
Bernard Nacke, Egbert Baake (Editors)

Induction Heating

Heating | Hardening | Annealing | Brazing | Welding

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Bernard Nacke, Egbert Baake (eds.)
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This book was prepared with much care and devotion. Nonetheless, authors, editor and publishing company do not assume responsibility for the correctness of data, comments, suggestions and possible printing errors.

Foreword

This Handbook Induction Heating is based on the German Handbook “Induktives Erwärmen” edited in 2012 and is aimed primarily at engineers who are concerned with the design and the configuration or operation of induction heating equipment. Moreover, it should also give a consolidated overview of induction heating methods under practical aspects, in particular for students of various disciplines as well as for engineers in practice who are new to this area.

This book contains fundamentals as well as process and plant descriptions. It conveys the physical fundamentals of induction heating and metallurgical fundamentals of heat treatment, calculation and design methods for induction heating processes, methods and applications of heating for deforming, for heat treatment and for joining and cutting. In addition, special processes are presented, which are already used to a large extent in practice or which are still not introduced to industrial applications and thus reflect the latest developments for induction heating. The last chapter is devoted to the various types of power supply for induction heating installations, especially of modern static frequency converters.

This book demonstrates impressively that induction heating is an extremely large field of different processes and applications which can be adequately covered only by a correspondingly large and diverse range of authors.

We are therefore extremely grateful to these authors and their employers. Our thanks also go out to the employees of Vulkan Verlag, represented by Dipl.-Ing. Stephan Schalm, whose expertise and commitment have also made a decisive contribution to the success of this work.

Hannover, 2016



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Preface

Among all heating processes that use electrical energy, induction heating is today the most widely used in many industrial sectors. The major reason of its large acceptance in the industry is linked to its unique properties, which make it the best and sometimes the only solution for many production processes.

In particular, its ability to produce high intensity heat sources inside the workpieces to be heated in very short times and to concentrate them in well-defined regions, lead to high production rates with repeatable high quality.

Other advantages of induction heating include energy efficiency, lower manufacturing costs, flexibility and automation of installations, reduction of floor space requirements and improvement of workplace operating environment.

Beside classical applications in metalworking industries for through heating, heat treating, welding, joining and cutting, induction heating is increasingly used in various other production fields like glass melting and forming, crystal growth, optical fibers draw processing, nanoparticle heating in hyperthermia, etc.

The main purpose of the present book is to provide to industrialists, end users, manufacturers and designers of induction heating equipment, an overview on the state of art of these technologies, but it will be useful also to students, engineers, scientists and technologists who are interested in this particular field or, more generally, in the efficient utilization of electrical energy.

A special feature of the book is that the different chapters have been prepared by specialists working in the various fields, so that the relevant information are the result of their direct industrial experience.

Therefore, after an introductory chapter on the theoretical background and physical principles of induction heating written by academic well-known experts in the field, the following chapters deal extensively with the technological aspects and new developments of the so-called conventional applications and the more innovative processes.

In conclusion, this book will constitute an excellent everyday support for University level study, Research & Development and industrial practical application.

Padua, 2016

Prof. Dr.-Ing. **Sergio Lupi**



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Up to 2 kg Ti /TiAl, 3 kg Steel, 1 kg Al/Mg, 3 kg Superalloys, e.g.

Production line for TiAl castings.

2 centrifugal casting units, 2 rotary hearth furnaces for mould preheating, post conveyor furnace for annealing of castings in inert gas.



Brazing, hardening, preheating for forging, melting.

High frequency generators up to 200 kW, 100 kHz - 27,12 MHz.

Medium frequency inverter up to 1000 kW, 2 - 100 kHz.

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1. Fundamentals of induction heating

1. Fundamentals of induction heating

Bernard Nacke, Egbert Baake

As an introduction the physical and technological basics of induction heating are described in this chapter and some industrial application examples are presented. Then, the mathematical laws for the description and calculation of electromagnetic and thermal fields in induction heating are provided. It follows an introduction to the numerical methods for the solution of the in general 3-dimensional and time-dependent mathematical field equations. The following chapter describes the basics for the practical design of induction heating installations. In the final section energy aspects, i.e. the energy efficiency of induction heating processes and equipments are explained.

1.1 Introduction

Induction heating belongs to the direct electrothermal methods [1.1]. Direct electrical heating methods of electrotechnology processes are characterized in that the heat is generated directly in the workpiece. In induction and conduction heating, the generation of heat occurs by electrical currents in the workpiece. Since electrical currents can arise only in conductive materials, the induction and conduction heating is used for high electrical conductive materials (metals), semiconductor materials, e.g. silicon or graphite, but also for electrically low conductive materials such as glasses or oxides.

In induction heating the currents are generated by induced eddy currents. For this purpose, an alternating current in the inductor is required, which causes an alternating magnetic field which leads to eddy currents in the conductive material in turn. Induction heating methods work without contact, that is, without direct electrical contact with the workpiece. The used frequencies are in a wide range and have to be selected individually for each requirement. For some applications line-frequency is used but in the vast majority of cases a higher frequency is required which is generated by frequency generators.

In addition to the generation of heat inside the workpiece induction methods are also often used due to the formation of the electromagnetic forces, the so-called Lorentz forces, for example for stirring and mixing of molten metal in case of induction melting processes. The impact of these Lorentz forces advantageous for induction melting must also be taken into account in the mechanical design of induction heating systems, as these electromechanical forces acting on the inductor and the workpiece, whereby the fixed clamping of the workpiece is necessary sometimes.

Induction heating has today a significant breadth of application, ranging from power and energy intensive applications in traditional fields such as in the steel industry to highly advanced applications in process-oriented areas such as processing of single crystals in the semiconductor industry.

For the high-powered heating systems in addition to the optimum process control the key objective is the energy efficient design of the processes and installations. In contrast, the energy aspect plays in many processes of the process-oriented applications only a subordinate role, while the optimum process control is significant.

In terms of direct or indirect heating methods, which include in addition to the induction heating also the conductive and dielectric heating, the conversion of electrical energy into heat occurs directly in the material, resulting in a number of advantages:

- High power densities
- High heating rates
- High thermal efficiency

- Targeted local power input
- Targeted time-dependent power input
- Heating without direct influence of a flame
- Application in any atmosphere or vacuum
- Very good control, measurement and metering of power or energy supply.

Induction methods have now become widespread in the application of process heat. Besides the classic applications for the melting of metals or the through heating for subsequent forging, found in recent years strengthened further developments rather than for induction heat treatment, e.g. for the induction surface hardening of complex geometries, for the induction joining, e.g. for induction welding of tubes and metal sheets and also in combination with other thermal methods such as laser heating as so-called hybrid methods.

As shown below thus the induction heating is well established in many manufacturing processes for years and has become indispensable and for new innovative production processes often is the key to success.

1.1.1 Induction heating for deforming

The industrial applications of induction heating can be found in many branches. The induction heating for deforming is used today in the forging industry as well as in the pressing and in rolling mills (**Figure 1.1**). Induction heating installations for forging (industrial installations see **Figure 1.2**) offer so many advantages that today in Germany more than 80 % of the die forging are using the induction heating, which offers many technical, economical and ecological advantages in comparison with competitive heating methods. The fast heating up (**Figure 1.3**) leads to scale formation below 0.5 %, which leads to small wearing of the high expensive forging dies and which is prerequisite for the high precision forging. The energy balance of a modern induction heater for forging of steel ingots shows an energy consumption of 400 kWh for 1 ton of steel (see Chapter 1.5). Especially the comparably low scale generation below 0,5 %,



Figure 1.1: Induction heating of steel bars in a rolling mill



Figure 1.2: Induction heaters for forging a) Induction pusher type heater for ingots (Source: SMS Elotherm); b) Induction walking beam type heater (Source: ABP Induction Systems)

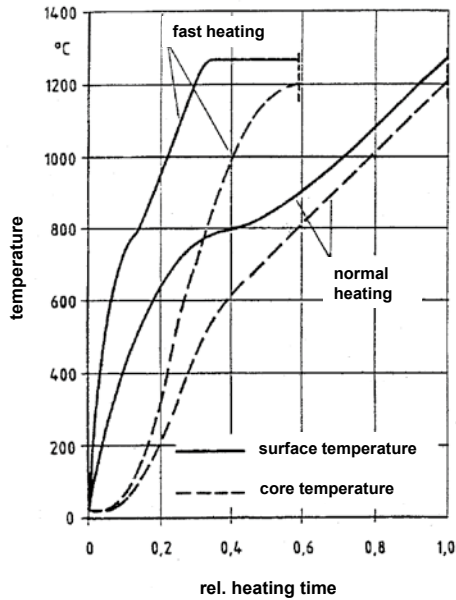
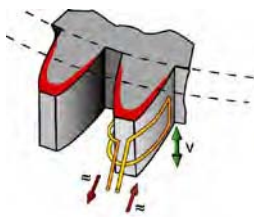


Figure 1.3: Typical temperature curves in an induction heater for forging



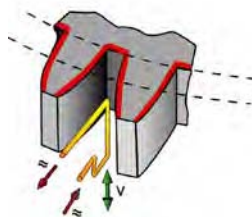
Figure 1.4: Hardening of crank shafts as typical example of surface hardening [1.2]

Single tooth flank hardening



$m \geq 3,5 \text{ mm}$

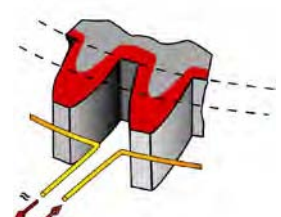
Single tooth gap hardening



$m \geq 2,5 \text{ mm (HF)}$

$m \geq 6,0 \text{ mm (MF)}$

All teeth hardening



$m \geq 2,0 \text{ mm}$

- m Module (mm)
- p Pitch
- d Circular pitch diameter (mm)
- d_a Tip circle diameter (mm)
- d_f Root circle diameter (mm)
- z Number of teeth
- h_a Addendum (mm)
- h_f Dedendum (mm)
- h Tooth height (mm)
- D_p Diametral Pitch

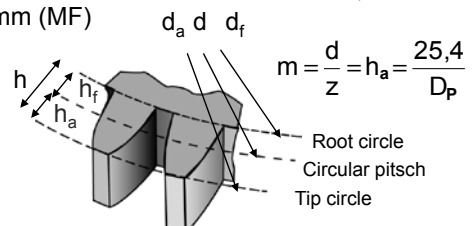


Figure 1.5: Different methods of surface hardening of gears (Source: EFD Induction)

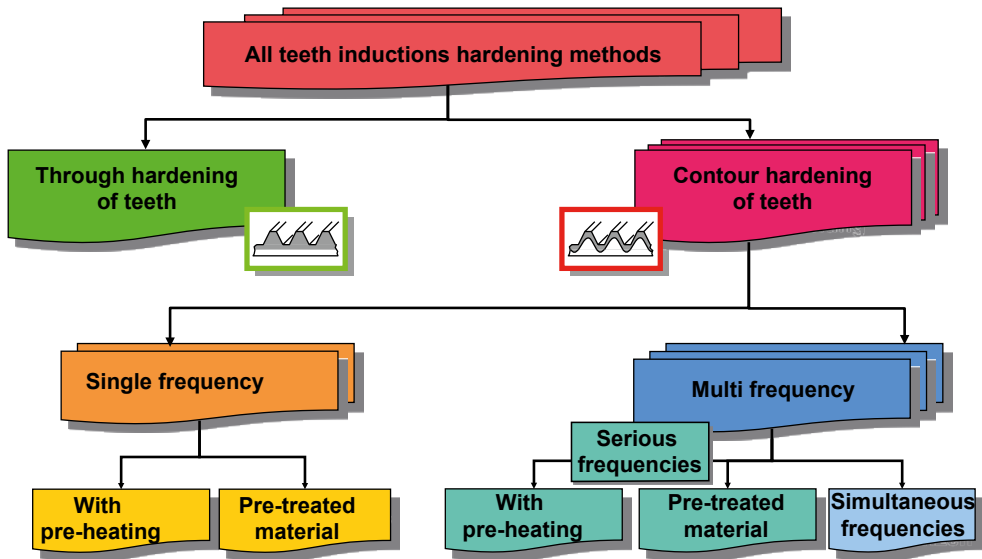


Figure 1.6: Method of one shot hardening of gears (Source: EFD Induction)

which leads to a very low wear of the deforming tools and which is indispensable for the innovative precision forging should be mentioned here.

1.1.2 Induction heat treatment

The induction heat treatment, like induction hardening, tempering or annealing are well established. The advantages of the induction hardening are especially the reproducible distribution of all hardening parameters in the workpiece. The induction surface hardening can be applied for geometries of complicated shape, like crank shafts (Figure 1.4). Very important were the developments in the field of surface hardening for gears, where a so called contour hardening is necessary (Figure 1.5). Different methods are applied (Figure 1.6), which use beside the classical single frequency also double or multiple frequency methods by using two or more different frequencies during the induction hardening process sequently or simultaneously, so that the hardening profile



Figure 1.7: Different designs of hardening inductors (Source: Steremat Elektrowärme)

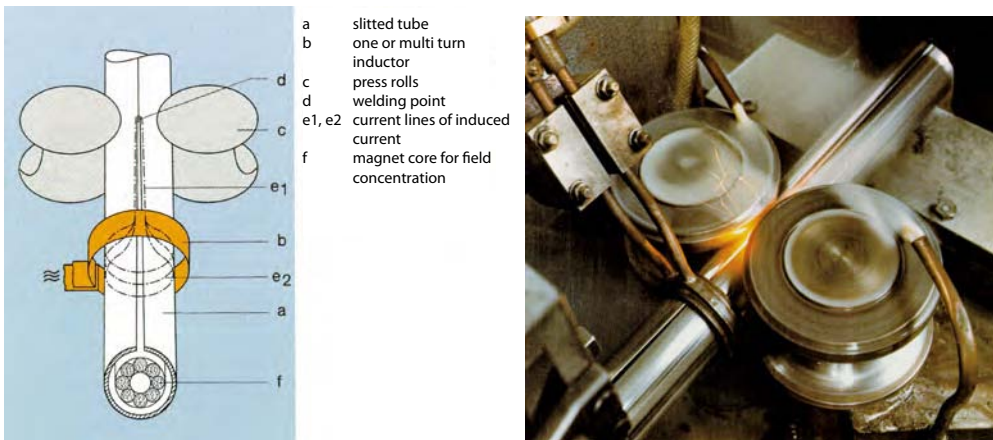


Figure 1.8: Induction tube welding [1.2]

can be adapted precisely to the requirements. A small drawback of induction hardening is that different workpiece geometries need generally adapted inductors of different shape (**Figure 1.7**) which mainly till now are based on experience and are designed with empirical methods. But more and more already mathematical simulation methods are used in order to find optimized solutions in case of very complex configurations. Due to the very fast heating up time the quality of the hardening is very high. Because of induction hardening installations need comparably small floor space and have a high level of automation, they can be easily integrated into production lines.

1.1.3 Induction heating for joining and welding

The induction heating is successfully applied for joining and cutting process also. Examples are the induction soldering or the induction welding, where latest is well established as the induction longitudinal tube welding (**Figure 1.8**), which allows a high welding speed in combination with high quality welding joint (see also Chapter 4.4.1).

1.1.4 Examples of actual developments

Beside the numerous industrial applications, which are well established since many years, the induction heating offers a big potential for new production technologies. Examples are the heating for the thixo-forming process or the heating for drying after joining the car body parts by gluing.

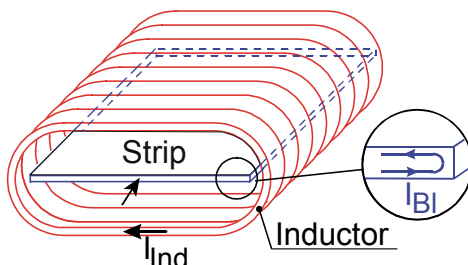


Figure 1.9: Induction heating of strips by longitudinal flux

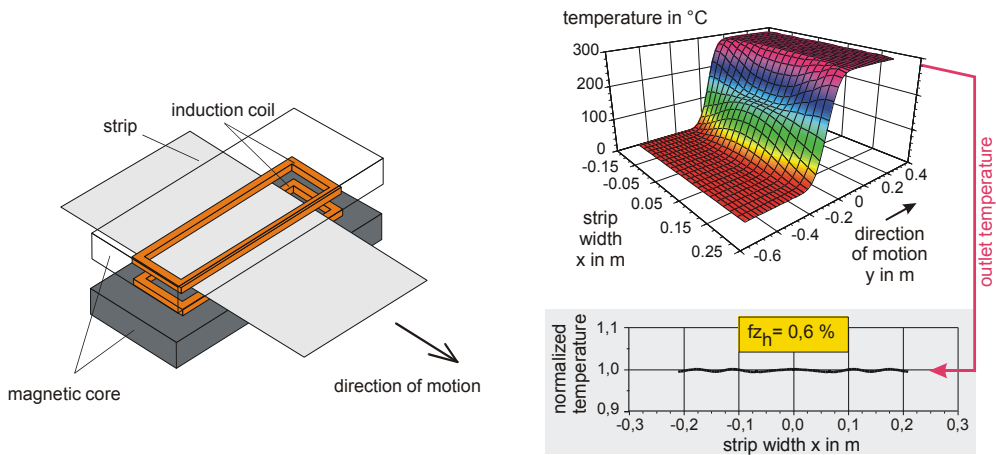


Figure 1.10: Induction heating of strips by transverse flux and homogeneous temperature distribution in the strip heated with an optimized transverse flux heater

For the thixo-forming process (see also Chapter 2.5) the workpiece has to be heated up before the deforming process to a homogeneous clear defined temperature distribution between the solidus and liquidus status. So the heating process must be very precise and reproducible due to the small process window in the semi-solid-region of the workpiece and can be economically realized only with induction heating.

Another highly interesting example for the innovative application of induction technology is the transverse flux heating (TFH) of metal sheets and strips. In comparison to the induction longitudinal flux heating, where the induction coil is arranged around the workpiece (Figure 1.9), in case of the transverse flux heating the inductors are located above and below the metal strip (Figure 1.10). This constellation allows heating up thin flat workpieces using comparably low frequencies. The TFH is a very flexible, high efficient and economical heating concept. Due to the complex design of transverse flux heating systems up to now the industrial break through is missing. Today the optimization of the TFH systems using new developed 3-dimensional simulation tools is possible and as a result of this very flexible, precisely tailored temperature distributions across the strip width can be realized (Figure 1.10).

In the last years the combination of different electrothermal processes with induction heating is used advantageous. A very innovative example is the combination of laser beam treatment supported by induction heating (Figure 1.11), see also Chapter 4.4.2. Extremely high power density of the laser beam leads to high temperature gradients in the material, which can cause high thermal stresses. In this case the pre- or post-heating via induction can reduce the thermal stress.

The examples presented here can show only a small part of the numerous possibilities and the wide spread spectrum of industrial applications of induction heating.



Figure 1.11: Combination of laser beam treatment supported by induction heating

1.2 Mathematical fundamentals and calculation of induction heating processes

Induction heating is based on effects of the electromagnetic field. The used frequencies are in the area of line frequency or even lower up to a few MHz. The material data are generally very strongly temperature dependent and therefore these dependencies have to be taken into account in the calculation. A special feature here is the magnetic permeability, which is also dependent on the field strength and is very important in the case of induction heating of ferromagnetic materials.

For heating solid workpieces, the calculation of the stationary or for heating-up the transient temperature field is necessary. The temperature dependence of the thermal material properties is of crucial importance for the temperature field calculation and must be taken into account. Since the electrical material properties are temperature dependent, see above, an exact calculation of a direct heating process can only be achieved by coupling the electromagnetic and thermal calculations. A difficulty are the boundary conditions at the surface of solid materials, which are characterized physically by convection and radiation heat transfer. They must also be taken into account.

In the following chapters the basic mathematical equations are described to calculate the different fields. To solve the mathematical relationships, especially in coupled systems, numerical simulations are now being used more and more. These numerical calculation methods can be used for complex, up to 3-dimensional systems thanks to modern computer technology. The current methods used today will be shortly described.

1.2.1 Electromagnetic field

The electromagnetic field is described by the Maxwell's equations

$$\text{rot } \vec{H} = \vec{S} = \kappa \vec{E} + \epsilon \frac{d\vec{E}}{dt} \quad (\text{Ampere's law}) \text{ and} \quad (1.1)$$

$$\text{rot } \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \quad (\text{Faraday's law}) \quad (1.2)$$

The term $\kappa \vec{E}$ describes the conduction current density and the term $\epsilon d\vec{E}/dt$ the displacement current density. For harmonic (sinusoidal) field values of $\vec{H}$ and $\vec{E}$ the Maxwell's equations are

$$\text{rot } \vec{H} = (\kappa + j\omega\epsilon) \vec{E} \quad (1.3)$$

$$\text{rot } \vec{E} = -j\omega\mu \vec{H} \quad (1.4)$$

$$\text{with } \vec{E} = \vec{E}(x, y, z)$$

$$\text{and } \vec{H} = \vec{H}(x, y, z).$$

If these two equations are linked the result is one differential equation for $\vec{H}$ or $\vec{E}$, which describes the electromagnetic system.

In electrical conductors with high electrical conductivity κ (in general valid for induction and conduction heating) the displacement current density $\epsilon d\vec{E}/dt$ can be neglected to the conductive current density $\kappa \vec{E}$.

Thus, the following differential equations apply to the magnetic field strength $\vec{H}$ and correspondingly to the electrical field strength $\vec{E}$ with harmonic (sinusoidal) field values $\underline{H}$ respectively $\underline{E}$ as follows:

$$\text{rot rot } \vec{E} + j\omega\mu\kappa\vec{E} = 0 \quad (1.5)$$

$$\text{rot rot } \vec{H} + j\omega\mu\kappa\vec{H} = 0 \quad (1.6)$$

1

with the eddy current constant (complex value)

$$\kappa^2 = -j\omega\mu\kappa [\text{m}^{-2}]. \quad (1.7)$$

These are the starting equations for the calculation of current and field distribution in electrical conductors for the induction heating, taking into account the skin effect.

In general, since a 3-dimensional system is present, will also have the field values $\vec{H}$ and $\vec{E}$ 3 components. Depending on the physical arrangement, the field value distribution can be described by Cartesian coordinates (x, y, z) or cylindrical coordinates (r, φ, z). The 3-dimensional calculation of eddy current fields (induction / conduction) is still a considerable computational effort. For many induction and conduction heating processes, the physical arrangements, however, can be simplified to a 2-dimensional rotationally symmetric calculation. Below is a simplified and in practice often used procedure described in more detail.

Solutions of the differential equation for the induction heating for rotationally symmetrical arrangements:

For induction heating, in many cases the general 3-dimensional arrangement can be reduced to a rotationally symmetrical arrangement. In this case, the spiral shape of the inductor is neglected and replaced by several ring-shaped turns which are connected together in series. This is possible in many cases, and thus the dependence of the field values can be reduced on the r and z dependence. This then results in a rotationally symmetrical system. The following field components result to zero,

$$H_\phi = 0, \quad E_r = 0, \quad E_z = 0$$

and the following components remain to be determined

$$H_r \neq 0, \quad H_z \neq 0, \quad E_\phi \neq 0.$$

For the calculation of the rotationally symmetrical electromagnetic field the so-called magnetic vector potential is introduced. As for the divergence of the induction

$$\text{div } \vec{B} = 0 \quad (1.8)$$

and generally is

$$\text{div}(\text{rot } \vec{A}) = 0 \quad (1.9)$$

a vector field $\vec{A}$ can be defined, so that is

$$\text{rot } \vec{A} = \vec{B}. \quad (1.10)$$

As the rotor-free field from a scalar potential, then the source-free field can be derived from a vector field.

In case of rotationally symmetric systems in which only the components B_r and B_z exist, the vector potential $\vec{A}$ has only one component in the φ direction,

$$\vec{A} = A \vec{e}_\varphi. \quad (1.11)$$

This simplifies the problem to the solution for only one component.

With the agreement $\text{rot } \vec{A} = \vec{B}$ the magnetic field strength is because of the relation $\vec{B} = \mu \vec{H}$

$$\vec{H} = \frac{1}{\mu} \text{rot } \vec{A}. \quad (1.12)$$

Substituting this expression into the first Maxwell's equation, we obtain

$$\text{rot} \left(\frac{1}{\mu} \text{rot } \vec{A} \right) = \vec{S}. \quad (1.13)$$

With the Ohm's law

$$\vec{S} = \kappa \vec{E} \quad (1.14)$$

follows

$$\text{rot} \left(\frac{1}{\mu} \text{rot } \vec{A} \right) = \kappa \vec{E}. \quad (1.15)$$

According to Faraday's law (second Maxwell's equation) is

$$\text{rot } \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (1.16)$$

or with $\text{rot } \vec{A} = \vec{B}$

$$\text{rot } \vec{E} = -\frac{\partial (\text{rot } \vec{A})}{\partial t}. \quad (1.17)$$

The electrical field strength is then

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - \text{grad } U. \quad (1.18)$$

The electric field may in addition to the vortex proportion still contain a potential component which disappears with the rotor operation.

Thus we get the differential equation for the magnetic vector potential to

$$\text{rot} \left(\frac{1}{\mu} \text{rot } \vec{A} \right) = -\kappa \frac{\partial \vec{A}}{\partial t} - \kappa \text{grad } U. \quad (1.19)$$

or, for harmonic field values

$$\text{rot} \left(\frac{1}{\mu} \text{rot } \vec{A} \right) = -j\omega\kappa \vec{A} - \kappa \text{grad } U. \quad (1.20)$$

In cylindrical systems with $\vec{A} = \underline{A}_\varphi(r, z) \vec{e}_\varphi$ is

$$\frac{\partial}{\partial r} \left(\frac{1}{\mu} \cdot \frac{1}{r} \cdot \frac{\partial}{\partial r} (r \underline{A}_\varphi) \right) + \frac{\partial}{\partial z} \left(\frac{1}{\mu} \frac{\partial \underline{A}_\varphi}{\partial z} \right) = -j\omega \kappa \underline{A}_\varphi - \kappa \text{grad} \underline{U}, \quad (1.21)$$

1

In which $\text{grad} \underline{U}$ describes the inductor voltage at the ends of the coil.

Derivation of the skin effect for the induction and conduction heating:

The skin effect (also called current displacement effect) can be derived from the differential equations for eddy current fields mathematically correct, and thus leads to the skin effect describing value of the electromagnetic penetration depth. The derivation shown here is valid exactly only for an ideal simplified arrangement, the so-called infinite conductive half-space. In practice, the electromagnetic penetration depth, however, can also be applied for non-idealized arrangements, e.g. for curved surfaces of cylindrical bodies. The results are then provided as an approximation, however, sufficiently accurate solutions can arise when certain conditions are met, which will be discussed in more detail later.

The infinite conductive half-space is derived from one in all three coordinate directions infinitely extended body that is only shared a flat surface at $x = 0$ (see **Figure 1.12**). The left half-space in Figure 1.12 is electrically non-conductive, the right half-space, however, conductive. For the left non-conductive half-space an undisturbed electromagnetic field with only the field components H_y and E_z exists, which penetrates the surface of the conductive half-space. Thus, in the conductive half-space the field components H_y and E_z exists, too, and because the right half-space is conductive, a current density J_z is generated due to the electric field strength E_z .

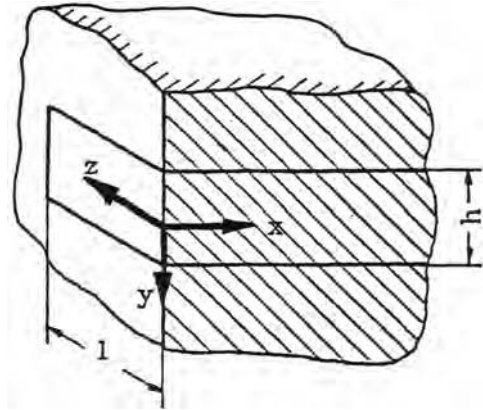


Figure 1.12: Definition of the infinite conductive half-space

What field and current density distribution in the conductive half-space exists, depends on the material properties of the conductive half-space and can be calculated from the solution of the differential equation for the electromagnetic field, as follows.

The magnetic field strength has in the conductive half-space therefore the component

$$\vec{H} = \vec{H}_y(x) = H_y \cdot \vec{e}_y \quad (1.22)$$

and the electric field strength the component

$$\vec{E} = \vec{E}_z(x) = E_z \cdot \vec{e}_z. \quad (1.23)$$

Both field components are only dependant on x , therefore independant on y and z and are harmonic values.

Thus, the differential equations can be simplified to the field equations

$$\frac{\partial^2 \underline{E}_z}{\partial x^2} - j\omega \mu \kappa \underline{E}_z = 0 \quad (1.24)$$

$$\frac{\partial^2 \underline{H}_y}{\partial x^2} - j\omega\mu\kappa \underline{H}_y = 0. \quad (1.25)$$

Due to the link of both field equations this results in the differential equation

$$\frac{\partial^2 \underline{E}_z}{\partial x^2} = j\omega\mu\kappa \underline{E}_z \quad (1.26)$$

with the solution approach

$$\underline{E}_z = \underline{E}_{z0} \cdot e^{ax} \quad (1.27)$$

this results in

$$\underline{a} = \pm \sqrt{j\omega\mu\kappa} = \pm \frac{1+j}{\sqrt{2}} \sqrt{\omega\mu\kappa} = \pm \frac{1+j}{\delta} \quad (1.28)$$

Thus, the solution for the electric field in the conductive half-space is

$$\underline{E}_z(x) = \underline{E}_0 \cdot e^{-\frac{1+j}{\delta}x} \quad (1.29)$$

with the electric field strength at the surface $\underline{E}_0$. In detail, the electrical field strength is described by

$$\underline{E}(x,t) = \text{Re}\{\underline{\hat{E}}_z \cdot e^{j\omega t}\} = \left| \underline{\hat{E}}_0 \right| \cdot e^{-\frac{x}{\delta}} \cdot \text{Re}\left\{ e^{j\left(\omega t - \frac{x}{\delta}\right)} \right\} = \underline{\hat{E}}_0 \cdot e^{-\frac{x}{\delta}} \cdot \cos\left(\omega t - \frac{x}{\delta}\right) \quad (1.30)$$

in which $\left| \underline{\hat{E}}_0 \right| e^{-\frac{x}{\delta}}$ is the magnitude of the field strength amplitude, which decreases exponentially

with the distance x from the surface of the conductive half-space. $\cos\omega t$ takes into account the time dependence of the electromagnetic field inside the conductive half-space and $\cos(x/\delta)$ describes a phase shift that the electromagnetic field shows at the penetration into the conductive half-space. **Figure 1.13** shows the variation of electric field strength magnitude in the conductive half-space. The exponential curve is described by the electromagnetic penetration depth δ as the characteristic value, where the magnitude of the field strength is decreased to $1/e$ of the surface value. This decay is a damping of the electromagnetic field in the conductive half-space with the damping constant $1/\delta$. The electromagnetic penetration depth is:

$$\delta = \frac{1}{\sqrt{\pi f \kappa \mu}}. \quad (1.31)$$

It is therefore dependent on the electrical conductivity and the permeability of the conductive half-space, means of the electric material properties, as well as on the frequency of the electromagnetic field. The frequency dependence is specifically used, as will be explained in more detail later, specifically to set a defined electromagnetic penetration depth and thus for setting the local generation of heat. The magnitudes of the magnetic field strength and current density in the conducting half-space have exactly the same curves as the electric field strength.

The induced power in the load depends quadratically on the magnitude of the electric field strength and therefore shows an exponential curve as in **Figure 1.14** having as a characteristic value for the exponential decay half of the electromagnetic penetration depth $\delta/2$.

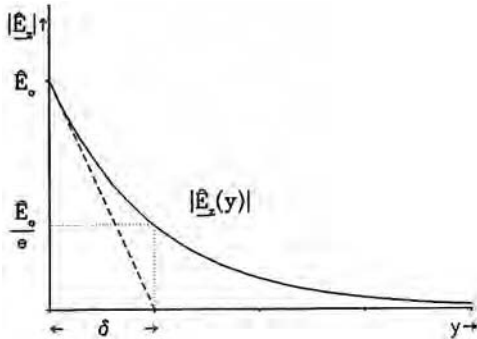


Figure 1.13: Distribution of electrical field strength in the infinite conductive half-space

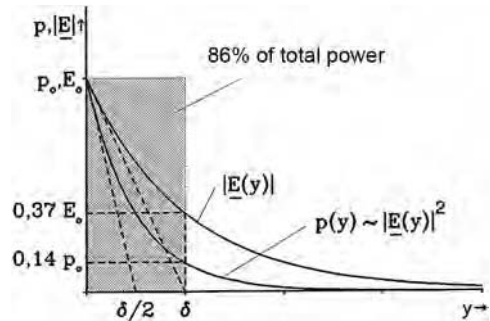


Figure 1.14: Distribution of power density in the infinite conductive half-space

1.2.2 Heat transfer, temperature field

To determine the temperature distribution in the material to be heated, the heat transfer within the material through heat conduction and the heat transfer over the surface of the material by convection and thermal radiation is taken into account. Therefore, initially the three heat transfer modes are described and finally the calculation of the temperature distribution in the material to be heated is illustrated.

1.2.2.1 Heat transfer modes

When heat is transferred three transport mechanisms are to be distinguished from each other, namely:

- Heat conduction
- Heat transfer by convection
- Heat radiation.

The heat transfer by conduction and convection is connected with material energy carriers such as molecules and atoms while, however, these material energy carriers are not needed for heat radiation. Because of the different transport mechanisms also different heat transfer laws describes the mechanisms.

a) Heat conduction

At heat conduction energy is transferred from an energy-rich particle of a material to an adjacent, less energy-rich particle by mutual interaction. The type of energy exchange is dependent on the physical state of the material. So in metals the energy transfer takes place by electron movements and in gases on the other hand by interaction between the molecules. In **Figure 1.15** a simple case of heat conduction is represented by a solid wall.

Under the described conditions at every point of the body at any time, a heat flux Φ (unit: W) is existing. In relation to a surface element perpendicular to its direction, one obtains the heat flux density (unit: W/m²) from the Fourier's law experience:

$$\vec{q} = -\lambda \text{ grad } \vartheta \quad (1.32)$$

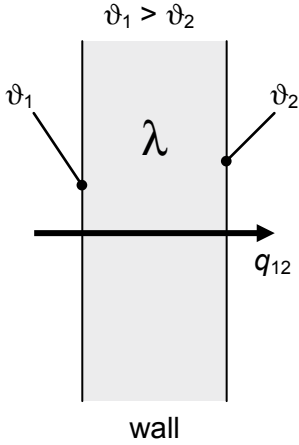


Figure 1.15: Heat conduction through a wall

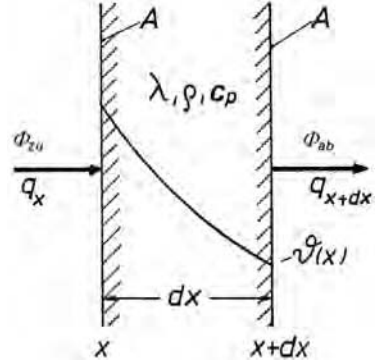


Figure 1.16: Control volume $A \cdot dx$ for derivation of the heat conduction equation

with the temperature distribution $\vartheta(x, y, z)$ and the thermal conductivity λ (unit: $W/(m \cdot K)$).

The main goal of an investigation of heat conduction processes is the determination of the time-varying temperature field in a body that is exposed on its borders to certain thermal boundary conditions. If this distribution is known, the heat flux and also the heat flux densities at any place of the body can be determined using the Fourier law.

