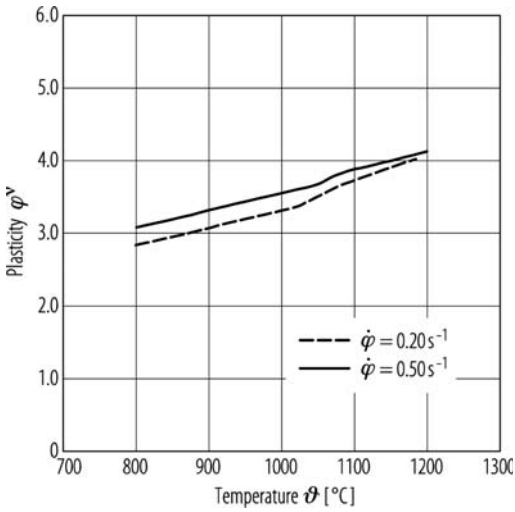


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Fig. 5.308.

34CrMo4. Deformed state. Austenitised at 1200 [°C]. Note: At hot deformation the relation of plasticity between as–cast and as-deformed state is: 0.50…0.85.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	41.36	474.82	10.87	7822.2	209.4
100	42.98	488.25	11.31	7795.6	203.6
200	42.89	501.53	12.04	7765.6	197.7
300	41.01	521.64	12.60	7733.5	191.6
400	38.4	546.06	13.12	7699.0	183.6
500	35.61	573.1	13.6	7662.1	172.9
600	32.75	602.24	14.17	7622.7	158.8
700	29.96	633.33	14.71	7580.5	141.4
800	23.50	696.63	13.00	7578.0	121.1
900	26.15	694.13	14.01	7526.2	98.8
1000	27.82	691.64	14.92	7472.1	75.8
1100	29.12	689.15	15.74	7415.8	53.9
1200	30.47	686.67	16.50	7357.5	45.6

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: 42CrMo4/1.7225

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.38…0.45	0.00…0.40	0.60…0.90	0.000…0.035	0.000…0.035	0.90…1.20
Mo					
0.15…0.30					

International comparison of standards

ISO		Euronorm		
~ 42CrMo4	683–18 (1996)	42CrMo4	10297–1 (06/2003)	
~ 42CrMo4E	4954 (1993)	42CrMo4	10305–1 (11/2002)	
United Kingdom		Russia		
~ 708 M40	970 Part 1 (1996)			
~ 709 M40	970 Part 1 (1996)			
Japan		China		
~ SCM 440 M	G 3311 (1998)	~ 42CrMo	T3077 (1999)	
~ SNB 7 Class 2	G 4107 (1994)	~ A30424	T 5954 (1999)	
USA				
ASTM		AMS	SAE	UNS
~ A 322 (4140)	A 322–01	~ 6349B	~ 4142	~ H41400
~ A 711 (4140)	A 711–01	~ 6381F	~ 4140	~ H41420

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

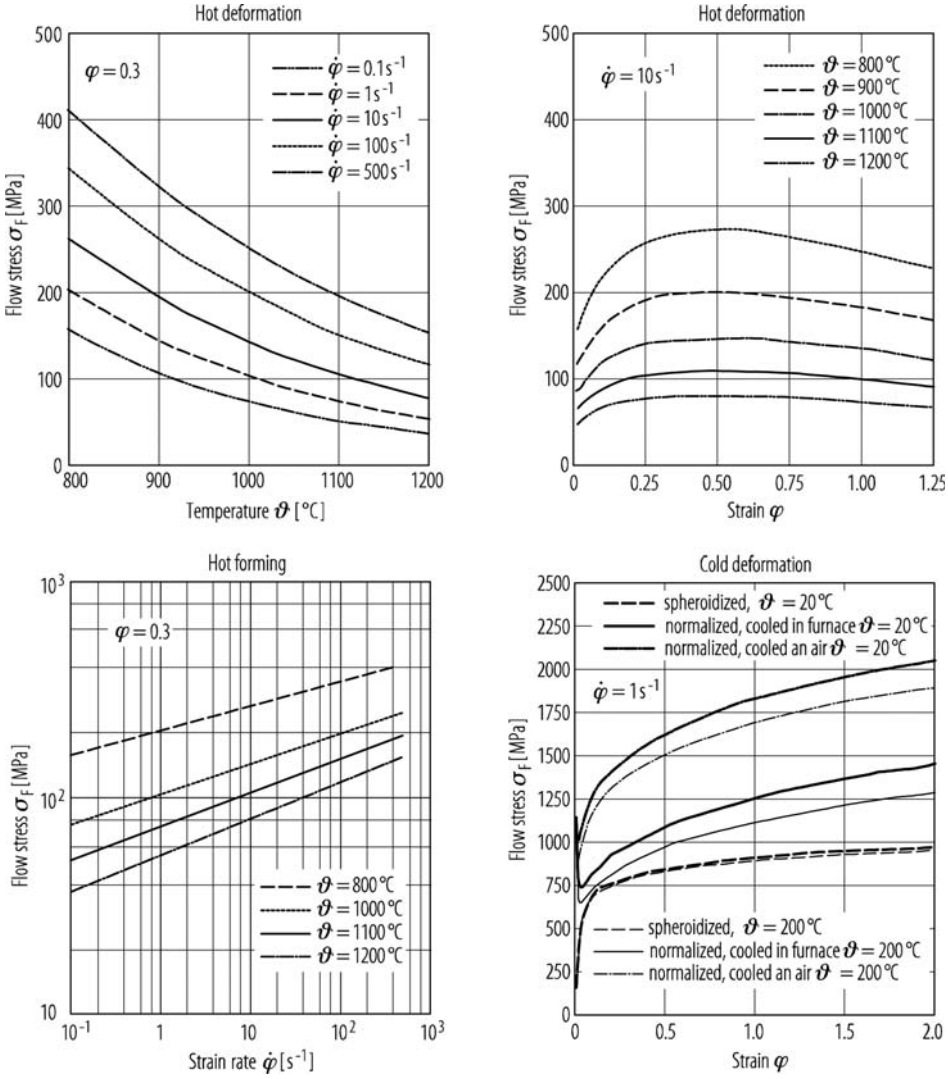
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Flow curves

State of material	Hot deformation	Cold deformation			
	deformed state	spheroidized	normalized/ air	normalized/ furnace	austempered
	austenite				
σ_{F0} [MPa]	119.01	708.7	1274.0	839.4	921.7
A	5050.38	929.822	1847.270	1264.890	1150.680
Effect of temperature K_ϑ					
m_1	−0.00332	−0.00064	−0.00044	−0.00064	−0.00098
Effect of strain K_φ					
m_2	0.31301	0.08896	0.16261	0.21041	0.09685
m_4	0.00331	−0.00802	−0.00011	0.00608	−0.00136
m_5	−0.00007				
m_7	−0.58370				
Effect of strain rate $K_{\dot\varphi}$					
m_3		0.01142	0.00553	0.01148	0.01490
m_8	0.000141				
Range of validity					
ϑ [°C]	800…1200	20…300	20…100	20…120	20…130
φ	0.04…1.25	0.04…2.00	0.04…2.00	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500	<500

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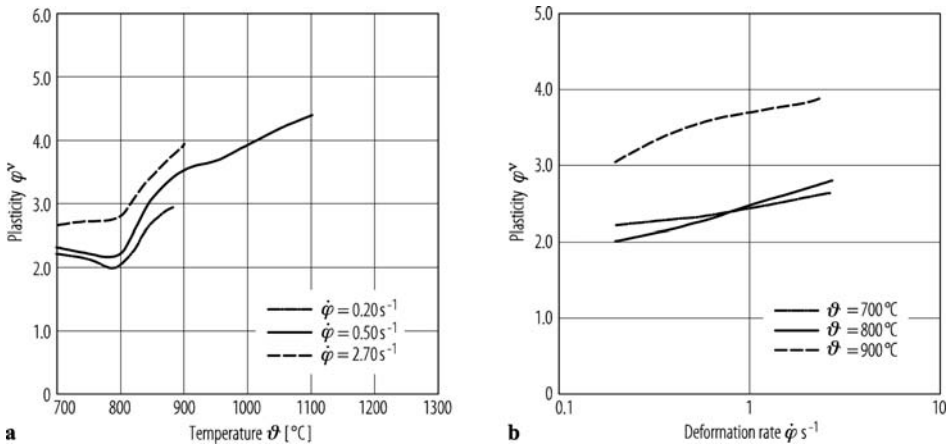
Fig. 5.309.
42CrMo4. Flow stress curves by hot and cold forming.



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Fig. 5.310.
42CrMo4. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformation rate: 0.2 [s^{-1}]. Deformed state. Austenitised at 1150 [°C].

Plasticity by torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	40.38	475.18	10.79	7818.7	
100	42.36	488.62	11.23	7792.3	
200	42.33	502.02	11.98	7762.5	
300	40.50	522.15	12.54	7730.4	
400	38.0	546.61	13.06	7696.1	
500	35.18	573.7	13.6	7659.4	
600	32.36	602.86	14.11	7620.1	
700	29.61	633.98	14.65	7578.1	
800	23.44	697.13	13.23	7570.5	
900	26.14	694.62	14.27	7517.4	
1000	27.87	692.13	15.21	7461.9	
1100	29.21	689.64	16.06	7404.2	
1200	30.60	687.16	16.85	7344.4	

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Steel symbol/number: 20MoCr5/1.7264

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.18…0.23	0.15…0.35	0.90…1.20	0.000…0.035	0.000…0.035	1.10…1.40
Mo					
0.20…0.30					

International comparison of standards

ISO		Euronorm		
		20MoCr4	10263–3 (06/2001)	
		20MoCr4	10084 (04/1998)	
United Kingdom		Russia		
20MoCr4	EN 10263–3 (04/2001)			
20MoCr4	EN 10084 (04/1998)			
Japan		China		
~ SCM 420 H	G 4052 (1979)	~ 20CrMnMo	T 3077 (1999)	
		~ A 34202	T 3077 (1999)	
USA				
ASTM		AISI	SAE	UNS
~ A 322 (4118)	A 322–01		~ 4118 H	~ G86200
~ A 711 (4118)	A 711–01		~ 4118 RH	~ H41180

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

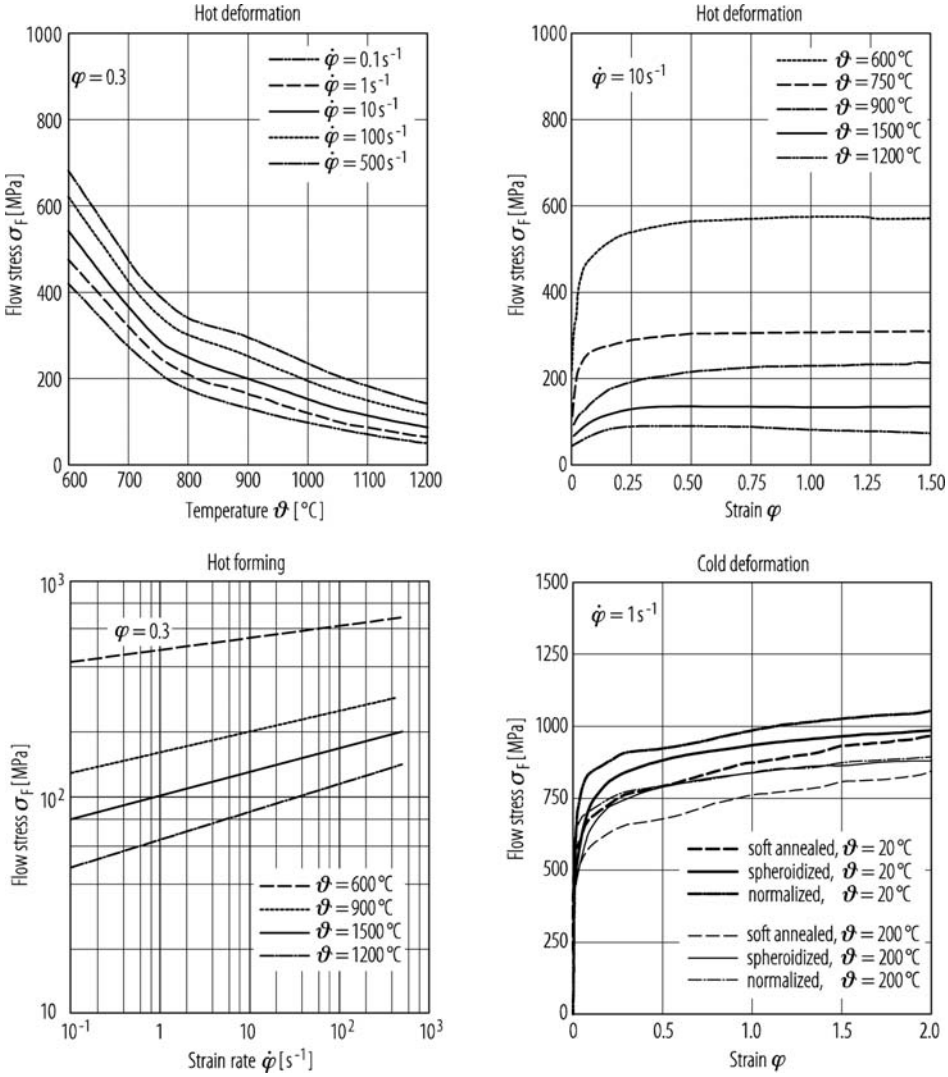
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Flow curves

State of material	Hot deformation		Cold deformation		
	deformed state		soft annealed	spheroidized	normalized
	austenite	ferrite+Fe_3C			
σ_{F0} [MPa]	118.98	(92.21)	752.0	702.5	860.4
A	3738.77	7562.54	958.09	912.487	999.517
Effect of temperature K_ϑ					
m_1	−0.00269	−0.00441	−0.00061	−0.00082	−0.00090
Effect of strain K_φ					
m_2	0.40355	0.07529	0.06769	0.10409	0.06355
m_4	0.00355	−0.0042	−0.01128	−0.00116	−0.00097
m_5	−0.001532	0.00012			
m_7	0.35763	−0.11737			
Effect of strain rate $K_{\dot\varphi}$					
m_3			0.0168		
m_8	0.40355	0.07529			
Range of validity					
ϑ [°C]	900…1100	600…800	20…300	20…300	20…250
φ	0.04…1.50	0.04…1.50	0.04…2.00	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<100	<100	<500

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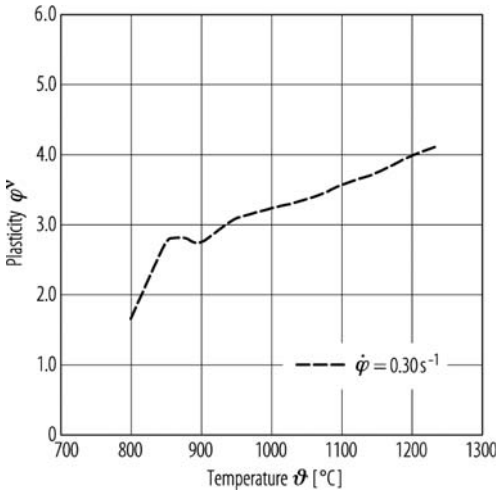
Fig. 5.311.
20MoCr5. Flow stress curves by hot and cold forming.