To derive the heat equation, a large extended body can be assumed from which, perpendicular to the x -direction, a slice of the thickness dx is cut out (**Figure 1.16**):

The conservation law of energy leads to a balance of the heat flows

$$\Phi_{zu} + P - \Phi_{ab} = \dot{Q}, \quad (1.33)$$

wherein the input heat flux

$$\Phi_{zu} = q_x \cdot A \quad (1.34)$$

is and the output heat flux

$$\Phi_{ab} = q_{x+dx} \cdot A \quad (1.35)$$

In the control volume $A \cdot dx$ of the body heat sources of density p (unit: W/m^3) can exist which result in a heat flux

$$P = p \cdot A \cdot dx \quad (1.36)$$

In addition, a change of the stored energy in the material within the control volume is effective. The part of the time change of the internal energy is

$$\dot{Q} = \frac{dQ}{dt} = c_p \cdot \rho \cdot A \cdot dx \cdot \frac{\partial \vartheta}{\partial t} \quad (1.37)$$

with $c_p \cdot \rho \cdot \frac{\partial \vartheta}{\partial t}$ as the time change per volume. With

$$q_{x+dx} = q_x + \frac{\partial q_x}{\partial x} \cdot dx \quad (1.38)$$

follows from the conservation law of energy, taking into account (1.34 – 1.38)

$$\begin{aligned} q_x \cdot A + p \cdot A \cdot dx - \left(q_x + \frac{\partial q_x}{\partial x} \cdot dx \right) \cdot A &= c_p \cdot \rho \cdot A \cdot dx \cdot \frac{\partial \vartheta}{\partial t} \\ \Leftrightarrow p - \frac{\partial q_x}{\partial x} &= c_p \cdot \rho \cdot \frac{\partial \vartheta}{\partial t}. \end{aligned} \quad (1.39)$$

using the Fourier law

$$q_x = -\lambda \cdot \frac{\partial \vartheta}{\partial x}$$

obtained after slight rearrangement.

$$c_p \cdot \rho \cdot \frac{\partial \vartheta}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \cdot \frac{\partial \vartheta}{\partial x} \right) + p. \quad (1.40)$$

This is the 1-dimensional form of the non-stationary heat conduction equation in Cartesian coordinates. It is an inhomogeneous differential equation of 2nd order. In the 3-dimensional case, the internal energy is also changed by the differences of input and output heat fluxes in the control volume in y and z direction, so that:

$$c_p \cdot \rho \cdot \frac{\partial \vartheta}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \cdot \frac{\partial \vartheta}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \cdot \frac{\partial \vartheta}{\partial y} \right) + \frac{\partial}{\partial z} \left(\lambda \cdot \frac{\partial \vartheta}{\partial z} \right) + p \text{ or.} \quad (1.41)$$

$$c_p \cdot \rho \cdot \frac{\partial \vartheta}{\partial t} = \operatorname{div} (\lambda \cdot \operatorname{grad} \vartheta) + p.$$

This is the general, 3-dimensional form of the heat conduction equation. Its solution delivers the desired temperature distribution depending on location and time: $\vartheta(x, y, z, t)$. The heat conduction equation describes the energy balance for each point considered a medium.

The differential equations specified allow the calculation of the temperature distribution when the physical conditions at the boundaries of the considered body and the initial boundary conditions are known at the time-dependent (transient) operations.

Initial condition

As the initial condition the temperature at each position of the system for time $t = 0$ is defined: $\vartheta_0 = \vartheta_0(x, y, z, t = 0)$. Usually the temperature distribution $\vartheta(x, y, z)$ is given at $t = 0$, in the simplest case it can be a constant initial temperature.

Boundary conditions

Below three typical boundary conditions are outlined. The conditions are indicated for the surface $x = 0$ for a 1-dimensional system. The heat transport takes place in the positive x -direction.

Constant surface temperature

The first boundary condition corresponds to a constant surface temperature ϑ_0 (**Figure 1.17**).

Constant surface heat flux

The second boundary condition corresponds to a constant heat flux density at the surface (**Figure 1.18**).

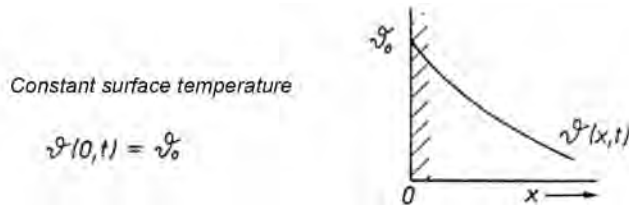


Figure 1.17: Constant surface temperature at $x = 0$

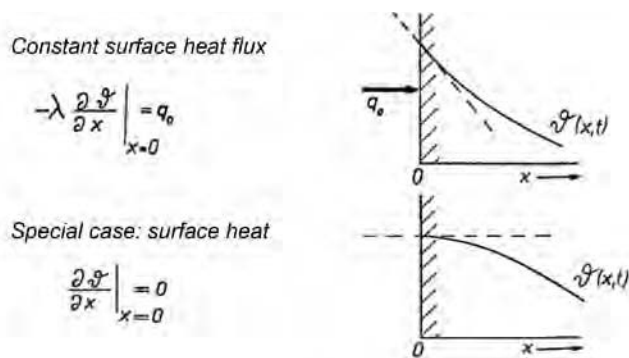


Figure 1.18: Constant surface heat flux density at $x = 0$

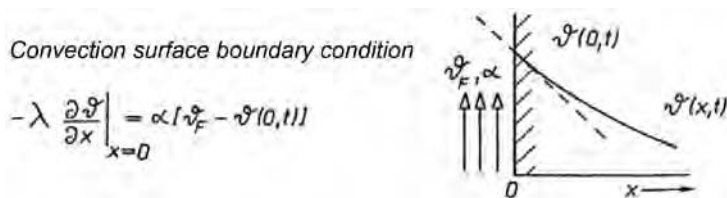


Figure 1.19: Convection surface boundary condition at $x = 0$

Convection surface boundary condition

The third and most common boundary condition considers a convective heat transfer between surface and the surrounding medium (**Figure 1.19**).

1

b) Heat transfer by convection

The convective heat transfer is based, in contrast to heat conduction to a macroscopic particle motion, which is possible only in gaseous or liquid (fluid) materials (**Figure 1.20**).

The heat flow is directly related to the particle motion and thus depends very much on the flow situation of the fluid. A distinction is made between free (natural) and forced convection, depending on whether the particle flow is forced by internal forces (buoyancy forces) or by external forces (fan, pump).

The heat flux density that is transferred from fluid materials to solid walls and vice versa, is described by Newton's law

$$q = \alpha \cdot (\vartheta_w - \vartheta_F) \quad (1.42)$$

with the temperature difference between the wall and fluid $\vartheta_w - \vartheta_F$ and the heat transfer coefficient α (unit: $\text{W/m}^2 \cdot \text{K}$).

The local heat flux density and/or the total heat flow are important at each heat convection problem. The determination of these values depends on the knowledge of local or mean heat transfer coefficients. The determination of these coefficients is the real problem in heat transfer by convection. The coefficients depend not only by physical properties such as density ρ , dynamic viscosity η , thermal conductivity λ and specific heat capacity c_p , but also by the surface geometry and the flow state:

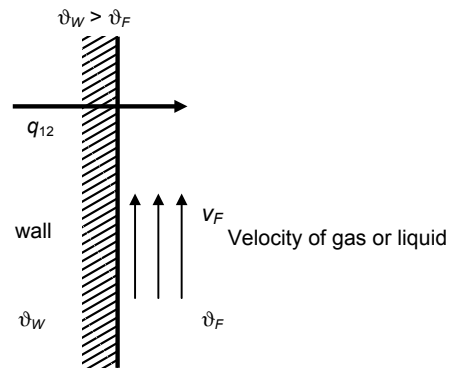


Figure 1.20: Heat transfer by convection from a surface to a fluid

$$\alpha = \alpha(c_p, \rho, \lambda, \eta; p, \vartheta, u; \text{Form})$$

Material characteristics
Surface geometry

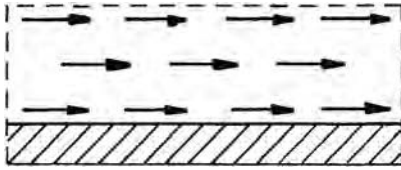
Thermodynamic characteristics

To get an insight into the mechanism of convection, the hydrodynamic processes in the flowing fluids must be considered in more detail first. The heat transfer by convection is a fluidic problem substantially.

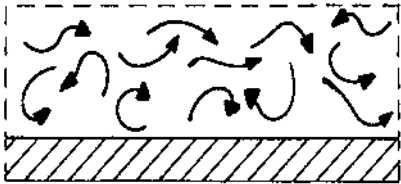
Laminar and turbulent flow

Liquids or gases (also referred to as fluids), whose flow is in a regular adjacent and superposed sliding of layers, flow laminar. It is called a laminar flow (**Figure 1.21**).

If the liquid particles or gas molecules run fluctuations around the average flow, this is called a turbulent flow (**Figure 1.22**).



Flow lines parallel

Figure 1.21:
Laminar flowFlow lines intertwined.
Fluid particles perform fluctuating movements around the central flow.**Figure 1.22:**
Turbulent flow

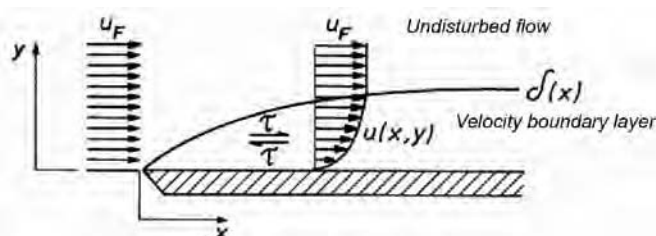
One particularly interesting area for the flow and the transfer of heat is the zone directly to the solid surface, the so-called boundary layer. In a flowing fluid the advance of the temperature field (conduction) and the take-away from heat superimpose by the flow (convection) superimpose. Therefore, a temperature field can not arbitrarily penetrate far into the flowing fluid. The flow always brings fresh cold fluid which has to be heated again. Thus, a steady state is formed from where the temperature front does not change its position relative to the warm wall. Convection is a combination of heat conduction and heat transport by flow.

Velocity boundary layer

The term of the boundary layer is explained at the example of a longitudinally flat plate (**Figure 1.23**). The flat plate is flown from an undisturbed flow constant velocity u_F .

At the plate surface due to friction or adhesion (sticking substances) between the fluid and the wall the flow velocity is zero (no-slip condition at the wall). Fluid particles that adhere to the wall, then act on particles, which flow into a layer over it and drag it. These in turn drag particles in another layer over it, etc. until, at a distance $y = \delta$ from the surface of the drag effect is negligible. The drag effect is due to the viscosity of the fluid.

The size δ is called boundary layer thickness. The velocity profile in the boundary layer shows how the velocity changes within the boundary layer depending on the y -coordinate. With increasing distance from the plate front edge the boundary layer thickness δ increases with increasing x .

**Figure 1.23:** Velocity boundary layer for a flat plate

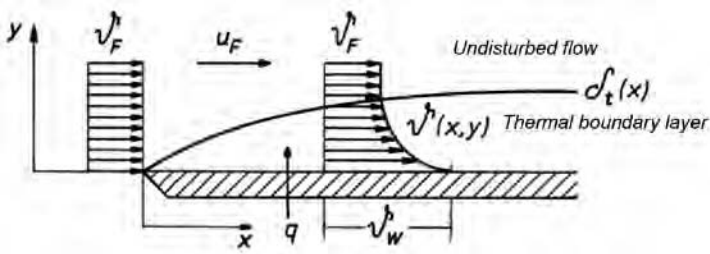


Figure 1.24: Temperature boundary layer for a flat plate

The kinematic viscosity

$$\nu = \frac{\eta}{\rho} \quad (1.43)$$

describes the ratio of friction to the inertia of the fluid and is a measure of the velocity of propagation of deceleration from the wall into the fluid and thus for the formation of the boundary layer flow.

Temperature boundary layer

Just as the velocity boundary layer is formed when a fluid flows over a surface, there is also a temperature boundary layer formed when the flowing fluid and the surface have different temperatures (**Figure 1.24**).

At the plate front edge a uniform temperature profile with $\vartheta = \vartheta_F$ exists. When the fluid particles touch the surface a thermal equilibrium between particles and surface occurred, means the fluid particles at the surface take over the surface temperature. These particles, in turn, exchange energy with those in the adjacent overlying layer, such that temperature gradients in the fluid are generated.

The temperature boundary layer has a thickness δ_t and generally differs from the thickness of the velocity boundary layer. The temperature boundary layer is determined by the thermal diffusivity

$$a = \frac{\lambda}{c_p \cdot \rho} \quad (1.44)$$

and describes the propagation speed of a temperature front in a body. The smaller the specific heat capacity and the greater the thermal conductivity, the faster a temperature change propagates.

Nusselt, Prandtl, Reynolds numbers

From the temperature boundary layer a relationship for the heat transfer coefficient can be derived. In any distance x from the plate front edge the local heat flux density for $y = 0$ can be described by Fourier's law

$$q = -\lambda_F \cdot \left. \frac{d\vartheta}{dy} \right|_{y=0} \quad (1.45)$$

The energy transfer is caused only by heat conduction, whereby the thermal conductivity λ_F is the thermal conductivity of the non-moving fluid. Similarly, the local heat flux can also be described by Newton's law

$$q = \alpha \cdot (\vartheta_W - \vartheta_F). \quad (1.46)$$

Combining both equation (1.45) and (1.46) results in

$$\alpha = \frac{-\lambda_F \cdot \left. \frac{d\vartheta}{dy} \right|_{y=0}}{\vartheta_W - \vartheta_F}. \quad (1.47)$$

This equation results in conjunction with Figure 1.24 to the following:

- The heat transfer coefficient α is decisively influenced by the conditions in the temperature boundary layer, in particular by the temperature gradient on the wall

$$\left. \frac{d\vartheta}{dy} \right|_{y=0}$$

- When the temperature difference $\vartheta_W - \vartheta_F$ over the plate length x is constant the temperature gradients in the boundary layer must decrease with increasing distance x from the plate front edge, since the thickness δ_t increases. This also means that the value of

$$\left. \frac{d\vartheta}{dy} \right|_{y=0}$$

is decreasing with increasing thickness δ_t and that consequently the local heat flux q and the local heat transfer coefficient α decrease with increasing distance x .

Nusselt number

Equation (1.47) for the heat transfer coefficient is generally written dimensionless and is after the onset of these expressions

$$\frac{\alpha \cdot L}{\lambda} = \left. \frac{d\vartheta^*}{dy^*} \right|_{y^*=0}. \quad (1.48)$$

The expression on the left side in the equation (1.48) is the Nusselt number

$$\text{Nu} = \frac{\alpha \cdot L}{\lambda} = \frac{\alpha}{\frac{\lambda}{L}} = \frac{\text{convective heat transfer}}{\text{heat conduction}}. \quad (1.49)$$

The Nusselt number can be interpreted physically as a ratio of actual heat flux in the fluid to the heat flux at pure heat conduction.

Prandtl number

A relationship between the velocity boundary layer δ_v and the temperature boundary layer δ_t can be defined using the Prandtl number

$$\text{Pr} = \frac{\nu}{a} = \frac{\eta \cdot c_p}{\lambda} \quad (1.50)$$

It represents the ratio of propagation of the deceleration of the flow at the wall to the propagation of the temperature front. It is an important number for the heat transfer.

Reynolds number

Beside the Prandtl number also the Reynolds number has a high importance for heat transfer by convection. It describes the ratio of inertia force to the viscous force in a fluid flow

$$\text{Re} = \frac{\rho \cdot u_F \cdot L}{\eta} = \frac{u_F \cdot L}{\nu} = \frac{\text{inertia force}}{\text{viscous force}} \quad (1.51)$$

and, therefore, it describes the flow state of a fluid (laminar or turbulent flow).

Forced convection

In **Table 1.1** the significant numbers for heat transfer in fluids by forced convection are summarized.

By means of the Prandtl number and the Reynolds number the Nusselt number for forced convection can be determined for different configurations and geometries. Corresponding equations for the Nusselt number are described in the literature, e.g. can be found in [1.3]. From the Nusselt number the heat transfer coefficient a can then be determined, see Table 1.1. For free convection the Grashof number has to be used instead of the Reynolds number which will be described in the following.

Number	Definition	Interpretation
Nusselt number	$\text{Nu} = \frac{\alpha \cdot L}{\lambda}$	Ratio of heat transfer by convection to heat conduction in a liquid layer with the thickness L
Prandtl number	$\text{Pr} = \frac{\eta \cdot c_p}{\lambda} = \frac{\nu}{a}$	Ratio of propagation of the deceleration of the flow at the wall to the propagation of the temperature front
Reynolds number	$\text{Re} = \frac{u_F \cdot L}{\nu}$	Ratio of inertia force to the viscous force in a fluid flow

Table 1.1: Characteristic numbers for heat transfer by forced convection

Free convection

The flow at free (natural) convection is caused by temperature differences. The free flow is a consequence of the difference in density $\rho(\vartheta)$, so of buoyancy forces, and will be laminar in most cases. **Figure 1.25** explains the distribution of flow velocity and temperature at the free convection on a flat vertical wall. If the wall is heated, a temperature boundary layer is formed between the wall and the contacting fluid in which the temperature $\vartheta(y)$ is decreasing steadily from the temperature of the wall ϑ_w to the temperature of the undisturbed fluid ϑ_F .

Depending on the temperature field a velocity field is formed. Due to with the temperature change associated density changes a buoyancy flow is generated which effects a heat transfer from the wall to the fluid. The process of heat transfer by free convection is thus approximately

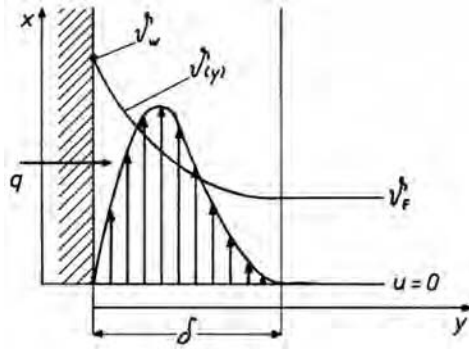


Figure 1.25: Temperature and velocity distribution for free convection at a heated vertical wall

to the same mechanisms as in the case of forced convection. The major difference lies only in the cause of the generated flow. In free convection, these are buoyancy forces.

The buoyancy forces in x-direction are

$$dF_{A,x} = \beta \cdot \rho \cdot g_x \cdot (\vartheta - \vartheta_F) \cdot dV, \quad (1.52)$$

where β is the expansion coefficient and g_x the gravitation coefficient. Derived from that equation the Grashof number results again as a dimensionless number:

$$\begin{aligned} \text{Gr} &= \frac{g \cdot \beta \cdot L^3 \cdot (\vartheta_w - \vartheta_F)}{\nu^2} \\ &= \frac{\text{buoyancy force}}{\text{viscous force}}. \end{aligned} \quad (1.53)$$

The Grashof number plays the same role in free convection as the Reynolds number in forced convection. The Nusselt number can then be determined by means of Prandtl number and the Grashof number for different configurations and geometries. Corresponding equations for determining the Nusselt number are also described in the literature, e.g. be found in [1.3]. From the Nusselt number the heat transfer coefficient α can then be determined.

Heat transfer with evaporation

A special case for the heat transfer by convection is the heat transfer with evaporation, ie in heat transfer processes in which the heat transferring fluid evaporates. The evaporation of the fluid during the heat transfer allows the transfer of very large heat fluxes and leads to very high heat transfer coefficients, which for cooling, e.g. for cooling of inductors or for quenching in induction surface hardening processes, may be advantageously applied.

A liquid is vaporized by heat as soon as the liquid has reached its boiling temperature ϑ_s and is moreover heated. Depending on the temperature rise of the wall over the boiling temperature $\vartheta_w - \vartheta_s$ (overtemperature of the wall) different evaporation modes are existing (**Figure 1.26**).

For small wall overtemperatures, the generated heat will be transported from the heating zone to the liquid surface by natural (free) convective buoyancy flow.

With increasing overtemperature the free convection becomes more intense until finally individual vapour bubbles occur. The nucleate boiling starts. At the solid wall bubbles are grown that are initially in equilibrium with the surrounding liquid. With sufficient buoyancy force the bubbles come off from the hot surface and rise. The rising bubbles increase the liquid circulation and thus the heat transfer. For further increasing overtemperature the growing of bubbles is even stronger and the bubbles begin to grow in size, that means, the evaporation is no longer exclusively on the heated surface rather than but to a large extent on the bubble surfaces in the vapour bubble inside. The bubble evaporation results in a significantly increased heat transfer compared to heat transfer without evaporation (Figure 1.26).

For very large overtemperatures, the bubbles grow into a film. This vapour film is initially localized and broken in places. In this area, the film evaporation of heat transfer is unstable. Only above a certain threshold temperature difference the vapour film closes and is stable. By the insulating effect of the vapour film (vapour has a much lower thermal conductivity compared to

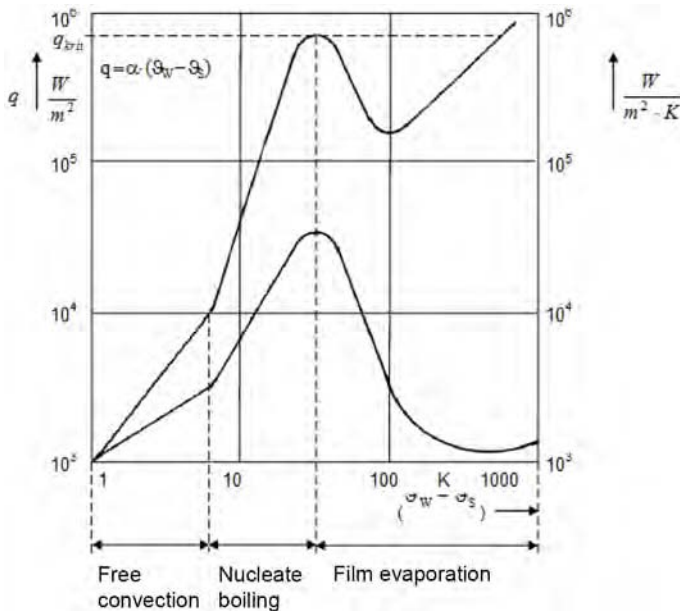


Figure 1.26: Heat flux density and heat transfer coefficient for evaporation of water at 1 bar as a function of the overtemperature $\vartheta_w - \vartheta_s$

a liquid) the heat transfer in this area is significantly decreased (Figure 1.26). Only with further increasing of the overtemperature the heat transfer increases as a result of radiation exchange between heating surface and liquid by the vapour film again.

Exploiting the range of nucleate boiling allows heat flux densities of up to 800 kW/m² for the case of cooling with water at a pressure of 1 bar. Higher pressures, as are usually present in cooling systems, and higher flow rates of the coolant additionally increase the transferable output density. Thus, the nucleate boiling can be advantageously used, however, a transition into the film evaporation must be avoided, since otherwise, as far as the cooling power is constant, impermissible temperatures at the components to be cooled can occur.

c) Heat radiation

The heat radiation does not require any material for the heat transfer process. Systems of different temperatures are in radiation interaction with each other (**Figure 1.27**). The systems exchange electromagnetic radiation (energy) and must be capable of radiating energy (emission) and receive (absorption). Each body with a temperature $T > 0$ emits radiation and each irradiated body absorbs heat. The heat transfer by radiation is thus characterized by two energy conversions: converting heat into electromagnetic energy at the emitter and vice versa at the absorber. The body of a radiated energy flux density (emissivity) is according to the law of Stefan and Boltzmann

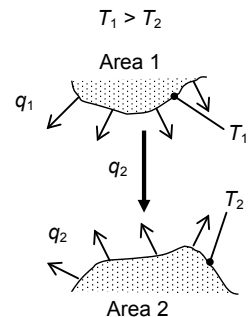


Figure 1.27: Heat radiation exchange between two systems

$$q = \varepsilon \cdot \sigma \cdot T^4 \quad (1.54)$$

with the Stefan-Boltzmann constant σ ($\sigma = 5.67 \cdot 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$). The value ε (emissivity) is primarily dependent on the nature of the surface conditions of the radiating body.

The entire spectrum of electromagnetic radiation is shown in **Figure 1.28** in dependence on the wavelength. The wavelength of heat radiation covers the range from $\lambda = 0.1 \text{ } \mu\text{m}$ to $\lambda = 100 \text{ } \mu\text{m}$, while the visible range of the spectrum is between $0.4 \text{ } \mu\text{m}$ and $0.8 \text{ } \mu\text{m}$.

The from a body surface emitted heat radiation covers a whole range of wavelengths, thereby the amplitude of the radiation is changing with the wavelength. It is called the spectral distribution (**Figure 1.29**) of the emitted radiation.

In addition to the spectral nature heat radiation has a directionality distribution (**Figure 1.30**), a second important feature. Both effects have to be considered for a correct quantitative description of the heat transfer by radiation.

The black body

The black body is an ideal surface with the following characteristics:

- All incoming radiation is absorbed by the black body, independent of wavelength and direction
- For a given temperature and wavelength, no surface can emit more energy than a black body
- Although the radiation emitted by a black body is a function of wavelength and temperature, it is independent of the direction. The black body is a diffuse emitter.

As an ideal absorber and emitter the black body therefore is used as a reference standard, on to which the radiation properties of real surfaces are referred.

The emitted radiation energy of a black body

$$W = W(\lambda, T) \quad (\text{Unit: } W_s = \text{J})$$

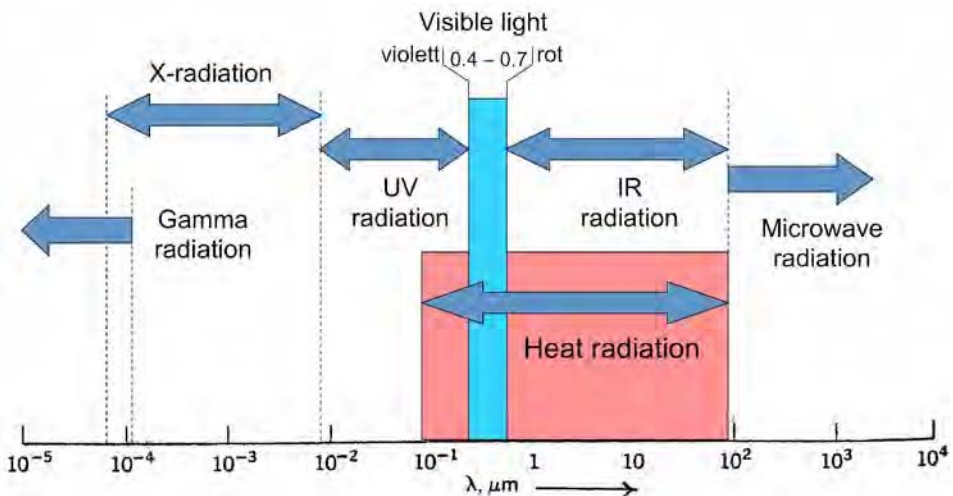


Figure 1.28: Spectrum of electromagnetic radiation

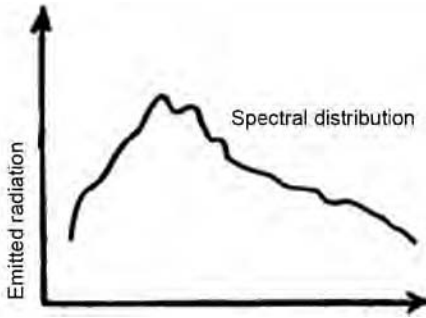


Figure 1.29: Emitted heat radiation from a surface: spectral distribution (schematic)

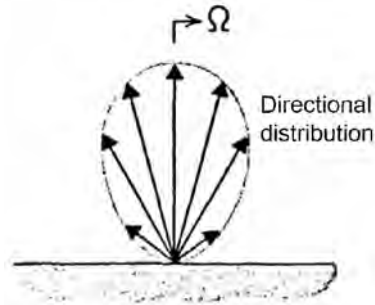


Figure 1.30: Emitted heat radiation from a surface: directionality distribution (schematic)

is uniquely determined by its temperature. The relation between the emitted radiation energy W and the emitted radiation flux or heat flow Φ is

$$\Phi = \frac{dW}{dt} \quad (\text{Unit: W}). \quad (1.55)$$

However, the emitted radiation energy is not distributed evenly across all wavelengths, therefore, with the dependence of the emitted radiation energy $W = W(\lambda, T)$ also the heat flux density q , which is also called the specific emitted radiation M_s , is a function of the wavelength and the temperature:

$$q = M_s = M_s(\lambda, T) = \frac{d\Phi(\lambda, T)}{dA} \quad (\text{Unit: } \frac{\text{W}}{\text{m}^2}). \quad (1.56)$$

The spectral distribution of the heat flux density is called the spectral specific emitted radiation M_λ :

$$M_\lambda = M_\lambda(\lambda, T) = \frac{dM_s(\lambda, T)}{d\lambda} \quad (\text{Unit: } \frac{\text{W}}{\text{m}^2 \cdot \text{m}}). \quad (1.57)$$

For a black body the spectral specific radiation is clearly defined for a certain temperature of the black body by the Planck's law:

$$M_\lambda = \frac{dM_s}{d\lambda} = C_1 \cdot \frac{\lambda^{-5}}{e^{\frac{C_2}{\lambda \cdot T}} - 1} \quad (\text{Unit: } \frac{\text{W}}{\text{m}^2 \cdot \text{m}}) \quad (1.58)$$

with $C_1 = 0.374 \cdot 10^{-15} \text{ W} \cdot \text{m}^2$,
 $C_2 = 1.438 \cdot 10^{-2} \text{ m} \cdot \text{K}$ und
 λ in m.

The distribution of the spectral specific emitted radiation of a black body is called the Planck distribution and shown in **Figure 1.31** for a few temperatures.

Important features of the Planck's distribution are:

- The emitted radiation varies continuously with the wavelength.
- For each wavelength, the value of the emitted radiation increases with increasing temperature.

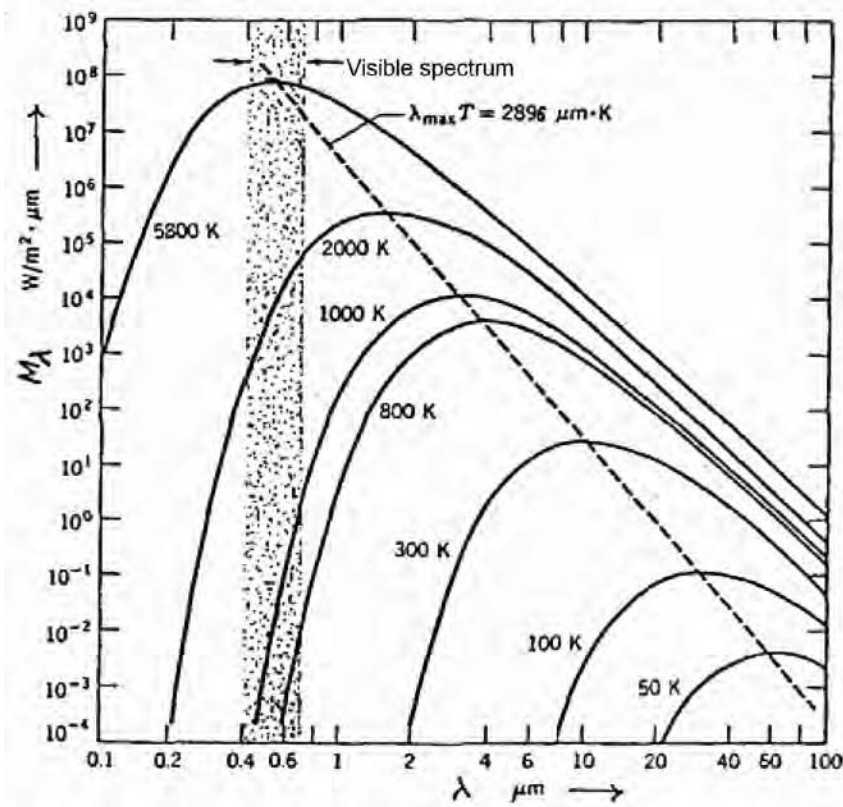


Figure 1.31: Distribution of the spectral specific emitted radiation of a black body

- The spectral range in which the radiation is concentrated depends on the temperature.
- A significant part of solar radiation, which can be regarded as the radiation of a black body with $T = 5,800$ K, is in the visible range of the spectrum. In contrast, for Figure 1.30: Emitted heat radiation from a surface: directionality distribution (schematic) $T \leq 800$ K, the emitted radiation is mainly in the infrared range of the spectrum and thus not visible.

By differentiating of the Planck equation, the wavelength can be established, in which the maximum power can be emitted. The position of the maximum is determined by the Wien's displacement law

$$\lambda_{\max} \cdot T = 2.896 \mu\text{m} \cdot \text{K} \quad (1.59)$$

with $\lambda_{\max}$ in μm and T in K. Thereafter, the maximum spectral emitted radiation shifts with increasing temperature towards smaller wavelengths. For this maximum is

$$M_{\lambda, \max} = C_3 \cdot T^5 \quad (1.60)$$

with $C_3 = 1.309 \cdot 10^{-5} \text{ W}/(\text{m}^2 \cdot \text{m} \cdot \text{K})$.

The integrating of the spectral emitted radiation over the entire wavelength range

$$M_S = \int_{\lambda=0}^{\infty} M_{\lambda}(\lambda, T) d\lambda \quad (1.61)$$

results in the specific emitted radiation (equal to the heat flux density q) which is called the Stefan-Boltzmann law for the black body

$$M_S = q = \sigma \cdot T^4 \quad (1.62)$$

with the Stefan-Boltzmann constant

$$\sigma = 5.67 \cdot 10^{-8} \frac{\text{W}}{\text{m}^2 \cdot \text{K}^4} \quad (1.63)$$

or in another form frequently used in practice

$$M_S = 10^8 \cdot \sigma \cdot \left(\frac{T}{100} \right)^4 = C_S \cdot \left(\frac{T}{100} \right)^4 \quad (1.64)$$

with the so-called radiation-constant of the black body

$$C_S = 5.67 \frac{\text{W}}{\text{m}^2 \cdot \text{K}^4} \cdot \quad (1.65)$$

Absorption, reflection and transmission

If radiation incident on a semi-transparent body, such as a layer of water or glass, so parts of the radiation are reflected, absorbed and transmitted, as shown in **Figure 1.32**.

The power balance of the radiation is then

$$\Phi = \Phi_r + \Phi_a + \Phi_{tr} \quad (1.66)$$

and with the characteristic coefficients

- Reflectance: $\rho = \frac{\Phi_r}{\Phi}$,
- Absorption coefficient: $\alpha = \frac{\Phi_a}{\Phi}$ and
- Transmittance: $\tau = \frac{\Phi_{tr}}{\Phi}$,

results in the balance

$$\rho + \alpha + \tau = 1, \quad (1.67)$$

wherein all parts of the spectrum are taken into account.

Nature knows neither the black nor the absolutely ideal white or translucent body. While the black body can be approximated by blackening of surfaces, provide highly polished metal surfaces closer to the ideal reflector (white body).

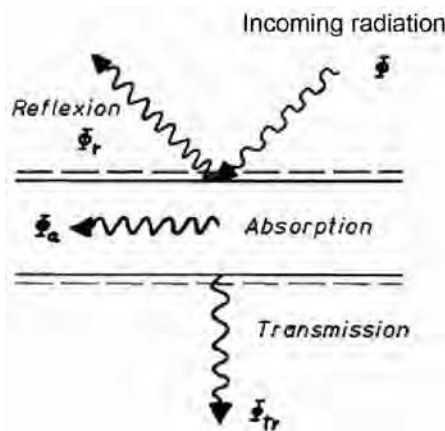


Figure 1.32: Absorption, reflection and transmission

Emissivity

The emissivity ε is the ratio of specific emitted radiation M of a body to the specific emitted radiation of a black body M_s at the same temperature,

$$\varepsilon = \frac{M(T)}{M_s(T)}. \quad (1.68)$$

For the steady state Kirchhoff's law can be applied:

$$\varepsilon = \alpha. \quad (1.69)$$

Emissivity = absorption coefficient.

The gray body

If a radiation emitting body has an emissivity lower than 1 it is called a gray body or a gray radiator. The emitted heat flux of a gray body heat flux (specific emitted radiation) is after Stefan-Boltzmann law

$$M = q = \varepsilon \cdot \sigma \cdot T^4 \quad (1.70)$$

or

$$M = q = \varepsilon \cdot C_s \cdot \left(\frac{T}{100} \right)^4, \quad (1.71)$$

where $\varepsilon = \frac{M}{M_s} < 1$ is applicable.

Heat transfer by radiation

The Stefan-Boltzmann law applies to bodies that emit heat radiation, but can not receive them. Usually, however, each emitting body is in radiation exchange with the environment that radiates itself, as long as their temperature is above absolute zero. Under environment are generally to be understood solid walls; because air is for heat radiation almost completely transparent ($\tau \approx 1$, $\alpha = \varepsilon = 0$).

For the heat transfer by radiation only the resulting heat flux from all emission, absorption and reflection processes of the two radiators is of interest (net heat flux), which is finally transferred from the warmer to the colder body. For simple arrangements the resulting heat flux can be analytically calculated.

Radiation exchange between two parallel plane walls

For two parallel plane walls (**Figure 1.33**) with the same area A and constant but different temperatures T_1 and T_2 the heat flux results to

$$\Phi_{12} = \frac{C_s}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \cdot A \cdot \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right], \quad (1.72)$$

wherein the term

$$C_{12} = \frac{C_s}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \quad (1.73)$$

is called the radiation exchange constant. The resulting heat flux (specific emitted radiation) is then

$$M_{12} = q_{12} = C_{12} \cdot \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right]. \quad (1.74)$$

Gray radiator with a complete enclosure

For the radiation exchange between a gray radiator and a complete enclosure (**Figure 1.34**) the following equation can be applied

$$\Phi_{12} = A_1 \cdot C_{12} \cdot \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right] \quad (1.75)$$

with

$$C_{12} = \frac{C_s}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2} \cdot \left(\frac{1}{\varepsilon_2} - 1 \right)}. \quad (1.76)$$

The equation applies to the heat exchange of concentric spheres and coaxial, infinitely long cylinders.

The exchanged radiation (heat flux) is greater the greater the surrounding area is, since with an increasing area A_2 the retroactive effect of the enclosure on the radiator 1 becomes smaller.

For $A_2 \gg A_1$ the heat flux Φ_{12} is only dependent on the emissivity of the enclosed body and it applies:

$$C_{12} = \varepsilon_1 \cdot C_s. \quad (1.77)$$

Effect of radiation screens

Radiation screens made of both side polished sheets with high reflectivity, but also such with high emissivity ε or absorption coefficient α , reduce the resultant radiation flux between two surfaces very effectively.

Figure 1.35 shows a radiation screen (area 3) between two large parallel plates.

Without the radiation screen the heat exchange between plate 1 and plate 2 is:

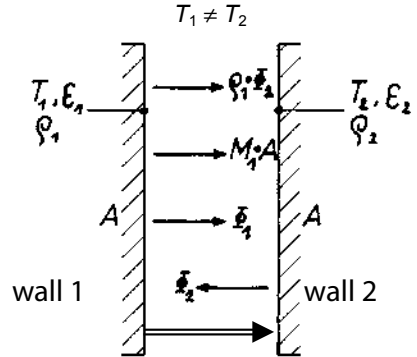


Figure 1.33: Heat radiation exchange between two parallel plane walls

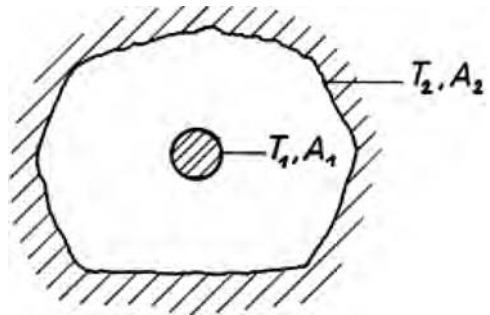


Figure 1.34: Heat radiation exchange between a gray radiator 1 and a complete enclosure 2

$$\Phi_{12_0} = \frac{A \cdot C_s \cdot \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right]}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \quad (1.78)$$

Analog to the calculation of the radiation exchange between two surfaces of different temperature and emissivities the resulting heat flow Φ_{12} can be calculated for two plates with a radiation screen between. For an arrangement in accordance with **Figure 1.35** and with the emissivities ε_1 , ε_2 , ε_{31} and ε_{32} follows:

$$\Phi_{12_1} = A_1 \cdot C_{12} \cdot \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right] \quad (1.79)$$

with

$$C_{12} = \frac{C_s}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} + \frac{1 - \varepsilon_{31}}{\varepsilon_{31}} + \frac{1 - \varepsilon_{32}}{\varepsilon_{32}}} \quad (1.80)$$

If the emissivities of all surfaces are approximately equal ($\varepsilon_1 = \varepsilon_2 = \varepsilon_{31} = \varepsilon_{32} = \varepsilon$) follows:

$$C_{12} = \frac{1}{2} \cdot \frac{C_s}{\frac{1}{\varepsilon} + \frac{1}{\varepsilon} - 1} \quad (1.81)$$

This is half the value of the radiation exchange constants without screen. Thus, with a radiation screen between radiation exchanging surfaces approximately applies:

$$\Phi_{12_1} = \frac{1}{2} \cdot \Phi_{12_0} \quad \text{and} \quad (1.82)$$

for several radiation screens

$$\Phi_{12_n} = \frac{1}{n+1} \cdot \Phi_{12_0} \quad (1.83)$$

with the number n of screens. The principle is often used in practice for high temperature screening.

d) Thermal transmission

A combination of heat conduction and heat transfer by convection occurs at the so-called heat transmission in which the heat from a warmer medium is transmitted through a partition wall (**Figure 1.36**). Heat transmission occurs for example in heat exchangers or in the walls of buildings. At heat transmission three kinds of heat transfer occur:

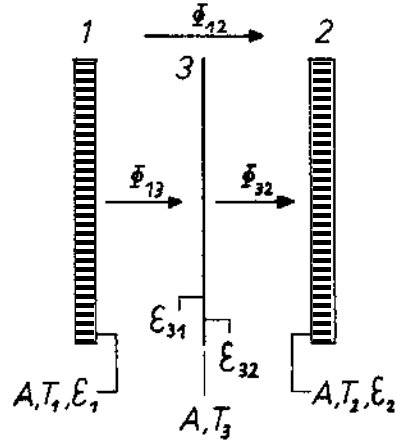


Figure 1.35: Configuration with a radiation screen

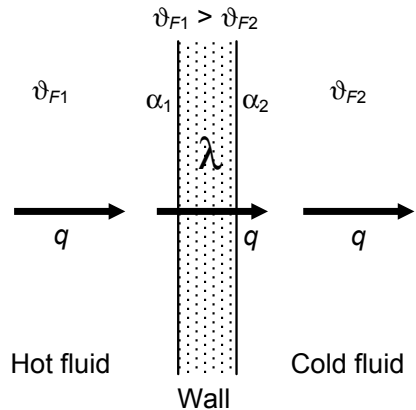


Figure 1.36: Heat transmission through a wall

- Heat transfer by convection 1 (Fluid 1 $\Rightarrow$ Wall),
- Heat conduction (Wall)
- Heat transfer by convection 2 (Wall $\Rightarrow$ Fluid 2)

The heat flux density at heat transmission is calculated according to

$$q = k \cdot (\vartheta_{F_1} - \vartheta_{F_2}), \quad (1.84)$$

where k is the heat transmission coefficient (unit: $\text{W/m}^2 \times \text{K}$) and is dependent on both λ as well as on α_1 and α_2 . The following applies:

$$\frac{1}{k} = \frac{1}{\alpha_1} + \frac{d}{\lambda} + \frac{1}{\alpha_2} \quad (\text{Unit: } \frac{1}{\text{W/m}^2 \cdot \text{K}}) \quad (1.85)$$

If the wall is made of n layers with the thickness d_i and the thermal conductivities λ_i , then:

$$\frac{1}{k} = \frac{1}{\alpha_1} + \sum_{i=1}^n \frac{d_i}{\lambda_i} + \frac{1}{\alpha_2}. \quad (1.86)$$

The heat transmission coefficient k in $\text{W/m}^2 \times \text{K}$ has the same unit like the heat transfer coefficient for pure convection.

1.2.2.2 Temperature field inside solid bodies

For the calculating of the temperature distribution within solid bodies the Fourier heat conduction equation is used

$$c_p \rho \frac{\partial \vartheta}{\partial t} = \text{div} \left(\lambda \text{grad} \vartheta \right) + p \quad (1.87)$$

or detailed for the Cartesian case

$$c_p \rho \frac{\partial \vartheta}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial \vartheta}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \frac{\partial \vartheta}{\partial y} \right) + \frac{\partial}{\partial z} \left(\lambda \frac{\partial \vartheta}{\partial z} \right) + p(x, y, z) \quad (1.88)$$

with the temperature distribution $\vartheta(x, y, z)$ as well as for the cylindrical case

$$c_p \rho \frac{\partial \vartheta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(\lambda r \frac{\partial \vartheta}{\partial r} \right) + \frac{\partial}{\partial z} \left(\lambda \frac{\partial \vartheta}{\partial z} \right) + p(r, \varphi, z) \quad (1.89)$$

with the temperature distribution $\vartheta(r, \varphi, z)$. Additional variables of the heat conduction equation are the specific heat c_p , the density ρ and the heat conductivity λ . The heat source density p describes the distribution of heat sources in the body.

The heat transfer or the heat exchange at the surface of the material due to radiation and convection is not covered by the heat conduction equation. This heat flow should be simulated on the body surface by suitably chosen boundary conditions. Radiation can be calculated directly from the exchange of radiation between different surfaces in complex arrangements.

1.2.3 Coupling of electromagnetic and thermal field

About the power source density p in the heat conduction equation, which arises within the electrically conductive bodies due to the electromagnetic field caused by eddy currents, the heat conduction equation is coupled with the differential equation of the electromagnetic field. In the case of induction heating for rotationally symmetric systems the curl part of the electric field strength is

$$\underline{E}_\varphi = -j\omega \underline{A}_\varphi \quad \text{or} \quad \underline{E} = -j\omega \underline{A}$$

and therefore the power source density p (Joule heat)

$$p = \kappa |\underline{E}|^2 = \kappa \omega^2 |\underline{A}|^2. \quad (1.90)$$

Thus, the heat conduction equation in the Cartesian case is

$$c_p \rho \frac{\partial \vartheta}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial \vartheta}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \frac{\partial \vartheta}{\partial y} \right) + \frac{\partial}{\partial z} \left(\lambda \frac{\partial \vartheta}{\partial z} \right) + \kappa \omega^2 |\underline{A}|^2 \quad (1.91)$$

and in the cylindrical case

$$c_p \rho \frac{\partial \vartheta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(\lambda r \frac{\partial \vartheta}{\partial r} \right) + \frac{\partial}{\partial z} \left(\lambda \frac{\partial \vartheta}{\partial z} \right) + \kappa \omega^2 |\underline{A}|^2. \quad (1.92)$$

All material properties

$$\kappa(\vartheta), \mu(H, \vartheta), \lambda(\vartheta), c_p(\vartheta), \rho(\vartheta)$$

are dependent on temperature and the magnetic permeability is additionally dependent on the magnetic field strength, so that the differential equations become non-linear.

An analytical solution of the equation system is usually not possible. Therefore proper numerical solution methods are described in more detail in the following.

1.3 Numerical simulation methods

Due to the strong increase in performance of today's computer systems in terms of memory size and computing speed, it is possible to solve complex and on many parameters dependent physical systems (by solving the describing mathematical equations). In contrast to a physical modeling, mathematical modeling makes some conditions necessary, such as

- the mathematical equations describing the physical system must be known
- the material properties used in the system and their dependencies on temperature, field strength etc. must be known
- boundary conditions must be specific and
- the mathematical model must be solvable at all and at a reasonable cost.

Using mathematical modeling, it is therefore not sufficient to only solve mathematical equations, but first of all, the physical relationships have to be investigated. Then it must be decided

- which physical laws are important for the description of the real system
- which physical laws can be neglected to simplify the model, if applicable
- which boundary conditions have to be chosen and
- in which form the material properties and their dependencies can be described mathematically.

The selection of a numerical method for calculating the fields depends primarily on the formulation of the problem. The main numerical methods are illustrated in **Figure 1.37**.

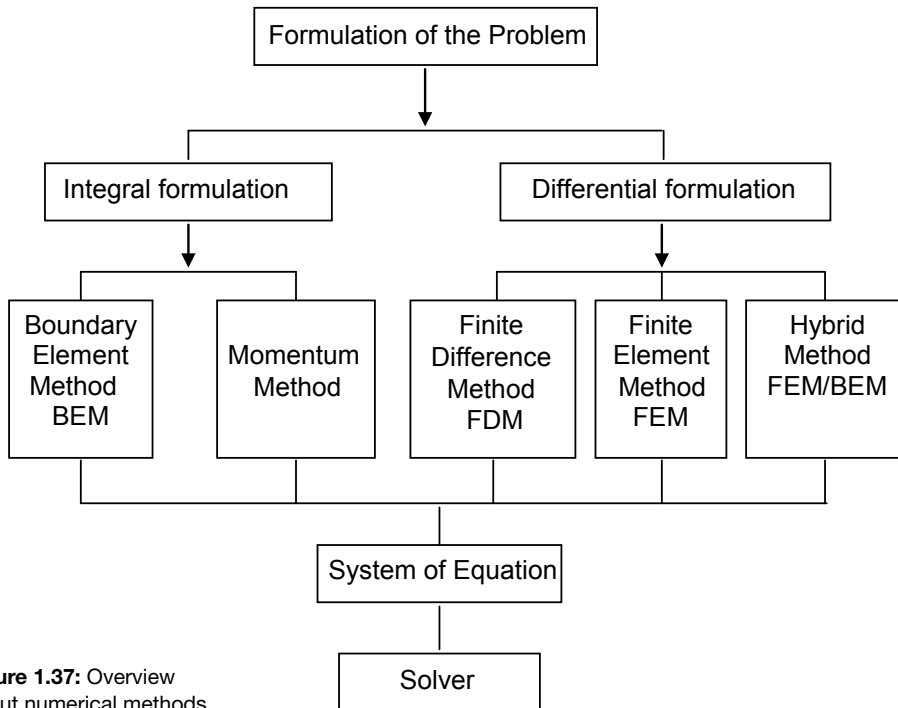


Figure 1.37: Overview about numerical methods

In numerical methods, a discretization is performed, depending on which method the total volume has to be taken into account or only the edge of the volume. The result of discretization and numerical procedure used in each process is that the solution is calculated only in discrete points and only approximately. In between the solution is usually approximated by constant, linear or quadratic functions. As a result of an analytical method however the solution is available in any point of the volume.

Finite Difference Method (FDM)

The oldest method is the numerical finite difference method (FDM). It is based on a discretization of the problem with a generally rectangular or at least regular mesh. The differential equation is locally transferred to the mesh nodes with the help of neighboring nodes to a difference equation. The discretization of the FDM is inflexible and so some disadvantages of this method are connected. The advantages and disadvantages of the FDM are:

- + the method schema, even in 3D, is simply, and thus easily understood by beginners and in regard to programming easy
- + the error estimation can be done easily
- + the matrices are diagonally dominant and only partly filled, which are predominantly symmetric and positively defined
- + for such matrices numerous and effective solvers are available
- + it is possible to work with a very high number of nodes and unknowns, as in the FEM
- + the method is for non-linear materials such as ferro-magnetic materials and semiconductor materials better suited than the FEM

- a regular topological mesh is required (Cartesian, circular cylindrical)
- approximations of higher order (p-adaptation) are difficult to achieve
- the local mesh refinement is unsatisfactory
- adaptive mesh generation (h-adaptation) is hardly possible
- the entire domain has to be discretized as in the FEM, also for linear materials, like volumes in the 3D case and cross-sectional areas in the 2D case.

Boundary Element Method (BEM)

The boundary element method is based, just like the finite element method (FEM), on the principle of weighted residuals. Here another way is used that makes it possible that, instead of a volume in which the field profile is searched, only the edge of the volume must be discretized. The geometrical discretization effort is reduced, which is noticeable especially for 3D problems. Also unlimited areas can be treated easily, which is impossible with the FEM and FDM because of the need to define a suitable, artificially produced outer boundary. The advantages and disadvantages of the BEM are:

- + unknown values of the equation system have to be calculated only on surfaces (3D) or on contour lines (2D)
- + By reducing the dimension (3D case: volume $\rightarrow$ surface, 2D case: cross-section $\rightarrow$ contour) results in a lower number of unknowns and a simplified data processing
- + the geometrical conditions are more transparent
- + unlimited domains are very suitable for the BEM
- + the generation of the system matrix (pre-processing) and the calculation of the field values or field plots (post-processing) are perfectly suited for parallel computing
- fully filled (for one area) or densely filled (with some few areas) system matrix with vector unknowns in 3D: several thousand unknowns, which can be found with a direct solver so that the limits of the computer memory are reached quickly
- Singular and nearly singular integrals have to be calculated for the determination of the system matrix coefficients, increasing the risk of numerical errors
- Nonlinear materials can be handled with the BEM method only in a complex solver process.

Moment method

The moment method is basically just another term for the weighted residuals. Therefore, it necessarily lacks the refinement of the principles of the FEM and BEM. With this method, mainly stray field and antenna problems with high conductive bodies are resolved. In this method the residual and the weight function are not subject to any limitations and thus a wide range of applications is given.

Finite Element Method (FEM)

The finite element method is today the most widely used method. Therefore, it should be explained in more detail than the other methods. The FEM divides the computational domain into a number of smaller areas, for which the individual field equations (integral equations, energy equations, etc.) are solved and linked with boundary conditions of the other areas. With the FEM, the formulation of the weighted residuals is transformed. As weight function the same, only locally existing form functions, are used which approximate the solution. This makes it possible to work with second order differential equations with simple linear form functions. Another strength of this method is the use of simple but flexible elements such as triangles and tetrahedrons. This only allows the generation of flexible meshes, which should be fine where high field gradients exist and can be roughly where the field gradients are small. An automatic meshing in this sense, the adaptive mesh generation, is

a key to the successful treatment of 3-dimensional problems, including with respect to subsequent optimization algorithms. The advantages and disadvantages of the FEM are:

- + the matrices are only partly filled and diagonally dominant, and
- + mostly symmetrical and positively defined
- + several effective equation solvers for such matrices are known
- + a high number of nodes and unknowns is possible
- + the FEM is suitable for complex geometries, relatively simple elements can be used: in 2D triangles and in 3D tetrahedron. Both are relatively simple in geometry, formulation, understanding, but also very adaptable in terms of geometry and suitable for 2D and 3D adaptive mesh refinement.
- + the FEM is suitable for non-linear materials such as ferromagnetic and semiconductor materials
- + as well as for anisotropic materials
- the whole domain has to be discretized, even for linear materials, volumes in 3D, cross-sections in 2D
- in comparison with the BEM, a better geometric imagination and a complex element implementation for 3-dimensional problems (tetrahedron) is required than for the corresponding surfaces (triangles) in the BEM

The concept of finite element method describes a method for the numerical solution of partial differential equations. It is used if a differential equation cannot be solved analytically. As the so-called discretization method, the FEM then provides an approximate solution of the differential equations.

Figure 1.38 shows a comparison of the FEM with the approaches of the FDM and the BEM. From the finite-difference method, the FEM is different in that not only discrete points (nodes) and the approximate solutions at these points are examined. The FEM form functions are defined over all elements (such as surfaces in two dimensions) which should be approximated the exact solution as the node-wise approach in the FDM. An important advantage of FEM is the greater flexibility in dealing with the mesh. While the FDM can be used for other than regular rectangular meshes, only with additional attempts the mesh selection for the FEM has no limits. In particular, the mesh spacing has no longer being constant, which opens up the possibility to choose a fine mesh only where it is really necessary.

In addition, the basic idea of the finite element method is presented. There are several explanations for this method. Here it is presented as a method of approximation. This statement is general and allows the use of FEM as a solution procedure for such as temperature or electromagnetic field calculations. There are also dynamic problems in structural mechanics, in technical acoustics (eg. propagation of sound waves or the dynamic behavior of bodies in a liquid) and many others that can be solved with the FEM. First, the general approach to mathematical approximations is described. Then, the FEM is specifically explained in brief.

In approximation methods differential equations are mostly used. With the aid of differential equations, the behavior of a structure at a differentially small part will be described. The Maxwell equations are a mathematical representation, for example, for electromagnetic fields. For bodies, that can be handled with one or two dimensions, the 3-dimensional differential equations can be simplified with negligible loss of accuracy. For the preparation of the differential equation a characteristic field value is required. This field value is generally described by a function. For temperature field calculations the field value is the temperature and for electromagnetic field calculations it is the electromagnetic vector potential. The main objective of the approximation method is to determine these functions (e.g. temperature field) approximately. Other functions (e.g. heat flux) are determined by the derivative of the functions.

To solve the differential equations, analytical and numerical methods are available. Often, the analytical methods are referred to as the “exact” method. These methods are “exact” only in theory. In

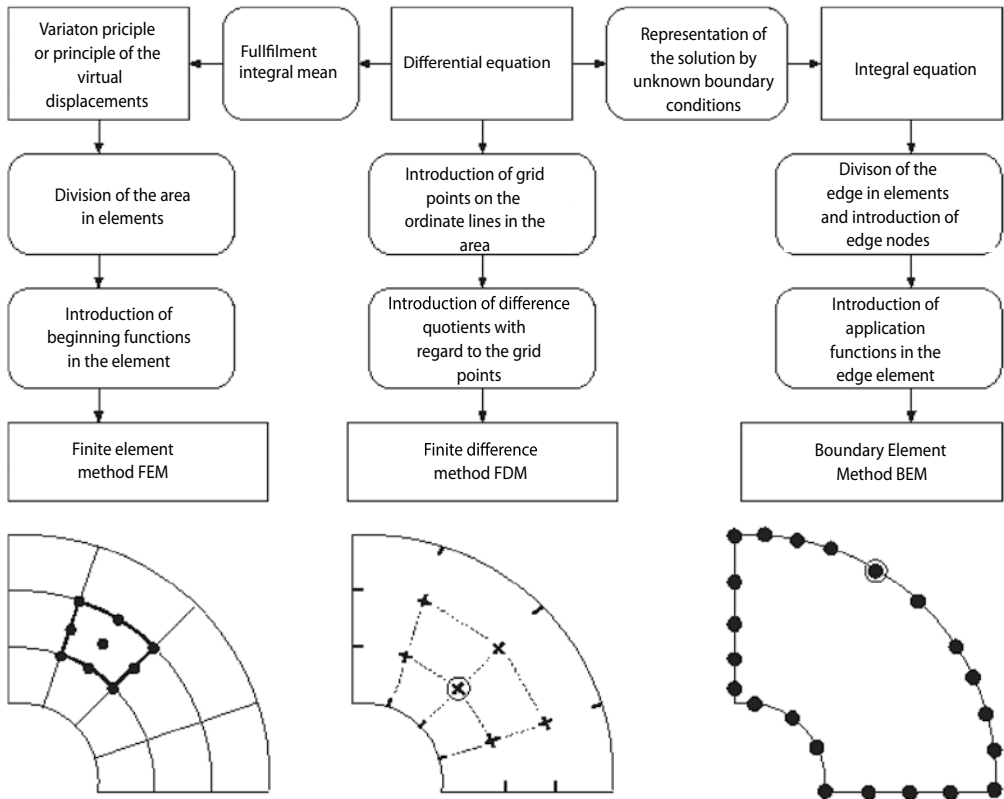


Figure 1.38: Comparison of FEM, FDM and BEM

reality, the results are very different due to the simplifying assumptions. The application of analytical methods is limited to a few special cases. Numerical methods are more suitable for practical tasks. Although they allow only approximate solutions, they are also applicable to complex geometries.

For numerical methods, an approximate approach for the unknown function is defined. The methods start either from the differential equations or from integral forms. The differential equation problem is transformed directly into an algebraic equation system. For the integral form an algebraic system of equations for the unknown coefficients is generated from the demand of an extremum (maximum or minimum). By solving the system of equations the coefficients are determined, and thus set the desired proximity function.

The finite element method is a partially applied numerical method. With the FEM approach functions are chosen which are valid only for subdomains of the entire domain. The approximate function for the entire domain is then composed from the solutions of the subdomains. The FEM is based on the integral form where an integral term is minimized. In many cases, the principle of the minimum potential energy is used.

As the basis of the finite element method, the method of weighted residuals is used, which has the advantage of being able to be used on all boundary value problems. On the other hand, however, it is more mathematically defined as physically.

For the FEM the domain is divided into elements (discretized). Via these elements the solution curve is approximated, e.g. by linear form functions. These values are initially known in the nodes, apart from the edge node. The resulting mesh has n nodes, thus also n unknowns exist. They are calculated from an equation system with n equations in which the field describing boundary value problem is transformed by the method of weighted residuals, the latter coupled with the local Galerkin method.

The procedure for a finite element analysis can be divided into 6 steps. These are:

1. Idealization (choice of the theory and the element type)
2. Division into subdomains (elements), in each subdomain a field function is assumed (e.g. a linear gradient). Unknown are the field values at the element boundaries (nodes)
3. Setting up the system of equations for determining the unknowns at the nodes. The element stiffness matrices are the
4. Entire stiffness matrix, that is the entire equation system
5. Re-calculation to the element level (e.g. temperature in the element)
6. Post-processing of results.

The FEM is advantageous if it is a clearly limited domain, such as in the flow calculation in a harbor or the interior acoustics of a vehicle. Similarly, it is the same for the study of electromagnetic fields. More and more interesting is the aspect to handle coupled field problems, such as electromagnetic/thermal, electromagnetic/thermal/fluidynamic or thermo-mechanical tasks.

Summarizing the different methods, all methods, apart from simple analytical solutions, lead to the solution of a matrix of equations that is typically fully or densely filled by the moment method and the BEM and sparsely filled and diagonal dominant by the other methods.

Non-linear materials can be relatively easily handled with the FDM, FEM and coupled FEM/BEM and more difficultly handled with the pure BEM (large computation times).

With a coupling of FEM and BEM, the advantages of both methods are combined. The FEM then should be applied for enclosed domains and non-linear materials, the BEM for the unlimited domains.

1.4 Design of induction heaters

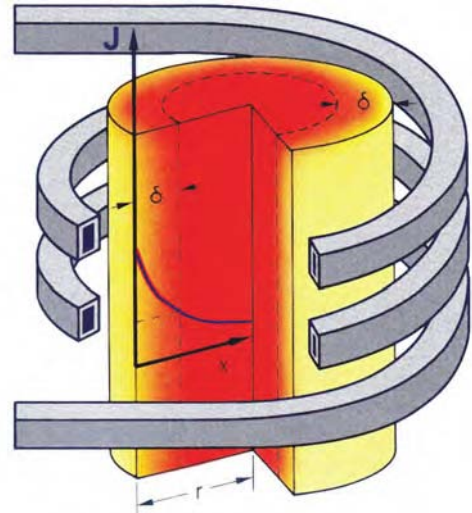
The induction law, well known from electrical transformers, electrical engines and generators, is the physical basic also for induction heating. The effect of an alternating magnetic field generates electrical voltage and therefore electrical current inside of any electrical conductive body. The induced electrical currents are running in re-circulating loops and therefore they are called eddy currents. According Joule's law the eddy currents lead to heating up of the body due to the heat losses. Therefore the induction heating method is a direct heating process, because the heat sources are generated inside the workpiece itself and the heat is not transferred into the workpiece through the surface by heat conduction, convection or radiation.

The primary alternating magnetic field, which penetrates from outside into the electrical conductive body is typically generated by an induction coil with alternating current, which is called in general 'inductor' (**Figure 1.39**). The secondary magnetic field, which is caused by the eddy currents inside the workpiece, leads to the dumping of the primary magnetic field. Due to this physical effect, which is called skin effect, the spatial distribution of the current density inside the workpiece shows a maximum value at the surface of the workpiece and decreases inside the workpiece (**Figure 1.40**). This characteristic spatial distribution of current density inside the workpiece is determined by the specific electrical conductivity κ and the magnetic permeability μ of the workpiece material and especially by the frequency f of the inductor current. This current density distribution is quantitatively described by the electromagnetic penetration depth δ :

$$\delta = \frac{1}{\sqrt{\pi f \kappa \mu}} \quad (1.93)$$

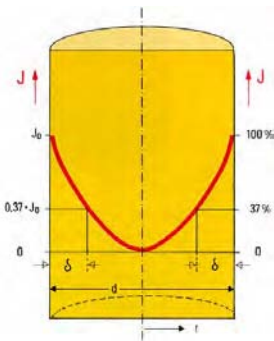
see also exact mathematical description in chapter 1.2.1. The electromagnetic penetration depth (1.93), also called skin depth, is the key factor for the induction heating. Inside the skin depth layer 86% of the total induced heat is generated. Only 14% of the total induced energy is absorbed in deeper located layers inside the workpiece. Due to the fact, that the electromagnetic penetration depth depends directly on the frequency, the thickness of the direct heated surface layer of the workpiece can be precisely determined by the operating frequency of the inductor current.

The ratio of workpiece size (diameter, thickness) to electromagnetic penetration depth is an important factor for the induced power in the workpiece (the power absorption in the workpiece) and for the resulting electrical efficiency (**Figure 1.41**) which describes the ratio of the induced power in the workpiece to the overall used power. The overall used power is the sum of induced power in the workpiece and the eddy current losses in the inductor (coil losses).



J: current density

Figure 1.39: Principle of induction heating of a metal-cylinder [1.2]



$$\delta = \sqrt{\frac{\rho}{\pi \cdot f \cdot \mu}}$$

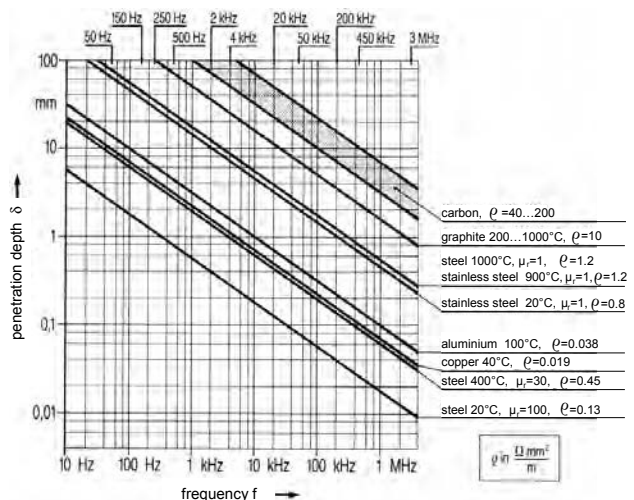


Figure 1.40: Distribution of current density and electromagnetic penetration depth in dependence on frequency and material [1.2]

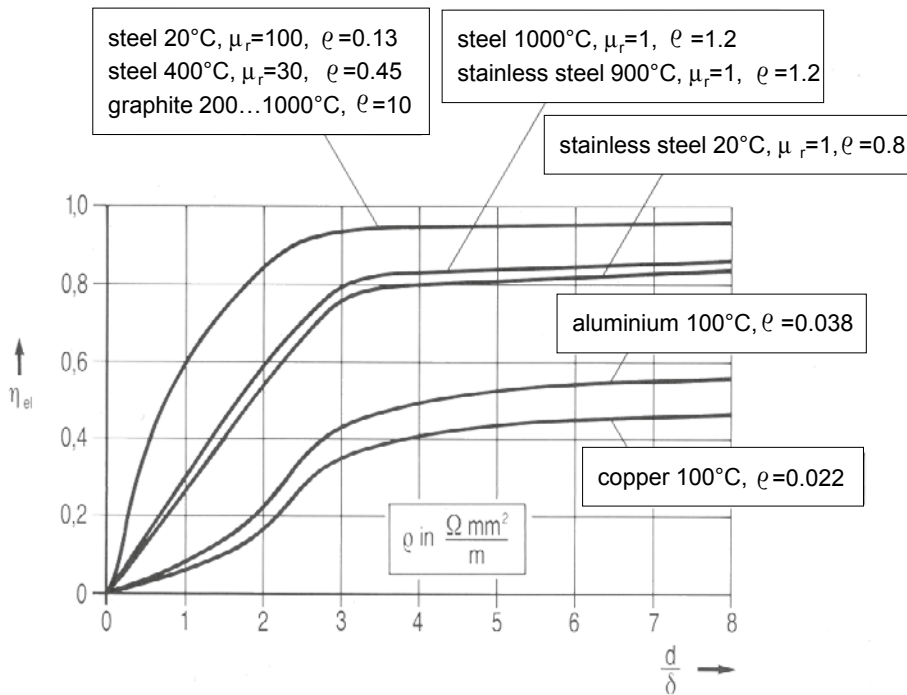


Figure 1.41: Inductor efficiency of an induction heating installation in dependence on electromagnetic penetration depth to diameter ratio [1.2]

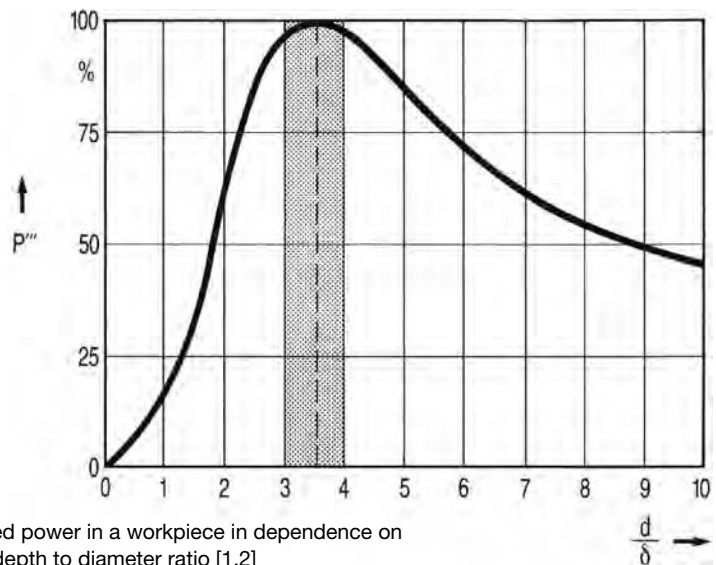


Figure 1.42: Averaged induced power in a workpiece in dependence on electromagnetic penetration depth to diameter ratio [1.2]

If the skin depth is required to be very small, e.g. in case of the induction surface hardening, the frequency has to be relatively high. If the workpiece should be heated completely through, e.g. heating for forging, the frequency has to be chosen comparably lower. A homogeneous temperature distribution in the cross-section of a cylindrical workpiece can be realized very effectively in a short time if the diameter of the workpiece is 3.5 times larger than the penetration depth (**Figure 1.42**). This characteristic ratio between workpiece diameter and penetration depth is a kind of compromise between the homogeneously distributed heat sources and therefore direct heating up in the whole cross-section using relatively low frequency and increasing electrical efficiency with higher frequency.

Today the practical applied frequency range for induction heating has a wide range from line frequency (50/60 Hz) up to several mega-Hertz. The generators for the energy supplying the induction heating systems is mainly realized today by static frequency converters, which are working in dependence on the frequency and power with semi-conductors, e.g. transistors, or vacuum tubes.

The heart of each induction heating system is the induction coil, the so-called inductor. It generally consists of a water-cooled copper conductor, which is adapted in its shape to the geometry of the workpiece and the heating task. This may be a cylindrical or flat coil, but also linear or hairpin-shaped coil forms are used (see also Figure 1.7). In addition, sometimes elements for guiding the magnetic field, such as magnetic cores (laminates), or cores made from ferrites or soft magnetic material, are required. The design of the inductor-workpiece configuration earlier was based exclusively on analytical methods and empirically obtained data and experiences, but today more and more numerical calculation programs for the design and optimization are used.

The design of induction heaters varies and depends on the specific heat problem. Generally, it can be stated that for induction heaters for deforming (forging, rolling) numerical simulation methods are used for many years, as for many cases 2-dimensional calculation methods are sufficient. For heat treatment applications, especially for induction surface hardening, only recently suitable numerical methods have been developed, because in most cases only 3-dimensional models can be applied [1.4].