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Fig. 5.312.
20MoCr5. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as–cast and as-deformed state is: 0.60…0.85.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	41.53	474.84	10.89	7828.3	210.1
100	43.09	488.14	11.32	7801.7	204.8
200	42.98	501.45	12.05	7771.7	195.3
300	41.09	521.55	12.61	7739.5	184.9
400	38.5	545.97	13.13	7704.9	174.9
500	35.68	573.0	13.6	7668.0	165.2
600	32.81	602.14	14.18	7628.5	155.1
700	30.02	633.22	14.72	7586.3	142.3
800	23.51	696.55	12.97	7584.6	123.7
900	26.15	694.05	13.97	7532.9	
1000	27.82	691.56	14.88	7478.9	
1100	29.11	689.07	15.69	7422.8	
1200	30.45	686.59	16.45	7364.7	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: 20MoCr4/1.7321

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.17…0.23	0.00…0.40	0.70…1.00	0.000…0.035	0.000…0.035	0.30…0.60
Mo					
0.40…0.50					

International comparison of standards

ISO		Euronorm		
		20MoCr4	10263–3 (06/2001)	
		20MoCr4	10084 (04/1998)	
United Kingdom		Russia		
20MoCr4	EN 10263–3 (04/2001)			
20MoCr4	EN 10084 (04/1998)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS
∼ A 322 (4118)	A 322–01		∼ 4118 H	∼ G86200
∼ A 711 (4118)	A 711–01		∼ 4118 RH	∼ H41180

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

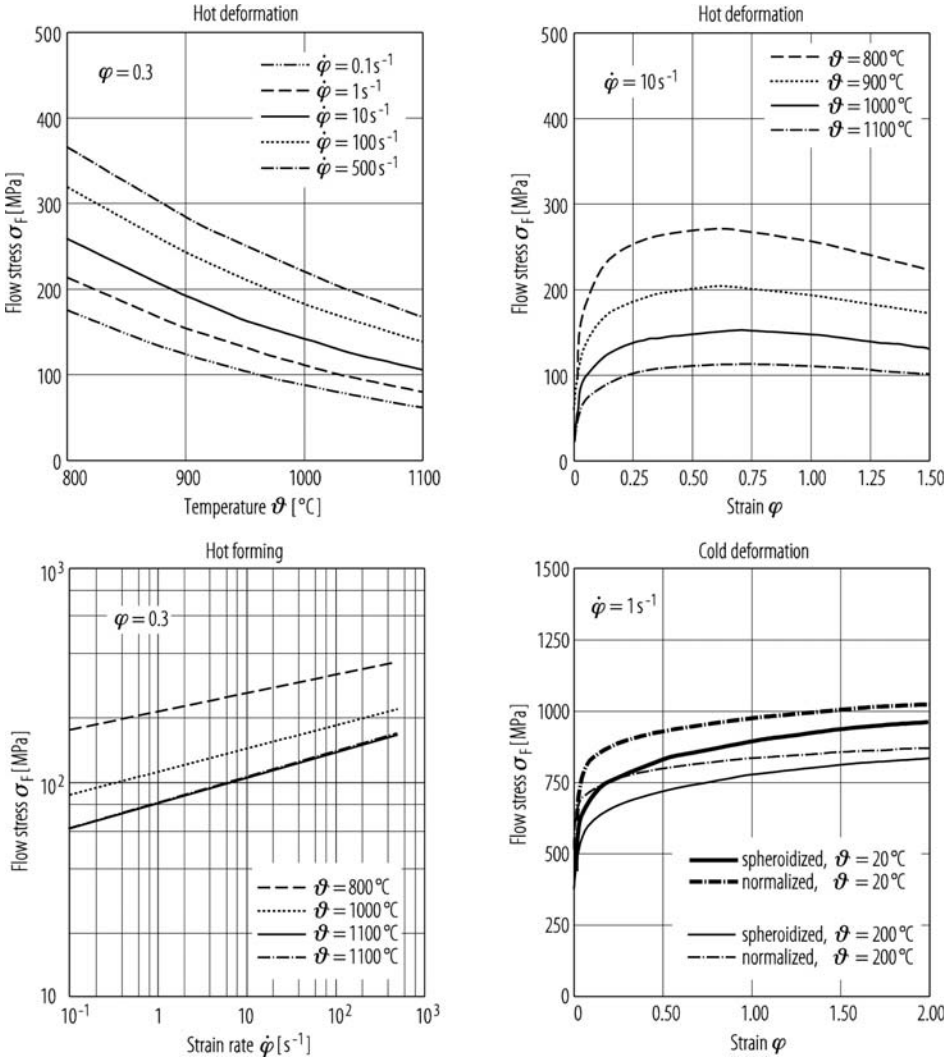
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	spheroidized	normalized
	austenite		
σ_{F0} [MPa]	115.60	702.5	860.4
A	4391.7	912.487	999.517
Effect of temperature K_ϑ			
m_1	−0.00341	−0.00082	−0.00090
Effect of strain K_φ			
m_2	0.17999	0.10409	0.06355
m_4	−0.00567	−0.00116	−0.00097
m_5	0.00060		
m_7	−0.64343		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.00267	0.01049
m_8	0.000109		
Range of validity			
ϑ [°C]	800…1100	20…300	20…250
φ	0.04…1.50	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<100	<500

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Fig. 5.313.
20MoCr4. Flow stress curves by hot and cold forming.



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Physical properities

Temperature	Thermal conductivity-	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	44.86			7837.0	
100	45.06	493.36	11.55	7809.9	
200	44.72	499.97	12.23	7779.5	
300	42.68	519.98	12.77	7746.9	
400	40.0	544.30	13.29	7712.0	
500	37.01	571.2	13.8	7674.7	
600	34.02	600.27	14.34	7634.7	
700	31.12	631.24	14.89	7592.0	
800	23.76	694.96	12.46	7602.6	
900	26.23	692.46	13.38	7554.0	
1000	27.75	689.97	14.19	7503.3	
1100	28.90	687.49	14.94	7450.7	
1200	30.12	685.02	15.62	7396.3	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: 13CrMo4–5/1.7335

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.08…0.18	0.00…0.35	0.40…1.00	0.000…0.025	0.000…0.010	0.70…1.15
Mo	Cu	N			
0.40…0.60	0.00…0.30	0.000…0.012			

International comparison of standards

ISO		Euronorm		
~ 14CrMo4–5	9330–4 (2000)	13CrMo4–5	10028–2 (06/2003)	
~ 13CrMo4–5	9329–2 (1997)	13CrMo4–5	10216–2 (05/2002)	
United Kingdom		Russia		
13CrMo4–5	EN 10028–2 (06/2003)	~ 15ChM	4543 (1971)	
13CrMo4–5	EN 10216–2 (05/2002)	~ 12ChM	5520 (1979)	
Japan		China		
~ STPA 22	G 3458 (1988)	~ A30122	6479 (2000)	
~ STBA 22	G 3462 (1988)	~ 12CrMo	6479 (2000)	
USA				
ASTM		AISI	SAE	UNS
~ A 182 (F 12 Cl.1)	A 182–02			~ K11562
~ A 335 (P 12)	A 335–02			~ K11757

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

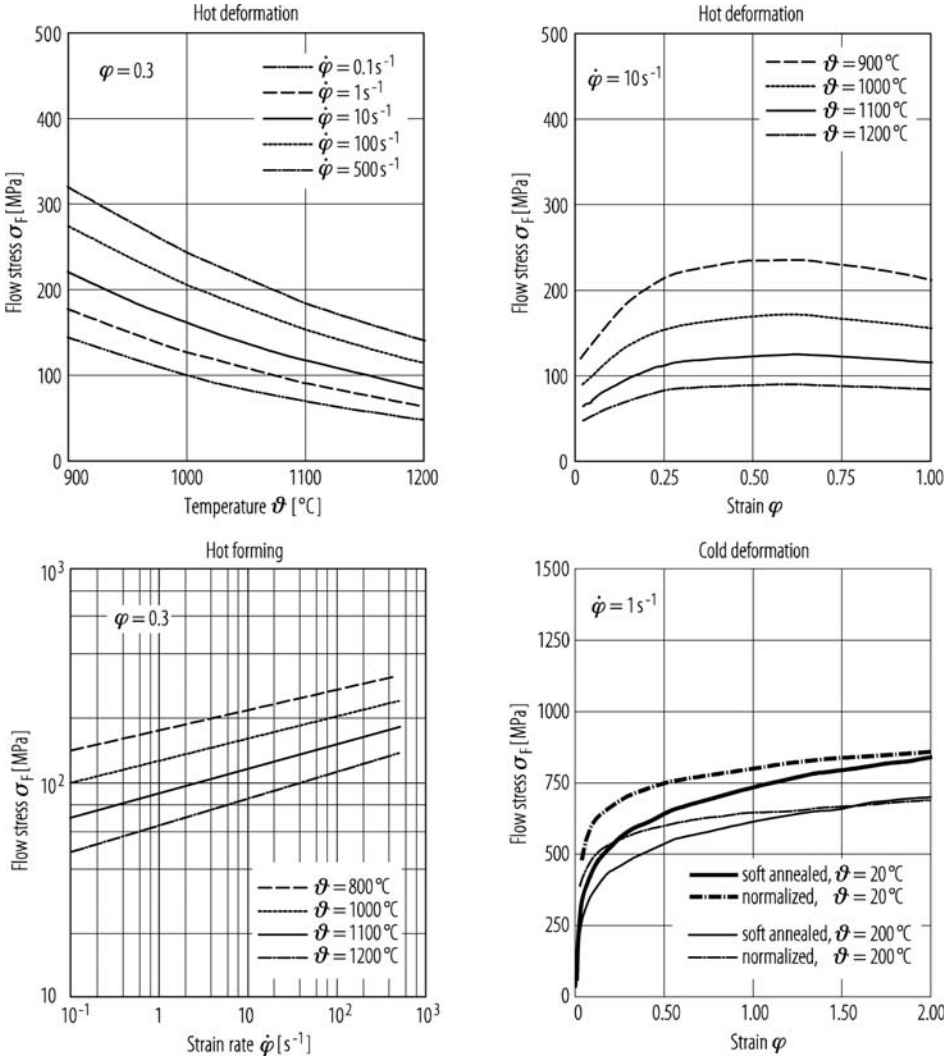
DOI: 10.1007/978-3-540-44760-3_169
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	normalized
	austenite		
σ_{F0} [MPa]	120.60	455.6	616.7
A	8362.2	761.050	831.317
Effect of temperature K_ϑ			
m_1	−0.00346	−0.00104	−0.00126
Effect of strain K_φ			
m_2	0.44741	0.17952	0.09132
m_4	0.00844	−0.01051	−0.00886
m_5	0.00017		
m_7	−0.88908		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.01136	0.01105
m_8	0.000104		
Range of validity			
ϑ [°C]	900…1200	20…300	20…250
φ	0.04…1.00	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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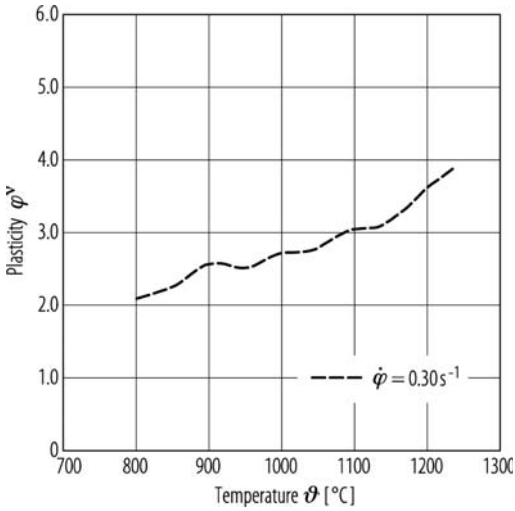
Fig. 5.314.
13CrMo4–5. Flow stress curves by hot and cold forming.



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Fig. 5.315.
13CrMo4–5. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.85.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	43.81	473.92	11.07	7845.6	213.0
100	44.46	487.32	11.49	7818.5	206.5
200	44.19	500.42	12.18	7788.2	200.0
300	42.20	520.45	12.73	7755.7	193.6
400	39.5	544.80	13.24	7720.9	185.8
500	36.61	571.8	13.8	7683.6	175.6
600	33.66	600.83	14.30	7643.7	162.2
700	30.79	631.83	14.84	7601.1	145.6
800	23.67	695.45	12.59	7608.5	125.9
900	26.20	692.95	13.53	7558.9	103.7
1000	27.76	690.46	14.37	7507.3	80.1
1100	28.96	687.98	15.14	7453.7	56.5
1200	30.21	685.51	15.84	7398.2	44.8

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Steel symbol/number: 10CrMo9–10/1.7380

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.08…0.14	0.00…0.50	0.40…0.80	0.000…0.020	0.000…0.010	2.00…2.50
Mo	Cu	Al			
0.90…1.10	0.00…0.30	0.000…0.070			

International comparison of standards

ISO		Euronorm		
~ C34AH	4991 (1994)	10CrMo9–10	10028–2 (06/2003)	
		10CrMo9–10	10216–2 (05/2002)	
United Kingdom		Russia		
10CrMo9–10	EN 10028–2 (06/2003)	~ 12Ch8	550 (1975)	
~ 622	3604 Part 2 (1991)			
Japan		China		
~ STBA 24	G 3462 (1988)	~ 12Cr2MoG	5310 (1995)	
~ SCPH 32–CF	G 5202 (1991)	~ A30138	5310 (1995)	
USA				
ASTM		AISI	SAE	UNS
~ A 182 (F 22 Cl.1+3)	A 182–02			~ K21390
~ A 335 (P 22)	A 335–02			~ K21590

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

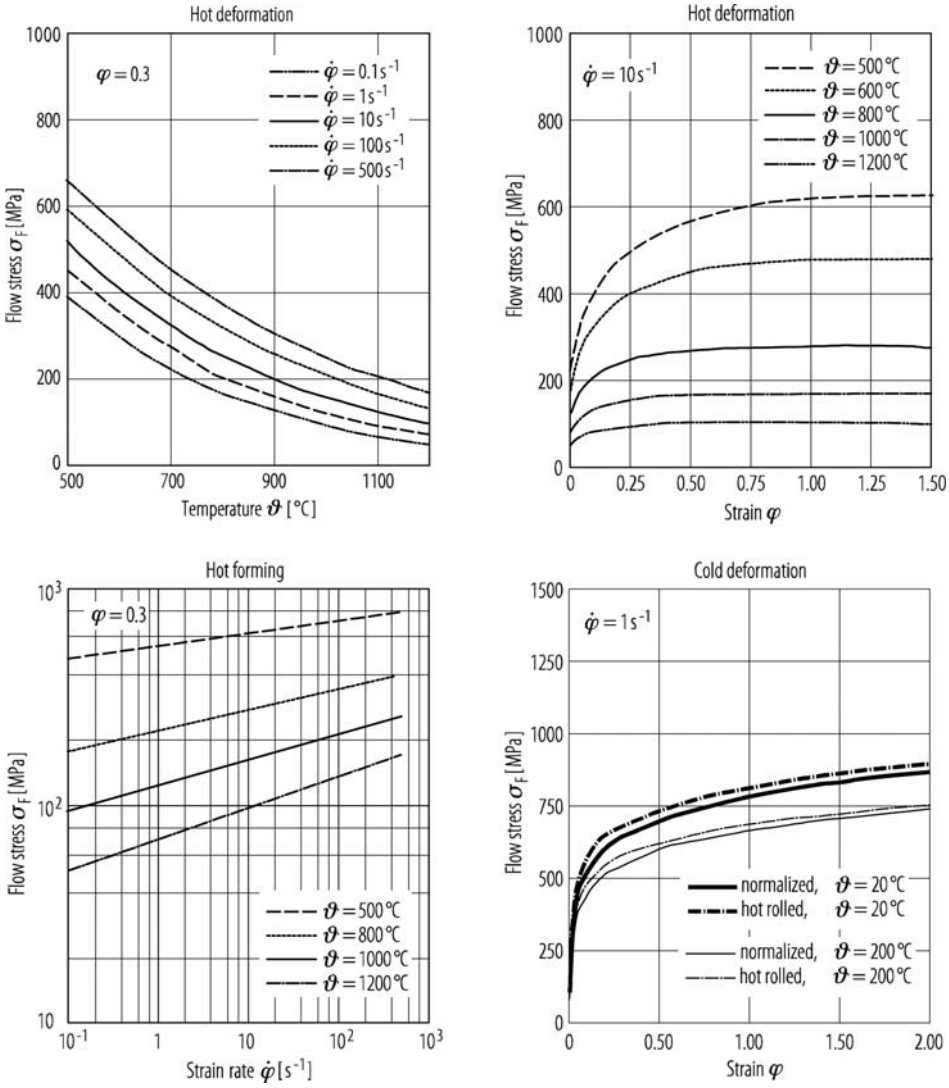
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Flow curves

	Hot deformation		Cold deformation	
	deformed state		normalized	hot rolled
State of material	austenite	ferrite+Fe_3C		
σ_{F0} [MPa]	129.36	(131.62)	517.9	577.6
A	2389.97	2423.24	801.28	838.246
Effect of temperature K_ϑ				
m_1	−0.00261	−0.00243	−0.00088	−0.00099
Effect of strain K_φ				
m_2	0.23900	0.3081	0.14846	0.12543
m_4	0.00091	0.00157	−0.00682	−0.00885
m_5	−0.00028	−0.00059		
m_7	−0.12539	−0.09275		
Effect of strain rate K_φ				
m_3			−0.00383	0.01072
m_8	0.000119	0.000120		
Range of validity				
ϑ [°C]	750…1200	500…700	20…250	20…250
φ	0.04…1.50	0.04…1.50	0.04…2.00	0.04…2.00
$\dot{\varphi}$ [s^{-1}]	<500	<500	<100	<500

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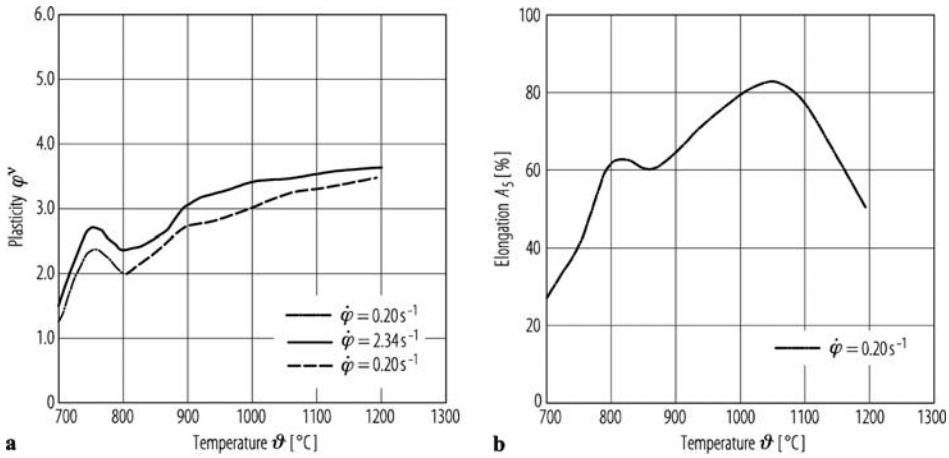
Fig. 5.316.
10CrMo9–10. Flow stress curves by hot and cold forming.



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Fig. 5.317.
10CrMo9–10. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	37.63	475.75	10.68	7842.3	213.8
100	37.20	489.25	11.13	7816.2	203.9
200	38.50	502.65	11.90	7786.4	197.6
300	38.50	522.82	12.46	7754.4	194.1
400	37.8	547.32	12.98	7720.2	190.4
500	36.76	574.4	13.5	7683.5	184.0
600	35.48	603.66	14.03	7644.3	173.7
700	34.08	634.83	14.57	7602.4	158.8
800	24.64	697.75	13.56	7587.1	139.7
900	26.45	695.25	14.66	7532.0	117.5
1000	27.84	692.75	15.64	7474.4	81.0
1100	29.18	690.26	16.53	7414.5	62.7
1200	30.69	687.78	17.36	7352.4	48.5

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Steel symbol/number: G X12CrMo10–1/1.7389

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.08…0.15	0.30…0.50	0.50…0.80	0.000…0.035	0.000…0.035	9.00…10.00
Mo					
1.10…1.40					

International comparison of standards

ISO		Euronorm		
United Kingdom		Russia		
~ B6	3100 (1991)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS
~ A 217 (C12)	A 217–02			~ J82090
~ A 426 (CP9)	A 426–02			

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

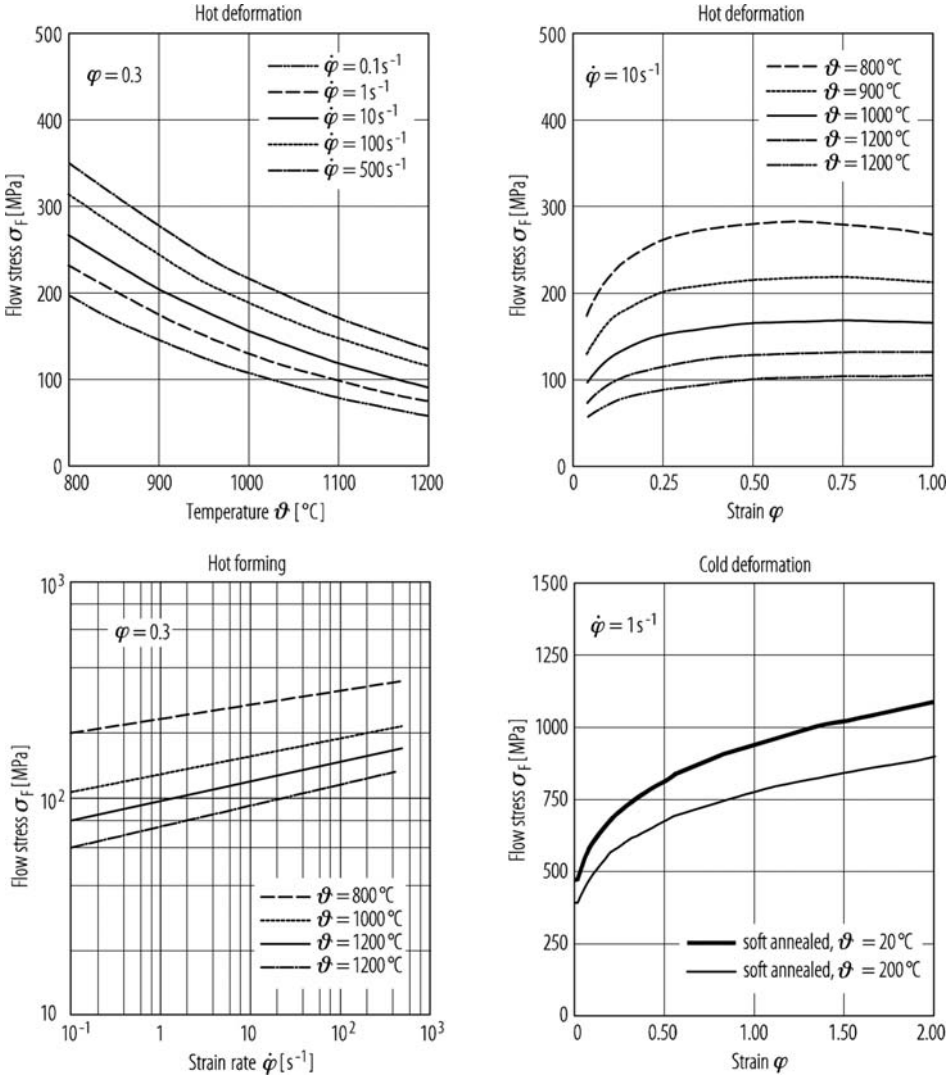
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	125.40	612.4
A	3577.4	960.206
Effect of temperature K_ϑ		
m_1	−0.00305	−0.00107
Effect of strain K_φ		
m_2	0.19026	0.20689
m_4	−0.00497	0.00223
m_5	0.00064	
m_7	−0.65187	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01117
m_8	0.000083	
Range of validity		
ϑ [°C]	800…1200	20…300
φ	0.04…1.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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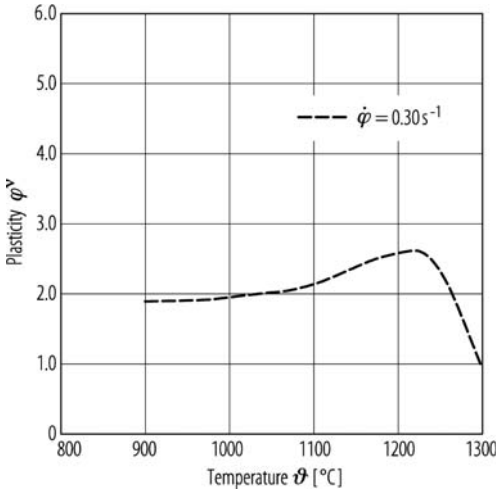
Fig. 5.318.
G X12CrMo10–1. Flow stress curves by hot and cold forming.



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Fig. 5.319.
G X12CrMo10–1. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.35…0.80.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	23.34	459.80	10.18	7783.0	
100	23.52	476.35	10.43	7758.7	
200	23.75	497.23	10.76	7734.3	
300	23.98	517.00	11.10	7705.2	
400	27.75	536.76	11.45	7676.0	
500	24.46	556.93	11.82	7645.1	
600	24.70	577.70	12.19	7612.3	
700	24.94	599.13	12.57	7577.5	
800	25.19	621.29	12.97	7540.7	
900	25.44	644.22	13.38	7501.8	
1000	25.69	667.97	13.80	7460.7	
1100	25.94	692.57	14.24	7417.3	
1200	26.20	718.05	14.69	7371.4	

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Steel symbol/number: X15CrMo5–1/1.7390

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.18	0.00…0.40	0.30…0.80	0.000…0.025	0.000…0.015	4.00…6.00
Mo					
0.45…0.65					

International comparison of standards

ISO		Euronorm		
		X15CrMo5–1	10269–8 (10/1999)	
United Kingdom		Russia		
X15CrMo5–1	EN 10269–8 (10/1999)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

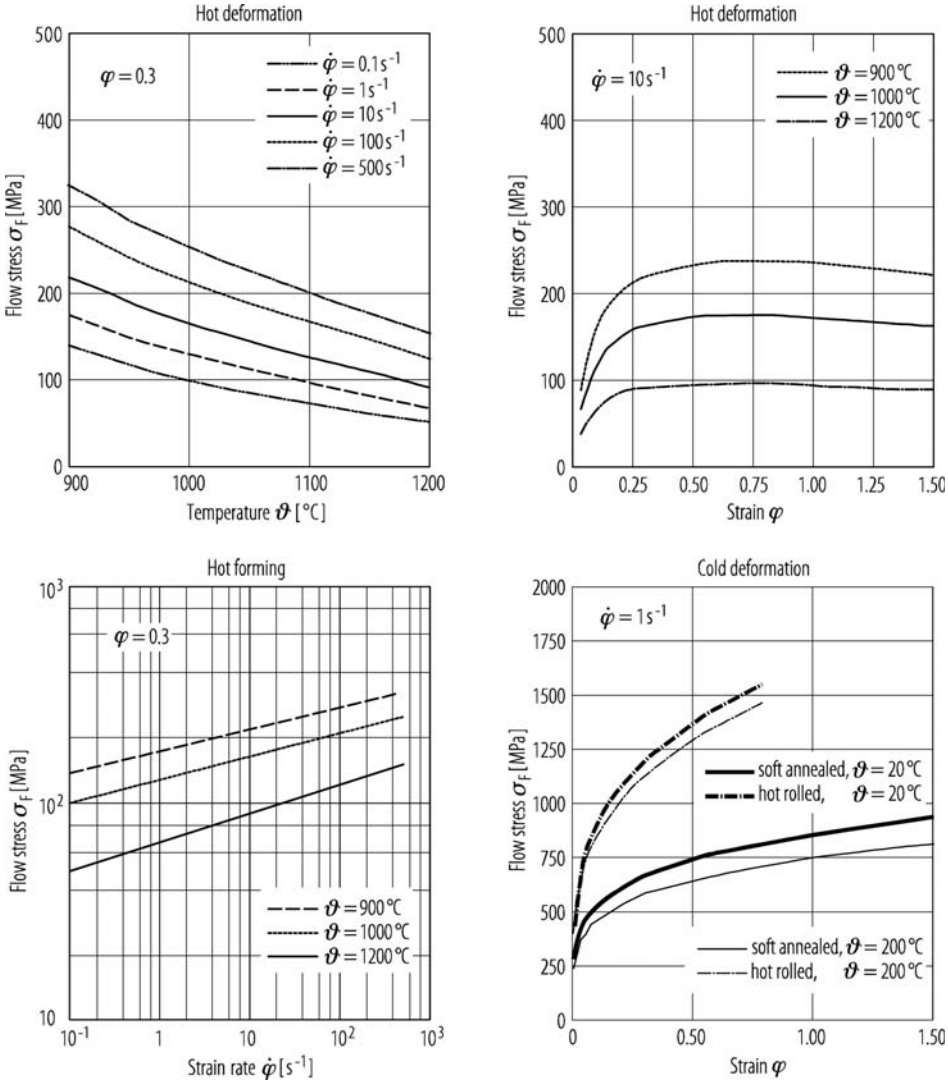
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Flow curves

State of material	Hot deformation	Cold deformation	
	deformed state	soft annealed	hot rolled
	austenite		
σ_{F0} [MPa]	119.94	556.2	924.1
A	4379.894	871.621	1648.293
Effect of temperature K_ϑ			
m_1	−0.00313	−0.00076	−0.00033
Effect of strain K_φ			
m_2	0.16537	0.21005	0.26337
m_4	−0.03031	−0.00022	0.00000
m_5	−0.00023		
m_7	−0.17006		
Effect of strain rate $K_{\dot\varphi}$			
m_3		0.02251	0.01235
m_8	0.000110		
Range of validity			
ϑ [°C]	900…1200	20…300	20…300
φ	0.04…1.50	0.04…1.50	0.04…0.80
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.320.
X15CrMo5–1. Flow stress curves by hot and cold forming.

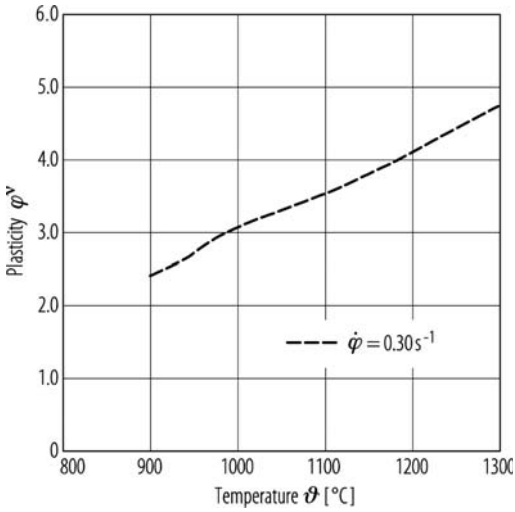


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Fig. 5.321.

X15CrMo5–1. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.70.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	20.78	448.30	10.18	7806.0	212.7
100	20.94	467.63	10.43	7741.0	208.2
200	21.15	486.02	10.76	7755.6	202.3
300	21.35	505.34	11.10	7728.0	195.1
400	21.56	524.65	11.45	7698.7	185.8
500	21.78	544.38	11.82	7667.7	173.9
600	21.99	564.67	12.19	7634.8	159.2
700	22.21	585.62	12.57	7599.9	141.5
800	22.43	607.28	12.97	7563.0	121.2
900	22.65	629.70	13.38	7524.0	100.8
1000	22.87	652.91	13.80	7482.8	80.1
1100	23.10	676.95	14.24	7439.2	59.1
1200	23.32	701.86	14.69	7393.2	40.7

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: 30CrMoV9/1.7707

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.26…0.34	0.00…0.40	0.40…0.70	0.000…0.035	0.000…0.035	2.30…2.70
Mo	Ni	V			
0.15…0.25	0.00…0.60	0.10…0.20			

International comparison of standards

ISO		Euronorm		
		30CrMoV9	10250–3 (10/1999)	
United Kingdom		Russia		
30CrMoV9	EN 10250–3 (10/1999)	~ 30Ch3MF	4543 (1971)	
Japan		China		
USA				
ASTM		AMS	SAE	UNS
~ A 29 (E 4340)	A 29–99–	~ 6109B	~ E4340	~ G43406
~ A 331 (E4340)	A 331–00	~ 6415P		~ K21590

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

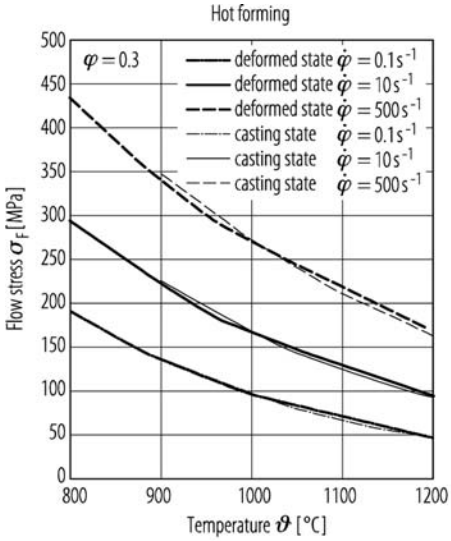
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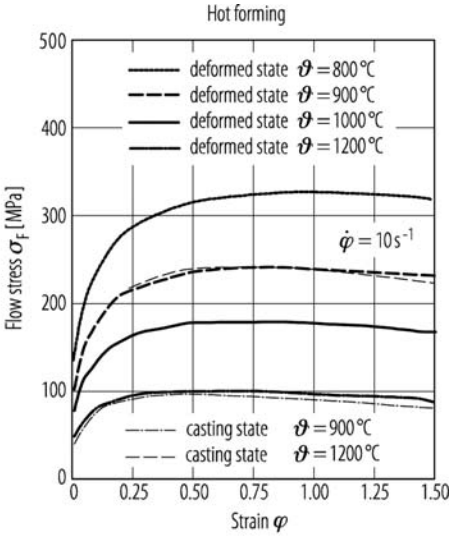
Flow curves

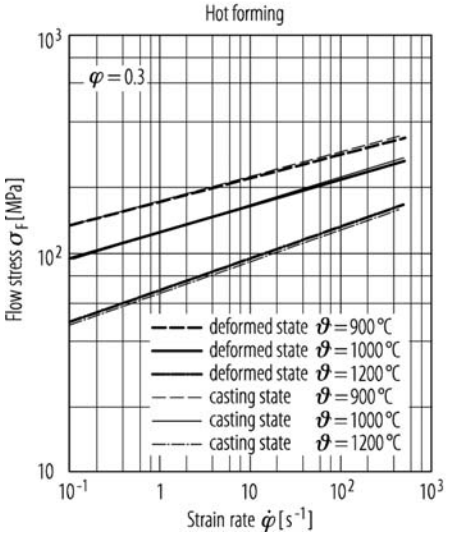
	Hot deformation		Cold deformation
	deformed state	casting state	
State of material	austenite	austenite	
σ_{F0} [MPa]	135.32	133.4	
A	4190.42	5147.57	
Effect of temperature K_ϑ			
m_1	−0.00295	−0.00307	
Effect of strain K_φ			
m_2	0.30810	0.34836	
m_4	0.00157	0.00173	
m_5	−0.00059	−0.00068	
m_7	−0.09275	−0.13863	
Effect of strain rate $K_{\dot\varphi}$			
m_3			
m_8	0.000120	0.000122	
Range of validity			
ϑ [°C]	800…1150	900…1200	
φ	0.04…1.50	0.04…1.50	
$\dot\varphi$ [s^{-1}]	<500	<500	

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Fig. 5.322.
30CrMoV9. Flow stress curves by hot forming.