The basic procedure for designing induction heaters is similar to that of induction melting furnaces, however, for induction heaters the determination of the precise space and time-dependent temperature distribution in the workpiece stands in the foreground. In induction heaters for through heating (forging, rolling) a very homogeneous temperature distribution in the workpiece at the end of the heating section is necessary. The heating time or in continuous operating systems the optimal heater length have an influence on the homogeneity of the temperature distribution and have to be designed according to specific requirements. The optimal frequency is selected according to Figure 1.42. Since the penetration depth can change significantly during the heating process, due to the temperature dependence of the material data, the condition $d/\delta > 3$, as shown in Figure 1.42, has to be considered at all times of the heating process. Accordingly, the optimum frequencies for through heating are dependent on the material and the dimensions of the workpieces.

In induction surface hardening usually only a thin surface layer is heated up to a temperature of 900 to 1,000 °C and thereafter cooled down (quenched) immediately. The resulting hardness profile corresponds approximately to the thickness of the surface layer in which a temperature above 850 °C has existed before quenching. Thus, the generated heat should not flow into the workpiece inside by heat conduction. The heating times have to be configured to be extremely short and correspondingly high power ratings have to be applied. Standard heating times are in the range of 100 ms to several seconds. The frequencies used are in the range of 10 to 300 kHz depending on the required thickness of the hardened surface layer. A particular challenge is the design of the inductor, which is often equipped with magnetic field guiding elements to achieve a homogeneous hardening of the workpiece surface. For this a lot of practical experience is still used today. First

developments, again using numerical simulation, to determine the optimum inductor geometry have meanwhile commenced.

1.5 Efficiency and energy balances of induction heating

Induction heating processes for the generation of heat use electrical energy that is usually provided from the electrical grid. The necessary electrical supply power generally ranges from a few kW to several MW. Depending on the amount of required power the electrical energy is obtained from different voltage levels of the electrical grid.

To provide electrical energy the energy stored in the primary fuel sources such as coal, gas or nuclear power (primary energy) must be converted into electrical energy (final energy) in power plants (**Figure 1.43**). Due to the conversion efficiency in power plants final and primary energy for the electric energy differ very strongly. In Germany, the conversion efficiency is in average about 40 %, which means that only 40 % of primary energy is converted into final energy.

This gives rise to a drawback of electro-thermal methods, which means that electrical energy is compared with other fossil fuels more expensive and that the overall energy balance of the required primary energy accordingly be higher. In many applications, however, the much higher process efficiency (thermal efficiency) of electro-thermal processes, in particular induction processes, results compared with fossil-fired heating processes to a high degree of alignment or even improve the overall energy balance. The increasing share in the future of regenerative electrical energy will lead also to the fact that the overall energy balance for the generation of process heat by electrical power will be significantly improved.

Particular impact this development will have on CO₂ emissions of process heating installations. Already today, the CO₂ emissions of electro-thermal processes taking into account the energy conversion in power plants in many cases are lower than for fossil-fired heating processes. The CO₂-free generation of electric energy will result in the future in a further reduction of CO₂ emissions of electro-thermal processes.

In the following these aspects (primary energy, CO₂ emissions) will be no more discussed. The following energy balances and efficiencies are related to final energy and do not include the power plant efficiency. The energy balance for electrothermal processes generally is focused on the electrical energy demand from the electrical supply grid.

1.5.1 Process efficiency chain

For induction heating as for all other electro-thermal processes, electrical and thermal efficiency of the heating system must be distinguished. The electrical efficiencies are composed mainly of transmission and conversion efficiencies. The thermal efficiencies, also known as process efficiencies, are taking all thermal losses into account during the heating or holding process. The process efficiency used in

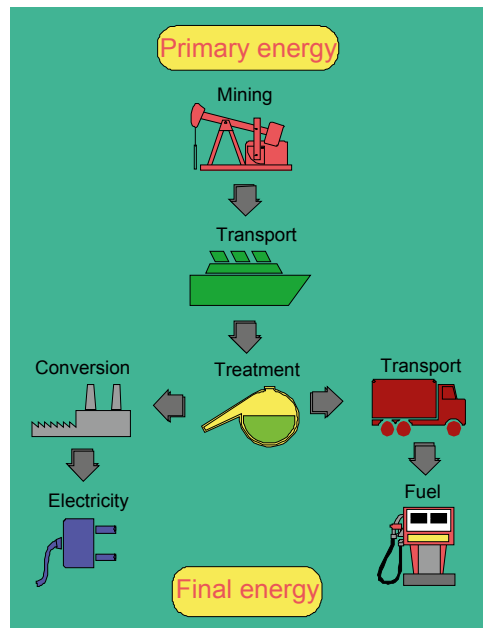


Figure 1.43: Energy conversion chains

electro-thermal processes means the pure heating process of a thermal process and is thus a part of the total of a process heating installation. The total efficiency of an electro-thermal installation is given by

$$\eta_{ges} = \eta_{el} \cdot \eta_p \quad (1.94)$$

where η_{el} is the product of all electrical efficiencies of the efficiency chain and η_p the process efficiency (thermal efficiency).

The main transmission elements in electro-thermal installations, which have a corresponding conversion and transmission efficiency, are:

- transformer
- frequency generator or converter, if existing
- power connections (cables, current bars)
- capacitors for compensation, if existing
- electro-thermal energy conversion system (e.g. inductor-workpiece)

Accordingly, each transmission element has a corresponding efficiency which leads connected in series to an efficiency chain. **Figure 1.44** shows such an efficiency chain for an induction through heating installation for forging.

The thermal losses of an electro-thermal process are depending on the thermal insulation of the process and particularly on the heating rate. **Figure 1.45** shows two heating processes with the same process temperature ϑ_p , but for different load powers P_E .

The thermal efficiency (process efficiency) represents an energy efficiency (instead of typically used power efficiencies) and results generally to

$$\eta_p = \frac{\int_0^{t_1} P_E \cdot dt - \int_0^{t_1} P_V \cdot dt}{\int_0^{t_1} P_E \cdot dt} \quad (1.95)$$

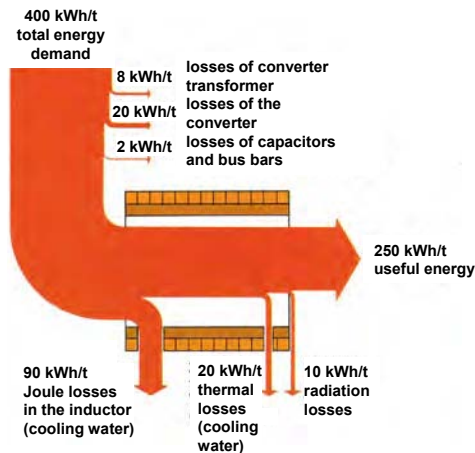


Figure 1.44: Energy flow diagram of an induction heater for forging [1.2]

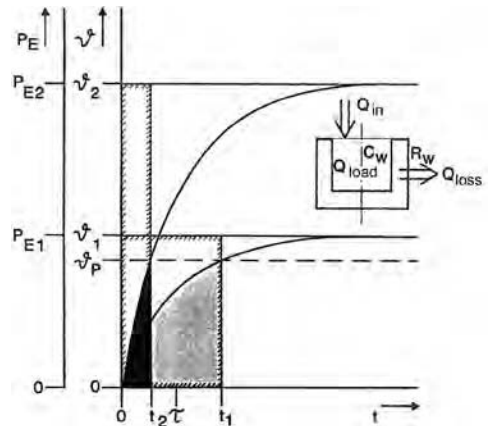


Figure 1.45: Heating curves and process efficiency for different load powers

with the power supplied to the load P_E , the heat losses occurring during the heating process P_v and the heating time t_1 . For a simplified heating process as shown in Figure 1.45 of a load with the heat capacity C_W and the thermal resistance R_W , through which heat as heat loss is flowing to the environment, the process efficiency is

$$\eta_P = \frac{R_W C_W}{t_1} \left(1 - e^{-\frac{t_1}{R_W C_W}} \right), \quad (1.96)$$

where the product of R_W and C_W results in the thermal time constant of the heating unit.

The result shown in Figure 1.45 with a double power supplied to the load P_{E2} is a process efficiency $\eta_{P2} = 0,75$. For the use of the power P_{E1} the process efficiency is only $\eta_{P1} = 0,48$. This example shows that the process efficiency is highly dependent on the amount of power supplied to the load and thus on the heating rate. In real electro-thermal processes is mostly worked with much higher power, so that process efficiencies up to 99 % can be achieved. This is especially valid for the direct electro-thermal methods (inductive, conductive, dielectric) in which very high thermal efficiencies can be achieved due to their high power densities and heating rates. Typical examples of thermal efficiency for direct heating methods are:

- induction melting in crucible furnaces 95 – 97 %
- induction heating for forging 90 – 95 %
- induction surface hardening 98 – 99 %
- conductive heating of bars 90 – 95 %

In indirect heating methods, the thermal efficiencies are considerably lower and depends strongly on the furnace design, furnace insulation and process operation (fast heating, slow heating, holding temperature) and are comparable to heating processes in fuel fired furnaces. Only thermal losses by exhaust gases do not exist here.

1.5.2 Efficiencies for induction heating

Especially for direct electro-thermal process: and, therefore, also for induction heating processes the efficiency of the electro-thermal energy conversion or energy transfer are strongly dependent on the material properties to be heated. As an example, the efficiency of the induction heating can be explained in more detail. For a simple system of a cylindrical induction coil and a cylindrical workpiece, both of which are ideally assumed to be very long compared to the diameters, the transfer efficiency, here called inductor efficiency, results according to Figure 1.41.

The transfer efficiency of the inductive heating depends firstly on the ratio of the electromagnetic penetration depth to the workpiece diameter d/δ and on the other hand on the electrical conductivity and the permeability of the workpiece material.

The ratio d/δ is usually controlled by the operating frequency of the inductor so that values are reached greater than 3 and thus the drop of the transfer efficiency on the left side of the diagram is avoided. The influence of the material can however not be further optimized. This means that the induction heating of workpieces made of steel or iron, in particular made of ferromagnetic steel with $\mu_r > 1$, achieves inductor efficiencies higher than 80 %. In contrast, electrically high conductive materials such as copper and aluminium achieve only moderate inductor efficiencies of 50 – 60 %. Particularly high efficiencies are obtained for low conductive materials such as graphite or glasses and oxides in the molten state.

Examples of energy balances for induction and conduction heating processes

In Figure 1.44 has been already referred to the efficiency chain and the energy balance for an induction heating process for heating of steel billets for forging. Here, it can be clearly seen that the

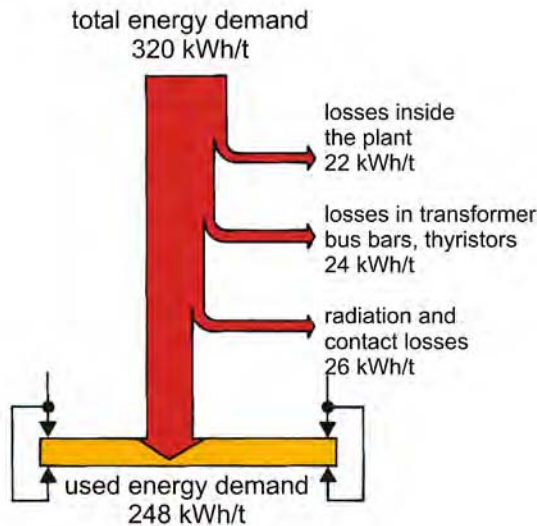


Figure 1.46: Energy flow diagram of a conductive heater for forging [1.2]

major energy losses are due to the inductor efficiency and result in energy losses of 90 kWh/t or 22.5 % of the net energy demand. The thermal losses of 30 kWh/t equal to 7.5 % of the losses is relatively low, as the transfer losses of the transformer, medium frequency converter, bus bars and capacitors. The overall efficiency of such a heater results to be 62.5 % and leads to a useful energy in the workpiece of 250 kWh/t which corresponds to a heating temperature of 1,250 °C.

The loss of energy in the inductor is avoided in a conduction heating. **Figure 1.46** shows a corresponding energy flow diagram for the heating of steel billets by conduction heating to a heating temperature of 1,250 °C.

At almost the same required energy demand of 248 kWh/t, the conduction heating needs due to the significantly higher overall efficiency only 298 kWh/t grid energy demand (excluding internal line losses corresponding to energy flow diagram of Figure 1.46). However, the conduction heating has significant disadvantages due to the necessary contacts to the workpiece compared to the induction heating, so that the conduction process is not a competitive heating method for forging despite the much better overall efficiency.

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2. Heating for Forming

2. Heating for Forming

2.1 Forging and Rolling

Robert Jürgens, Markus Langejürgen

2.1.1 Introduction

Along with conductive heating, induction heating is considered one of the direct heating methods. The induction-generated heat in the charge can be easily managed and its use as a source of process heat is, therefore, now well established in many areas of the metal-working industry. Since there is no heat transition resistance between the heat source and surface of the charge, unlike with almost every other heating process, induction heating is particularly suitable before metal shaping. The fact that the heating process can be easily managed and the heating times reduced, since the heat sources are found in the charge itself, has resulted in this heating method finding many applications in the metal industry. The following chapters describe just a few of these applications

A precise calculation of the heating process in induction heating plants involves a great deal of time and effort and nowadays is performed using numeric calculation methods. In order to explain the physical principles, however, one must first use simple analog calculation models which give us an easy insight into the physical relationships within induction heating. In the following chapters the various designs of induction plants were chosen so that they offer an overview of examples of the variety of possible technical solutions associated with induction heating of electrically conductive materials.

2.1.2 Principles

Everything found between utility connection ports and the inductor, from storing materials to transferring them to the next machining or shaping unit, is considered a component part of an induction heating plant. These components are presented below using a simple block illustration, **Figure 2.1**.

1. System supply

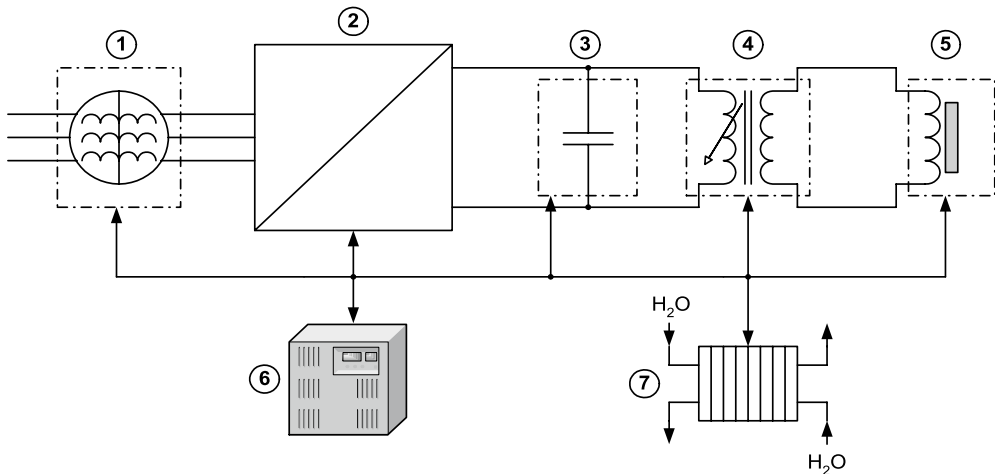
Induction heating plants usually require a large mains connected load. In most cases, therefore, they are supplied via their own power transformer from the medium voltage network supply. For maintenance and repair work the plant must be de-energized in compliance with safety regulations as per EN 50519. A mains switch for isolating the supply is usually provided for this purpose. The mains switch is often located on the low-voltage side of the power transformer.

2. Frequency converter

Frequency converters generate the application frequency required for the respective heating process. Depending on the type – there is a huge variety worldwide – they are capable of generating frequencies of just a few hertz right up to several hundred megahertz. Their output power also ranges from just a few kilowatts to several thousand kW. An almost unlimited output power can be provided by connecting several frequency converters parallel. High-power frequency converters are normally water-cooled. Due to the particular significance of this energy source for induction heating, the frequency converters are considered in detail in chapter 6.

3. Power factor correction

A large amount of induction reactive power is required to generate the electromagnetic field. To ensure this is not taken from the public network, it is compensated by capacitive reactive power



1 System supply; 2 Frequency generator; 3 Power factor correction; 4 Matching transformer (not always required); 5 Inductor-workpiece arrangement; 6 Control cabinet with PLC control system; 7 Re-cooling system

Figure 2.1: Components of an induction heating plant

close to the inductor. The requisite capacitors can, therefore, be connected in series or parallel to the inductor. This requires either voltage resonance (resonant circuit) or current resonance (anti-resonant circuit).

Note: The frequency converter and oscillating circuit must be matched appropriately.

4. Matching transformer

A matching transformer is required if a variety of different heating tasks are performed in the plant (e.g. during hardening). Matching transformers are also used for low or very high inductor voltages. They are usually designed for a limited frequency range only (e.g. 3 to 10 kHz; 8 to 30 Hz; 150 to 400 kHz). Medium-frequency and high-frequency transformers up to 10 kHz are made from grain-oriented electrical sheet and cut strip-wound cores and above 10 kHz from ferrite cores. Coreless transformers are also used for very high frequencies. The windings are usually manufactured as a disc winding from copper hollow section. Primary and secondary windings are interleaved to provide better power distribution. Core and windings are water-cooled.

5. Inductor-charge arrangement

The inductor-charge arrangement is determined by the heating method chosen and is described in detail in the chapters below.

6. Control cabinet

The signals relating to all actuators and sensors for the individual plant components are grouped together in the control cabinet. Modern heating plants have a PLC (programmable logic controller), which contains both the control code and control data. Fully automatic operation of the heating plant can, therefore, be easily realized and is now used as standard with the interlinked operation of an induction heating plant and shaping machine.

7. Water re-cooling plant

Depending on the application, between 10 and 60 % of the energy taken from the network in the current-carrying parts of the induction heating plant are current heat losses. These are cooled with water and dissipated. Since the water flows through live parts it must only have a low degree of conductivity. As a rule, therefore, demineralized water is used, with an anticorrosive agent and algicidal biocide added. The water volume, heat exchanger, pump capacity, number of cooling circuits and flow rates should be considered very carefully. They play a crucial role in determining the service life of the plant, especially that of the inductors.

Now that an overview has been given of the components of an induction heating plant, a calculation model for the inductor-workpiece arrangement – which has proved its worth across the wide variety of heating tasks for continuous flow and standard heating and with which the geometrical field structure can be traced back to a simple electrical equivalent circuit diagram – will be presented. This enables the terminal impedances of the complex inductor-workpiece arrangements to be determined using the calculation methods for an electrical circuit. A calculating accuracy for the terminal impedance of about 5 % is usually sufficient to ensure a reliable design and layout of the plant components.

Calculation of inductor impedance

The simplified calculation of the induction load circuit is explained by means of a cylindrical coil in which a steel cylinder is located. Karl Schönbacher [2.1] developed this calculation method which is derived from the schematic presentation of the magnetic circuit. Current flows through an inductor in which a steel cylinder is located. It generates a magnetic flux which is separated in the inductor into a partial flow through the charge and into a further partial flow which flows between the charge and the inductor, **Figure 2.2**. The magnetic return path is via the coil outer chamber. If one looks at the parts of the magnetic flux, the magnetic partial resistances can be easily converted into electrical resistances of an electrical circuit. The electrical resistances are reciprocal to the resistances of the magnetic circuit. The electrical equivalent circuit diagram, **Figure 2.3** obtained this way, can then be calculated according to the rules for passive two-terminal networks.

The charge resistance R_H and the charge reactance X_H must be precisely determined. A precise calculation is complicated and is covered later in this chapter. The leakage reactance X_S , return reactance X_R , coil loss resistance R_{Cu} and coil reactance X_{Cu} can be calculated more easily.

The leakage reactance is calculated from

$$X_S = n^2 \cdot 2\pi f \cdot \mu_0 \cdot \frac{A_S}{h} \quad (2.1)$$

This includes: n the number of coil windings, f the operating frequency of the plant, μ_0 the magnetic field constant, A_S the air-gap surface area between the winding and charge and h the charge length in the inductor. The charge length h in the formula must not be greater than the inductor length L .

The return reactance is calculated from

$$X_R = n^2 \cdot 2\pi f \cdot \mu_0 \cdot \frac{A_{Ind}}{h_R} \quad (2.2)$$

with A_{Ind} as the inductor inside surface area, h_r as the equivalent field return length, L the inductor length and D the inductor diameter.

e.g.: $h_r = L - h + 0.46 D$ (for forge heating coils)

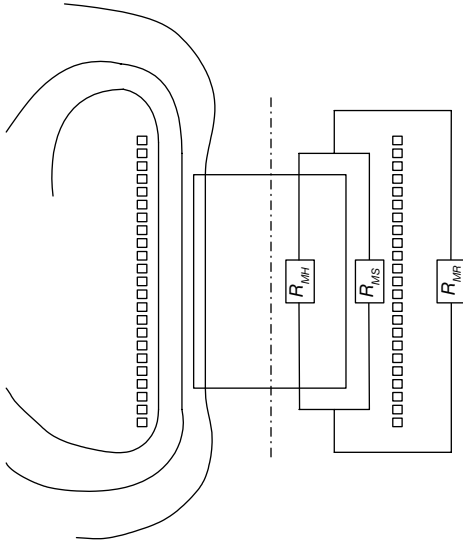


Figure 2.2: Field and equivalent circuit diagram of the magnetic circuit

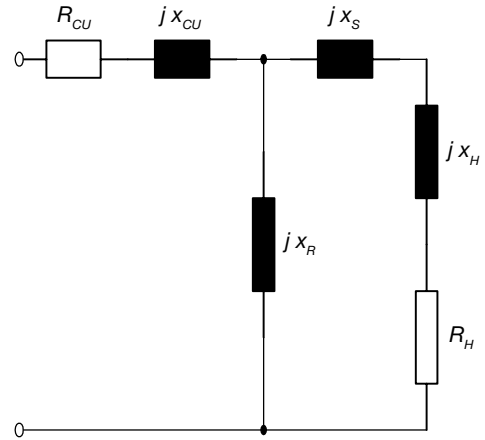


Figure 2.3: Equivalent circuit diagram for calculating the inductor current and voltage using the Schönbacher method

The coil loss resistance R_{Cu} and the internal conductor reactance X_{Cu} of the copper conductor are calculated from

$$R_{Cu} = X_{Cu} = n^2 \cdot \frac{\pi \cdot D}{\delta \cdot \chi \cdot L \cdot \sqrt{f_s}} \quad (2.3)$$

with f_s as the copper fill factor, δ as the electromagnetic penetration depth and χ electrical conductivity of the coil.

The equivalent circuit diagram can be further broken down into the load impedance Z_L , with the components of the load effective resistance R_L and the load reactance X_L .

$$Z_L = R_L + j \cdot X_L \quad (2.4)$$

$$R_L = R_{Cu} + R_H \cdot \left(\frac{X_R}{X_S + X_R + X_H} \right)^2 \quad (2.5)$$

$$X_L = X_{Cu} + (X_S + X_H) \cdot \frac{X_R}{X_S + X_R + X_H} \quad (2.6)$$

The electrical efficiency of the inductor can be easily determined from (2.3) and (2.5).

$$\eta_{el} = \frac{R_L - R_{Cu}}{R_L} \quad (2.7)$$

Once all variables are known, the effective power, power loss and reactive power can be measured and the components of the induction heating plant can be dimensioned accordingly.

The charge resistance R_H and the charge reactance X_H must be precisely determined. A precise calculation is complicated and is covered later in this chapter. The leakage reactance X_S , return reactance X_R , coil loss resistance R_{Cu} and coil reactance X_{Cu} can be calculated more easily [2.1].

Heat source and coupled temperature distribution

The calculation of the local temperature distribution and time-temperature curve in the charge is perhaps the most important aspect for planning the plant. The process following heating requires a temperature distribution in the charge, whereby the characteristics of such a temperature distribution are determined by the process itself. Since additional plant or process-specific marginal conditions must often be taken into consideration, a temperature profile should be agreed with the customer for each induction heating plant. The result calculated is compared to the customer's requirements and re-calculated until these have been met. Although the customer frequently only gives the temperature distribution over the cross-section in the charge at the time of shaping or further processing, the heating time chart can rarely be chosen at random. During heating, specific differences in temperature in the charge must not be exceeded. Structural transformations require a minimum heating time at a certain temperature level, etc. Despite the fact that temperature profiles can be easily calculated nowadays using PC programs, it is important that the principles, the solution to the heat equation with distributed heat sources, of such programs are presented here too.

The calculation of the heat source and temperature distribution in the charge is based on Maxwell's equations and the coupled heat conduction equation. Detailed information about the procedure of heat source and temperature calculations is given in chapter 1.2.2.1. Additional specific equations for current density and heat source distribution in the charge are given in the following.

It is senseful for the calculation using a coordinate system, which is adapted to the geometry of the workpiece. This makes the solution of the heat conduction equation with distributed heated sources in the workpiece more simple. In the cartesian coordinate system the differential equation for the temperature is:

$$c_p \rho \frac{\partial \vartheta}{\partial t} = \text{div}(\lambda \text{grad } \vartheta) + p(x, y, z, t). \quad (2.8)$$

with c_p specific heat, ρ density, λ heat conduction and p heat source density.

With constant heat conductivity the heat conduction equation can be simplified to

$$c_p \rho \frac{\partial \vartheta}{\partial t} = \lambda \left(\frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2} + \frac{\partial^2 \vartheta}{\partial z^2} \right) + p(x, y, z, t). \quad (2.9)$$

For the cylindrical coordinate system follows

$$c_p \rho \frac{\partial \vartheta}{\partial t} = \lambda \left(\frac{\partial^2 \vartheta}{\partial r^2} + \frac{1}{r} \frac{\partial \vartheta}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \vartheta}{\partial \varphi^2} + \frac{\partial^2 \vartheta}{\partial z^2} \right) + p(r, \varphi, z, t). \quad (2.10)$$

For the solution of the heat conduction equation it is necessary to calculate first the distribution of the heat sources in the workpiece. This is in general very ambitious using analytical approaches and therefore today the calculation of the heat source distribution and the calculation of the temperature distribution is done applying numerical methods using a PC or a work station. Using numerical calculations today it is possible to simulate the entire process and to get detailed information about the not visible physical phenomena inside the workpiece. Nevertheless the analytical approximation solution of the heat source distribution for more simple geometries is useful to

get a good physical understanding and it is helpful for the engineer to understand the dependence of the calculation results on the geometry and the material properties. Therefore in the following chapter the analytical approach to calculate the heat source distribution and the power density distribution will be considered more in detail.

Current density and heat source distribution in the workpiece

The following observations are valid within a one-dimensional space. The magnetic field intensity has only a z component. On the surface of a metal wall, which is infinite on one side, the indicator of the complex magnetic field intensity H_z has the value H_0 .

$$H_z(x=0, t) = H_0 e^{-j\omega t}. \quad (2.11)$$

The current density induced in the wall by the magnetic field intensity can be described by

$$S_y(x, t) = S_0 e^{-\frac{x}{\delta}} e^{j\left(\omega t - \frac{x}{\delta}\right)} \quad (2.12)$$

with S_0 as the amplitude of the current density on the surface of the even wall, x as the distance from the surface, δ as the electromagnetic penetration depth and ω as the angular frequency.

In terms of δ and ω the following applies:

$$\delta = \sqrt{\frac{1}{\pi \chi f \mu}} \quad \text{and} \quad \omega = 2 \pi f.$$

The electromagnetic penetration depth δ is a material and frequency-dependent length usually shown in mm. It is determined by the current frequency f , the electrical conductivity χ and the magnetic permeability μ of the material in which the induced current flows. The electromagnetic penetration depth δ is often referred to as the depth of penetration of the electrical current I . The penetration depth is used as a simple means of calculating the AC resistance of a charge and the power converted in the charge. This way the power induced in a cylindrical block, which has a length of h and a diameter of d , can be calculated using the formula (2.13), where I , f , χ , μ and thus also δ are known, **Table 2.1**.

$$P = \frac{\pi d}{\chi \delta h} \cdot I^2 \quad (2.13)$$

The induced power in the charge can be calculated according to (2.13). However, this is not sufficient for calculating the temperature distribution in the charge. In order to make a precise calculation, the Joule heat losses at each spatial point of the body to be heated must be determined. In the one-dimensional case the distribution of the heat source density is calculated from

$$p(x) = \frac{S_{\text{eff}}^2(x)}{\chi} \quad (2.14)$$

Frequency	Steel 20 °C	Steel 1,000 °C	Copper 20 °C
50 Hz	3.9	78	9.42
600 Hz	1.13	22.5	2.71
1,000 Hz	0.87	17.5	2.11
2,000 Hz	0.616	12.3	1.49
5,000 Hz	0.39	7.8	0.942
10 kHz	0.276	5.5	0.666
20 kHz	0.195	3.9	0.471
50 kHz	0.124	2.46	0.297
100 kHz	0.087	1.75	0.211
200 kHz	0.0616	1.23	0.149
500 kHz	0.039	0.78	0.0942

Table 2.1: Table with electromagnetic penetration depth in mm

The heat converted in the body (induced power) can then be calculated from:

$$P = \frac{1}{2} A \frac{1}{\chi} \int_0^{\infty} S_0^2 e^{-\frac{2x}{\delta}} dx \quad P = \frac{1}{2} A \frac{1}{\delta \chi} S_0^2 \quad (2.15)$$

By relating the power to the respective surface area, the local surface power density q_w can be obtained:

$$q_w(x) = \frac{P(x)}{A(x)} = \frac{1}{2} \frac{1}{\delta \chi} S_0^2 \cdot \left(1 - e^{-\frac{2x}{\delta}}\right) \quad (2.16)$$

At a distance δ from the surface the power density flowing in is reduced to 14 % of its initial value. Therefore, 86 % of the heat is generated within the depth of penetration δ . The surface power density and heat source density are interlinked. The following applies:

$$p(x) = -\frac{dq_w(x)}{dx} \quad (2.17)$$

The heat source density distribution can be calculated from the power density distribution. There is also another way to establish the power density. It can be determined using the Poynting vector. This represents an energy flux from the open space into the charge. Using

$$\bar{q} = \frac{1}{2} (\bar{E}_o \cdot \bar{H}_o) \quad (2.18)$$

the energy flux can be calculated. E_o and H_o are the electrical and magnetic surface field intensity, respectively. The energy flux value corresponds to the average time value of apparent power. This can be divided into a real and imaginary part

$$\bar{q} = -\bar{E}_o \cdot \bar{H}_o = q_w + j q_b \quad (2.19)$$

Here q_w is the active power and q_b the reactive power of the apparent power applied to the surface. In the Cartesian coordinate system the precision solution to the complex surface power density in one-dimensional terms is

$$\bar{q} = \frac{1}{2} \frac{1}{\chi \delta} H_o^2 \cdot \left(\Phi_w \left(\frac{x}{\delta} \right) + j \Phi_b \left(\frac{x}{\delta} \right) \right) \quad (2.20)$$

This includes Φ_w and Φ_b as so-called correction functions. In (2.20) the first part of the product represents the amount of energy flux flowing into the infinitely thick metal wall. For $x \gg d$, Φ_w and Φ_b are close to 1. The reactive power is then identical to the real power of the energy flux. The phase shift between the source voltage and the heating current is 45°.

It is not the aim of this presentation to deal with the correction functions for the plate and full and hollow cylinders. Further details can be found in the literature listed in the bibliography.

The correction functions are used not only when determining the power and heat source density distribution but also when calculating the load impedance. Looking at (2.20), if in the cylinder coordinate system the magnetic field intensity on the surface of the charge is replaced by

$$H_o = \sqrt{2} \frac{nI}{L} \text{ applies only to long inductors } (L \gg D) \quad (2.21)$$

and the power values calculated, as in equation (2.15), then the result obtained is

$$P_H = d\pi h \cdot \frac{\rho}{\delta} \cdot \left(\frac{n}{L}\right)^2 \cdot I^2 \cdot \Phi_w \left(\frac{r_o}{\delta} \sqrt{2}\right) \quad \text{and} \quad Q_H = d\pi h \cdot \frac{\rho}{\delta} \cdot \left(\frac{N}{L}\right)^2 \cdot I^2 \cdot \Phi_b \left(\frac{r_o}{\delta} \sqrt{2}\right). \quad (2.22)$$

Similar to (2.13), the charge resistance and charge reactance can be shown as

$$R_H = d\pi h \cdot \frac{1}{\chi \delta} \cdot \left(\frac{n}{L}\right)^2 \cdot \Phi_w \left(\frac{r_o}{\delta} \sqrt{2}\right) \quad \text{and} \quad X_H = d\pi h \cdot \frac{1}{\chi \delta} \cdot \left(\frac{n}{L}\right)^2 \cdot \Phi_b \left(\frac{r_o}{\delta} \sqrt{2}\right) \quad (2.23)$$

The analytical solutions found for simple charge geometries are used in straightforward numerical programs for calculating the temperature distribution in the charge. The heat source density distribution is implemented in the calculation program as a default value. Despite this lack of accuracy the end results are sufficient for evaluating the temperature distribution in the charge. For continuous heating plants the temperature deviation between the temperature distribution calculated and the temperature distribution measured at the end of the heating process is usually less than 5 %.

Heating characteristics

The temperature progression over time when heating a non-magnetic material can be divided into four sections, as shown in **Figure 2.4**. First the shell temperature (ϑ_o) of the charge increases rapidly. After a period of time referred to as t_{H1} , which largely depends on the material thickness, the temperature of the material core (ϑ_k) also rises. At a constant heat input (power density is constant) the temperatures of the core and shell begin to rise evenly after a period of time t_{H2} . The transient is completed and the temperature rises by the same amount at each spatial point of the charge. The rate of increase of the mean temperature and the temperature differences between the individual points in the body are in direct relation to the power fed in. If the heat supply is switched off at a point in time t_H , the process of temperature homogenization begins. The temperatures at all spatial points of the charge tend towards the temperature corresponding to the heat content. The term “enthalpy temperature” has found widespread use in the forging industry. It is often known as the mean temperature. The homogenization process is considered complete at a point in time t_E . The temperature deviations in the body are now less than 5 %.

As already mentioned, there is a fixed connection between the power supplied, which causes the temperature to rise from ϑ_A to ϑ_E , and the temperature difference between ϑ_o and ϑ_k . For plates and cylinders the holding time can be calculated from one of the two formulae given below:

$$t_H = \frac{1}{2} \frac{s^2 (\vartheta_E - \vartheta_A)}{a (\vartheta_o - \vartheta_k)} f\left(\frac{\delta}{s}\right) \quad (2.24)$$

applies to the plate.

$$t_H = \frac{1}{4} \frac{r_o^2 (\vartheta_E - \vartheta_A)}{a (\vartheta_o - \vartheta_k)} f\left(\frac{\delta}{r_o}\right) \quad (2.25)$$

applies to the cylinder with a as the thermal conductivity, ϑ_A and ϑ_E the initial and final temperature and ϑ_o and ϑ_k as the surface and core temperature of the charge.

2.1.3 Numerical plant layout

As for the conventional design of induction heating plants, the first stage of a

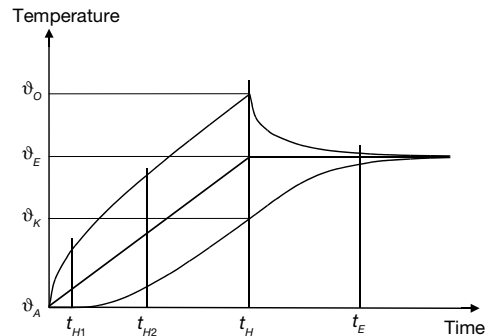


Figure 2.4: Schematic time-temperature curve during heating of a non-magnetic solid cylinder

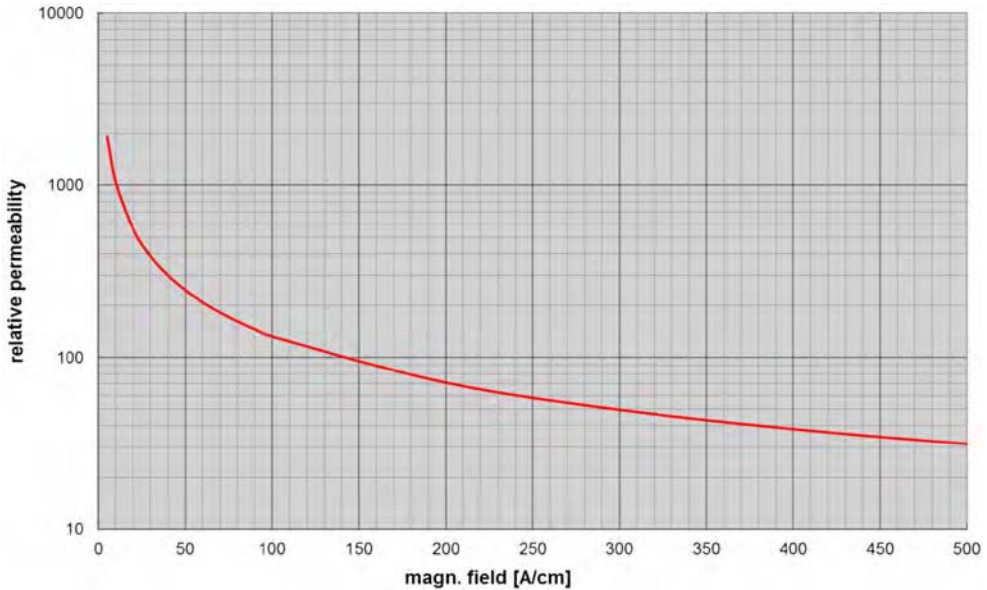


Figure 2.5: Relative magnetic permeability as a function of the magnetic field intensity

numeric-based plant layout is to determine the target temperature and required throughput. If no heating from room temperature occurs, it is important to analyze the pre-conditions exactly so that the entry temperature distribution of the heating process can be determined as precisely as possible. Once these conditions have been fixed, the energy required in the workpiece and the power requirements of the converter can be roughly established.

If we are dealing with simple symmetrical charge geometries, with which both the heat source distribution and heat equation with these distributed heat sources can be approximately solved using the previous analytical calculations, then these methods are usually sufficient for attaining a reliable plant layout. If irregular shapes are to be heated, however, such methods are limited in regard to both the electrical layout and temperature profile calculation. This is where numeric programs are used. There are various approaches here which essentially differ in terms of complexity of the tasks to be solved. At this point we will deal with just a few of these. However, such information can never be exhaustive nor always up to date.

A distinction must be made between commercial universal FEM programs, such as COMSOL-Multiphysics or ANSYS-Workbench, and freely available codes, which are then adapted to the specific problem. These packages can be used for multi-physics applications, whereby the individual physical disciplines can to some extent be solved coupled together. For induction heating of solid bodies this coupling results from the influence of the temperature on the electrically relevant material parameters, such as the specific electrical resistance and magnetic permeability. Furthermore, movements of the charge within the low-frequency range can influence the electromagnetic field. A further coupling is provided by electromagnetic forces acting on mechanical assemblies, the structural dynamics of which can then also be examined using a relevant model. With induction heating the coupling between electromagnetically induced heat sources and the solution for the heat equation plays a crucial role. This coupling is bidirectional, as both the electromagnetic field influences the temperature distribution and the temperature in turn acts on the heat source distribution via the mechanisms described above.

Figure 2.6: Simulated temperature distribution of a conical steel billet upon passing through a heating plant with cylindrical inductors (Source: SMS Elotherm)

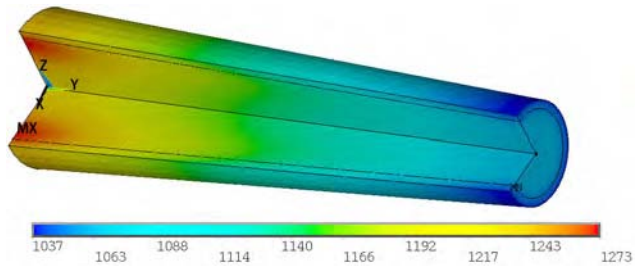
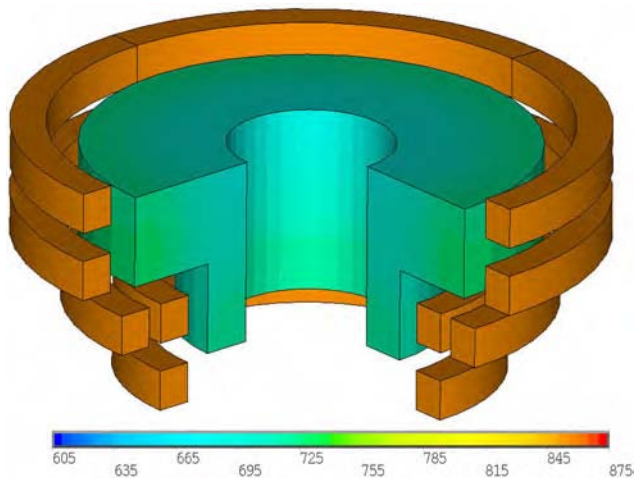


Figure 2.7: Simulated temperature distribution of a flange following single heating with a specially adapted inductor (Source: SMS Elotherm)



If simulating heating processes for ferromagnetic material below the Curie temperature, it should also be noted that the magnetic permeability depends not just on the temperature but also on the magnetic field intensity H , **Figure 2.5**.

The result of an electromagnetic calculation thus influences the assumed material parameters of the calculation, such that iterative methods have to be used that come as close to the correct solution as possible.

A clear example of what happens if this influence is ignored is provided when thin strip is heated close to the Curie temperature of 768°C or slightly higher. A calculation using a constant permeability value would result in an even temperature distribution across the width of the strip with slightly under-cooled edges. In practice, overheating of the strip edges takes place above a limit rating which depends on the strip thickness. This effect only disappears upon further increase of the power density.

As a result of the “saturation” of the ferromagnetic material, the magnetic characteristics disappear even below the Curie temperature if the field intensity is correspondingly high. This effect starts from the strip middle and ends at the edges, thereby resulting in measurable overheating.

The modelling of this effect varies in the different program packages or is not in fact implemented at all. If the package does not offer the possibility of simulating the material behaviour as standard,

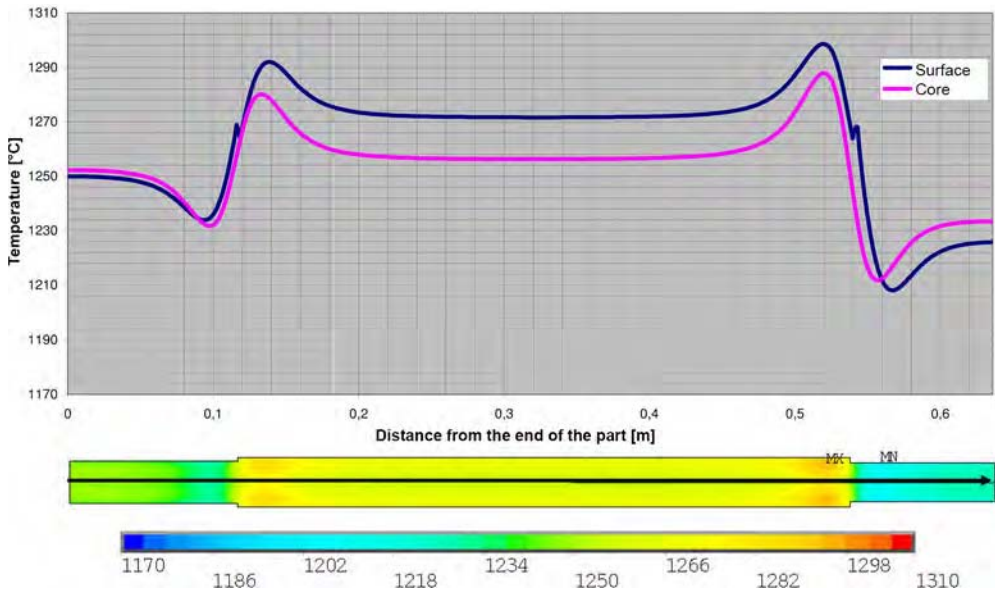


Figure 2.8: Temperature distribution and profiles of the surface and core of a preformed shaft upon passing through an induction heating plant (Source: SMS Elotherm)

one option may be iterative loops outside of the simulation runs. Implementing this, however, requires precise knowledge of the procedures and sequences in the respective program packages.

Examples of an irregular design include preformed shafts, flanges, cones or products which are not conveyed continuously.

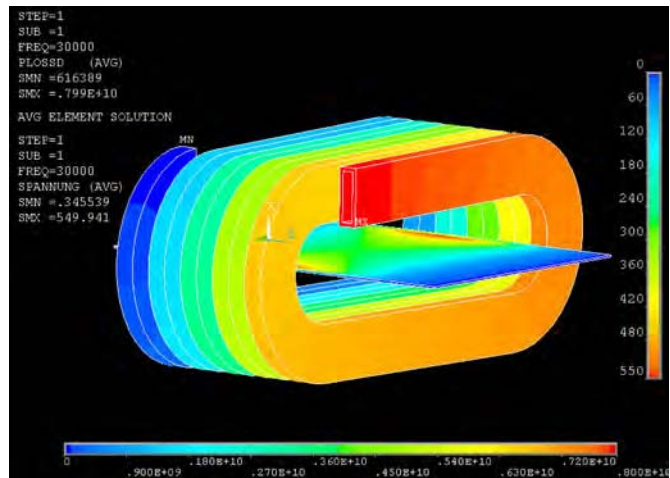
Figure 2.6 shows a cone following heating in a continuous pass. The coil must by necessity be cylindrical to allow continuous transportation. Two opposing effects can then be expected. On the one hand, the induced power density is reduced at the smaller end due to the greater coupling distance while, on the other hand, the mass to be heated is smaller in this area. The illustration clearly shows that the greater coupling causes the power density to decrease too severely, despite the smaller mass, and this area remains too cold.

An axis-symmetrical FEM model can also be used for designing coils for a standard heating system as shown in **Figure 2.7**. Neither the coil design nor the calculation of the temperature distribution can be determined with sufficient accuracy using analytical methods, such that the only alternative is practical testing.

The picture is similar for the shaft shown in **Figure 2.8**. Here the temperatures for the individual areas can be roughly determined by analytical means. However, without a simulation the distribution at the transition points can only be estimated. The part of the shaft with the greater radius overheats at the transition points while the stepped shaft sections show a large drop in temperature. Since the differences in the radius are not the same at both transition points, the amplitude of these transition effects also varies.

In such cases a simulation of the attainable final temperature can usually be achieved with 2-dimensional FEM calculations as long as the design is cylindrical. If there is no such symmetry then

Figure 2.9: Example of a 3-dimensional FEM calculation taking the coil pitch in the winding into account (Source: SMS Elotherm)



3-dimensional modelling normally has to be used which can be relatively time-consuming to produce with long computational times in addition. Even with the continuous increase of computational capacity there are still processes which cannot be mapped fully numerically as the computational times are not sufficient to permit this. Therefore, with problems such as these, too, it is advisable to look for means of simplification. This could be used where there is mirror symmetry or also cyclical repetitions.

If simplification is not an option, then the entire calculation range must be modelled. As shown in **Figure 2.9**, the result is a complete model which provides the electrical parameters on the one hand and the temperature distribution in the material on the other. In addition, material movements can also be incorporated into simulations for continuous processes. The coil voltage and heating power density in the material are shown here.

2.1.4 Methods and equipment

All induction plants more or less utilize the heating characteristics described above. Equipment used for induction surface hardening are found exclusively in the first section of the temperature curve as only the surface to be hardened needs to be brought to hardening temperature. Equipment used for hot shaping usually requires a consistent temperature distribution in the shaping area. "Through-heating" is the term used here. It is, therefore, moved into the third section of the characteristic heating curve. This equipment class is broken down into two sub-classes. All designs featuring continuous material throughput belong to the first class. Equipment, which heats stationary material either fully or in part, is assigned to the second class.

Equipment for continuous material throughput

In the case of continuous heating plants the charge is continuously or almost continuously transported through the induction coils. This type of plant is again subdivided according to the time-temperature curve characteristics.

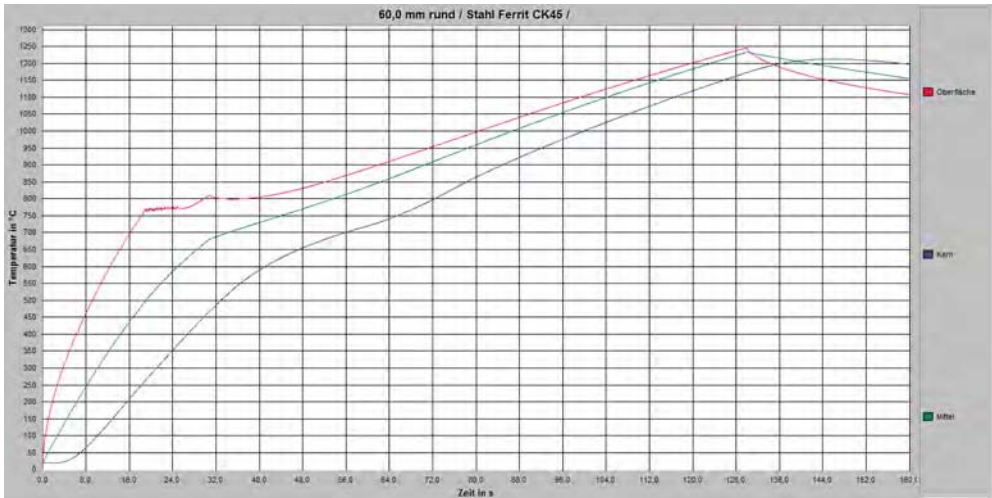


Figure 2.10: Normal heating of a solid cylinder made from steel $d = 60$ mm (Source: SMS Elotherm)

Normal heating

If a material is heated in an inductor, which is operated using a constant voltage, a natural time-temperature curve is produced. Such heating is termed normal heating. It depends only on the material data of the charge, the magnetic field intensity in the inductor and the chosen operating frequency. If at the end of the heating process for a steel cylinder a temperature difference between the shell and core of 80 K, for example, is required, then the heating time and the magnetic field intensity to be chosen are fixed. The surface power density applied to the material must not exceed

$$q_H \leq \frac{2\Delta\vartheta\lambda}{r_o} + q_{Abstr.} \quad (2.26)$$

In the example shown in **Figure 2.10** this would be approximately 32 W/cm². Typical plants offering this type of heating are bar heating plants, **Figure 2.11**, in which steel rounds with a diameter of 70 mm, for example, are heated to forging temperature.

Rapid heating

As shown in (2.24) and (2.25), the heating time increases with the material thickness on a square value basis. Long heating times and high material throughputs result in long inductor routes and, therefore, high costs. To ensure more rapid through-heating of the material, the power is supplied in sections at varying heating power densities. For example, the power density in a line of inductors with four individual inductors can be divided at a ratio of 4:3:2:1, **Figure 2.12**. Here the power density of the inductor at the exit end is chosen as a rating basis for the entire heating plant. Since through-heating takes place within a shorter period of time than for normal heating, it is called rapid heating. The conventional induction heating plant with rapid heating properties is the walking beam-type heating plant. Here squares with a larger diameter are transported by a walking beam conveyor through the line of inductors. If designed optimally, the through-heating time can be reduced to approximately 60 % of the normal heating time. With a heating plant, which is optimally designed for the through-heating time, the material throughput can only be reduced to a limited



Figure 2.11: Bar heating plant upstream of a horizontal press (Source: SMS Elotherm)

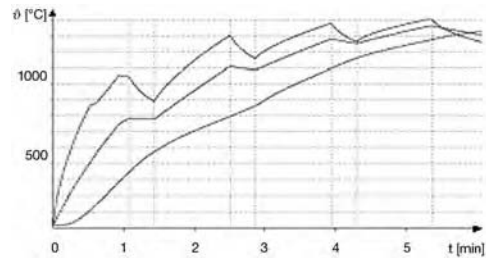


Figure 2.12: Rapid heating of a solid cylinder made from steel $d = 120$ mm

extent. The power supplied in the last inductor upstream of the shaping machine must not be less than the surface radiation losses. Otherwise, the charge would already start to cool down in the heating section.

Other types of heating

Due to the fact that production lines are becoming increasingly fully automated and induction heating systems are being progressively incorporated into operational processes, the heating characteristics must also take different optimization objectives into account.

Optimization targets, such a high level of availability and cost efficiency of the entire production line, are steadily becoming a top priority. That is why heating concepts were developed which enable plant owners to react to material flow anomalies that occur in the production line in such a way that the heating process in the induction plant no longer needs to be interrupted. Key developments here include: Multi-converter, go-slow, reverse and stop & go operation. The heating system of these plants is characterized by a modified normal heating curve. The heating times are slightly longer than for normal heating.

2.1.5 Examples of applications

Heating of slugs

Axle parts for the automotive industry form a large part of the production process in the field of closed-die forging. The starting material for this component family is induction heated in more than 85 % of all applications (> 85 % induction; remainder: fuel-fired furnaces). It is cold-sheared or cut to length. The cut lengths are usually between one, two or three times the cross-sectional width of the charge. In the majority of cases the billet diameter is between 40 and 110 mm (both rounds and squares). The press cycle for this component family is usually between 4 and 12 s. In fully automated lines cycle times of less than 2 s are also attained. The material throughput in such press lines ranges from a few hundred kilograms to several thousand kilograms per hour. **Figure 2.13** and **Figure 2.14** show typical induction heating systems for block material.

When it comes to heating these types of parts, a compact design, which is more or less identical, has become the preferred choice for all manufacturers of induction heating plants worldwide. The material feeding conveyor, the inductor train and the material discharge conveyor are mounted on a compact substructure. A material switch junction, for differentiating between correctly and



Figure 2.13: Induction heating plant in a forging line for billets (Source: ABP Induction)



Figure 2.14: Induction heating plant in a forging line for billets (Source: SMS Elotherm)

incorrectly heated material, is integrated in the discharge system. This is detected by means of a surface temperature measurement of the semi-finished products. The system supply with power breaker, one or more static frequency converters, the capacitors for power factor correction, the plant control system and the water supply and discharge systems are installed in the substructure.

Heating of bars

If a greater material throughput needs to be attained in a forging line, bars are used as semi-finished products. This is done within the 20 and 90 mm size range upstream of hot-stage presses that operate at up to 120 strokes per minute. Even with large material diameters ($90 \text{ mm} < d < 200 \text{ mm}$) bars are used as semi-finished products in the forging line. The forging blanks are sheared off the bar at forging temperature in one step.



Figure 2.15: Induction bar heating line with bar magazine (Source: SMS Elotherm)

Given the task they perform, these induction heating plants have come to be known as “bar heaters”. A bar heating line, **Figure 2.15**, includes the bar magazine, roller table, heating section with several inductors, capacitor cabinet as the leading reactive power generator, control cabinet, static frequency converter and the system supply with a corresponding power transformer. These induction heating plants often feature an electrical connected load of several thousand kilowatts. Nowadays, these plants are fully automated and run in a three-shift operation with a maximum of one operator.

2.2 Reheating of long products in minimills

Klaus von Eynatten, Markus Langejürgen, Dirk M. Schibisch

The basic idea of a minimill is the production and processing of steel for long products in an integrated factory. The hot billets from the caster are fed through an induction heating system directly into the rolling mill. The induction system detects the billet's incoming temperature and equalizes the surface and core temperatures on demand, in order to provide an optimum rolling temperature. Important to notice with regard to the sustainability is the fact that no fossil fuel combustion furnace is needed. This setup allows for significant energy and cost savings and causes less emission.

2.2.1 Continuous Mill Technology

In conventional minimills the cast billets are fed either hot or cold from the continuous caster into a combustion furnace then brought to rolling temperature before being conveyed to the rolling mill. For many years this process was the global standard, however it did have several disadvantages. First, the thermal energy contained in the billet is eliminated when the billet cools down after the casting process and then needs to be restored in the combustion furnace, which costs both time and money. Secondly, scale formed on the billet surface during conventional heating processes results in a loss of output. Furthermore, the condition of the scale leads to low roll service life in the mill, while considerable quantities of offgas are emitted into the environment from the combustion furnace.

A key feature of the continuous mill technology is the replacement of the conventional gas- or oil-fired furnace with an induction plant positioned directly inline between the continuous caster and rolling line. Here the heat stored in the billet from the casting process is used for the direct rolling process, and the temperature is merely equalised over the length and cross-section and adapted to the optimum rolling temperature. Overall, therefore, far less energy is consumed here, compared to the traditional method, than would be the case if the entire billet had to be re-heated from room temperature or any other intermediate temperature to the optimum rolling temperature at the inlet section of the first roll stand, **Figure 2.16**.

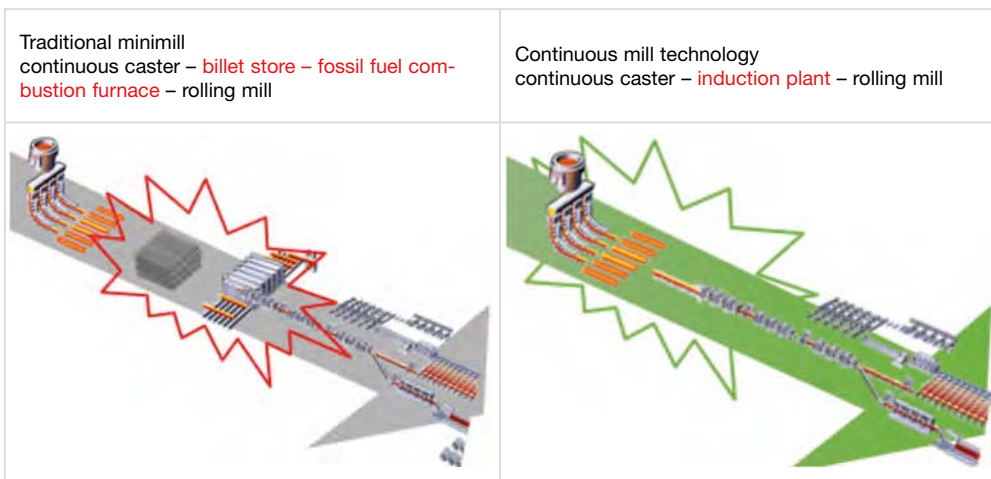


Figure 2.16: Arrangement of a minimill with continuous mill technology compared to the traditional layout (Source: SMS Concast)

CMT™ core data	CMT™ 1	CMT™ 2	CMT™ 3+
Annual capacity [1,000 t/a]	100 to 350	350 to 700	500 to 1,000+
Line productivity [t/h]	15 to 55	55 to 110	80 to 150+
Steel grades	Structural steel and high-grade steel (carbon steel)		
Casting radius [m]	6.0 to 10.25		
Cast cross-section [mm]	100 to 150		
Billet length [m]	“endless”	12 to 16	
Temperature homogenization	Induction heating with various output capacities		
	2 units	2 to 4 units	variable
Number of roll stands	18 for structural steel, 24 for rod		variable
Number of casting strands	1	2	variable

Table 2.2: Overview of various minimill layouts depending on annual production

Depending on the planned annual production, minimills with continuous mill technology are used at varying capacities in terms of casting, heating and rolling output, **Table 2.2**.

2.2.2 Key benefits of minimills with continuous mill technology and integrated induction technology

High cost efficiency

The major benefits of this innovative minimill configuration with integrated induction technology above all include:

- Lower investment costs
- Lower operating costs.

The lower investment costs are primarily achieved by dispensing with a conventional combustion furnace and reducing the logistics associated with billet production, e.g. storage facilities or crane tracks, as well as the reduced requirements with regard to space and accordingly to warehouse stock.

The reduced operating costs can mainly be attributed to the energy savings from lower primary energy costs and higher output; this is covered in more detail later on. Furthermore, the capital stock is reduced by eliminating the billet store. Additional savings can be made as a result of a reduction in the maintenance work which would be required on a conventional reheating furnace, and by reducing manpower requirements for operating personnel.

Using residual heat to save energy

Traditional minimill operation is usually broken down as follows: 30 % of the billets are fed cold into a conventional combustion furnace from the billet store before the rolling process, 70 % are conveyed directly out of the continuous caster and through this furnace with residual heat. The specific energy consumption depends on the required rolling temperature and type of furnace (pusher, roller

Production capacity	CMT™ minimill with induction 100 % direct rolling	Conventional minimill with combustion furnace (30 % cold + 70 % warm)
	Specific energy consumption	
	20 to 25 kWh/t	~155 to 160 kWh/t
300,000 t/a	6,750 MW/a	47,250 MW/a
500,000 t/a	11,250 MW/a	78,750 MW/a
800,000 t/a	18,000 MW/a	126,000 MW/a

Table 2.3: Specific energy consumption for different production layouts

hearth, walking beam furnace), which in turn depends on the productivity of the rolling plant. With this type of production programme (30/70) and an entry temperature of 1,000 °C at roll stand 1, around 155 to 160 kWh/t of specific energy consumption can be taken as a general guideline value.

With minimills with continuous mill technology the picture is different: here 100 % of the cast billets are fed directly – with no rerouting involved – through the induction furnace to the rolling line. The design of the induction plant substantially depends on the workshop layout, i.e. the distance from the continuous caster to the first roll stand, the required rolling temperature and the relevant rates of production of both the continuous caster and rolling line.

In minimills with continuous mill technology that are optimally laid-out and feature casting strand insulation to prevent heat losses and a compact continuous caster/rolling line set-up, the specific energy consumption for heating a billet to 1,000 °C is between 20 and 25 kWh per ton. This equates to a reduction of around 700 %, **Table 2.3**.

Any decision in favour of the innovative continuous mill technology with integrated induction heating system is essentially based on the primary energy costs for fossil fuels (gas, heavy oil) or electric power, as well as their regional availability in each case.

The benefits of modern continuous technology minimills with integrated induction reheating prevail significantly in cases where fossil fuel costs are far greater than electricity costs. The following applies as a rule of thumb: The benefits of the continuous technology minimill concept with induction furnace can be fully brought to bear if the electricity/natural gas cost ratio is lower than 0.75. And this only takes the energy costs into consideration. Looking at other advantages such as output, low investment and space requirements or fewer operating personnel, to name just a few, this ratio increases even further, with the result that the number of plant operators able to benefit from induction-assisted minimill technology over the long term also continues to rise.

Figure 2.17 shows the industry prices for natural gas and electricity in Germany (in 2013) and the savings that plant owners can achieve if they use an induction-assisted minimill and direct rolling instead of a conventional minimill with combustion technology. It is clear that even with existing minimills the break-even point for necessary investment is very quickly reached through the primary energy savings alone. If other factors, such as those as described above, are included in the cost-efficiency analysis, then a decision in favour of an induction-assisted minimill becomes all the more obvious.

Higher output with negligible scale

With the conventional reheating process the cast billet is fed either cold or with some residual heat into the fossil fuel-fired furnace. The formation of scale, which depends on the time factor as well

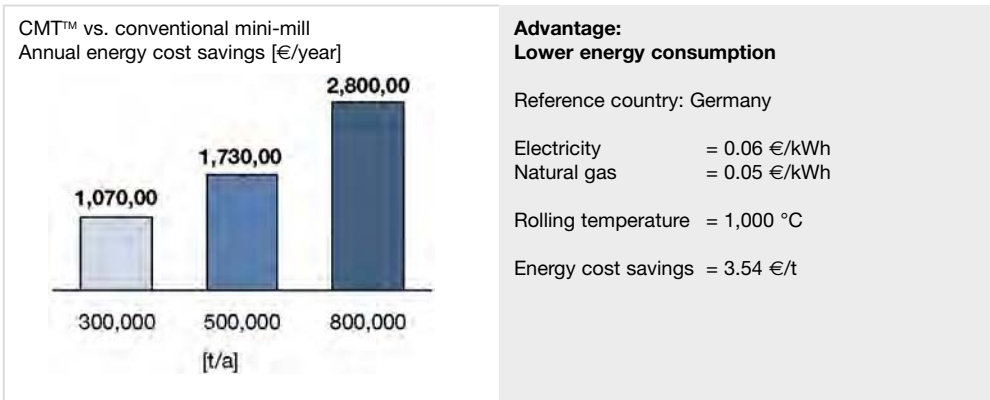


Figure 2.17: Energy savings based on various production figures in Germany (Source: SMS Concast)



Figure 2.18: Annual production increase using low-scale induction technology in a CMT™ minimill (Source: SMS Concast)

as a few material-related variables, increases above a temperature of around 900 °C. In other words: the longer a billet is held in the reheating furnace above 900 °C, in order for it to be “heated through”, and the higher the furnace outgoing temperature is, the more primary scale is formed. Today’s modern combustion furnaces with optimal temperature adjustment and combustion air regulation in the holding zone are capable of achieving values of around 0.6 % scale loss.

In minimills with continuous mill technology the billets are brought directly to rolling temperature in induction heating systems at very high heating rates. At less than 60 seconds the holding time within the critical temperature range above 900 °C is very short, with the result that virtually no scale is able to form. Compared to an atmosphere furnace, the level of scale formation with induction heating is, at around 0.02 %, lower by a factor of 30 and therefore negligible. This results in a higher metal yield of approx. 0.6 % which, given the high production volumes, very quickly adds up in terms of cost efficiency (**Figure 2.18**). By comparison with conventional minimills this increased output can be viewed as “cost-free” production. In minimills with an annual production volume of

Country	Energy input [Cost / Unit]			D Energy	D Output (primary scale only)	Overall cost savings
	Electricity	Natural gas	Sales price of structural steel *			
	[€/kWh]	[€/Nm³]	[€/t]	[€/t]	[€/t]	[€/t]
Brazil	0.11	0.40	845	-4.4	-5.1	-9.5
China	0.04	0.22	400	-2.9	-2.4	-5.3
Germany	0.06	0.28	515	-3.5	-3.1	-6.6
India	0.08	0.37	510	-4.4	-3.1	-7.5
Russia	0.04	0.05	400	+0.2	-2.3	-2.1
Middle East	0.03	0.05	510	-0.2	-3.1	-3.3
East Asia	0.07	0.30	430	-4.8	-2.6	-7.4
USA	0.05	0.10	545	-0.6	-3.3	-3.9

* Platts, SBB steel prices, Dec. 2013 (€ 1 = US\$ 1.3)

Table 2.4: Long-term economic benefit of a CMT™ minimill with integrated induction heating system compared to conventional facilities with a gas furnace

800,000 tons, the economic effect from the higher material output alone amounts to almost 2.2 million euros each year.

Moreover, further benefits can be gained from the low-scale billet surfaces in the subsequent rolling process. The brittle-hard scale has an abrasive effect and results in the rolls becoming worn. Low-scale surfaces following induction heating mean the service life of the rolls increases significantly, which in turn also leads to a higher level of availability of the overall plant, since less maintenance is required.

Long-term overall savings

The overall cost reductions are thus the result of various individual cost reductions such as energy costs, increased output thanks to the higher metal yield as well as other factors. In the example of Germany given above, savings of around 5 million euros per year or 6.25 euros per ton of structural steel produced for a steel mill with 800,000 t/a output can be made from the point of view of energy costs and material yield alone. What's clear, therefore, is that an investment in state-of-the-art continuous mill technology very quickly pays for itself.

Table 2.4 shows the long-term savings offered by a minimill with integrated induction technology compared to a conventional line with gas furnace based on an international comparison. It should be noted here that the price and availability of gas are heavily dependent on the regional situation with regard to production. In cases where gas is not available, expensive heavy oil supplied by road tanker is usually used as fuel. This means additional costs which further promote the use of induction technology.

If one brings together the various individual benefits in terms of energy costs and material output, then the picture gained is quite clear: In all major industrialised countries with significant steel production and processing industries the superiority of the continuous mill technology with integrated induction is plain to see. Even in countries with a high availability of natural gas resources and

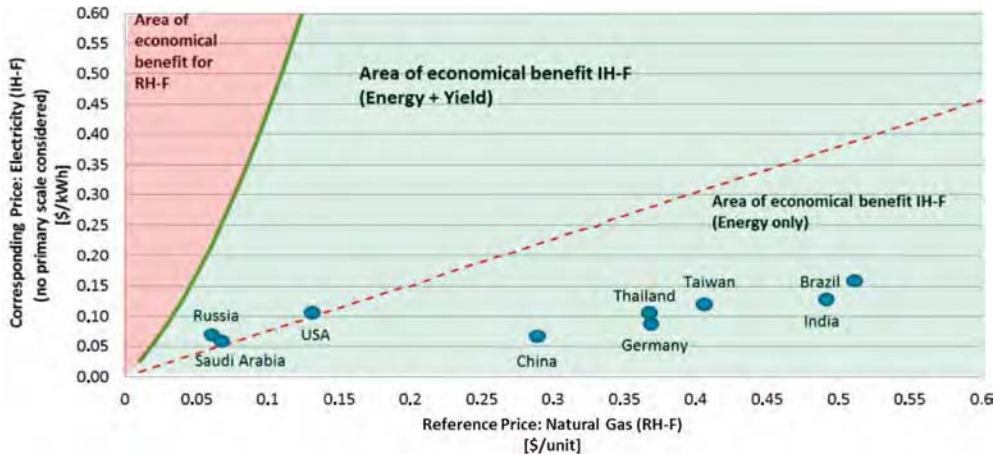


Figure 2.19: Preferred concepts for reheating systems in minimills, depending on energy costs and primary output by international comparison (Source: SMS Concast).

correspondingly low gas prices, a minimill equipped with induction technology pays off through increased material output, **Figure 2.19**.

Up to now attention was paid only to the monetary aspects associated with the use of induction technology in minimills. In addition to this, however, aspects relating to ecological sustainability, which may well be of greater importance in future, should be taken into consideration.

Eco-friendly production

Traditional minimills featuring conventional furnace technology for reheating billets use either natural gas or heavy oil as fuel. When looking at the general environmental impact, it is not just the combustion process alone that needs to be considered but the upstream manufacturing, transportation and storage processes, too.

The burning of fossil fuels produces greenhouse gases such as CO_2 , NO_x and SO_x . These gaseous substances are emitted into the atmosphere during the burning process, thus contributing to the greenhouse effect by absorbing some of the infrared radiation given off from the ground which would otherwise escape into space. This interference with the natural equilibrium which makes life on earth possible in the first place ultimately leads – through anthropogenic causes such as, for example, the combustion of gas and heavy oil for reheating billets – to global warming and all its known consequences.

Furthermore, carbon dioxide as well as sulphur and nitrogen oxides are considered some of the main causes of what we call acid rain, and the effects thereof on our ecosystem are well-known.

The use of heating technology that minimises the negative impact on the environment can help improve the situation. By using induction technology instead of conventional combustion furnaces, direct emissions of CO_2 , NO_x and SO_x when heating the billets before the rolling process are completely eliminated in the minimill with continuous mill technology. **Figure 2.20** shows that with a conventional minimill featuring combustion technology and an annual production of 800,000 tons, for example, 53,000 tons of CO_2 and 73 tons of NO_x would be produced; using an induction system eliminates this.

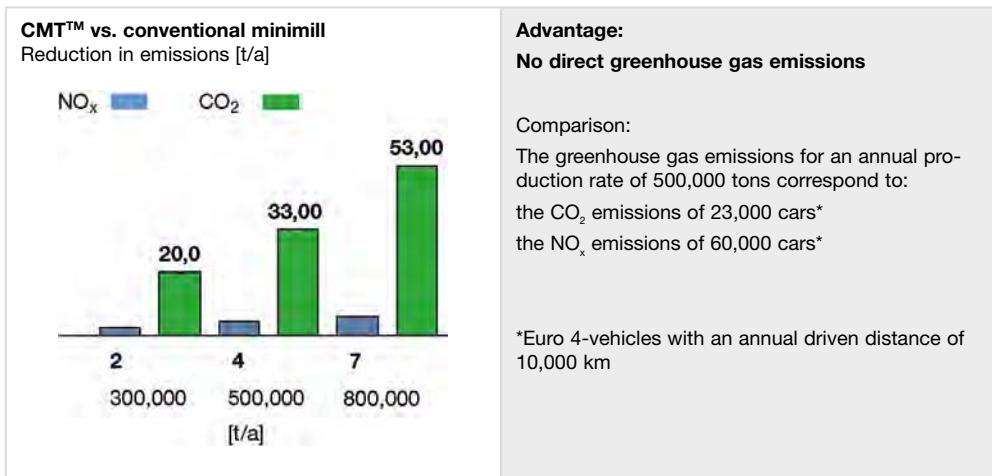


Figure 2.20: CMT™ technology with integrated induction heating reduces greenhouse gas emissions (Source: SMS Concast)

2.2.3 Reheating using the induction process

Before we look at the design and implementation of an induction system which is integrated in a minimill with continuous mill technology, a brief explanation should be given of the technology involved.