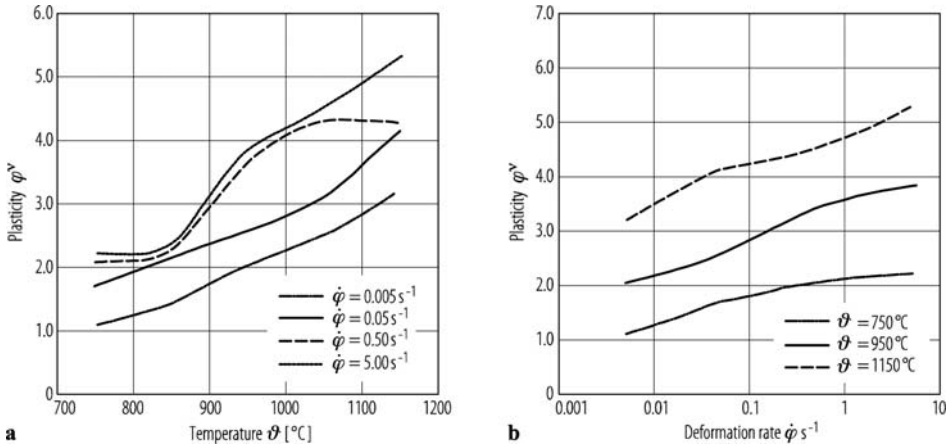




DOI: 10.1007/978-3-540-44760-3_173
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Fig. 5.323.
30CrMoV9. Hot plasticity as a function of the temperature and deformation rate. (a) Deformed state. Direct heating on deformation temperature. (b) Deformation rate: 0.2 [s^{-1}]. Deformed state. Direct heating on deformation temperature.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	35.46	476.57	10.50	7814.9	
100	35.82	490.84	10.97	7789.1	
200	37.18	503.63	11.76	7759.7	
300	37.22	523.88	12.33	7728.2	
400	36.6	548.44	12.85	7694.3	
500	35.57	575.6	13.4	7658.1	
600	34.34	604.93	13.90	7619.4	
700	32.98	636.18	14.43	7578.0	
800	25.20	698.69	14.19	7548.7	
900	26.63	696.18	15.37	7490.5	
1000	27.69	693.68	16.43	7429.6	
1100	28.72	691.19	17.40	7366.1	
1200	29.95	688.71	18.29	7300.3	

DOI: 10.1007/978-3-540-44760-3_173
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Steel symbol/number: 14MoV6–3/1.7715

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.10…0.18	0.00…0.40	0.40…0.70	0.000…0.025	0.000…0.015	0.30…0.60
Mo	V	Al	Sn		
0.50…0.70	0.22…0.28	0.000…0.020	0.000…0.025		

International comparison of standards

ISO		Euronorm		
		14MoV–3	10216–2 (05/2002)	
		14MoV–3	10222–2 (02/2000)	
United Kingdom		Russia		
14MoV6–3	EN 10216–2 (05/2002)			
14MoV–3	EN 10222–2 (02/2000)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS
				~ K11591

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

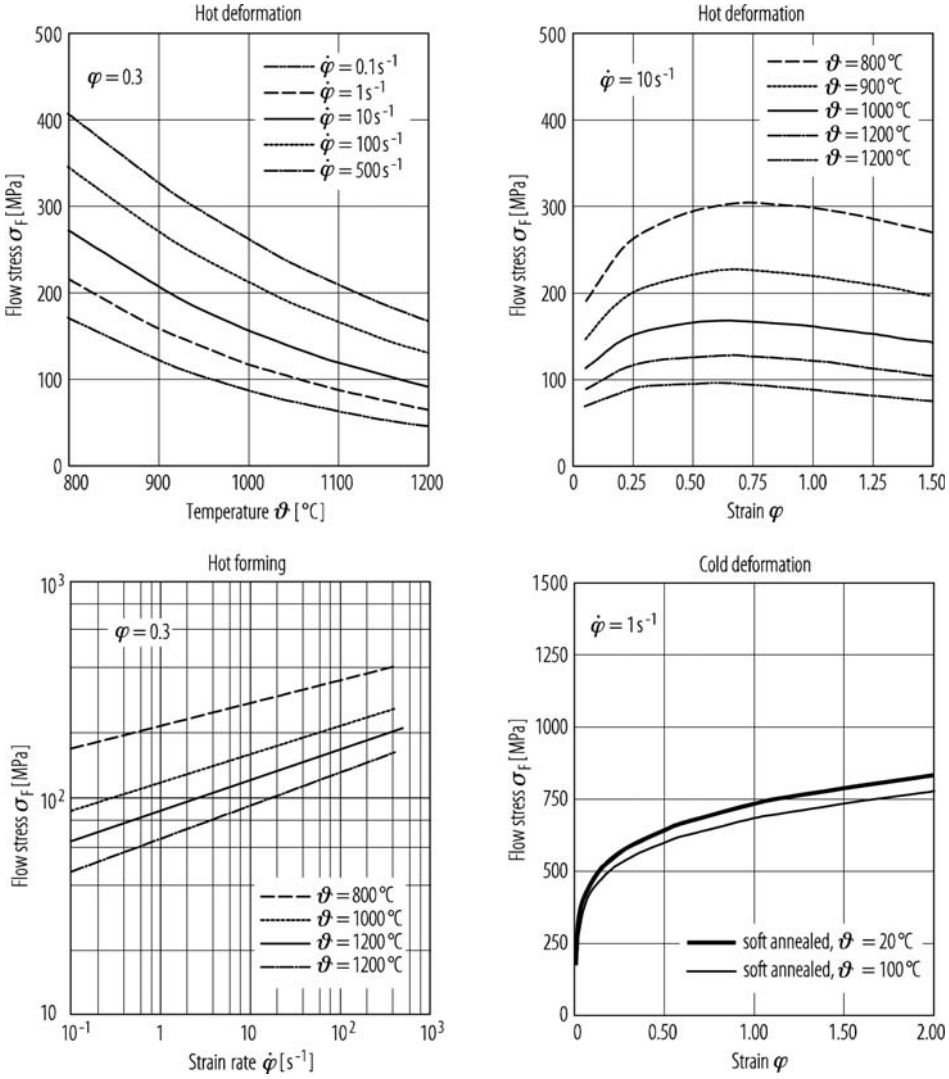
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	124.12	492.6
A	4626.87	749.435
Effect of temperature K_ϑ		
m_1	−0.00284	−0.00089
Effect of strain K_φ		
m_2	0.51783	0.17966
m_4	0.021996	−0.00303
m_5	−0.00069	
m_7	−0.34993	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01831
m_8	0.000128	
Range of validity		
ϑ [°C]	800…1200	20…120
φ	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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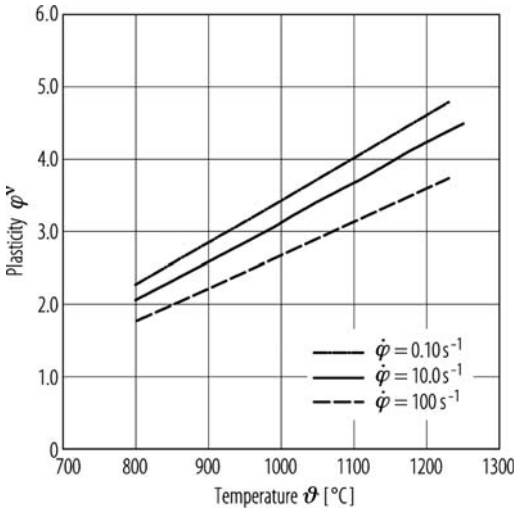
Fig. 5.324.
14MoV6–3. Flow stress curves by hot and cold forming.



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Fig. 5.325.
14MoV6–3. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.80.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	44.52	473.73	11.12	7852.7	212.8
100	44.87	486.93	11.53	7825.6	208.6
200	44.55	500.11	12.22	7795.2	201.6
300	42.53	520.13	12.76	7762.6	193.8
400	39.8	544.46	13.28	7727.6	185.9
500	36.88	571.4	13.8	7690.2	177.9
600	33.91	600.44	14.33	7650.2	169.3
700	31.01	631.42	14.87	7607.5	145.9
800	23.73	695.12	12.50	7617.1	127.7
900	26.22	692.62	13.42	7568.1	101.8
1000	27.75	690.13	14.25	7517.1	80.3
1100	28.92	687.65	15.00	7464.1	60.3
1200	30.15	685.18	15.69	7409.3	41.4

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Steel symbol/number: 20CrMoV13–5/1.7779

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.17…0.23	0.15…0.35	0.30…0.50	0.000…0.025	0.000…0.020	3.00…3.30
Mo	Ni	V	Al	Cu	
0.50…0.60	0.00…0.30	0.45…0.55	0.000…0.040	0.00…0.30	

International comparison of standards

ISO		Euronorm		
		20CrMoV13–5–5	10216–2 (05/2002)	
United Kingdom		Russia		
20CrMoV13–5–5	EN 10216–2 (05/2002)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

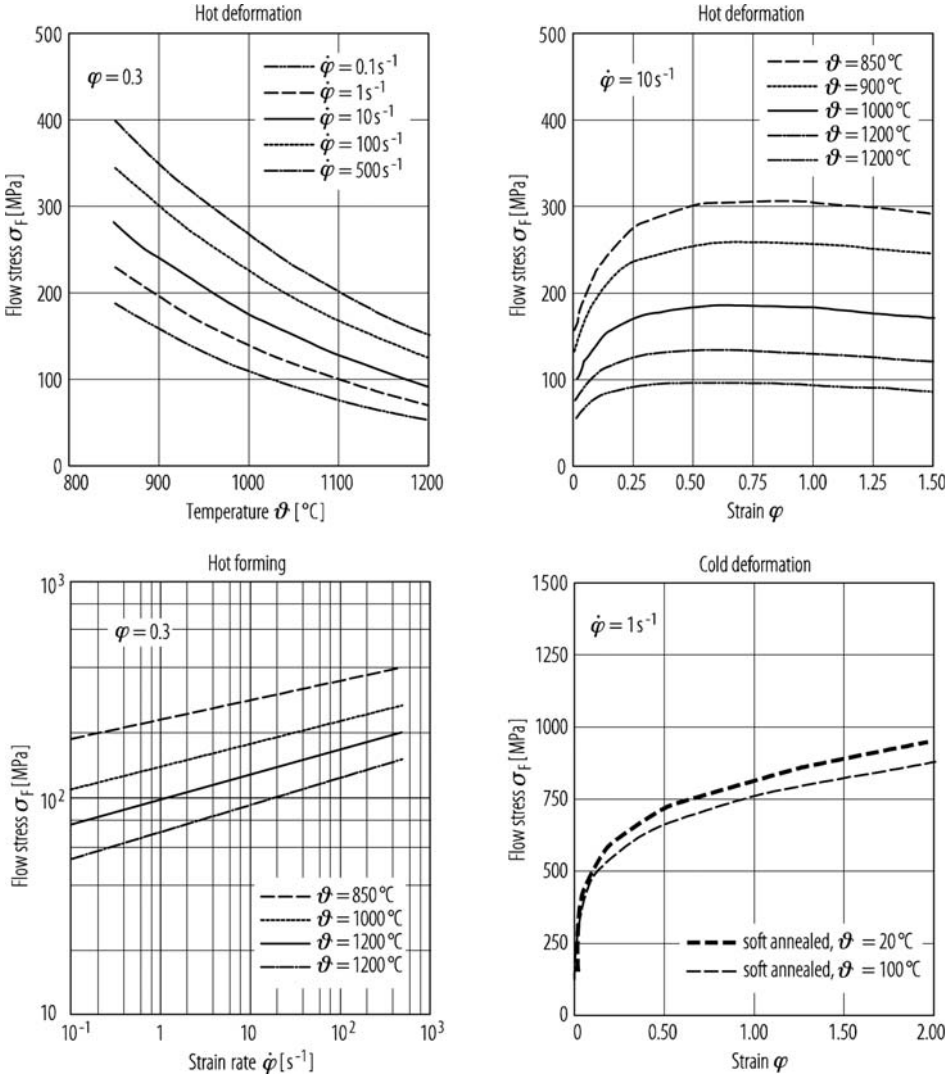
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation soft annealed
σ_{F0} [MPa]	144.32	518.6
A	6047.78	843.245
Effect of temperature K_ϑ		
m_1	−0.00324	−0.00102
Effect of strain K_φ		
m_2	0.30298	0.19674
m_4	0.00278	−0.00456
m_5	−0.00056	
m_7	−0.11673	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.01428
m_8	0.000104	
Range of validity		
ϑ [°C]	850…1200	20…120
φ	0.04…1.50	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500

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Fig. 5.326.
20CrMoV13–5. Flow stress curves by hot and cold forming.

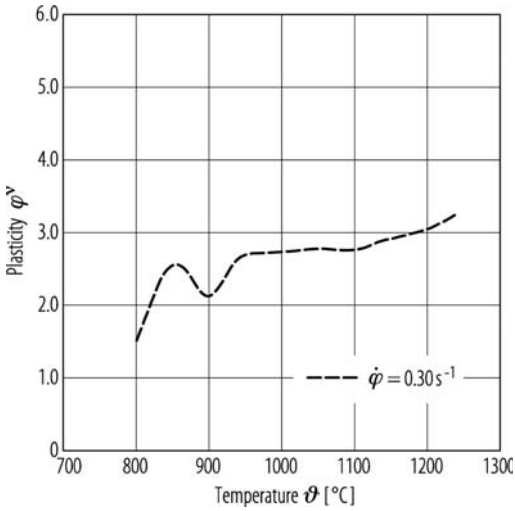


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Fig. 5.327.

20CrMoV13–5. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.70.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	33.96	477.04	10.38	7820.5	
100	34.85	490.49	10.86	7795.0	
200	36.25	504.32	11.66	7765.8	
300	36.31	524.61	12.23	7734.4	
400	35.7	549.22	12.76	7700.8	
500	34.73	576.5	13.3	7664.8	
600	33.53	605.81	13.80	7626.3	
700	32.21	637.12	14.33	7585.1	
800	26.16	699.32	14.72	7544.3	
900	27.33	696.81	15.97	7483.4	
1000	28.16	694.30	17.09	7419.6	
1100	28.99	691.81	18.11	7353.1	
1200	30.05	689.32	19.06	7284.0	

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Steel symbol/number: 10MnCrMoV5–5–5–2/1.7950

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.00…0.12	0.15…0.30	1.10…1.60	0.000…0.015	0.000…0.011	0.0200…0.050
Cr	Mo	V			
1.00…1.60	0.30…0.60	0.12…0.25			

International comparison of standards

ISO		Euronorm	
United Kingdom		Russia	
Japan		China	
USA			
ASTM	AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

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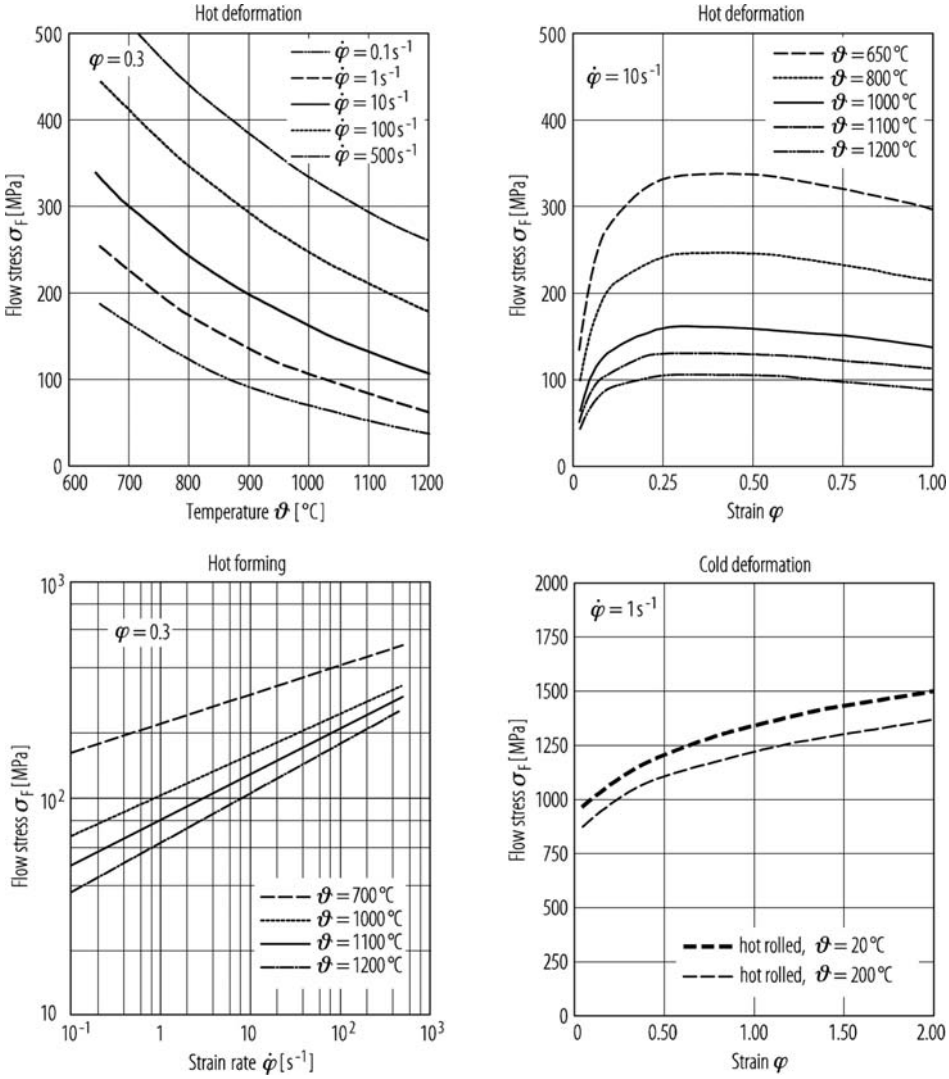
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Flow curves

State of material	Hot deformation	Cold deformation
	deformed state	hot rolled
	austenite	
σ_{F0} [MPa]	133.90	1012.7
A	2052.23	1347.512
Effect of temperature K_ϑ		
m_1	−0.00247	−0.00054
Effect of strain K_φ		
m_2	0.21986	0.15862
m_4	−0.01192	0.00679
m_5	−0.00024	
m_7	−0.48728	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00977
m_8	0.000190	
Range of validity		
ϑ [°C]	640…1150	20…120
φ	0.04…1.00	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500

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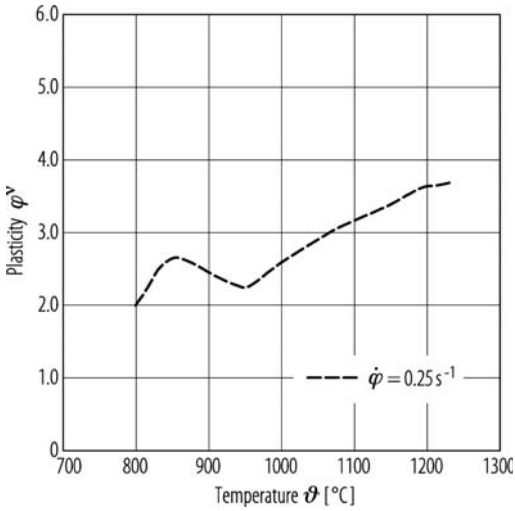
Fig. 5.328.
10MnCrMoV5–5–5–2. Flow stress curves by hot and cold forming.



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Fig. 5.329.
10MnCrMoV5–5–5–2. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.80.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	41.14	474.95	10.86	7835.5	
100	42.84	488.60	11.30	7808.9	
200	42.76	501.64	12.03	7778.9	
300	40.89	521.75	12.58	7746.7	
400	38.3	546.18	13.11	7712.2	
500	35.51	573.2	13.6	7675.3	
600	32.66	602.38	14.16	7635.8	
700	29.88	633.47	14.70	7593.6	
800	23.49	696.75	13.05	7590.0	
900	26.15	694.24	14.07	7537.8	
1000	27.83	691.75	14.98	7483.3	
1100	29.14	689.26	15.81	7426.6	
1200	30.50	686.78	16.58	7367.9	

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Steel symbol/number: 10CrSiMoV7/1.8075

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.12	0.90…1.20	0.35…0.75	0.000…0.035	0.000…0.035	1.60…2.00
Mo	V				
0.25…0.35	0.25…0.35				

International comparison of standards

ISO		Euronorm	
United Kingdom		Russia	
Japan		China	
USA			
ASTM	AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

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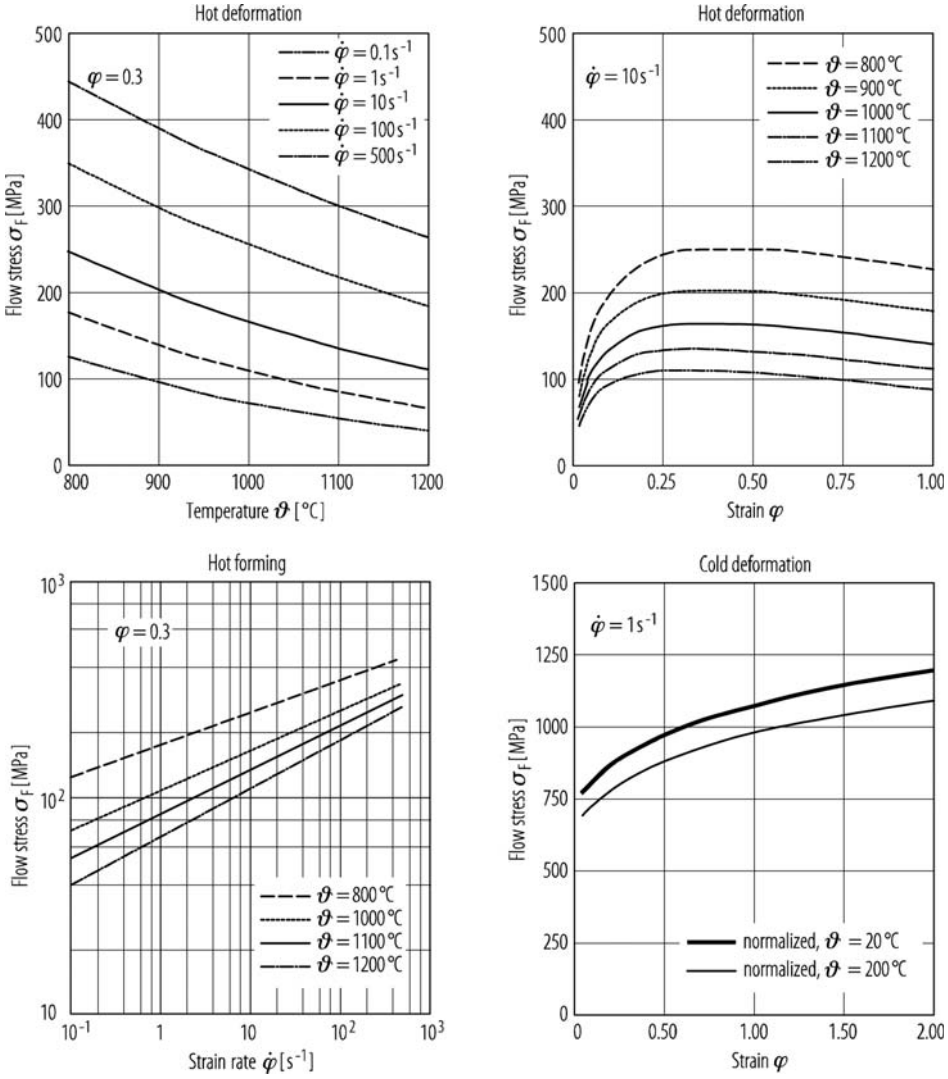
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Flow curves

State of material	Hot deformation deformed state austenite	Cold deformation normalized
σ_{F0} [MPa]	139.76	812.7
A	1991.1	1081.389
Effect of temperature K_ϑ		
m_1	−0.00225	−0.00054
Effect of strain K_φ		
m_2	0.29281	0.15862
m_4	−0.00909	0.00679
m_5	−0.00077	
m_7	−0.28533	
Effect of strain rate $K_{\dot\varphi}$		
m_3		0.00977
m_8	0.000186	
Range of validity		
ϑ [°C]	800…1200	20…250
φ	0.04…1.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<100

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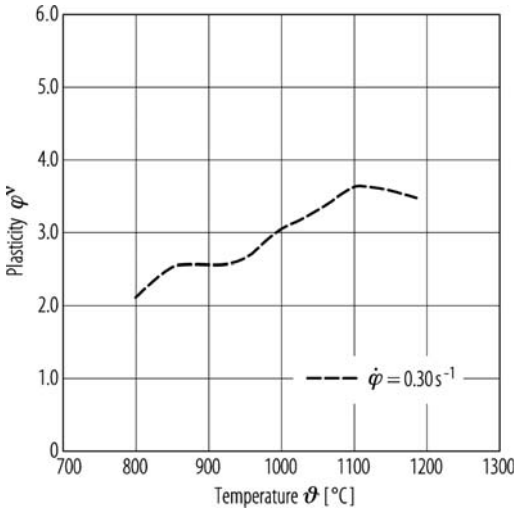
Fig. 5.330.
10CrSiMoV7. Flow stress curves by hot and cold forming.



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Fig. 5.331.
10CrSiMoV7. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.50…0.80.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	36.22	474.88	10.86	7778.5	
100	36.31	488.31	11.03	7752.8	
200	37.65	503.28	11.81	7723.4	
300	37.68	523.50	12.37	7691.9	
400	37.0	548.05	12.90	7658.1	
500	36.00	575.2	13.4	7621.9	
600	34.75	604.48	13.95	7583.3	
700	33.37	635.70	14.48	7541.9	
800	24.90	698.37	13.95	7518.0	
900	26.46	695.86	15.10	7461.3	
1000	27.64	693.36	16.13	7402.0	
1100	28.77	690.87	17.07	7340.3	
1200	30.10	688.38	17.94	7276.2	

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Russian standards such as GOST 5632-72, TU 14-1-5241-93,TU 5.961-11804-2002, TU14-1-5477-2004 and so on.

Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: 51CrV4/1.8159

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.47…0.55	0.00…0.40	0.70…1.10	0.000…0.035	0.000…0.035	0.90…1.20
V					
0.10…0.25					

International comparison of standards

ISO		Euronorm		
~ 51CrV4	683–18 (1996)	51CrV4	10089 (12/2002)	
~ FDCrV–A	8458-3 (2002)	51CrV4	10250–3 (10/1999)	
United Kingdom		Russia		
51CrV4	EN 10089 (12/2002)	~50ChFA	14959 (1979)	
~ 735 H 51	970 Part 2 (1988)	~50ChGFA	14959 (1979)	
Japan		China		
~SUP 10 M	G3311 (1998)	~ 50CrVA	T 8162 (1999)	
~SUP 10–CSP	G4802 (1999)	~ A23503	T 8162 (1999)	
USA				
ASTM		AISI	SAE	UNS
~A 29 (6150)	A 29–99	~ 6145	~ 6145	~G61500
~A 304 (6150 H)	A 304–02			~H61500

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

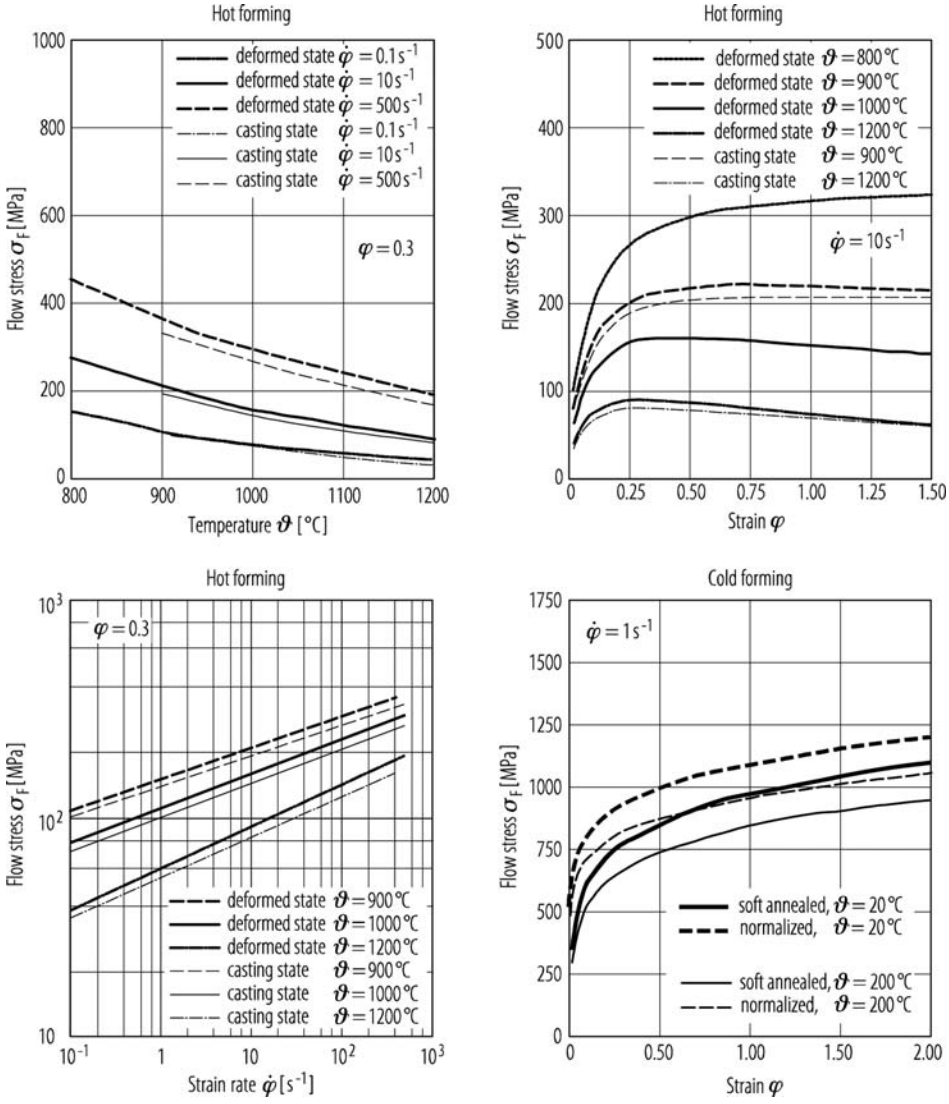
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Flow curves

	Hot deformation		Cold deformation	
	deformed state	casting state	soft annealed	normalized
State of material	austenite	austenite		
σ_{F0} [MPa]	122.84	111.81	630.4	826.2
A	3840.05	3909.21	997.51	1111.371
Effect of temperature K_ϑ				
m_1	−0.00260	−0.00274	−0.00080	−0.00076
Effect of strain K_φ				
m_2	0.44666	0.43209	0.17008	0.13238
m_4	−0.00279	−0.00355	−0.00818	0.00008
m_5	−0.00203	−0.00188		
m_7	0.41373	0.38379		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.01324	0.00986
m_8	0.000159			
Range of validity				
ϑ [°C]	800…1200	900…1200	20…300	20…300
φ	0.04…1.50	0.04…1.50	0.04…2.00	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<100	<100

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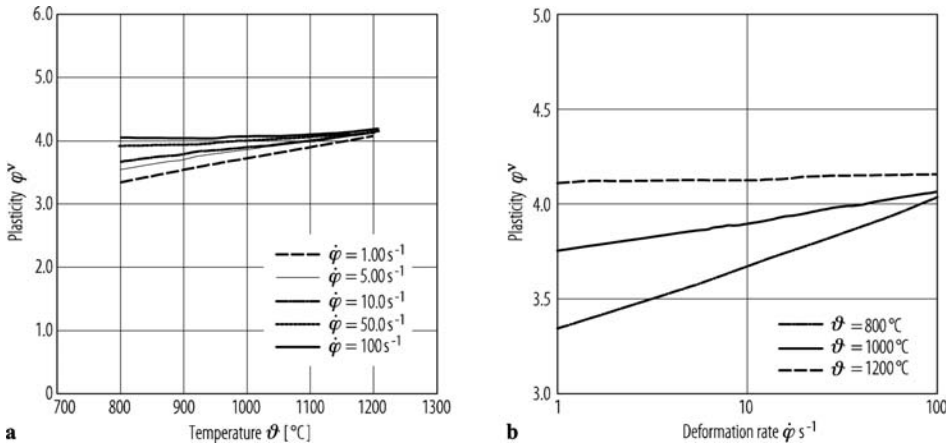
Fig. 5.332.
51CrV4. Flow stress curves by hot and cold forming.