As already explained in the preceding sections, a key feature of the induction technology used in a minimill with continuous mill technology is the very rapid and therefore low-scale induction heating it offers, as well as the fact that fossil fuels and the resulting emissions are completely eliminated.

Due to the geometry of the billet longitudinal-field heating is used in minimills with continuous mill technology. Here the workpiece is fully encompassed by the coil. The resulting eddy currents run along the slab surface at the current penetration depth. The simple design of the longitudinal-field inductors makes them very robust and capable of being integrated into the rolling mill process.

The high power density values that can be achieved can be used to full advantage in minimills, thereby enabling compact heating systems with high thermal efficiency levels to be integrated into the processing lines. As the following example of Tung Ho Steel in Taiwan shows, a total output capacity of 8,700 kW has been installed over a length of approx. 8 m. This output capacity is sufficient, for example, for a temperature rise of more than 200 K at a production rate of 100 metric tons/h. This effectively compensates for temperature level fluctuations in the upstream processes and ensures constant conditions at the inlet section of the rolling mill. This means no equalising through the rolling mill is required, plus any spares or reserves in terms of the layout and design as well as increased wear and tear are avoided.

Figure 2.21 shows the options available using two randomly selected, typical examples. With both dimensions, 100 mm and 195 mm square section, the temperature at the mill entry can be maintained at a constant level. An alteration of the production speed of between 3 and 9 m/min has been taken into account here.

As the thermal conditions at the rolling mill entry are being stabilised, the temperature over the cross-sectional area of the material is homogenised. As shown in **Figure 2.22**, the result is a temperature profile during transportation from the casting machine to the rolling mill whereby the

surface is 173 K colder than the centre. This situation is often referred to as a natural temperature profile. This temperature profile changes due to the rapid heating process in the induction heating system, such that the highest temperatures occur on the surface. This is caused by the typical

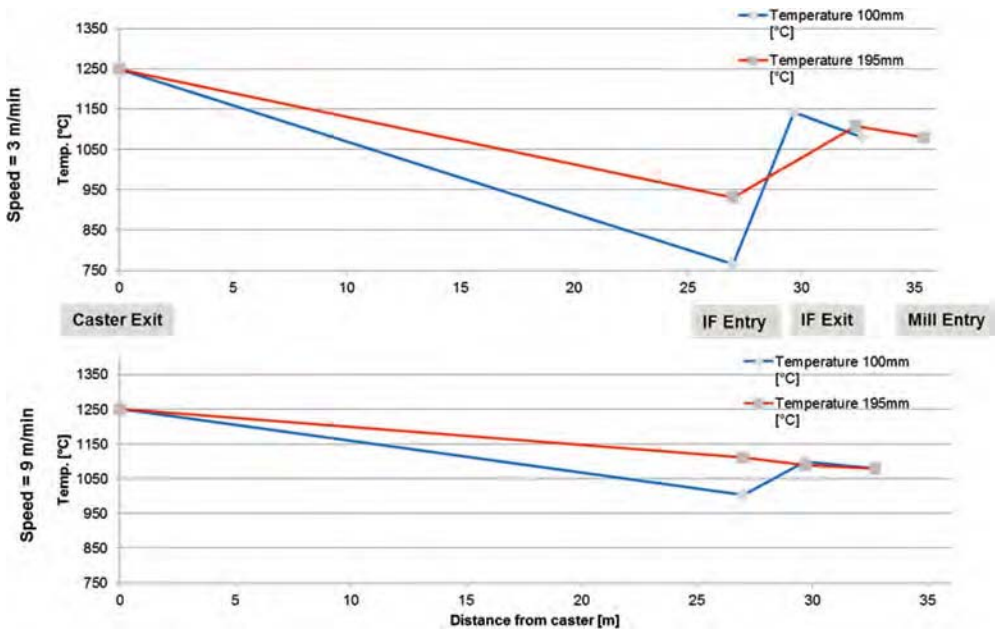


Figure 2.21: Typical temperature curves with the inductive heating of square material with dimensions of 100 mm and 195 mm at a conveying speed of 3 m/min and 9 m/min (Source: SMS Elotherm)

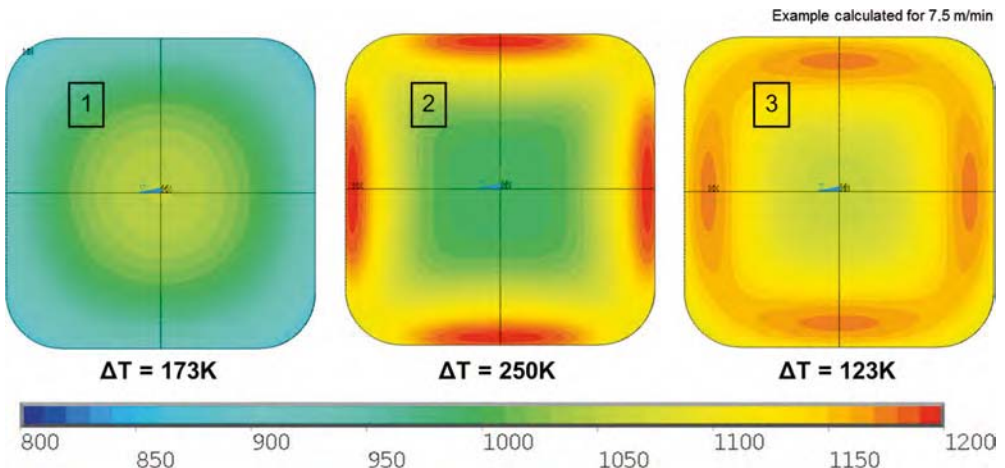


Figure 2.22: Example of a typical temperature profile for a 160 mm square section on entering the induction unit from the continuous caster (1), following induction heating (2) and at the rolling mill entry (3) (Source: SMS Elotherm)

[mm]	100	105	110	115	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190	195	rolling speed [m/s]
	3030	3315	3613	3924	4247	4584	4934	5297	5673	6061	6463	6878	7305	7746	8199	8666	9145	9637	10143	10661	0,15
	2945	3221	3510	3811	4125	4451	4790	5141	5505	5881	6270	6672	7086	7512	7951	8403	8867	9343	9833	10334	0,145
	2861	3128	3407	3699	4002	4318	4646	4986	5338	5702	6078	6466	6866	7279	7704	8140	8589	9050	9523	10008	0,14
	2777	3035	3305	3587	3880	4185	4502	4830	5170	5522	5886	6261	6647	7046	7456	7878	8311	8756	9213	9682	0,135
	2693	2942	3203	3475	3758	4052	4358	4675	5003	5343	5693	6055	6429	6813	7209	7615	8034	8463	8903	9355	0,13
	2609	2849	3101	3363	3636	3920	4214	4520	4836	5163	5501	5850	6210	6580	6961	7353	7756	8170	8594	9028	0,125
	2525	2757	2999	3251	3514	3787	4071	4365	4669	4984	5309	5645	5991	6347	6714	7091	7478	7876	8284	8703	0,12
	2441	2664	2897	3139	3392	3655	3927	4210	4503	4805	5117	5440	5772	6115	6467	6829	7201	7583	7975	8377	0,115
	2358	2571	2795	3028	3270	3522	3784	4055	4336	4626	4926	5235	5554	5882	6220	6567	6924	7290	7666	8051	0,11
	2274	2479	2693	2916	3149	3390	3641	3900	4169	4447	4734	5030	5335	5649	5973	6305	6646	6997	7357	7725	0,105
	2191	2387	2592	2805	3027	3268	3498	3746	4003	4268	4542	4825	5117	5417	5726	6043	6369	6704	7047	7399	0,1
	2107	2295	2490	2694	2906	3126	3355	3591	3836	4090	4351	4621	4899	5185	5479	5782	6092	6411	6739	7074	0,095
	2025	2203	2389	2583	2785	2994	3212	3437	3670	3911	4160	4418	4681	4953	5233	5520	5816	6119	6430	6749	0,09
	1942	2111	2288	2472	2664	2863	3069	3283	3504	3733	3969	4212	4463	4721	4986	5259	5539	5826	6121	6423	0,085
	1860	2020	2187	2362	2543	2732	2927	3129	3339	3555	3778	4008	4245	4489	4740	4998	5263	5534	5813	6098	0,08
	1778	1929	2087	2252	2423	2601	2785	2976	3173	3377	3588	3805	4028	4258	4494	4737	4987	5242	5505	5774	0,075
	1696	1839	1987	2142	2303	2470	2644	2823	3009	3200	3398	3601	3811	4027	4249	4477	4711	4951	5197	5449	0,07
	1615	1749	1888	2033	2184	2340	2503	2671	2844	3023	3208	3399	3595	3796	4004	4217	4436	4660	4890	5125	0,065
	1535	1660	1789	1925	2065	2211	2362	2519	2680	2847	3019	3196	3379	3566	3759	3958	4161	4369	4583	4802	0,06
	1456	1571	1692	1817	1947	2083	2223	2367	2517	2672	2831	2995	3164	3337	3516	3699	3887	4079	4277	4479	0,055
	1378	1484	1595	1711	1831	1955	2084	2217	2355	2497	2643	2794	2948	3109	3273	3441	3614	3790	3972	4157	0,05
	1 Modul (2 inductors)		2 Modules (4 inductors)		3 Modules (6 inductors)		4 Modules (8 inductors)		5 Modules and more												

Table 2.5: Installed power for a temperature rise of 200 K in relation to the rolling speed and the bar steel's dimension (Source: SMS Elotherm)

power density distribution of induction heating. However a crucial factor here is the fact that, on entering the rolling mill, the temperature differences over the cross-section can be reduced by around 30 % compared to natural cooling. Billets with a homogeneous temperature distribution can be more easily formed and therefore ensure a stable rolling process. Since less rolling force is required for forming billets with higher absolute and relative heat, there is also less roll wear and the rolls last longer.

In order to better understand the power requirements of minimills with continuous mill technology and integrated induction, **Table 2.5** shows the installed induction power in relation to the rolling speed and the bar steel's dimension. The calculation is based on an average temperature increase of 200 K. The colour code identifies the required number of modules, each consisting of a frequency converter, a capacitor cabinet and two inductors. The available converter power is 2,900 kW. The roller's pitch of 1,500 mm ensures compact and powerful heating units.

Example of application:

As an emerging economic power, Taiwan is faced with huge challenges. Oil and gas have to be imported. So energy costs are correspondingly high. Therefore, Tung Ho Steel decided to install a CMT™ minimill – with a high production capacity and low energy consumption and reduced emission values thanks to the integrated induction technology – in its works near Taipei.

What's more, this minimill is a shining example of how a heavy oil-fired combustion furnace can be replaced by a compact yet powerful induction heating system, thus resulting in sustainable and measurable ecological and economic success. As there was no natural gas available at the site, heavy oil would have had to be used. Using induction heating technology meant that Tung Ho Steel was able not only to save almost 20 €/t of rolled steel but reduce its emissions in particular. This

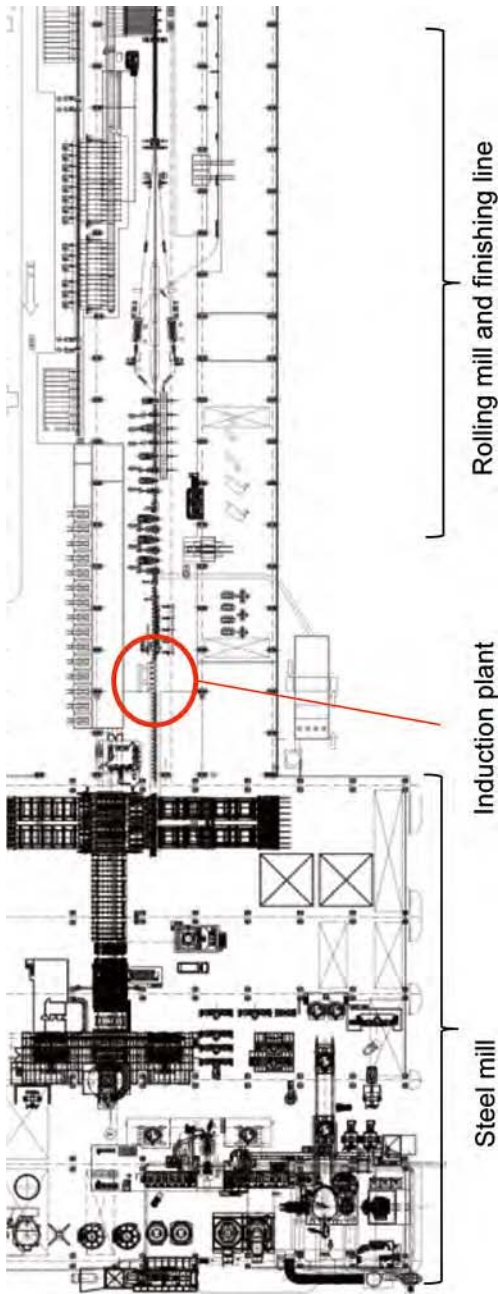


Figure 2.23: Integration of an induction heating plant between a continuous caster and a rolling mill (Source: SMS Concast)

workshop at Tung Ho is therefore now capable of reducing its emissions by around 72,000 t/a CO_2 , 410 t/a SO_2 and 225 t/a NO_x – year in, year out.

The steel mill is equipped with a 120 t electric arc furnace (EAF), a ladle furnace and a caster with 5 strands. At a production rate of 40 – 45 t/h per casting strand, this results in an annual capacity of around 1.2 million tons of cast billets. The attached rolling mill produces around 800,000 tons of rolled structural steel every year.

The induction heating system was integrated inline between the casting machine and rolling mill, **Figure 2.23** and **Figure 2.24**.

The induction plant comprises 3 individually controllable modules with two induction coils each, **Figure 2.25**. With an overall length of around 8 m the plant has an installed capacity of 8.7 megawatts. This ensures both a temperature rise of around 150 K and a consistent temperature distribution of the billets between the continuous caster and rolling mill. So on the one hand high process speeds of 140 t/h, as previously mentioned, can be attained in the rolling mill, while on the other hand optimal forging processes can be conducted with only minimal wear.

For this the induction heating plant is equipped with state-of-the-art IGBT converters, which themselves feature transistors and can therefore be flexibly adapted to the respective heating process and help to achieve a high level of overall plant availability.

Figure 2.26 shows the calculated temperature profile between the casting machine and the entry section of the rolling mill at Tung Ho Steel. The green curve shows the temperature of the surface, the first third of which is influenced by the secondary cooling and contact with the support rolls. Following complete solidification upstream of the cutting torch position, the material goes through an even cooling-down phase, whereby any losses are minimised by radiation protection measures.

The induction heating section is identified by a red circle in **Figure 2.26** and shown in detail in **Figure 2.27**. This is where adjustments and

Figure 2.24: Induction heating plant with 6 induction coils at Tung Ho Steel in Taiwan (Source: SMS Elotherm)



stabilisation of the thermal conditions for optimum rolling process preparation take place. The penetration depth at a frequency of 300 Hz is ~30 mm, ensuring near-surface heating can be achieved. The colder temperature at the core is equalised by means of heat conduction around 5 m after the



Figure 2.25: Billet before reheating in the induction heating at Tung Ho Steel in Taiwan (Source: SMS Elotherm)

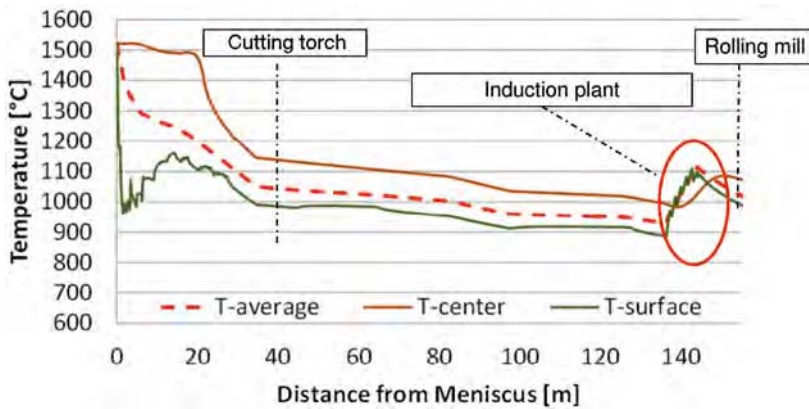


Figure 2.26: Temperature profile of the billet with a cross-section of 150 mm at Tung Ho Steel in Taiwan (Source: SMS Concast)

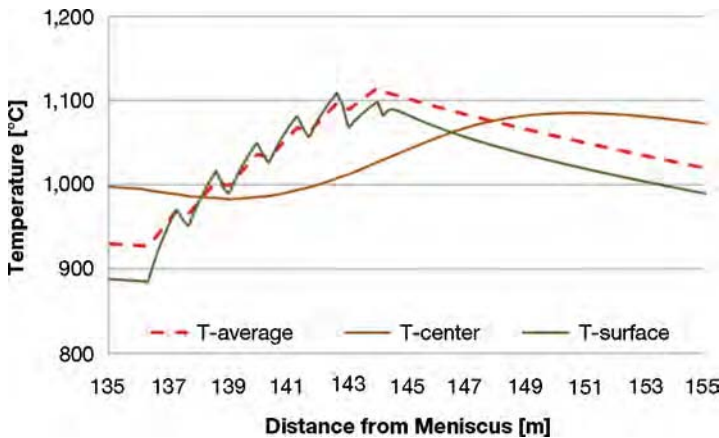


Figure 2.27: Illustration of a temperature increase through the six induction coils and core temperature homogenisation by means of heat conduction (Source: SMS Concast)

billet exits the last induction coil, in order that a homogeneous temperature can be achieved over the billet cross-section for the purpose of the rolling process.

Conclusion

The demands being made by plant owners for flexible steel production in terms of the production volumes, the discussions currently being held with regard to low-emission production methods as well as the regional and limited availability of fossil fuels have been translated into innovative production concepts by manufacturers of plant and equipment for steel and rolling mill technology.

One result is continuous minimill technology with integrated induction technology for energy-efficient reheating. As well as a variety of innovative solutions in the steel and rolling mill sections of these minimills, special mention should be made at this point of the benefits of integrated induction technology: individual, rapid attainment of the optimum rolling temperature despite variable incoming temperatures, no energy consumption during downtimes and stoppages, increased metal yield with low-scale heating and above all no direct emissions – these are the means with which plant owners can secure their competitive edge on the international stage.

In future higher costs for CO₂ certificates will further increase the pressure on production costs for steel products. Plant owners would be well advised to bear in mind the economic advantages that can be attained with energy-efficient induction technology, both on an individual level and in terms of the total costs of a minimill over its lifetime. The continuous minimill concept offers manufacturers of rolled products a variety of solutions here, especially as any investment in most cases quickly pays for itself, even with revamps of existing lines.

2.3 Flat products, strips and sheets

Robert Jürgens, Markus Langejürgen

Application areas

Similar to the manufacturing processes for long products, there are both integrated and separate production lines for flat products. In particular, the integrated processes, **Figure 2.28**, which run successively through all stages from the liquid steel to the coil or sheet, require precise temperature control.

Furthermore, the issue of energy input is increasingly gaining significance, with the result that new process chains are now being offered that enable both economic and ecological advantages thanks to the coordinated combination of conventional furnace technology and modular induction plants. One example of this is the continuous production of thin strip. Sheet with a

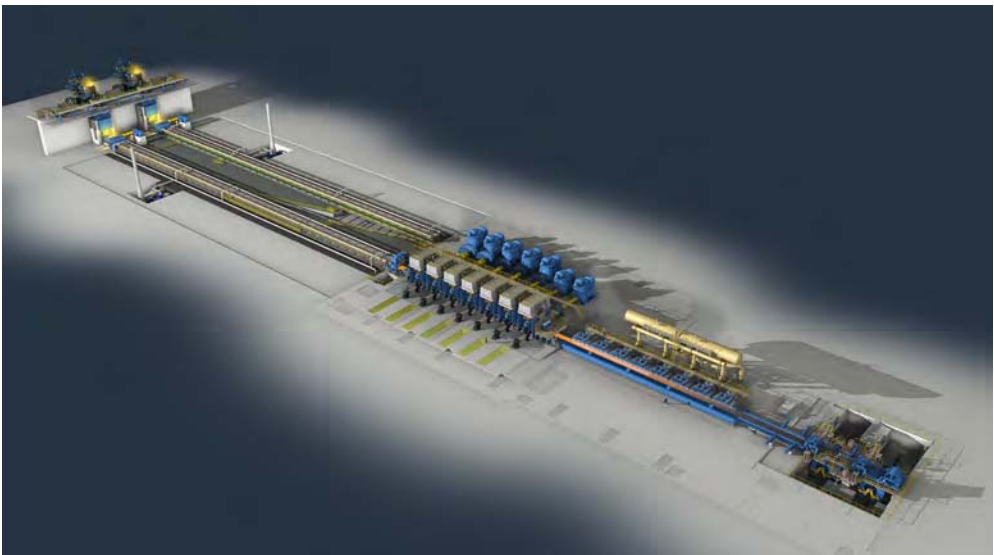


Figure 2.28: Components of an integrated production facility for flat products
(Source: SMS Siemag AG)



Figure 2.29: Example of an induction plant between the tunnel furnace and mill line for adapting the temperature level (Source: SMS Siemag AG)

finished thickness as thin as 0.8 mm is produced in plants such as these. The pre-shape is often manufactured in curved casting machines to a thickness of approx. 50 to 100 mm. While passing through a soaking furnace it is rolled to less than 2 % of its original thickness. High temperatures at the inlet section of the mill line are required for this purpose to ensure that there is still sufficient energy in the strip for the final shaping process.

On the other hand, the same plant needs to be capable of producing tube-quality steel and corresponding dimensions. These steel grades, however, are required in thicknesses of over 25 mm, which is less challenging in terms of the required entry temperature. The used soaking furnaces convey the pre-rolled strip on rollers through a furnace chamber several hundred meters long; it is not possible to alter their temperature rapidly whenever required. This is where high-performance induction plants can be used to quickly adapt the temperature to the rolling process requirements, **Figure 2.29**.

Principles

There are many production lines worldwide that are used for the manufacture of flat products. Correct control of the product temperature plays a key role in achieving cost efficiency in the manufacturing process, as already explained in the previous section. Although these can be very complex, when taking the entire length of the line into consideration, it is possible to draw conclusions about the physical aspects involved in regard to the temperature distribution across the strip cross-section. Flat products largely have a homogeneous initial temperature over the entire cross-section at the beginning of the manufacturing process. During this process the temperature drops as a result of radiation and convection losses. The power losses on the surface of the flat products ultimately determine the temperature distribution inside them. The following simple assumptions facilitate a

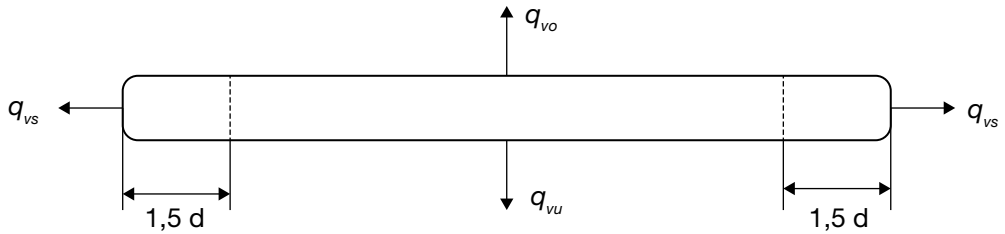


Figure 2.30: Power losses with flat product: side face losses q_{vs} ; top surface losses q_{vo} ; bottom losses q_{vu}

2

further analysis of temperature deviations in the flat products over the length of the production line and the options for implementing temperature corrections, **Figure 2.30**.

The radiation losses on the narrow faces and on the top side and underside are not of the same magnitude.

With slabs the edge area is up to 1.5 times the material thickness and with thin strip it can be up to 200 mm.

Consequently, the temperatures following cooling during the production process differ on the top side, side faces and underside. The mean temperatures in the individual zones may, therefore, differ and display deviating rolling characteristics. To eliminate this interference in the production process, there are essentially four types of used induction heating plants:

1. Induction heating plants with all-round inductor, **Figure 2.31**
2. Induction heating plants with separable inductors, **Figure 2.32**
3. Induction transversal-field heating plants
4. Induction edge heating plants.

Induction longitudinal-field heating for reheating pre-rolled strip

Induction longitudinal-field heating is used when even heating of rolled product is desired and the flat material to be heated is sufficiently thick. The wall thickness to penetration depth ratio is then

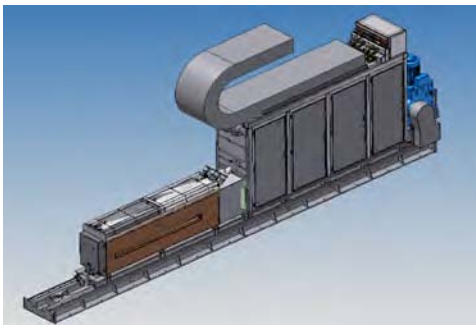


Figure 2.31: Example of a slab heater with all-round inductors and a modular capacity of 4,500 kW (Source: SMS Elotherm)



Figure 2.32: Example of a slab heating plant with separable inductors (Source: SMS Elotherm)

between 2.5 and 5. This provides both a good level of electrical efficiency and sufficiently homogeneous heat source distribution.

$$2,5 \leq \frac{d}{\delta} \leq 5 \quad \text{mit} \quad \delta = \sqrt{\frac{\rho}{\pi \mu f}} \quad (2.27)$$

Here d is the strip thickness, δ the penetration depth, ρ the specific electrical resistance, μ the magnetic permeability and f the current frequency.

The operating efficiency depends, among other things, on the size of inductor opening required. On the one hand, the space between the inducing coil and work piece should be as small as possible for electromagnetic coupling of the material while, on the other hand, safe conveyance of the slab also demands a spacing which is sufficient to prevent collisions with the inductor in the event of deviations from the ideal shape expected.

All round longitudinal-field inductors are used at the outlet section of the tunnel furnace or between the roll stands. The material thicknesses range between 50 and 120 mm in the area downstream of the tunnel furnace and between 12 and 20 mm between the stands with the result that longitudinal-field heating plants can be used within the 2 to 10 kHz frequency range. If the material is conveyed directly out of the tunnel furnace, anomalous contours can be identified in time and intercepted in a multi-stage safety chain. The height and width of the opening are an appropriate compromising solution between safety aspects on the one hand and electrical operating efficiency on the other.

At the end of the casting machine the material is cut into slabs using a shear. This cutting process may cause deformation of the slab end. The slab then assumes a roof-like shape, which is why the term "shear roof" is commonly used. This shear roof may result in a collision with the inductor upon reaching a critical height. This is something that must be prevented at all costs.

If contact with the strip cannot be safely ruled out, because the speeds are so high, for example, that the spacing required for safe stopping of the strip cannot be implemented, then separable longitudinal-field inductors, as shown in Figure 2.32, may be an alternative. This type of inductor can be used in the event of critical operating conditions, as is the case when the strip head is run in, and thereby provides sufficient spacing between the inductor and strip. Before being switched on, the inductor halves are brought together and moved to the strip surface at an optimum coupling distance.

With induction longitudinal-field heating, the equivalent power density applied to the strip, q_H , ranges between 1,500 and 2,000 kW per m² strip surface. An output of 4,000 kW per meter of plant length represents a guidance value for induction heating plants of this type.

Transversal-field heating for reheating thin strip before rolling

Induction transversal-field heating is used when the sheet or strip is very thin. The strip width is greater than the thickness by a factor of 100. As a rule, the strip thickness to penetration depth ratio is between 0.05 and 0.3 with transversal-field heating. A transversal-field inductor basically comprises the components shown in **Figure 2.33**. To provide a better overview only the inductors above the strip are shown. An identical arrangement can also be found under the strip and can be seen as a mirror image of the inductors at the center of the strip. These inductors have a coiling head, the design of which varies on one side. This head influences the power density distribution on the strip edge. An open inductor branch is located on the opposite side. The power density cannot usually be influenced on this side. Due to this side-related asymmetrical power density distribution, a further inductor with reverse side orientation is required. This compensates for the asymmetry and ensures a symmetrical temperature profile at the outlet section of the inductor line. Arrangements of this kind can be supplied over a length of 1,100 mm from converters with a

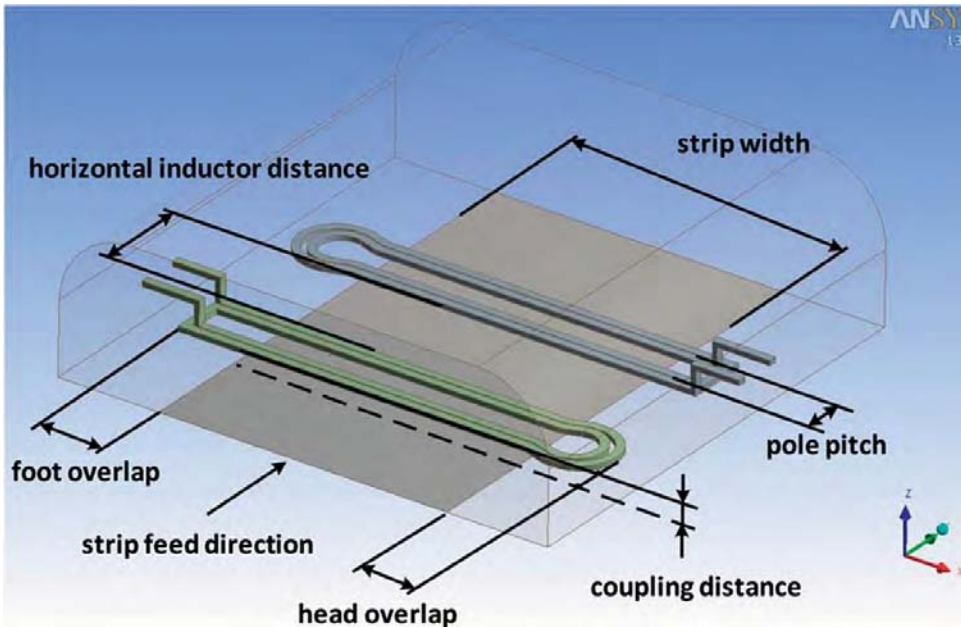


Figure 2.33: Conductor layout and design parameters of a transversal-field heating inductor (Source: SMS Elotherm)

capacity of up to 6,400 kW, such that length-related output power levels of above 5,000 kW/m can be achieved. Important design parameters for such plants are shown in the drawing. To enable these inductors to be used for various strip widths, the inductors must be capable of moving crosswise to the strip feed direction. Depending on the selected frequency and the desired feed voltage, the inductors can be designed with multiple windings. The illustration shows a two-winding design. The coupling distance does not act as directly on the operating efficiency as is the case with the longitudinal field. Furthermore, transversal-field inductors can usually be adjusted in terms of the opening height, with the result that safety strategies similar to those implemented with separable longitudinal-field inductors, as described above, are used.

Figure 2.34 shows the distribution of the magnetic flux density (plan view top left, side view top right), current density (bottom left) and the resulting heat source distribution in the strip. The effects at the strip edge are well visible with all sizes and can be analyzed by means of a numeric simulation. The induced current attempts to flow as a mirror image of the inductor current in the strip level. This also works in terms of the conductor branches, although the current paths are concentrated at the strip edge, with the power density being concentrated at these points, too.

The resulting temperature distribution while passing through the plant is shown in **Figure 2.35**. Starting from a temperature profile with slightly undercooled edges, the heating process commences in the mid-section upon passing through the first inductor branch. The strip edges are disproportionately heated between the supply and return conductor of the first inductor, thereby resulting in overheating. Such heating characteristics are again found for all three subsequent inductor branches and the area.

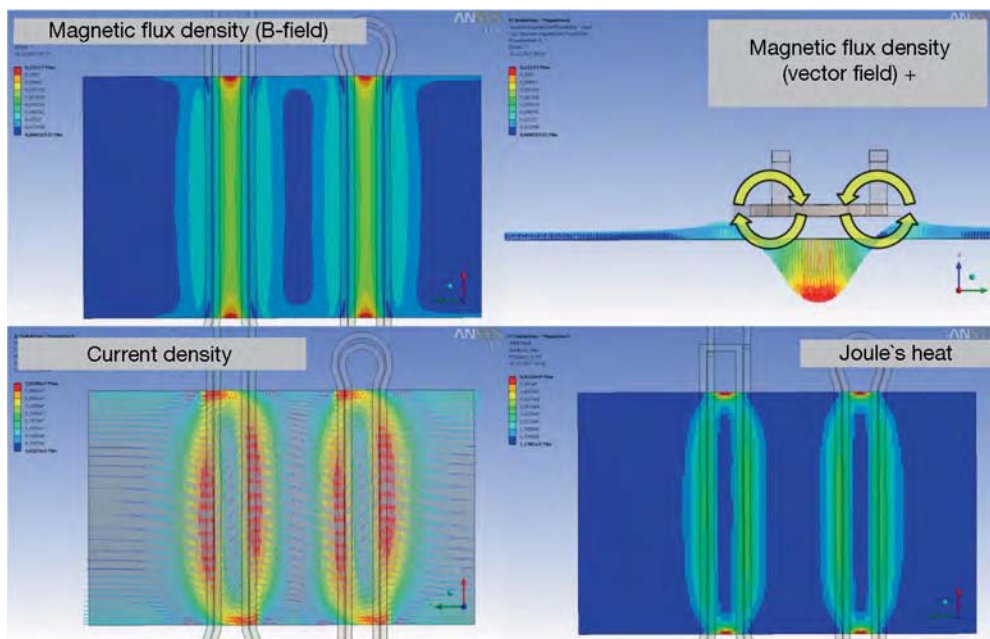


Figure 2.34: Distribution of magnetic flux density, current density and induced output power with transversal-field heating (Source: SMS Elotherm)

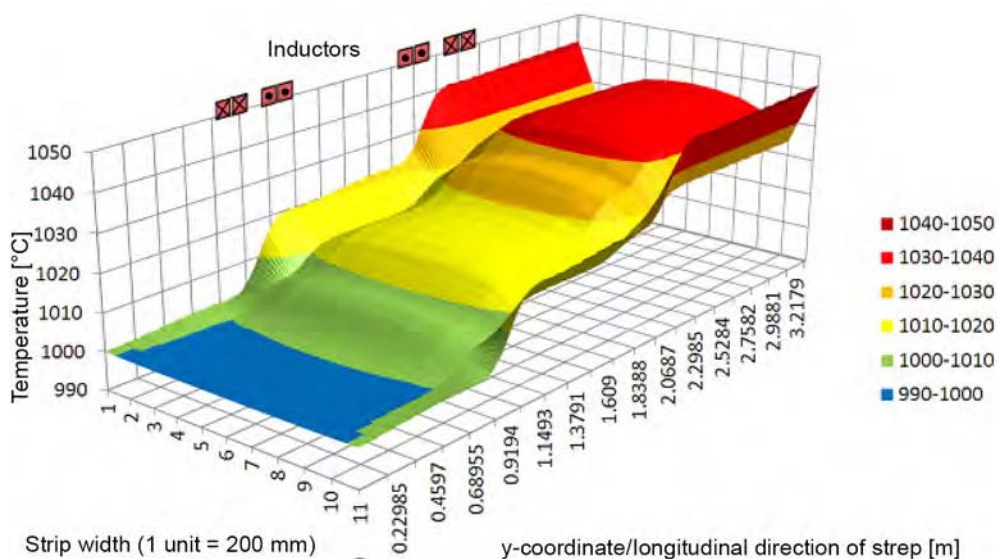


Figure 2.35: Simulated temperature distribution for a transversal-field inductor (Source: SMS Elotherm)

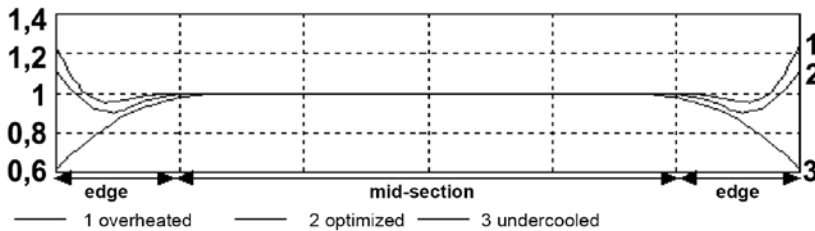


Figure 2.36: Schematic diagram of normalized temperature distribution across the strip width with transversal-field heating. The magnetic field, current path and, thus, the temperature in the strip edge areas can be influenced by the pole shape (Source: SMS Elotherm)

The transversal field-induced current flows inside the strip at an almost constant current density across the strip thickness. The supply and reverse currents flow at different points in the direction of the strip. Both current path sections meet along the strip edge. The pole shape of the magnetic field positioned vertically to the strip level plays a key role in determining the path of the current in the strip and at the strip edges. It can be used to influence the temperature distribution across the strip width, particularly in the strip edge areas. For rolling mill operators, this offers the possibility of adapting the strip edge temperature to suit process requirements, **Figure 2.36**.