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Fig. 5.333.
51CrV4. Hot plasticity as a function of the temperature. (a) Deformed state. Direct heating on deformation temperature. (b) Deformed state. Direct heating on deformation temperature.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	39.29	476.22	10.56	7826.1	
100	41.64	489.87	11.14	7799.9	
200	41.69	502.60	11.90	7770.2	
300	39.91	522.77	12.46	7738.3	
400	37.4	547.27	12.99	7704.1	
500	34.69	574.4	13.5	7667.5	
600	31.91	603.60	14.04	7628.3	
700	29.20	634.77	14.58	7586.5	
800	23.39	697.71	13.53	7571.9	
900	26.15	695.20	14.62	7517.0	
1000	27.93	692.70	15.60	7459.7	
1100	29.33	690.21	16.49	7400.1	
1200	30.77	687.73	17.31	7338.3	

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Steel symbol/number: 34CrAlNi7–10/1.8550

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.30…0.37	0.00…0.40	0.40…0.70	0.000…0.025	0.000…0.030	1.50…1.80
Mo	Ni	Al			
0.15…0.25	0.85…1.15	0.80…1.20			

International comparison of standards

ISO		Euronorm		
		34CrAlNi7	10085 (03/2001)	
United Kingdom		Russia		
34CrAlNi7	EN 10085 (03/2001)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS
∼A 355 (C)	A 355–00			∼K52440

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

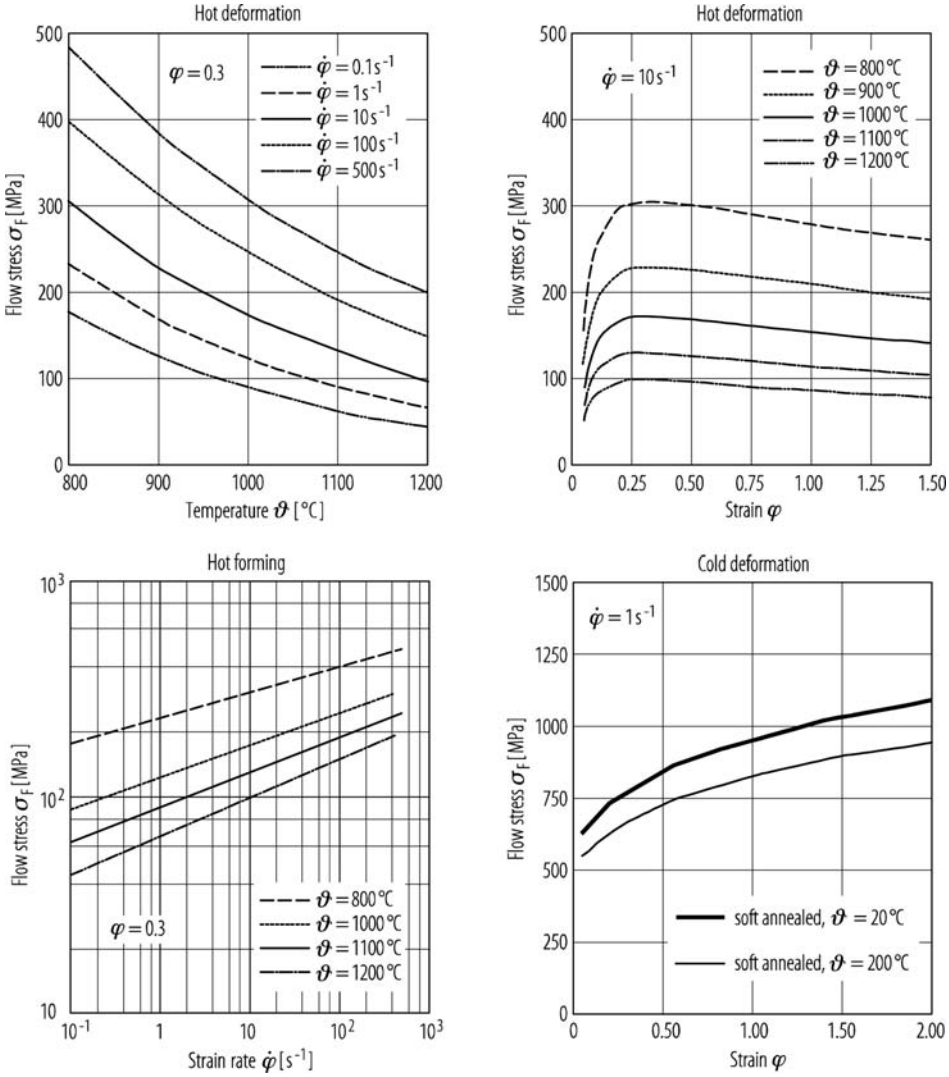
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Flow curves

State of material	Hot deformation	Cold deformation
	deformed state	soft annealed
	austenite	
σ_{F0} [MPa]	140.19	677.86
A	3025.99	962.310
Effect of temperature K_ϑ		
m_1	−0.00309	−0.00079
Effect of strain K_φ		
m_2	−0.11351	0.19394
m_4	−0.05601	0.00856
m_5	−0.00027	
m_7	0.01714	
Effect of strain rate K_φ		
m_3		0.01145
m_8	0.000148	
Range of validity		
ϑ [°C]	800…1200	20…300
φ	0.04…1.50	0.04…2.00
$\dot{\varphi}$ [s^{-1}]	<500	<500

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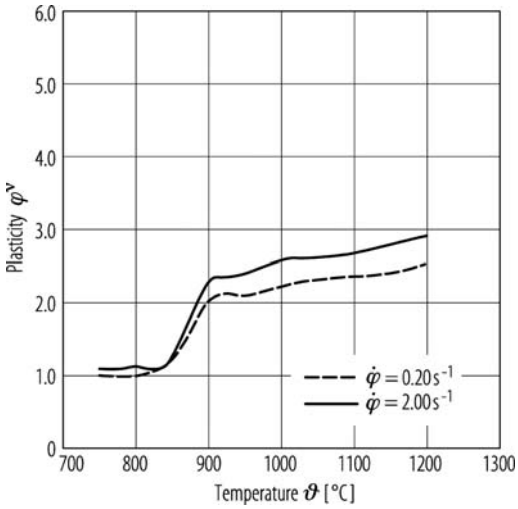
Fig. 5.334.
34CrAlNi7–10. Flow stress curves by hot and cold forming.



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Fig. 5.335.
34CrAlNi7–10. Hot plasticity as a function of the temperature. Deformed state. Direct heating on deformation temperature. Note: At hot deformation the relation of plasticity between as-cast and as-deformed state is: 0.40…0.75.

Plasticity in torsion



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Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	31.52	477.86	10.17	7768.2	
100	33.21	491.55	10.66	7743.4	
200	34.67	505.45	11.49	7714.7	
300	34.78	525.83	12.06	7683.9	
400	34.2	550.52	12.59	7650.9	
500	33.29	577.8	13.1	7615.5	
600	32.15	607.29	13.62	7577.7	
700	30.89	638.69	14.15	7537.4	
800	29.02	700.30	15.76	7474.5	
900	29.73	697.79	17.13	7408.9	
1000	30.15	695.28	18.38	7340.0	
1100	30.64	692.78	19.51	7268.2	
1200	31.42	690.29	20.55	7193.6	

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Steel symbol/number: S420N/1.8902

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.20	0.00…0.60	1.00…1.70	0.000…0.035	0.000…0.030	0.00…0.30
Mo	Ni	V	Al	Cu	Nb
0.00…0.10	0.00…0.80	0.00…0.20	>0.020	0.00…0.70	0.000…0.025
Ti	N	B	Zr		
0.00…0.03					

International comparison of standards

ISO		Euronorm		
~E420 CC	4951–2 (2001)	S420N	EN 10113–2 (03/1993)	
United Kingdom		Russia		
S420N	EN 10113–2 (03/1993)	~16G2AF	19281 (1989)	
Japan		China		
~SM 490 YB	G 3106 (1999)	~Q 420 C	T 16270 (1996)	
USA				
ASTM		AISI	SAE	UNS
~A 350 (LF6)	A 350–02			~K12202

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

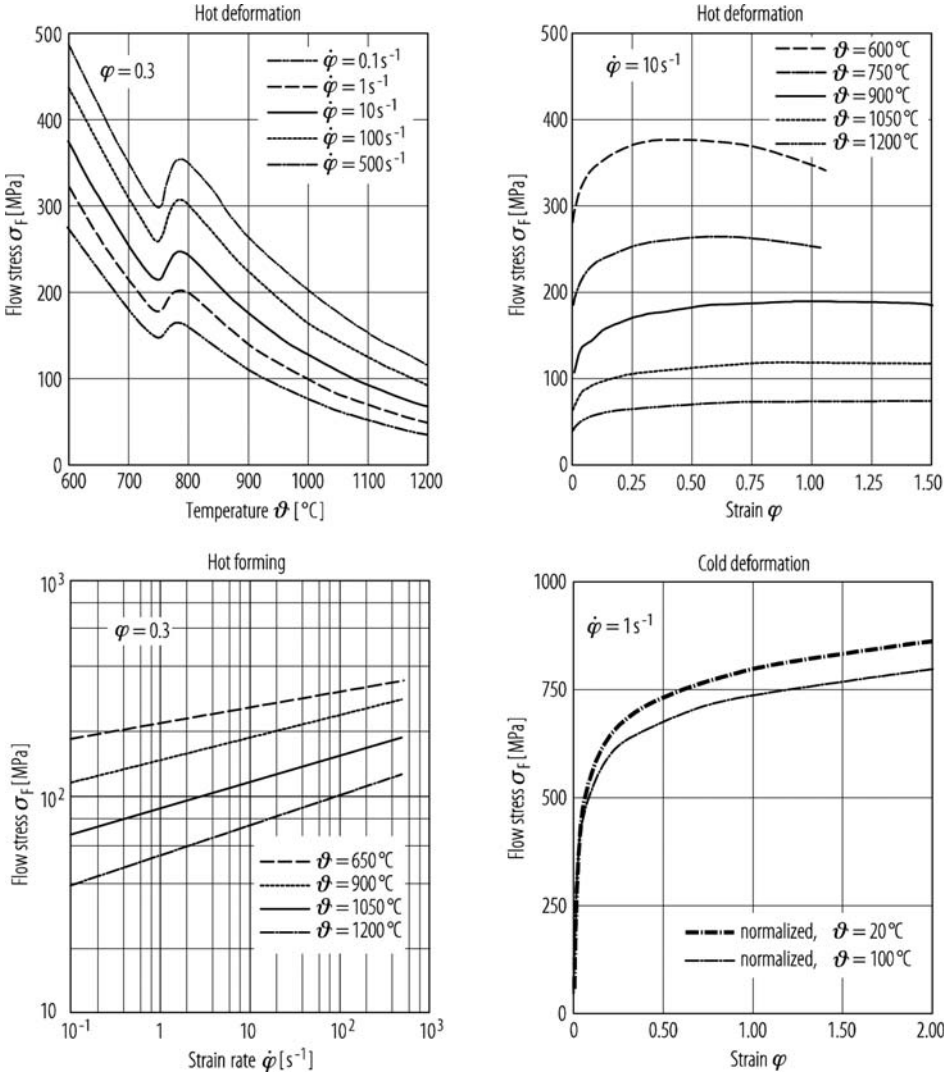
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Flow curves

State of material	Hot deformation		Cold deformation
	deformed state		normalized
	austenite	ferrite+Fe_3C	
σ_{F0} [MPa]	109.7	(68.6)	570.7
A	3870.45	4927.16	823.56
Effect of temperature K_ϑ			
m_1	−0.00349	−0.00438	−0.00102
Effect of strain K_φ			
m_2	0.14056	0.08306	0.09804
m_4	0.000029	0.00022	−0.01329
m_5	0.00012	0.00142	
m_7	−0.19306	−0.76953	
Effect of strain rate $K_{\dot\varphi}$			
m_3			0.00533
m_8	0.000115	0.000112	
Range of validity			
ϑ [°C]	790…1200	600…750	20…120
φ	0.04…1.50	0.04…1.00	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500	<100

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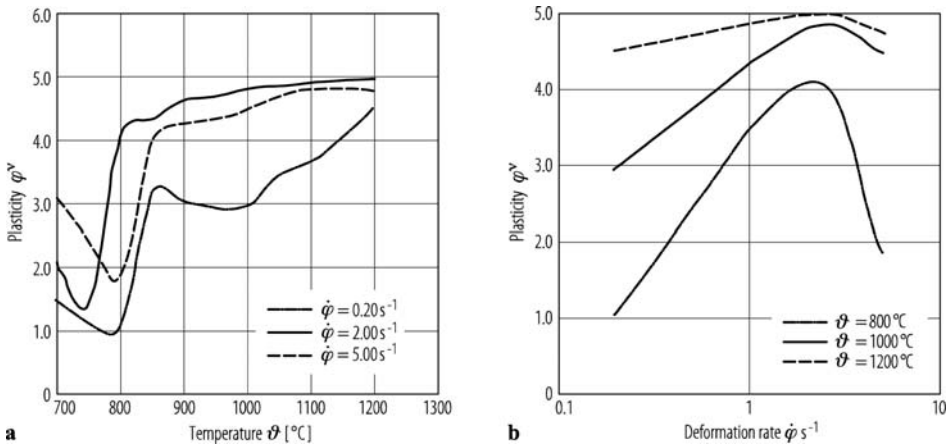
Fig. 5.336.
S420N. Flow stress curves by hot and cold forming.



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Fig. 5.337.
S420N. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Austenitised at 1150 [°C].

Plasticity by torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	50.57	447.7	11.05	7840.1	
100	47.86	493.9	11.47	7813.6	
200	46.34	500.5	12.17	7786.6	
300	43.19	520.6	12.71	7750.9	
400	39.48	544.9	13.23	7716.1	
500	35.70	571.9	13.75	7678.8	
600	32.03	601.0	14.28	7639.0	
700	28.60	632.0	14.83	7596.5	
800	23.63	695.6	12.62	7603.1	
900	25.34	693.1	13.57	7553.4	
1000	26.68	690.6	14.41	7501.6	
1100	27.95	688.1	15.18	7447.8	
1200	29.37	685.6	15.89	7392.0	

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Steel symbol/number: S890QL1/1.8925

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.20	0.00…0.80	0.00…1.70	0.000…0.020	0.000…0.010	0.00…1.50
Mo	Ni	V	Al	Cu	Nb
0.00…0.70	0.00…2.00	0.00…0.12	>0.018	0.00…0.50	0.000…0.060
Ti	N	B	Zr		
0.00…0.05	0.000…0.015	0.000…0.050	0.000…0.150		

International comparison of standards

ISO		Euronorm		
		S890QL1	10137 (09/1995)	
United Kingdom		Russia		
S890QL1	EN 10137 (09/1995)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

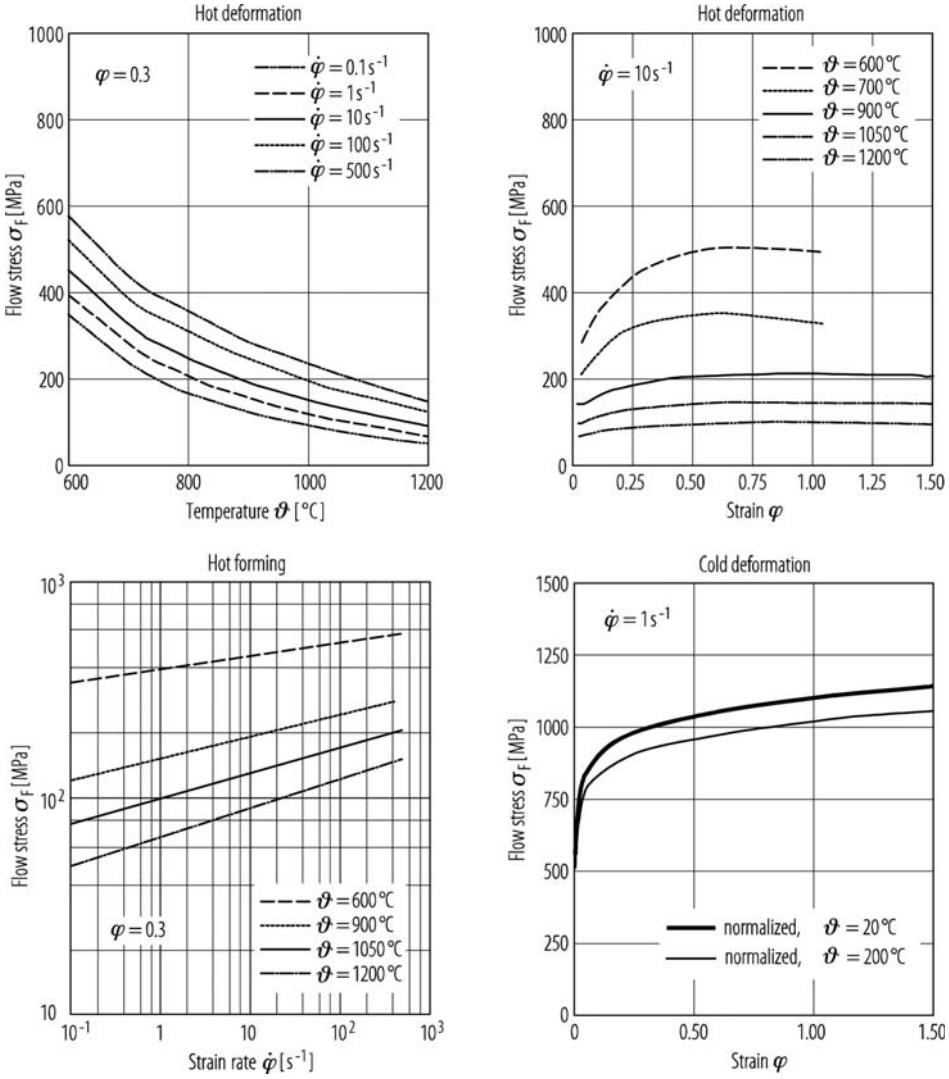
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Flow curves

State of material	Hot deformation		Cold deformation
	deformed state		normalized
	austenite	ferrite+Fe_3C	
σ_{F0} [MPa]	123.50	(100.39)	885.7
A	2807.44	6162.82	1115.16
Effect of temperature K_ϑ			
m_1	−0.00280	−0.00313	−0.00045
Effect of strain K_φ			
m_2	0.26883	0.52033	0.08285
m_4	0.00695	0.01448	−0.00158
m_5	−0.00006	−0.00157	
m_7	−0.26415	−0.14468	
Effect of strain rate $K_{\dot\varphi}$			
m_3			−0.00643
m_8	0.000112	0.000101	
Range of validity			
ϑ [°C]	750…1200	600…700	20…320
φ	0.04…1.50	0.04…1.00	0.04…1.50
$\dot\varphi$ [s^{-1}]	<500	<500	<100

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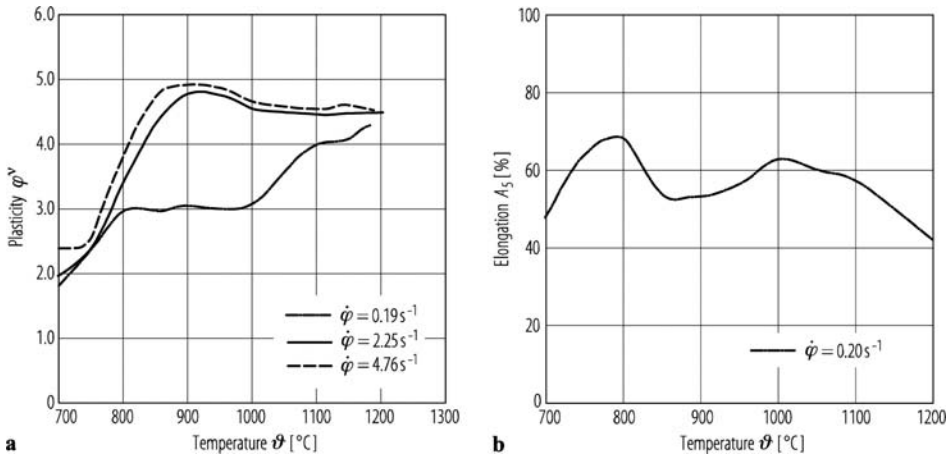
Fig. 5.338.
S890QL1. Flow stress curves by hot and cold forming.



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Fig. 5.339.
S890QL1. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	35.35	476.54	10.49	7833.9	210.1
100	35.75	490.09	10.96	7808.1	205.7
200	37.11	503.68	11.75	7778.6	200.4
300	37.16	523.93	12.32	7747.0	194.0
400	36.5	548.50	12.85	7713.1	185.2
500	35.51	575.7	13.4	7676.8	173.4
600	34.28	604.99	13.89	7638.0	158.0
700	32.93	636.25	14.43	7596.5	139.2
800	25.26	698.74	14.23	7566.4	117.3
900	26.67	696.23	15.41	7507.8	93.0
1000	27.71	693.73	16.48	7446.6	67.6
1100	28.72	691.24	17.45	7382.8	42.4
1200	29.94	688.75	18.34	7316.6	19.6

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Steel symbol/number: L385/1.8970

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.00…0.23	0.00…0.55	1.00…1.50	0.000…0.040	0.000…0.035	> 0.020
V					
0.00…0.12					

International comparison of standards

ISO		Euronorm	
United Kingdom		Russia	
Japan		China	
USA			
ASTM	AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

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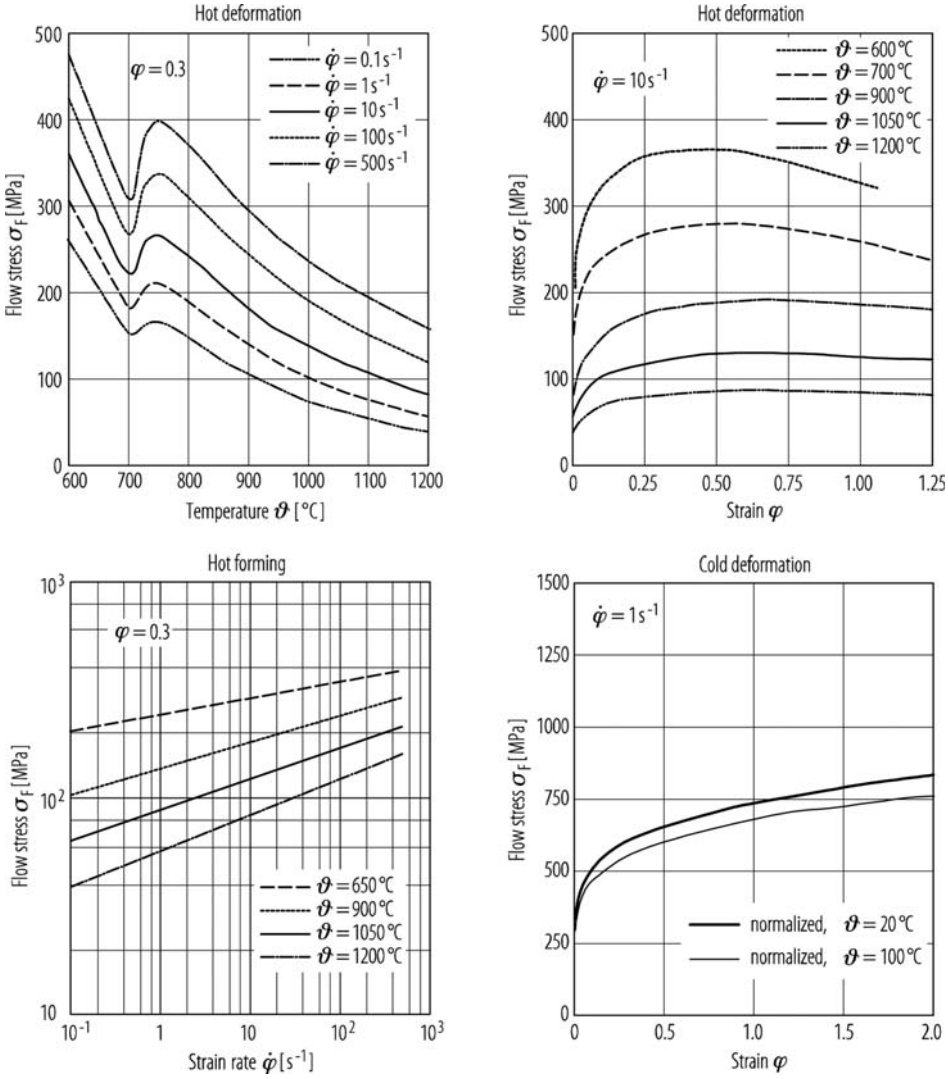
Flow curves

State of material	Hot deformation		Cold deformation
	deformed state		normalized
	austenite	ferrite+Fe_3C	
σ_{F0} [MPa]	(113.67)	53.98	507.1
A	2830.02	9413.15	758.444
Effect of temperature K_ϑ			
m_1	−0.00288	−0.00537	−0.00114
Effect of strain K_φ			
m_2	0.26611	0.13867	0.16634
m_4	0.00094	−0.00028	0.00021
m_5	−0.00013	0.00163	
m_7	−0.32166	−0.98446	
Effect of strain rate $K_{\dot\varphi}$			
m_3			0.00050
m_8	0.000136	0.000119	
Range of validity			
ϑ [°C]	750…1200	600…705	20…120
φ	0.04…1.25	0.04…1.25	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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Fig. 5.340.

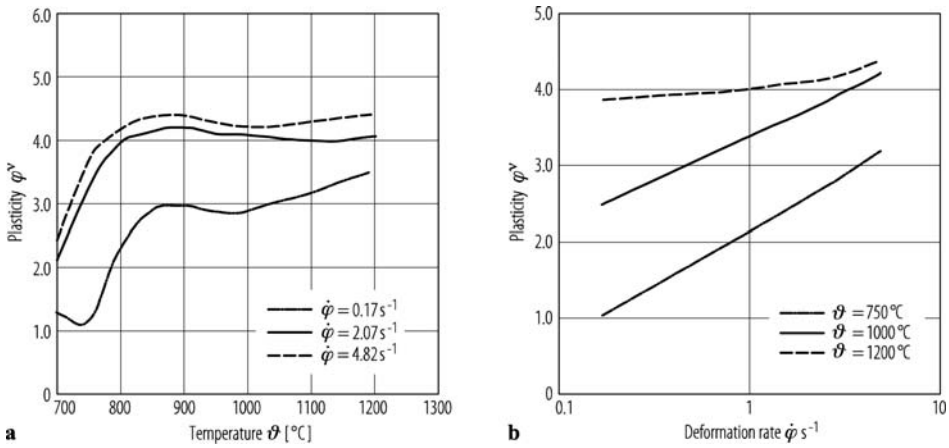
L 385.7H. Flow stress curves by hot and cold forming.



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Fig. 5.341.
L 385.7H. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Austenitsed at 1200 [°C].

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	45.91	473.26	11.22	7813.4	
100	45.64	486.47	11.62	7786.1	
200	45.22	499.53	12.28	7755.8	
300	43.14	519.52	12.82	7723.2	
400	40.4	543.81	13.34	7688.3	
500	37.39	570.7	13.9	7651.0	
600	34.37	599.72	14.39	7611.0	
700	31.43	630.66	14.93	7568.4	
800	23.85	694.47	12.36	7581.6	
900	26.28	691.98	13.25	7533.9	
1000	27.75	689.49	14.04	7484.2	
1100	28.86	687.01	14.77	7432.6	
1200	30.05	684.54	15.43	7379.3	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: L415NB/1.8972

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Al
0.00…0.21	0.00…0.45	0.00…1.60	0.000…0.025	0.000…0.020	0.015…0.060
Cr	Cu	Mo	N	Nb	Ni
0.00…0.30	0.00…0.25	0.00…0.10	0.000…0.012	0.000…0.050	0.00…0.30
Ti	V				
0.00…0.04	0.00…0.15				

International comparison of standards

ISO		Euronorm		
		L415NB	10208–2 (08/1996)	
United Kingdom		Russia		
L415NB	EN 10208–2 (08/1996)			
Japan		China		
USA				
ASTM		API	SAE	UNS
		API 5LX60		

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

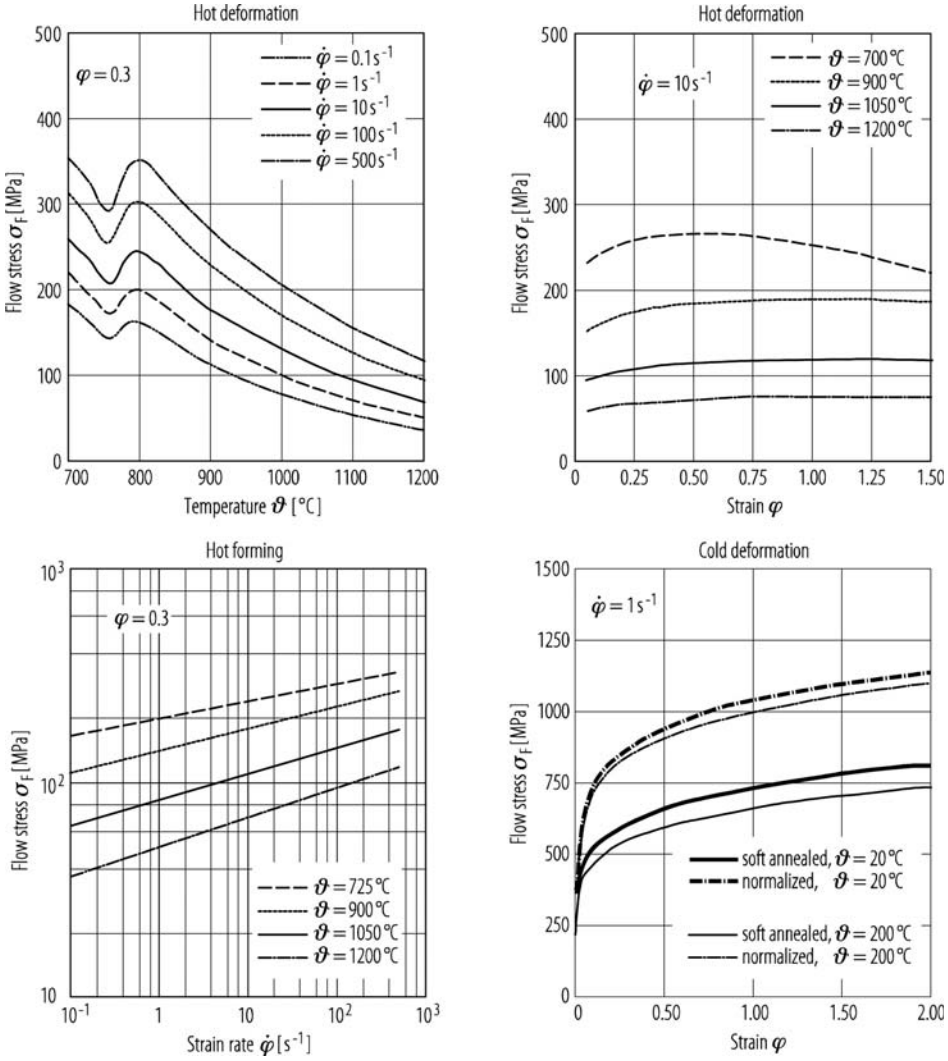
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Flow curves

	Hot deformation		Cold deformation	
	deformed state		soft annealed	normalized
State of material	austenite	ferrite+Fe_3C		
σ_{F0} [MPa]	116.49	(73.87)	532.1	733.46
A	3813.34	4759.84	751.163	1053.12
Effect of temperature K_ϑ				
m_1	−0.00348	−0.00433	−0.00128	−0.00049
Effect of strain K_φ				
m_2	0.12988	0.07254	0.15220	0.12843
m_4	0.00328	0.00179	0.00072	−0.00529
m_5	0.00012	0.00138		
m_7	−0.18456	−0.75904		
Effect of strain rate $K_{\dot\varphi}$				
m_3			0.01045	−0.00144
m_8	0.000115	0.000112		
Range of validity				
ϑ [°C]	800…1200	700…760	20…120	20…120
φ	0.04…1.50	0.04…1.50	0.04…1.25	0.04…1.25
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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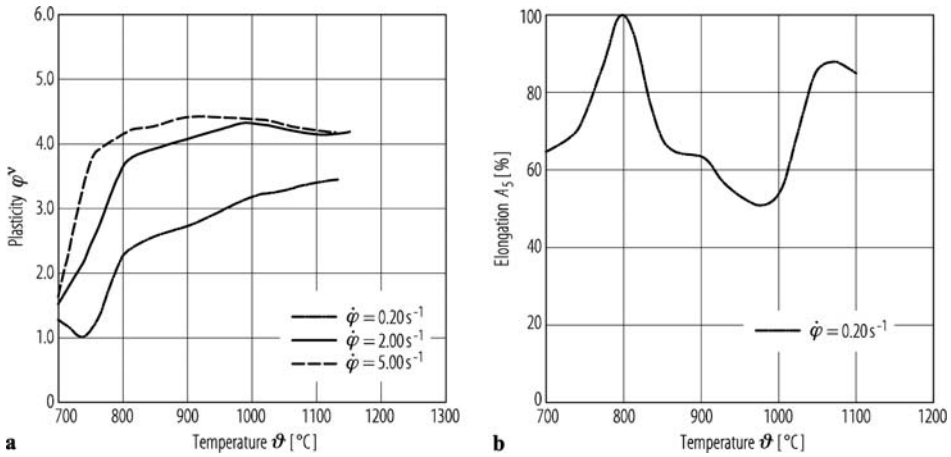
Fig. 5.342.
L415NB. Flow stress curves by hot and cold forming.