With transversal-field heating the power density applied to the strip ranges between 600 and 1,200 kW per square meter. For reheating thin specialty strip with a strip width of 1,450 mm, a thermal output of 8,000 kW can be induced in the strip on a 4 m long stretch of roller table.

Edge reheating of slabs and strip

In the case of slabs, thin slabs (> 40 mm thickness) and strip (< 40 mm), it is often only the strip edges that are colder. Therefore, these are only partially heated. Edge reheating takes place at high charge travel speeds. There is usually little space available for a heating plant. This results in a short time window for heating the edges. Induction edge heaters feature a very high specific heating power density. Edge heating with line inductors, **Figure 2.37**, in front of the side surface of a thin slab can be performed at a power density of up to 9,000 kW per square meter. The edge heaters are operated using low frequency to ensure that the heat sources reach the layers deep inside the material. They can be operated fully automatically in the rolling mill.

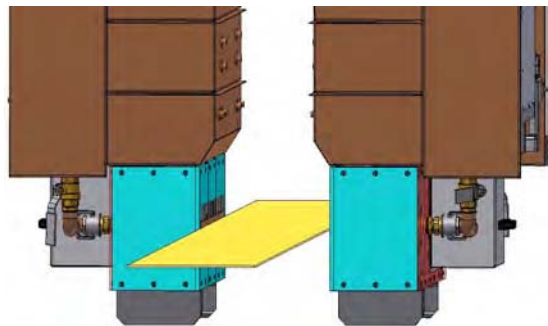


Figure 2.37: Induction edge heating for strip (Source: SMS Elotherm)

2.4 Billet heating for extrusion applications

Stefan Beer

Introduction

Extrusion is a forming process for producing bars, wire rod, tubes and irregular-shaped sections. With this method a metal billet, heated to forming temperature, is pressed through a die using an extrusion stem. Shown below are a schematic representation of the extrusion process using the direct extrusion method (**Figure 2.38**) and an extrusion press (**Figure 2.39**).

This method is primarily used for aluminium and aluminium alloys as well as copper and copper alloys. The use of extrusion applications for special materials such as titanium, steel or magnesium alloys is far less widespread, however induction heating systems are widely used here due to their performance capability (**Table 2.6**)

The advantages of the extrusion process are that complex profile forms can be made even from materials which are difficult to form, while tooling costs are kept relatively low at the same time.

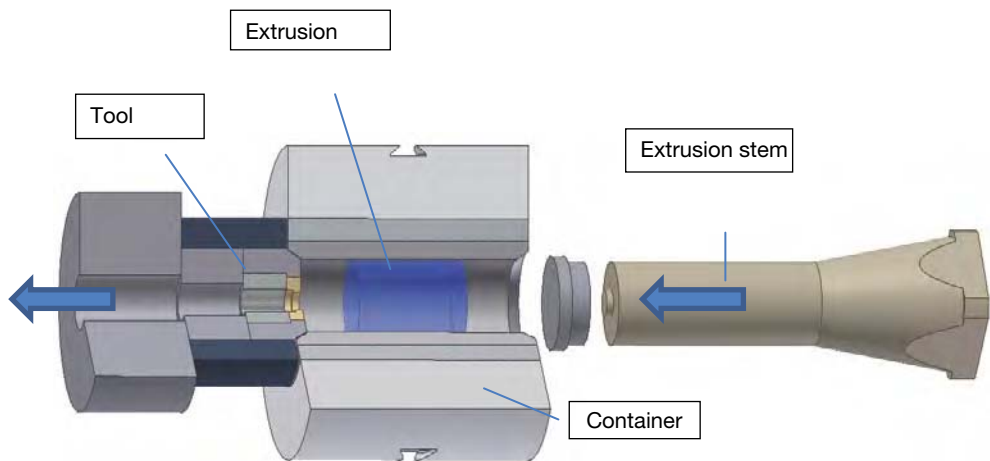


Figure 2.38: Schematic representation of extrusion process
(Source: Schmidt + Clemens GmbH + Co. KG)

Starting material	Starting material diameter D [mm]	Starting material lengths	Process temperatures at the end of heating (typical values)	Energy consumption values from ambient temperature [kWh/t]
Aluminium alloys	120 – 800 mm	300 – 2,500 mm	380 – 550 °C	180 – 270
Copper and copper alloys	100 – 500 mm	300 – 1,600 mm	700 – 1050°C	150 – 220
Steel alloys	120 – 550 mm	300 – 2,500 mm	1,150 – 1,300 °C	380 – 480

Table 2.6: Typical coefficients of induction furnaces for extrusion applications

Likewise, the extrusion process is extremely flexible and cost-effective with small batch sizes in particular. The temperature of the billet, which must be precise and above all reproducible, is of crucial importance for cost-efficient extrusion press operations that meet quality standards. Since the furnace design is based first and foremost on the process requirements, it makes sense to differentiate between the various types of alloy.

Modern switchgear unit designs with infinitely variable transistorized converters, low-loss and wear-resistant switchgear as well as modern billet handling concepts demonstrate the various possibilities of continuously adapting the induction furnace technology to the demands of the extrusion industry [2.2, 2.3].

Based on the present technological state of the art, there are essentially three variants of billet heating in an extrusion plant:

- Multi-billet furnaces (continuous system with several individually controllable heating sections)
- Combined tandem system comprising a gas furnace for basic heating and multiple-zone induction furnaces designed as a parallel or inline system
- Single-billet furnaces with several individual zones operating independently of one another (several furnaces are installed in parallel depending on the throughput required)

Induction billet heating plants for aluminium extrusion plants

The problems faced nowadays by the aluminium industry in terms of the heating process can, as a rule, be divided into two subtasks: Heating the billet to extrusion temperature and generating an axial temperature profile (taper), which compensates for the temperature rise during the forming process in such a way that isothermal extrusion is attained. [2.2]

With aluminium extrusion, in particular, the leading-end billet temperature is important, as with complex profile structures considerable mechanical loads are exerted on the forming tool at the beginning of the extrusion process. At the same time, the axial gradient ensures a higher level of productivity and a constant temperature profile within the aluminium strand at the press outlet.

In recent years the demands placed on process technology in terms of temperature control during heating of the aluminium billet have risen continuously. Likewise, far greater flexibility with regard to heating concepts is needed due to the ever increasing range with regard to both starting materials and batch sizes.

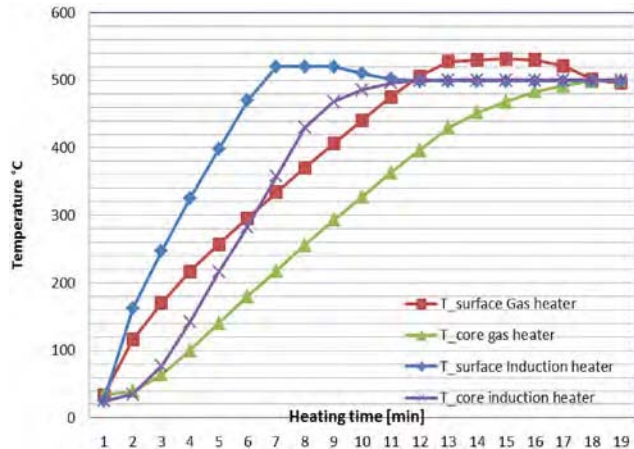
As a result of these varied requirements, the single-billet induction furnace is the preferred choice, particularly when it comes to larger aluminium extrusion plants. Its most significant advantage – by contrast with the gas furnace – is the fact that it is extremely flexible yet requires very little space at the same time. Here the advantages of an extremely flexible and reproducible heating system balance out the slightly higher energy costs compared to a purely gas-fired billet heating plant.

With induction furnaces the induced power is converted into heat directly in the workpiece, thereby avoiding the risk of overheating on the billet surface at high power densities, particularly in the case



Figure 2.39: View of an extrusion press with a press force of 15,000 t
(Source: SMS Meer GmbH, Mönchengladbach)

Figure 2.40: Typical heating curve for a billet geometry of 16.5" x 1,650 mm



of large billet diameters. Compared to gas furnace heating alone, the rates of the temperature rise to be attained for aluminium are greater by a factor of 6–10, depending on the starting material diameter, within typical strip widths of 200 to 400 mm. Shown below is a heating curve, recorded under real conditions, for a billet geometry of 16.5" x 1,650 mm. (Figure 2.40)

Combined heating plants

Given the facts presented above, one method which has proved worthwhile for many applications for large-format starting material over recent years is the combination of a gas heating system and multi-zone induction furnaces. Basic heating is performed using a conventional multi-zone gas furnace, while defined temperature adjustments are attained using a multi-zone induction furnace. (Figure 2.41)



Figure 2.41: Example of a 45 MN press line with upstream gas furnace and billet manipulator (the separate billet delivery system can be seen in the foreground) (Source: IAS GmbH)



Figure 2.42: Inline furnace with downstream hot saw for 14" billet diameters (Source: IAS GmbH)

The specified fine adjustment of the desired billet temperature is performed in the induction furnace, whereby the process management system can be provided with all the necessary data via standardized communication modules, thereby helping to ensure complete and comprehensive documentation, especially in the case of profiles used in the field of automotive and power engineering.

In conjunction with these complex control systems, considerable increases in productivity are being seen due to the improved temperature control offered by multi-zone induction furnaces.

One exceptional application of a combined gas and induction heating system – used exclusively for aluminium – is the “inline solution”, as it is known, whereby an induction furnace is positioned in line with a gas furnace. There are advantages to this concept when upgrading existing process lines using the space and conveyor technology already available. (**Figure 2.42**)

Fine adjustments of the temperature are performed in the induction furnace and bars can be used as starting material, such that a maximum of two billets may, in principle, be in circulation, thereby enabling operators to react quickly to process modifications [2.4].

Billet heating using only induction plants

This plant concept has proved useful when maximum flexibility in the heating process is desired. Here, the high-performance furnace with low-loss winding and several axial heating zones has come to be regarded as the state of the art. (**Figure 2.43**) As a rule, however, due to the limited throughput with the single-billet furnace, there are several furnaces – usually 2 to 3 – arranged in parallel. (**Figure 2.44**)

The disadvantage of this type of plant, however, is that the rate of throughput drops as the length of billet decreases, owing to the power density distribution. However there are means of remedying this using so-called booster modules, which basically just means that the inverter can be operated at a higher capacity. Here, an electronic switchgear unit is used to increase the power density as the length of the billet decreases, in order to improve the throughput with shorter billet lengths. Of course, one must bear in mind that the maximum possible power density in the inductor coil winding limits the rate of throughput.

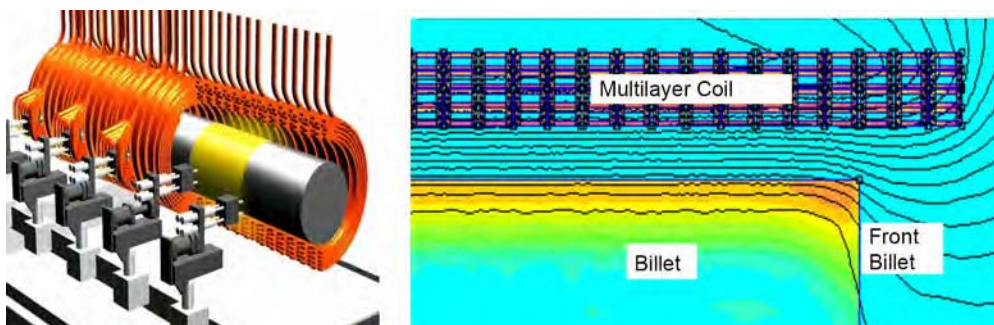


Figure 2.43: Multi-layer winding and a power density distribution in the front zone of 540 kW/m²
(Source: IAS GmbH)



Figure 2.44: Two parallel single-billet induction furnaces with individually controllable heating sections, with a total capacity of 2x1,500 kW and billet dimensions of D 545 x 1,800 mm (Source: IAS GmbH)



Figure 2.45: Example of a copper billet heating plant with gas pre-heating and two downstream single-billet induction furnaces (Source: IAS GmbH)

Multi-billet furnace

Another solution is a “long induction furnace”, with an integrated taper zone. This furnace corresponds in essence to the induction furnace that was used in the past and functions as a pusher-type furnace. By integrating several heating zones that can be controlled independently of one another into the outlet zone, there is also the possibility of applying an axial temperature profile to the billet. Pre-sawn billets are required to make use of this solution. A system that works in conjunction with a downstream hot shear is not usually practicable due to the necessarily higher non-productive times involved. In terms of the heating process there are two different principles of operation:

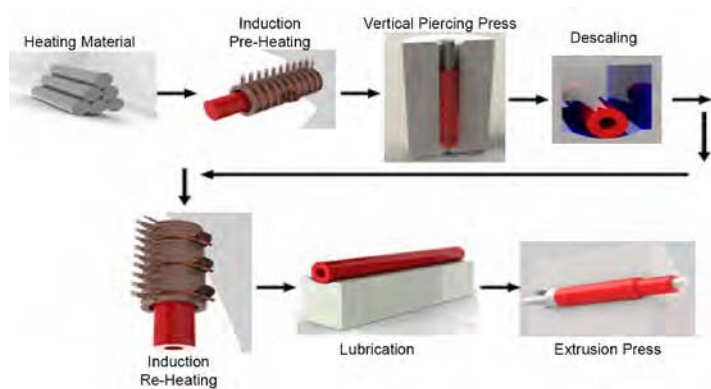
- Continuous cycle mode with a short stroke in conjunction with a downstream resistance-heated equalizing chamber
- Continuous cycle mode with one billet length each, whereby a variable stroke and precise billet tracking are required.

This furnace design has some limitations with regard to process control, e.g. with different alloys and longer stoppages due to the production technology, and it is for this reason that the design is no longer in widespread use, particularly in the aluminium industry. With the induction heating of special steel, this furnace design still plays a significant role, as the batch sizes are usually larger here.

Induction billet heating plants for copper extrusion applications

In the case of copper extrusion, very high throughput levels are normally required, and with a solution based solely on induction this results in very high connected power loads. At the same time brass and copper nickel alloys have relatively poor thermal conductivity values, which has an adverse effect on cost-efficient solutions based solely on induction, since long through-heating times are required with low power applications. The gas-fired furnace has found widespread use throughout the extrusion industry for heating copper alloys. The use of induction single-billet furnaces as re-heating systems is, in the meantime, becoming more widespread at least. (**Figure 2.45**)

Figure 2.46: Process chain for manufacturing special steel tubes using the extrusion method



This can be attributed on the one hand to the higher flexibility offered and, on the other hand, to the longer heating billets, to which an axial temperature gradient is applied for longer press cycles for special brass. Using downstream induction single-billet furnaces, however, also compensates for any process-related disadvantages associated with gas furnaces.

These include the relatively high process temperatures that cause the gas furnace to wear considerably as well as scale to form on the starting material during prolonged holding periods in the gas furnaces, which can only be reduced by costly protective gas equipment.

Induction billet heating plants for steel extrusion applications

In the case of complex special steels, the extrusion temperature range remains within a very narrow temperature range, which is why the induction furnace is the preferred choice in spite of the higher energy costs. The lower energy costs associated with gas heating are primarily of significance in cases where the alloys are rarely changed. In recent years useful combinations of both heating concepts have been implemented here, whereby in the case of modern induction furnaces in particular, the level of operating efficiency has been improved through the implementation of appropriate measures. Its primary application is for seamlessly extruded tubes and special sections. **Figure 2.46** shows a process chain for manufacturing special steel tubes using the extrusion method [2.5].

The following heating concepts are implemented by a wide variety of users in the industry:

- Horizontal basic induction heating with vertical final induction heating (induction pre-heating is shown in **Figure 2.47** below)
- Gas-fired rotary-hearth furnaces with reduced atmosphere and vertical induction re-heating
- With smaller billet dimensions of up to 180 m and when operating without a piercing press, horizontal induction pre-heating systems are used for higher throughput levels (**Figure 2.48**)
- Gas pre-heating up to around 700°C as well as vertical inductive intermediate heating and re-heating in single-billet furnaces. **Figure 2.49** shows for a view of the plant upstream of the piercing press with subsequent final heating.

Once basic heating, in which the billets are heated to a temperature of approx. 950 – 1100°C, has been performed, the billet is fed into a vertical piercing press. There it is expanded to a set diameter. During this forming process and subsequent onward transportation, the billet cools down in part and has an extremely inconsistent temperature profile before entering the re-heating station. A



Figure 2.47 : Horizontal induction billet heating with an installed capacity of 2 x 3,600 kW (Source: IAS GmbH)



Figure 2.48: Horizontal induction heating plant with 6 individual zones with an installed capacity of 3,300 kW (Source: IAS GmbH)



Figure 2.49: Intermediate heating for piercing press (used only in tube production) and vertical final heating (Source: IAS GmbH)



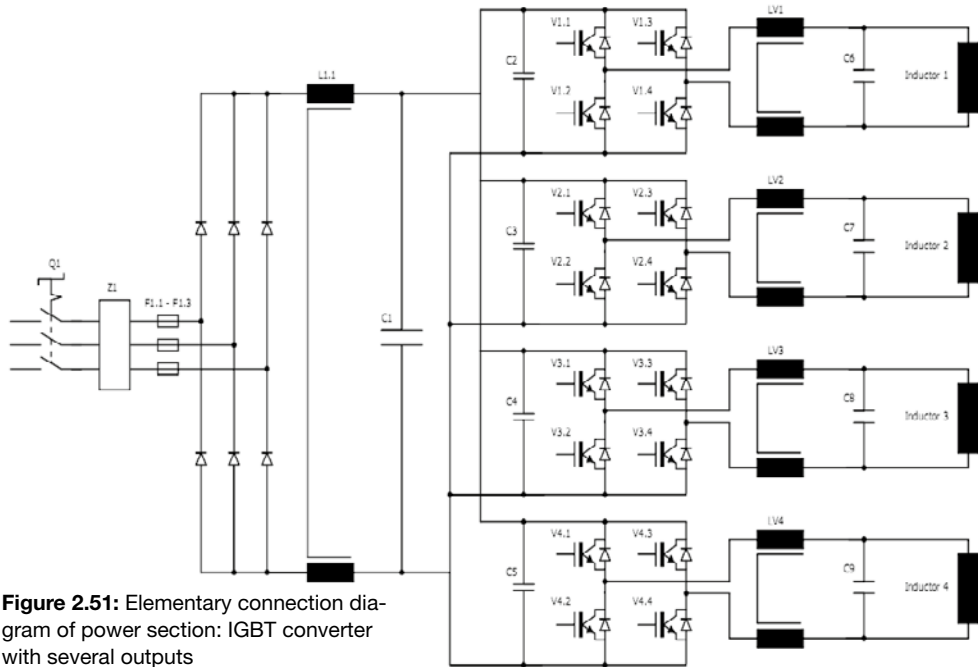
Figure 2.50: Heated billet of D 280 mm x 1,100 downstream of the piercing press, showing the temperature profile (Source: IAS GmbH)

billet with a typical temperature profile such as this is shown in **Figure 2.50**; it is characterized by significant temperature losses of around 300 °C on the surface as well as the front and end faces.

In order to correct this temperature profile, which cannot be used for the subsequent process, and raise the process temperature back up to 1,200 – 1,300 °C, the system of induction re-heating plays a crucial role within the overall process.

One of the most significant developments within this field is based on the partial heating of the billets in the vertical final heating process. By dividing the coils into several subzones which are laid out in an axial arrangement and can be activated separately, it is possible to meet the requirements of the process, whereby the billet is specifically heated in various zones without causing local over-heating of the material (**Figure 2.51**, **Figure 2.52**).

To minimize the adverse impact of heat dissipation and completely avoid the negative influence of the guide rails on the temperature distribution in the billet within a horizontal heating line, the billet is turned 90° and so brought from a horizontal position into a vertical position during the steel



2

Figure 2.51: Elementary connection diagram of power section: IGBT converter with several outputs

heating process. The billet may have various lengths. To ensure defined positioning of the billet in the coil, a counterhold is installed above. Using a special device, the billets are turned and moved into the multi-zone coil in a defined manner until the top set position is reached.

For this type of application, the coils each comprise electrically isolated and individually controllable single coils with a maximum capacity of 250 kW. The maximum possible useful length of the



Figure 2.52: ITN-3 converter with 4 outputs
(Source: IAS GmbH)



Figure 2.53: Re-heating plant with 3 individual coils and 4 control zones each
(Source: IAS GmbH)

entire coil is based on the starting material length and may be up to around 1,500 mm. In order to be able to heat shorter billets, too, while safeguarding the reliability of the process, specially-developed, uncooled field distributors are used at the push-in unit. Owing to the high specific resistance of the starting material, longer coil projections are required to ensure homogeneous heating of the billet ends, too. (**Figure 2.53**)

By using low-loss, multi-layer coils, which guarantee high operating efficiency levels, it is possible to achieve low operating costs and improved temperature control at the same time, in conjunction with a wear-resistant switchgear unit.

Electrical efficiency levels of up to 81% can be attained depending on the configuration and starting material [2.6].

Induction billet heating plants for special applications in extrusion plants

This field covers special applications for heating billets made from titanium, zirconium and molybdenum alloys (**Figure 2.54**). The materials are used in the aerospace industry (titanium alloys), as shroud pipes for nuclear fuel rods (zirconium alloys) in the field of power engineering, as well as for special industrial applications. All the materials mentioned are characterized by high their reactivity with atmospheric oxygen, which is why the induction furnace is a particularly effective system, given the rapid heating capacity.

The process temperatures for zirconium are around 700 °C, for titanium alloys around 1,100°C and for molybdenum alloys around 1,300°C. As a rule, single-billet furnaces with corresponding variable length adjustment systems are used here.

Particularly high electrical efficiency levels can be attained here as a result of the high specific resistance of the starting material. Levels of up to 83 % can even be attained for titanium alloys when using the multi-layer coil design. The conductor layout of the coil winding has a significant influence on the cost efficiency of the system.

Summary:

Due to the high system capability and low floor space requirements, modern induction billet heating plants in extrusion press lines are an important part of the process chain. They are capable of meeting all relevant requirements in terms of precise and above all reproducible temperature control, while being extremely flexible at the same time.



Figure 2.54: Vertical heating of titanium on a 3,500 t extrusion press line (Source: IAS GmbH)

2.5 Thixoforming

Thomas Gräf

2.5.1 Process fundamentals

The technology of thixoforming describes a technological forming process in which an alloy respectively a binary system is transformed from the “solid” into the “liquid” condition. This happens with the aid of mechanical stress without changing the portions of the solid and the liquid phase. The viscosity is decreasing under the action of shearing-strain and -speed but the initial value is recovered reversibly if the strain is disappearing. A further feature is the microstructure, which is characterised by globulitic components in a liquid matrix. The resulting forming-properties of the semi-solid respectively the semi-liquid metal alloys are significantly different from the forming-properties of metals in the solid or the liquid condition.

Different methods with distinct process steps have been developed for the technological area of thixoforming. Some of them are utilizing the energy, which is contained in the melt for the formation of nuclei for the crystallization of an alloy with thixotropic properties. Other methods are based on appropriate special semi-finished blank material usually in the form of continuously cast round strand sections which are heated from the solid to the semi-solid condition. To start with thixocasting – the most widely spread application – the basic process steps are: the production of appropriate alloys with thixotropic properties, well defined and process-proof reheating to the solid-liquid-interval and the adequate mode of thixoforming.

High demands for the heating- and the cooling-process of the semi-finished slugs – usually cut strands from continuous castings – have to meet with high precision of the heating operation and the temperature control due to the very small process-window. **Figure 2.55** shows the binary phase diagram for the alloys AlSi7Mg as well as for AlMgSi1 where the ranges of temperature are given. Within this area these alloys are formed under thixotropic condition. It is also necessary for that purpose to exactly observe the course of the temperature [2.7].

The alloy-related temperature intervals for the processing of the individual alloy can certainly be seen from the binary phase diagram in Figure 2.55, but it does not indicate the requirements for the quality of the heating technology securing the process.

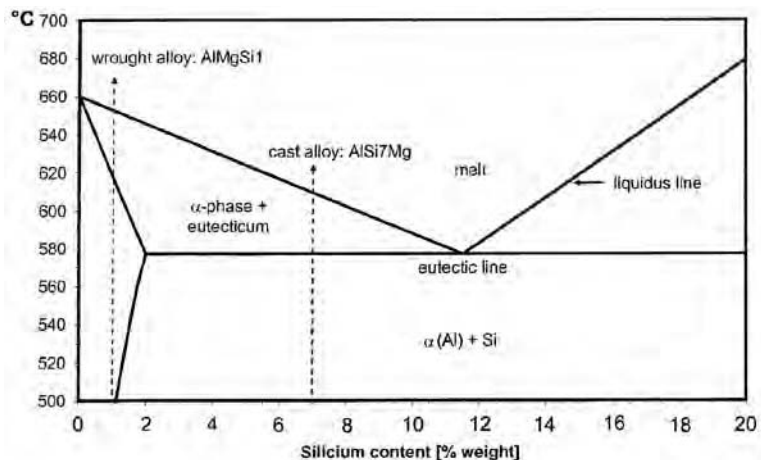


Figure 2.55: Binary phase diagram Al-Si

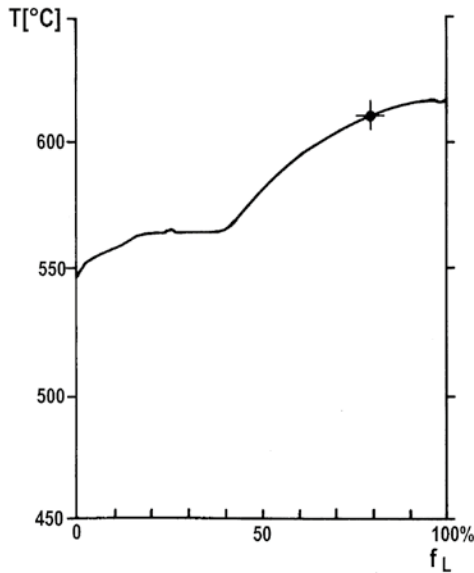


Figure 2.56: Solid portion versus temperature for the alloy AlSi7 [2.8]

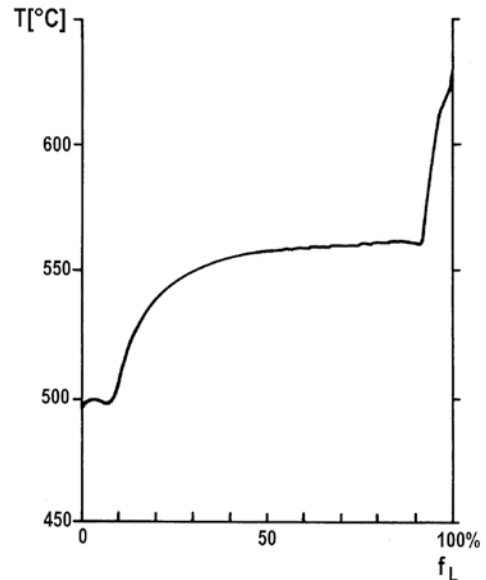


Figure 2.57: Solid portion versus temperature for the alloy AlSi2 [2.8]

Figure 2.56 shows an increasing liquid portion for the AlSi7-alloy beginning from 550 °C which then rises permanently. A small temperature variation at 565 °C however, affects a large increase of the liquid portion of the alloy AlSi1 (**Figure 2.57**) [2.8]. The Figures 2.56 and 2.57 are therefore clearly demonstrating that – depending on the individual alloy – temperature variations can result in different solid respectively liquid portions. **Table 2.7** lists the variation of the liquid portion versus the temperature variation $\sim T$ for the two different alloys.

It can be derived from table 2.7 that the heating of a thixotropic-capable alloy in the form of a round slug must lead to a very uniform temperature distribution across the diameter as well as along the axis. A non-uniform temperature distribution causes different liquid phase portions which would have direct consequences for the quality of the forming and on the piece parts.

A significantly decreased heating time can be achieved by induction heating in comparison to the use of convection furnaces with large heating times. The energy transfer by the use of convection furnaces depends on the temperature difference between the slug surface and the surrounding atmosphere whereas at induction heating the heat sources are located inside the material. Induction heating application is characterized by several sections in the course of the heating. The solid

Alloy	Range of temperature	Liquid portion percentage in the related temperature range	Liquid phase variation per 1 K temperature variation
AlSi7	574-584 °C	43-51 %	0.8 %
AlSi1	635-645 °C	15-35 %	2 %

Table 2.7: Variation of liquid phase portions of alloys depending on temperature variation

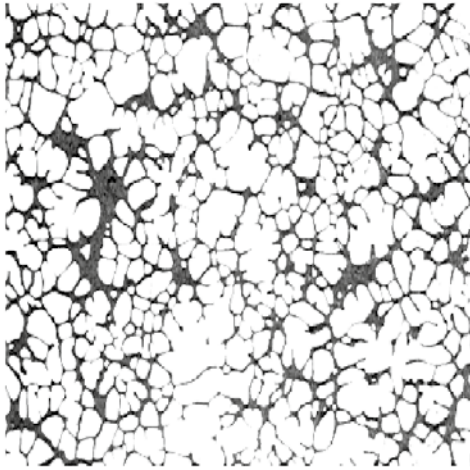


Figure 2.58: Microstructure of the alloy AlSiMg0,3 in the die cast condition

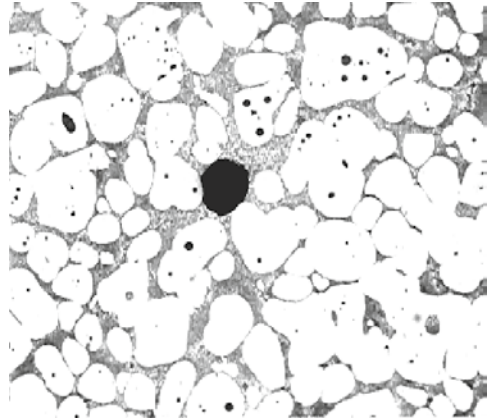


Figure 2.59: Microstructure of the alloy AlSiMg0,3 after reheating

material is first heated as quickly as possible to the solidus temperature as possible (phase 1). Additionally, the temperature is increased to that extent only that no unnecessary melting occurs at the surface but a uniform through heating by heat conduction is achieved nevertheless (phase 2).

The third heating phase does at last provide a sufficient time and energy for the metallurgical processes and for the formation of a homogeneous globulitic microstructure. The heating time is some minutes, depending on the diameter of the heated material and of the kind of alloy.

Figure 2.58 presents the picture of the microstructure of the cast alloy A 356 in the as cast condition. **Figure 2.59** shows the microstructure after reheating to the thixotropic condition and consequent cold water quenching. Both pictures clearly demonstrate the different formations of the microstructure, which in turn are influencing the mechanical properties of the produced piece parts.

Table 2.3 already illustrate before, that a uniform heating and heat treatment of the material is necessary in order to avoid inhomogeneous liquid-solid-ports. Therefore, precautions for the balance of the magnetic field at the front faces of the heated billets in the design of the equipment are necessary for induction heating application. One of the possibilities is a particular coil-turn design matching the eventual inhomogeneous field compensation.

However, this variant has the disadvantage of a special individual coil winding which is needed for almost each slug modification. Another method is the artificial “prolongation of the heated material” by placing field-guiding elements next to its frontfaces (**Figure 2.60**). These field-guiding elements are effecting a homogenisation of the magnetic field around the heated material thus avoiding frontal superheating or melting [2.9]. For slugs in upright position, inhomogeneous field distribution is leading to melting effects at the front-faces during induction heating which are causing unequal mass distribution under the influence of gravity, amplifying the effect of the inhomogeneous field. This unequal mass distribution along the heated slugs at forming temperature ends up in a changing material diameter. It is also known under the term “elephant-foot”.

Contrary to this method, heating of the slugs in horizontal position has increasingly prevailed in Europe during recent years. This does additionally offer the possibility for the increase of the liquid

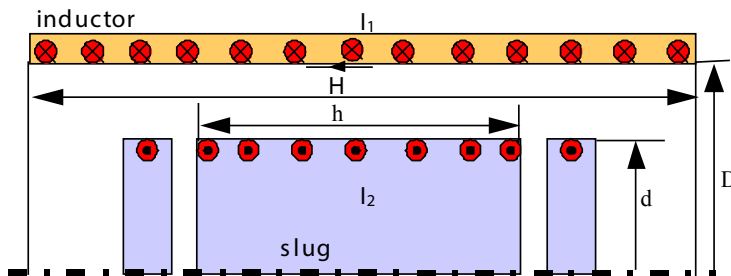


Figure 2.60: Principal arrangement of induction heating of a slug in horizontal position

phase portion in the workpiece if compared to heating in the upright position with the consequence of a positive effect on the consequent forming process in most cases.

2.5.2 Parameters for induction heating

Impacts on the heating process can be subdivided into values related a) to the blank material and b) to the heating installation, see **Table 2.8**.

2.5.3 Quality securing criteria for heating to thixotropic condition

Quality securing criteria are indispensable for the heating of alloys to the thixotropic condition. At the presence of characteristic variations, the parameters given in **Table 2.9** are leading at last also to variations of the solid-/liquid-proportion of the heated slug respectively to temperature variations from slug to slug. They must therefore be limited to aluminium, which can be executed technically and tolerated economically. The objective judgement of heating installations, of the quality of heating, of the process-reliability and finally of the economy is enabled by uniform quality securing criteria. **Table 2.10** gives a heating to thixotropic condition survey of criteria for heating of slugs to thixotropic condition and it can be used for the judgement of the process-capability of thixo-forming [2.9].

Method	Brief description with process steps
New rheocasting method	Dosing from a holding furnace, controlled cooling, temperature equalizing with reheating, dosing of semi-solid alloy for consequent forming
Single slug-method	Production of a semi-solid quantity of alloy corresponding to the piece part volume which is directly manufactured by controlled cooling from the liquid-area condition of a melt, heating for consequent forming
Thixocasting	Production of a blank material with thixotropic properties in the heated condition, heating, forming with a pressure die casting machine
Thixoforging	Production of a blank material with thixotropic properties in the heated condition, heating, forming with a press
Thixomoulding	Production of granulates of an alloy with thixotropic properties in the heated condition, forming with an injection moulding machine

Table 2.8: Semi-solid forming methods

Parameters related to the blank material	Parameters related to the heating plant
Geometrical- or weight tolerances	Geometrical data of inductor
Chemical composition	Position of slug
Physical material properties	Operating frequency
Solidification- and skin-microstructure	Precision of measurement data recording and control
Temperature of blank material	Environmental conditions
	Graph of heating power versus time

Table 2.9: Parameters of induction heating

2.5.4 Executed plant concepts for thixoforming

Turntable heating machines (Figure 2.61) with upright slug position and open-loop control which were developed in the past have been proven to be too inaccurate and too susceptible to failures due to its design, due to the occurring deformations during the heating process and due to the interlinked process management at the heating of individual slugs. The closed-loop process-control has principally prevailed upon the open-loop control for thixoforming.