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Fig. 5.343.
L415NB. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1150 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	49.57	473.96	11.16	7839.4	
100	48.55	486.29	11.57	7812.2	
200	46.89	499.89	12.24	7785.0	
300	43.66	519.90	12.78	7749.2	
400	39.90	544.22	13.30	7714.3	
500	36.06	571.14	13.82	7676.9	
600	32.36	600.17	14.35	7636.9	
700	28.88	631.13	14.89	7594.2	
800	23.74	694.87	12.44	7605.2	
900	25.43	692.38	13.35	7556.7	
1000	26.75	689.89	14.17	7506.2	
1100	28.00	687.41	14.90	7453.8	
1200	29.41	684.94	15.59	7399.5	

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Fürbacher, I., Macek, K. et al.: Lexikon technickych materialu, Verlag Dashöfer Praha (Prag) 1998

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Steel symbol/number: L485MB/1.8977

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.16	0.00…0.45	0.00…1.70	0.000…0.025	0.000…0.020	0.00…0.30
Mo	Ni	V	Al	Cu	Nb
0.00…0.10	0.00…0.30	0.00…0.10	0.015…0.06	0.00…0.25	0.000…0.060
Ti	N				
0.00…0.060	0.000…0.012				

International comparison of standards

ISO		Euronorm		
		L485MB	10208–2 (08/1996)	
United Kingdom		Russia		
L485MB	EN 10208–2 (08/1996)			
Japan		China		
USA				
ASTM		API	SAE	UNS
		API 5LX70		

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

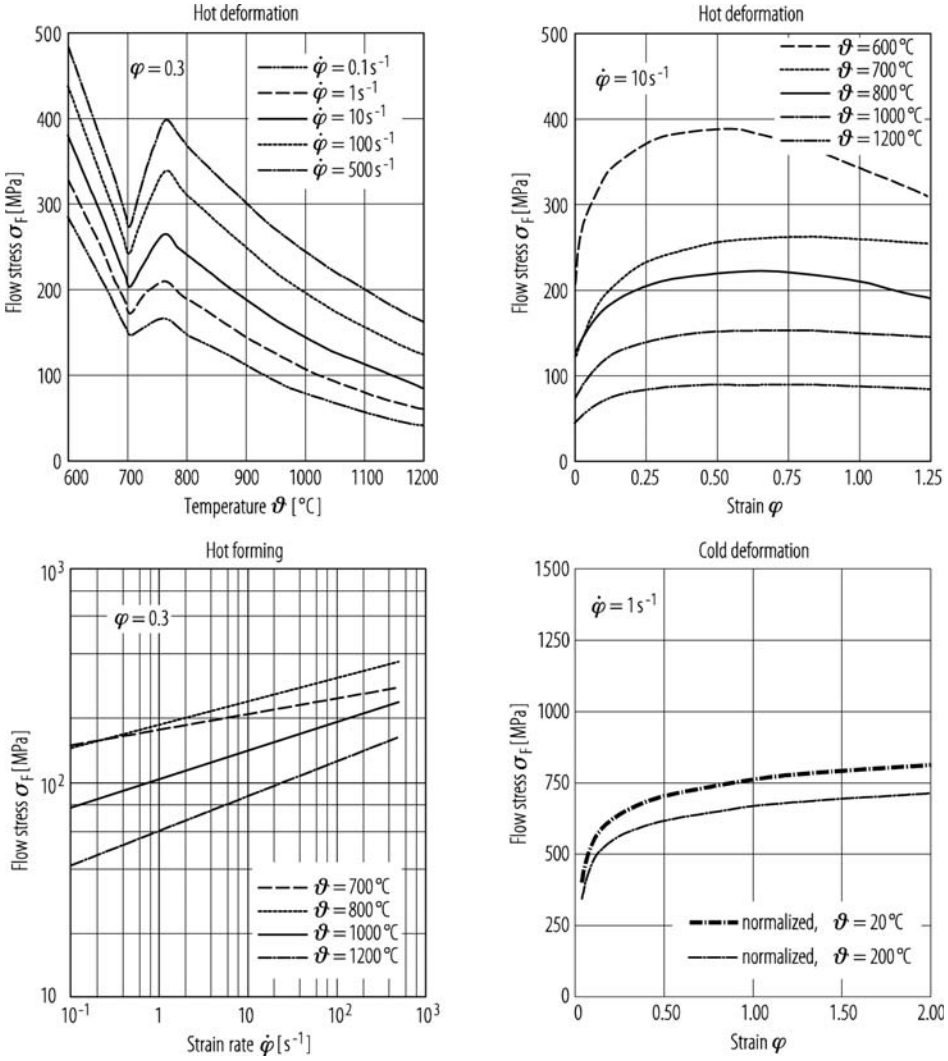
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Flow curves

State of material	Hot deformation			Cold deformation
	deformed state		casting state	normalized
	austenite	ferrite+Fe_3C	austenite	
σ_{F0} [MPa]	115.49	(35.95)	95.1	558.5
A	2903.89	22798.06	2414.29	782.393
Effect of temperature K_ϑ				
m_1	−0.00276	−0.00669	−0.00263	−0.00072
Effect of strain K_φ				
m_2	0.31836	0.16491	0.40652	0.08299
m_4	0.00246	0.00007	0.00859	−0.01606
m_5	−0.00048	0.00205	−0.00046	
m_7	−0.18954	−1.18099	−0.18918	
Effect of strain rate $K_{\dot\varphi}$				
m_3				0.01259
m_8	0.000134	0.000104	0.000134	
Range of validity				
ϑ [°C]	760…1200	600…705	900…1200	20…320
φ	0.04…1.20	0.04…1.20	0.04…1.20	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500	<500

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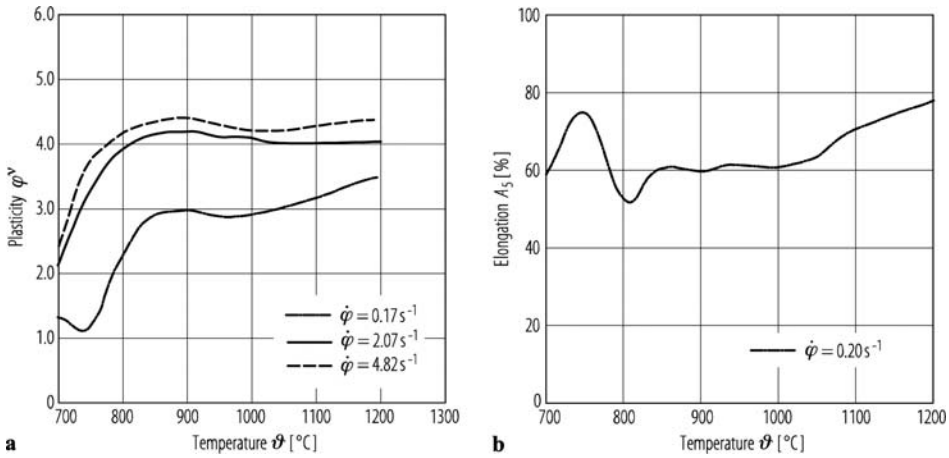
Fig. 5.344.
L485MB. Flow stress curves by hot and cold forming.



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Fig. 5.345.
L485MB. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity by torsion (left) and by tensile test (right)



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	45.03	473.54	11.16	7827.6	213.9
100	45.15	486.79	11.57	7800.4	204.9
200	44.80	499.90	12.24	7770.1	199.0
300	42.75	519.91	12.78	7737.5	195.3
400	40.0	544.22	13.30	7702.7	190.7
500	37.07	571.1	13.8	7665.3	182.7
600	34.08	600.18	14.35	7625.4	169.9
700	31.17	631.14	14.89	7582.7	151.6
800	23.77	694.88	12.45	7593.8	128.0
900	26.24	692.38	13.35	7545.3	100.3
1000	27.75	689.90	14.17	7494.9	70.5
1100	28.90	687.42	14.91	7442.5	41.2
1200	30.11	684.95	15.59	7388.3	16.4

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Steel symbol/number: S690QL1/1.8988

Metal Forming Data - Ferrous Alloys - deformation behaviour

Composition [Weight-%]

C	Si	Mn	P	S	Cr
0.00…0.20	0.00…0.80	0.00…1.70	0.000…0.020	0.000…0.010	0.00…1.50
Mo	Cu	B	Ni	V	Nb
0.00…0.70	0.00…0.50	0.000…0.005	0.00….2.00	0.00…0.12	0.000…0.060
Ti	Zr				
0.000…0.050	0.000…0.015				

International comparison of standards

ISO		Euronorm		
		S690QL1	10137–2 (09/1995)	
United Kingdom		Russia		
S690QL1	EN 10137–2 (09/1995)			
Japan		China		
USA				
ASTM		AISI	SAE	UNS

Note: Not in all cases the tolerance range for the chemical composition of steels, used in other countries, corresponds to DIN or EN.

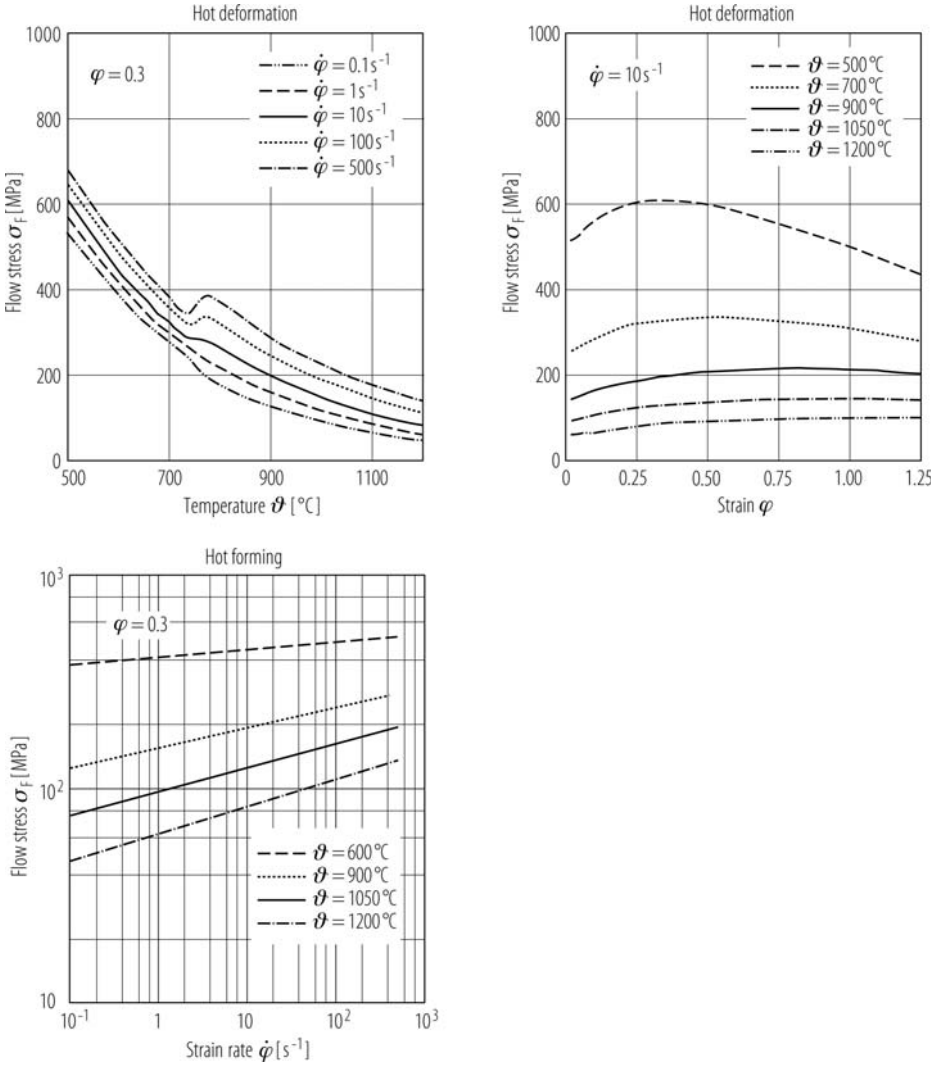
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Flow curves

State of material	Hot deformation		Cold deformation
	deformed state		normalized
	austenite	ferrite+Fe_3C	
σ_{F0} [MPa]	121.06	(109.95)	687.8
A	3994.33	4743.45	948.060
Effect of temperature K_ϑ			
m_1	−0.00332	−0.00368	−0.00062
Effect of strain K_φ			
m_2	0.20794	0.16400	0.09798
m_4	0.00519	0.00402	−0.01026
m_5	0.00074	0.00163	
m_7	−0.64064	−1.04987	
Effect of strain rate $K_{\dot\varphi}$			
m_3			0.00855
m_8	0.000106	0.000088	
Range of validity			
ϑ [°C]	780…1200	500…740	20…250
φ	0.04…1.25	0.04…1.25	0.04…2.00
$\dot\varphi$ [s^{-1}]	<500	<500	<500

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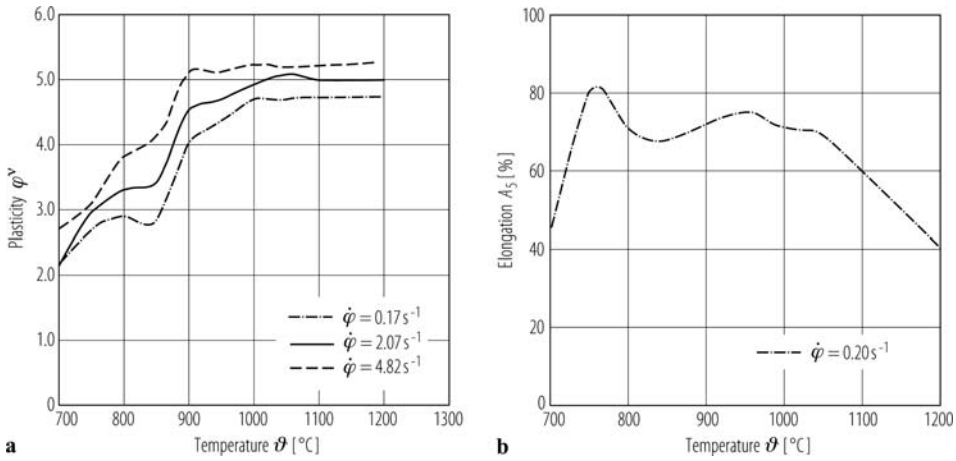
Fig. 5.346.
S690QL1. Flow stress curves by hot forming.



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Fig. 5.347.
S690QL1. Hot plasticity as a function of the temperature. (a) Deformed state. Austenitised at 1200 [°C]. (b) Deformed state. Direct heating on deformation temperature.

Plasticity in torsion



Physical properties

Temperature	Thermal conductivity	Mean specific heat capacities	Average coefficient of linear expansion	Density	Young's-modulus
ϑ [°C]	λ [W/m · K]	c_{pm} [kJ/kg · K]	$\alpha_m \cdot 10^{-6}$ [K^{-1}]	ρ [kg/m^3]	$E \cdot 10^5$ [MPa]
20	37.63	476.44	10.51	7837.0	213.6
100	40.51	490.07	10.98	7811.2	206.5
200	40.68	503.58	11.77	7781.6	200.4
300	38.97	523.82	12.33	7750.0	195.5
400	36.6	548.38	12.86	7716.0	190.1
500	33.90	575.6	13.4	7679.7	182.6
600	31.19	604.86	13.90	7640.8	171.9
700	28.54	636.11	14.44	7599.3	157.2
800	23.32	698.65	14.16	7570.7	138.0
900	26.18	696.14	15.33	7512.6	114.2
1000	28.05	693.63	16.39	7451.7	85.9
1100	29.53	691.14	17.35	7388.3	53.4
1200	31.05	688.66	18.24	7322.5	17.8

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