Using the heating method with closed-loop control, a sensor is generating an actuating signal Y for an adjustable energy source, which usually is a frequency converter. An inductor coil does create a magnetic field that transfers energy into the slug while the control equipment is effecting a control deviation X-W close to zero. Either a metering signal proportional to the field (where the field variation is proportional to the constitutional change (field metering sensor) [2.10]) is used for this purpose, or the energy conversion inside the slug is determined [2.11, 2.12, 2.7]. Following the latest development, both methods are including the destination of a master curve, which is guiding the heating process of the slug with exact repeatability.

Quality securing criteria for heating to thixotropic condition
Drop-off losses
Uniformity
Softness
Slug deformation
Liquid portion percentage
Energy content of slug
Microstructure
Grain size
Grain shape factor
Included eutectic
Molten primary silicium
Deviation from set heating values

Table 2.10: Quality securing criteria for heating to thixotropic condition



Figure 2.61: Turntable heating machine

The control of the heating process and the generation of thermal energy inside the heated material can be achieved by the use of different controlled variables and sensor signals. The converter output voltage, the converter output current, the oscillating circuit current, the frequency as well as a constitutional change describing sensor signal or the course of the energy of the real power over the time, which is generated within the slug, can serve as controlled variables.

2.5.5 Process control of induction heating for thixoforming

Figure 2.62 shows the distribution of the set value for the energy as well as the induced energy within the slug. Within the heating cycle at constant time intervals a new energy set value is calculated and has to be achieved at the end of the heating time interval. If the set value for the induced energy will not be reached an alarm signal will be generated and the heated slug will not be used for the forming process.

The determination of the induced energy within the slug is a result of an integrative value, which cannot describe the heating process under the aspect of quality assurance criteria. Additional

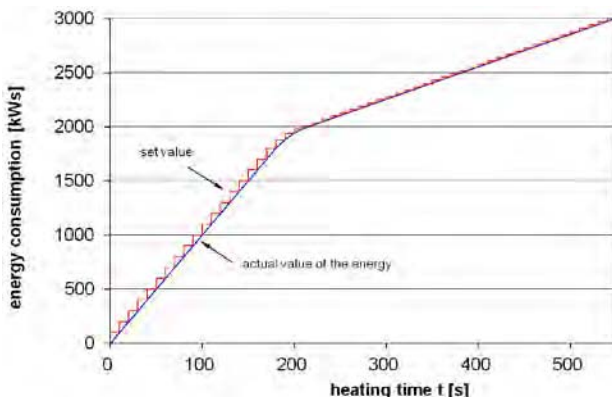
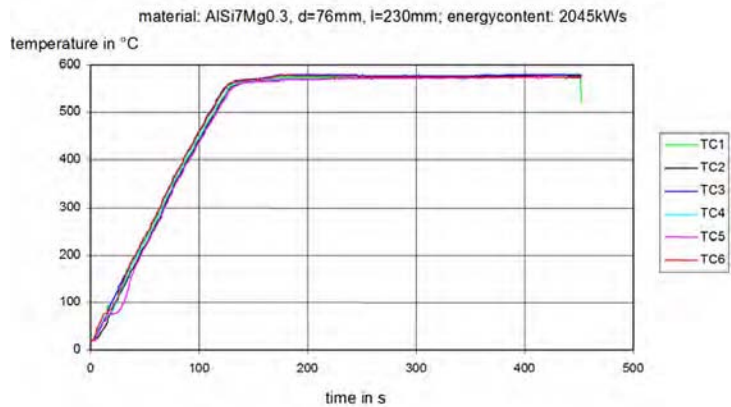


Figure 2.62: Energy control with master curve and set value

Figure 2.63: Measured temperature curves at different points around the circumference to the heated slug



important process describing parameters are measured like the inverter output voltage, the inverter output current and the resonant circuit current. At the end of the heating time interval the induced energy has to be achieved. For this purpose the gradient of the inverter voltage and current as well as the current of the resonant circuit are controlled.

Figure 2.63 shows the temperature distribution around the circumference of a heated slug. The temperature curve can be divided into an area up to $t = 130$ s when the surface of the slug will be heat up to the semi-solid-temperature, and an area when the growth and the forming of the grain homogenize until $t = 450$ s.

If process disturbances occur and the forming process stops, the heating process can be enlarged by holding the temperature at a constant level. This time interval of constant temperature can be used for short production discontinuity without the loss of an already heated slug. Investigations showed that a holding time of 12 minutes was possible without a negative influence to the grain structure or the mechanical properties of the final product [2.9, 2.11]. The temperature distribution of the different measuring points shows only a deviation of 2 K. The shown principle of the controlled energy for each workpiece linked with parameters of the ambient conditions allows a very high precision and the repeatable heating process and can be called process secured [2.13].

For the evaluation of the cost effectiveness of the thixoforming technology the material throughput, the needed invest for machines, qualified staff as well as services and maintenance need to be considered. The material throughput for an induction heating machine can be estimated by the station times of the following forming process. The production of thixoforming parts according the thixocasting process with die casting machines takes place within 30 s up to 75 s. Due to heating times of several minutes for slugs depending on the diameter, alloy and the length a couple of heating stations will be needed. These heating stations produce finally heated slugs according the cycle time of the die casting machine. Fully automated thixoforming production lines consists of a bar handling magazine, automatic saw, robot for shell handling, several induction heating furnace, die casting machine and a control centre for process and production control.

For the future it can be expected to find solutions for thixoforming for steel parts. The high temperatures will be a challenge for the temperature handling and process control as well for the machining tools, but this needs to be handled.

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3. Heat treatment

3. Heat treatment

3.1 Introduction

Wolfgang Bleck

According to the definition of DIN EN 10052 [3.1], heat treatment is “a process, in the course of which a workpiece or a section of a workpiece is purposely exposed to one or more temperature-time cycles and, if necessary, other additional physical or chemical influences in order to bring about the desired characteristics of processing and/or use.” According to the nature of the influences, the heat treatment processes can be divided into thermal, thermo-chemical and thermo-mechanical processes, **Figure 3.1**.

Among the thermal processes, annealing, hardening and tempering treatments are often differentiated. Annealing is generally concerned with influencing the microstructure in order to improve the processing qualities, such as machinability or cold formability. Hardening and tempering are primarily used to optimize the end-usage properties, such as hardness, toughness or wear resistance. A change in material properties is generally obtained by means of the following processes:

- Change in the size, shape and orientation of microstructural components (e.g. coarse grain annealing, soft annealing)
- Reduction of internal stress and change of its distribution (e.g. stress-relief annealing, tempering)
- Transformation of microstructural components whereby a state of equilibrium may be obtained or may be not obtained (e.g. normalising, hardening).

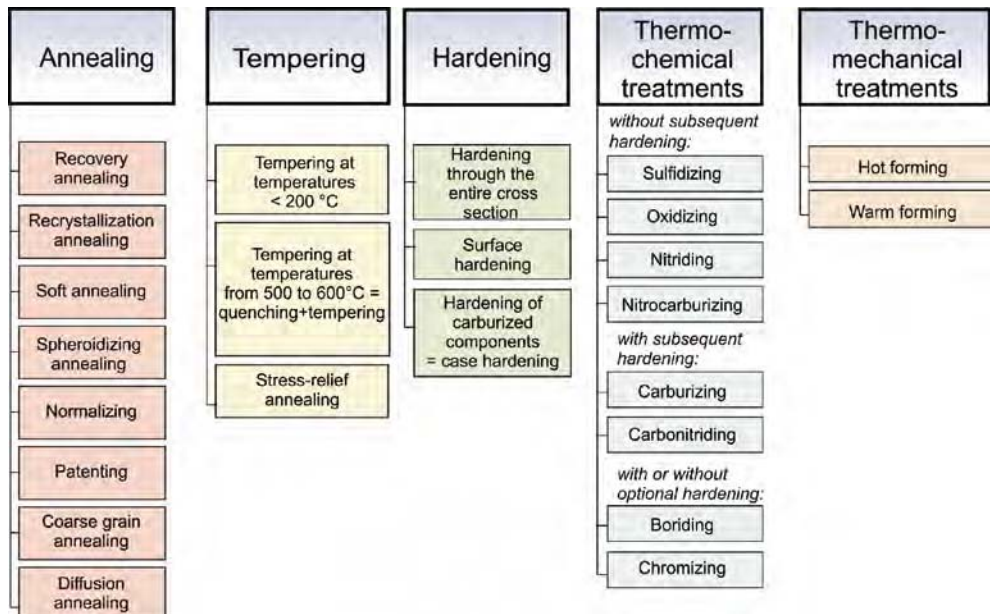
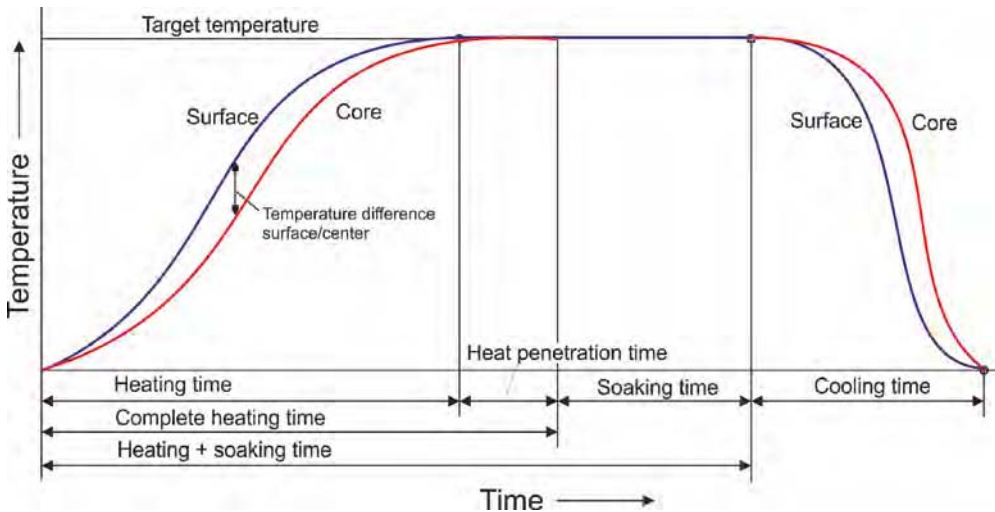


Figure 3.1: Important processes for the heat treatment of steel [3.2]



3

Figure 3.2: Temperature-time diagram of a heat treatment with characteristic parameters [3.3]

Every heat treatment consists of the following individual processes: heating to a target temperature, maintaining the temperature over the entire cross-section for a certain amount of time (holding) and cooling from the target temperature, **Figure 3.2**. Therefore, the course of a heat treatment can be represented in the form of a temperature-time diagram.

It is important to consider that not only the properties of the material, but also the size and shape of the workpiece and the duration of the individual processes have an influence on the selection of a heat treatment.

3.2 Hardening

3.2.1 Material aspects of surface hardening

Hansjürg Stiele

Hardening – a definition

The aim of hardening is that of producing a martensitic material state, since this state is characterized by greater hardness. As defined in DIN EN 10052 [3.1], hardening also includes states in which small amounts of bainite occur in the microstructure in addition to Martensite, since transformation solely to Martensite is not always possible, depending on the particular steel and the circumstances of hardening.

The steel microstructure

Iron has a crystalline structure, i.e., the spatial arrangement of every atom is precisely defined. The crystal system of iron is cubic. A cubic body-centered (bcc) or a cubic face-centered (fcc) lattice is present, depending on temperature (see **Figure 3.3**).

Cubic body-centered iron is referred to as α -iron. This exists in the temperature range between room temperature and 911 °C. The cubic face-centered lattice of γ -iron occurs at higher temperatures up to 1,392 °C as a result of the rearrangement of the iron atoms. A cubic body-centered δ -iron is again present at temperatures above 1,392 °C.

The ferrous materials steel, cast iron and sintered steel used technologically are alloys. In these metals, foreign atoms are incorporated, or are dissolved, either in place of an iron atom (substitutional) or in the interstices in the lattice (interstitial) (**Figure 3.4**).

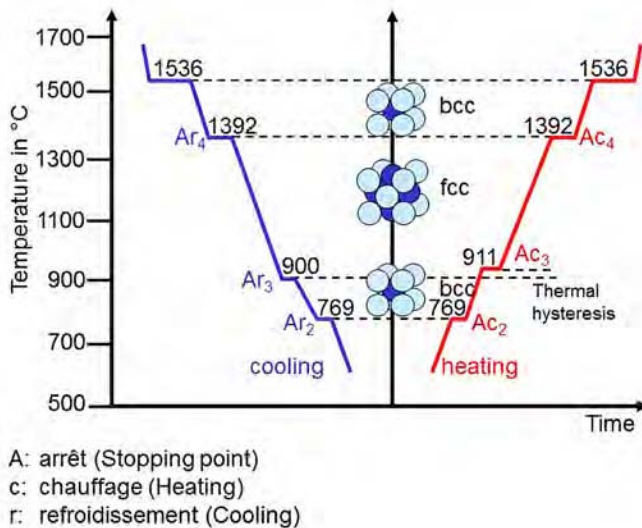


Figure 3.3: Transformation points and crystal structures of pure iron during cooling (curve at left) and heating (curve at right)

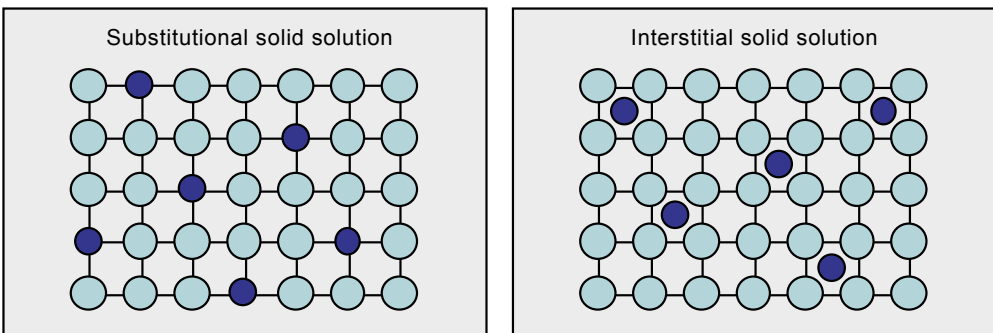


Figure 3.4: Possible alloy types (foreign atoms shown in blue)

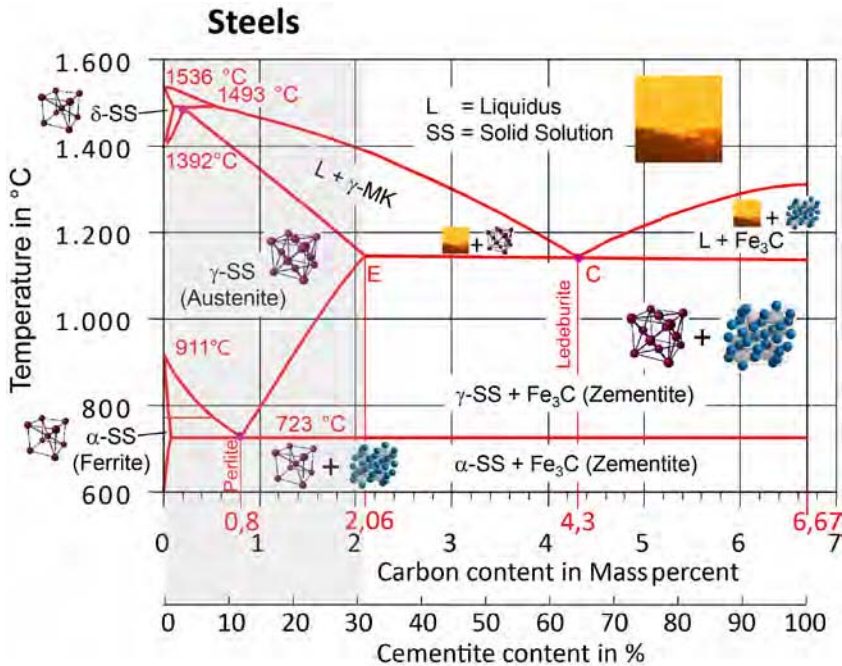


Figure 3.5: Metastable Fe-Fe₃C diagram

The pure iron crystal is thus transformed into a solid solution (SS).

Substitutional solid solutions occur in cases in which the foreign atoms are of a size similar to that of the iron atoms. This is true, for example, in the case of the elements chromium, molybdenum, vanadium, tungsten, and other metals. Foreign atoms smaller than the iron atoms, such as carbon, nitrogen and hydrogen, on the other hand, are incorporated interstitially, for which reason the term “interstitial solid solution” is used here. Carbon and nitrogen, in particular, also form compounds with the iron and the metal alloying elements (carbide-forming elements, nitride-forming elements).

The incorporation of carbon atoms into interstitial lattice sites transforms the cubic body-centered α -iron into an α solid solution (α -SS), called “Ferrite”. A maximum of 0.02 mass-% of carbon is soluble in this substance at 723 °C, and nearly non at room temperature. The incorporation of carbon generates from the cubic face-centered γ -iron a γ -solid solution (γ -SS) which is called “Austenite”. In an unalloyed steel, 0.80 mass-% of carbon can be dissolved in this at 723 °C, and a maximum of 2.06 mass-% of carbon at 1,147 °C. The result if the amount of carbon present in each case is greater is iron carbide – Fe₃C, also known as **Cementite** – containing 6.67 mass-% of carbon. Carbides are also generated with other metallic alloying elements. The crystal structure is then no longer cubic, but exhibits instead significantly more complex structures.

A mixture of Ferrite and Cementite lamellae is known as Pearlite. This designation derives from the shimmering mother-of-pearl-like appearance of this substance under the light microscope.

The existence ranges of the various iron/carbon solid solutions and of Cementite are described as a function of carbon content and temperature using the metastable Fe-Fe₃C diagram shown in **Figure 3.5**. Iron/carbon alloys are referred to as steel up to a carbon content of 2.06 mass-%, while alloys containing 2.06 to 6.67 mass-% of carbon are known as cast iron.

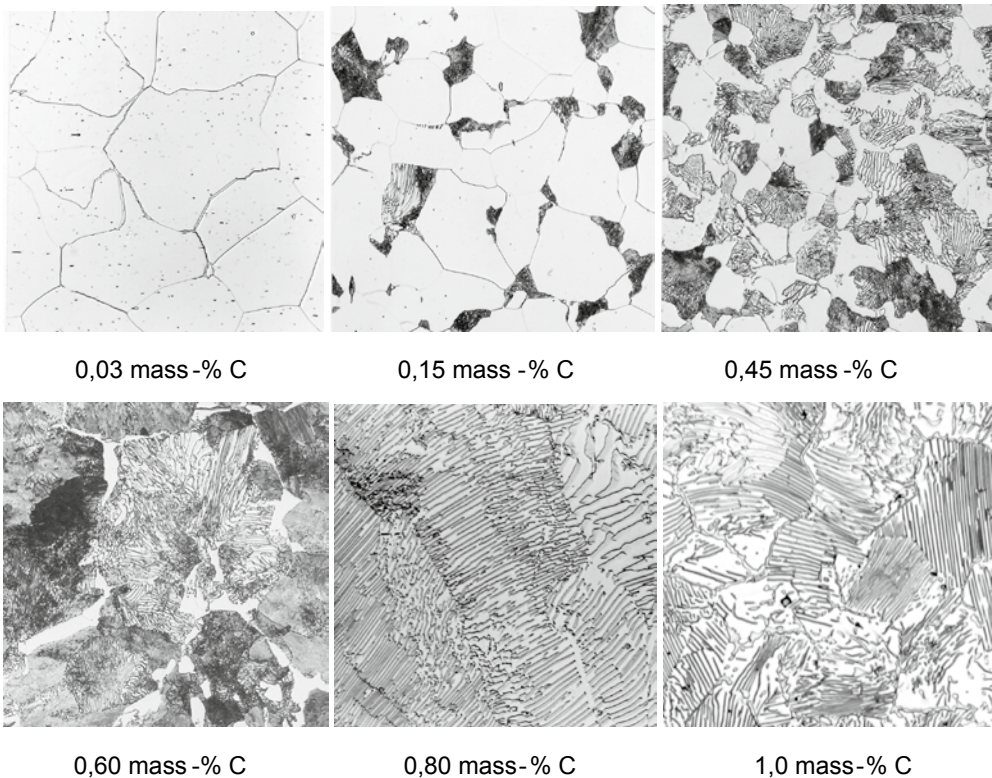


Figure 3.6: Normalized microstructure of steels with various carbon contents by mass

Attention is drawn at this point to the relevant literature for a detailed description of the Fe-Fe₃C diagram and the associated transformation processes.

The quantity of carbon present in a steel determines the composition and thus also the appearance of the microstructure. As can be seen in **Figure 3.6**, Pearlite content increases, and Ferrite content decreases, as carbon content rises.

The diversity of the iron lattice and the varied modes of alloy formation result in differing microstructures in ferrous materials and in the properties which depend on them, and open up possibilities of systematically modifying these by means of heat treatment.

Austenitizing

The microstructural state of a steel changes when it is heated. Above a temperature of 723°C, the Cementite degrades, and the cubic body-centered Ferrite becomes cubic face-centered Austenite. The carbon liberated by the degradation of the Cementite is dissolved in the Austenite. During further heating, and during pauses in heating, **Austenite, in which the carbon is more or less homogeneously distributed**, is gradually formed from the entirety of the Ferrite. In hypereutectoid steels, i.e., those with a carbon content of more than 0.8 mass-%, with an initial microstructure consisting of Pearlite and primary Carbides, the transformation begins with dissolution of the pearlite and

concludes with the disintegration of the somewhat more stable carbides. Heating and holding at a temperature for transformation of the microstructure to Austenite is known as austenitizing.

Where a process of Austenite formation determined by diffusion is taken as the starting point, this process can be subdivided into the following sub-processes:

- Nucleation
- Nucleus growth
- Carbon homogenization
- (Possibly) grain growth

It is necessary, in this context, to differentiate between the processes applicable to hypo- and hypereutectoid steels.

It should be noted here that unalloyed steels are, in technology, in fact multicomponent alloys on the basis of the iron/cementite system. In addition to iron and carbon, these contain elements such as, for example, manganese, chromium, silicon, nickel, etc.. These elements make it possible to impart a specific transformation behavior and, on the basis of this, the desired microstructure features and materials properties. In multicomponent systems, which include these unalloyed steels, this results in the fact that the A_{c1} line for the transformation α -SS (Ferrite) + M_3C (Pearlite) to γ -SS (Austenite) known from the Fe-Fe₃C binary system is divided into the A_{c1b} (start of transformation) and A_{c1e} (end of transformation) lines. Between these there is a three-phase region of the following composition: α -SS + γ -SS + M_3C (Ferrite + Austenite + metal carbide / Cementite). This is shown schematically in **Figure 3.7**.

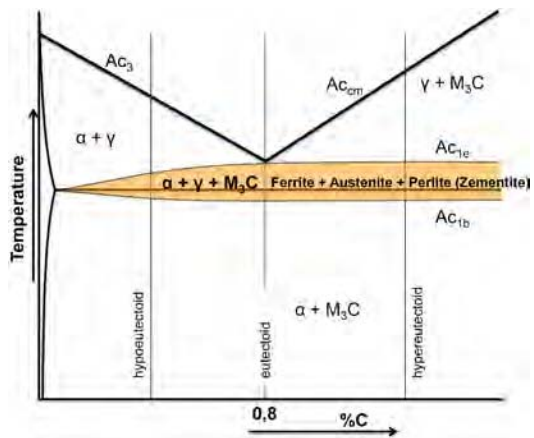


Figure 3.7: Excerpt from the Fe-M-C (M = Metal) ternary system [3.4]

Nucleation

The nucleation of hypoeutectoid steels begins when the A_{c1b} transformation temperature is exceeded (see Figure 3.7). The incubation time, i.e., the time required for the generation of nuclei, depends definitively on superheat temperature. The superheat temperature is the temperature needed for Austenite formation and is located above the equilibrium temperature known from the metastable Fe-Fe₃C diagram.

Formation of the Austenite nucleus occurs in this context on the boundary surface of iron carbide (Cementite) and Ferrite, i.e., in the Pearlite. The Carbides, as “carbon sources”, may be present in the initial microstructure either

- equiaxed (quenched+tempered, GKZ¹ annealed)
- lamellar (pearlite)

or in more or less shaped form [3.5].

The Austenite nucleus thereby contains more carbon than the original Ferrite. Nucleation occurs primarily on Ferrite grain boundaries and/or at triple points of Ferrite grains, and thus at discontinuities [3.7]. **Figure 3.8** shows nucleation in schematic form.

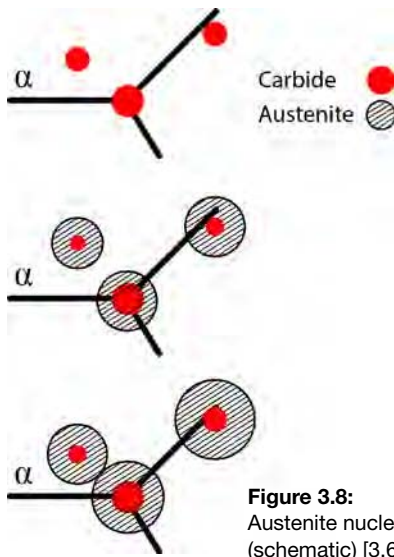


Figure 3.8:
Austenite nucleation
(schematic) [3.6]

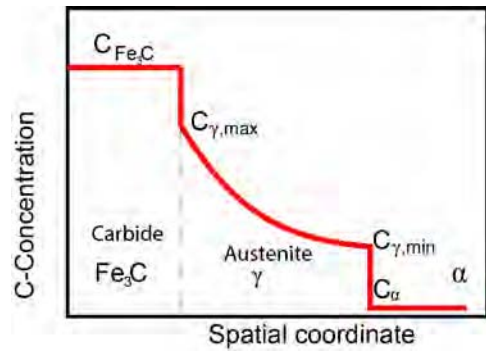


Figure 3.9: Carbon concentration at the Carbide/
Austenite phase boundary [3.5]

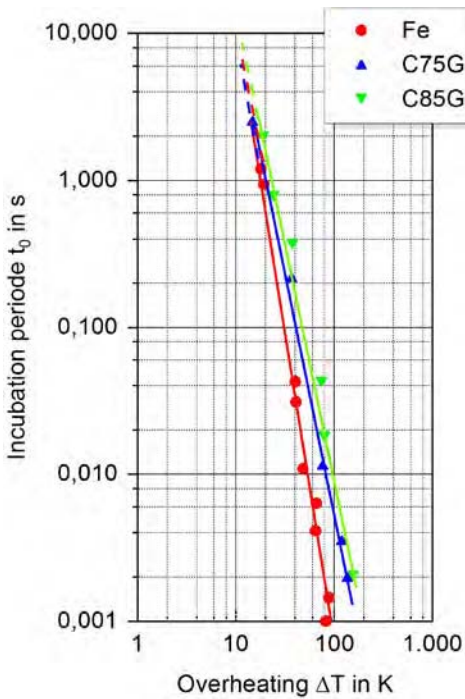


Figure 3.10: Incubation time as a function of
superheat [3.5]

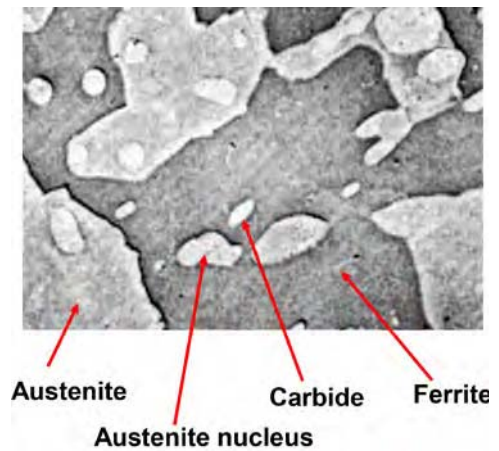


Figure 3.11: Nucleation at the Carbide/
Ferrite interface [3.8]

Austenite formation thus starts at the Ferrite/Carbide phase boundary, i.e., where diffusion paths are short. In a simplified model [3.7], the growth of the Austenite nuclei formed at the carbide/Ferrite ($\text{Fe}_3\text{C}/\alpha\text{-SS}$) boundary surface can be assumed as shown in **Figure 3.9** for conditions close to equilibrium and for spherical carbides. The carbon concentration (C content) is plotted here over the coordinate. In this model, the equilibrium concentration of carbon in the Austenite $c_{g,\max}$ stabilizes at the $\text{Fe}_3\text{C}/\alpha\text{-SS}$ phase boundary and the $c_{g,\min}$ concentration at the Austenite/Ferrite phase boundary.

As already noted, incubation time t_0 for nucleation is dependent on superheat ΔT . **Figure 3.10** shows incubation time t_0 as a function of superheat for electric heating. This illustration clearly shows that an increase in temperature by one power of ten shortens the incubation time by around four powers of ten.

This nucleation is apparent in the scanning-electron microscope image shown in **Figure 3.11**. The Austenite nucleus (light structured) forms at the boundary surface between carbide (light) and Ferrite (dark structured).

Nucleus growth and carbide dissolution

After completion of nucleation, austenitizing progresses via the growth of the nuclei into the surrounding Ferrite. **Figure 3.12** shows this growth for a hypereutectoid fully pearlitic C80 steel.

Figure 3.13 shows Austenite formation against time schematically. As already noted, at temperatures close to A_1 , nucleation can start even after short incubation times.

A steep rise, dominated by Austenite growth, occurs after the end of the incubation period. The curve for Austenite content becomes ever flatter at the end of the transformation time. The Austenite growth fronts meet. Austenite content remains largely constant in the A_3 (holding time) temperature range.

On the basis of the simplified model of the spheroidal carbides described above, “Austenite shells” form around the spheroidal carbides as transformation progresses. The reason for this can be found in the slow dissolution of the Carbides and in the retarded diffusion of carbon into the carbon-depleted zones of the Austenite just formed from the Ferrite. The Carbides dissolve in the Austenite and contribute to the continued supply of carbon.

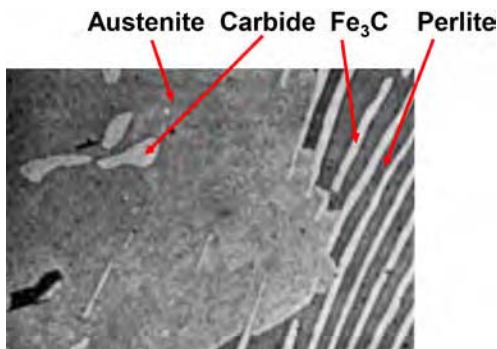


Figure 3.12: Austenite-in-Pearlite growth front (steel C80) [3.8]

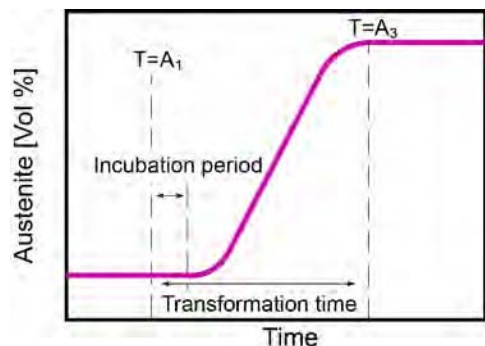


Figure 3.13: Austenite growth fronts [3.6]

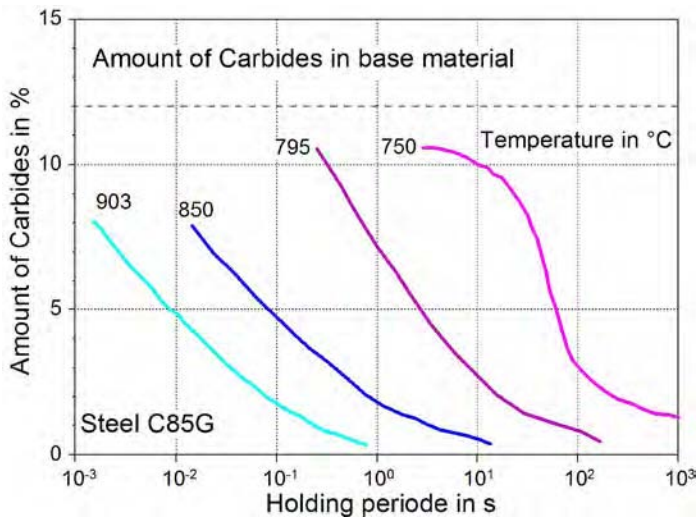


Figure 3.14: Isothermal Carbide dissolution [3.5]

Carbide dissolution, like nucleation, is highly temperature-dependent. An increase in temperature shortens carbide-dissolution time significantly. This correlation is shown for a C85G steel in **Figure 3.14**. In this steel, carbide content in the initial microstructure was around 11.5%. A temperature increase of approx. 150 K (from 750 to 903°C) shortens the holding time for complete carbide dissolution by approximately three powers of ten.

Ferrite dissolution, and thus nucleus growth, is completed when the growth fronts of adjacent Austenite grains meet.

Homogenization

Equalization of concentration and homogenization of the carbon occurs as a result of diffusion in the Austenite after complete dissolution of the carbides.

Changes in microstructure upon heating – The Time-Temperature-Austenitization (TTA) diagram

The processes described during heating to austenitizing temperature can be illustrated using time-temperature-austenitization (TTA) diagrams, as shown in **Figure 3.15**. Here, the existence ranges of the various microstructure states are shown as a function of time and temperature. Time is customarily plotted logarithmically on the abscissa, and temperature (from 700°C) linearly on the ordinate. The course of microstructure changes in case of heating can be tracked along the curves for the respective rate of heating. The heating curves shown on the right in Figure 3.15 represent slow heating, as is the case in furnaces. The curves on the left apply to surface hardening.

It can be seen from the TTA diagram for continuous heating that the start and end points of the transformation processes are dependent primarily on rate of heating. The faster the rate of heating, the higher the temperature at which transformation starts (A_{c1b}) and is completed (A_{c3}), and vice versa.

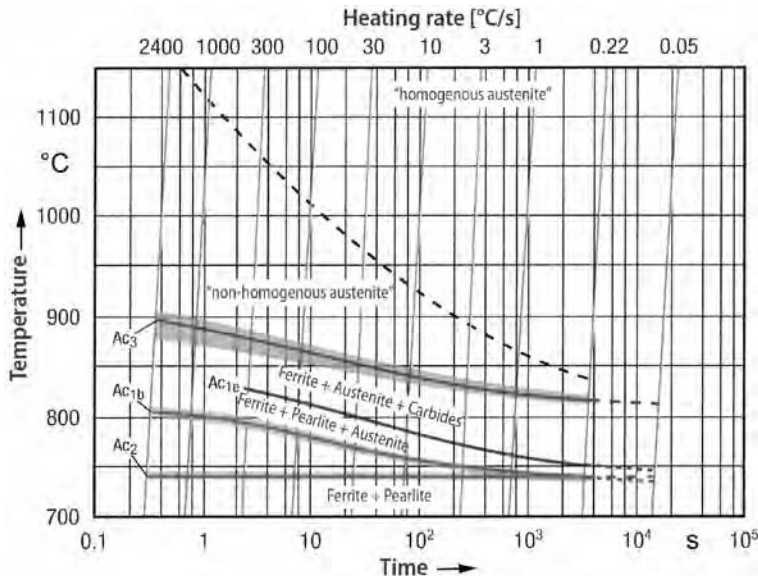


Figure 3.15: Time-temperature-austenitization (TTA) diagram for continuous heating of a 34CrMo4 steel [3.9]

The initial microstructural state also has an effect on the course of austenitization: the coarser the carbides, and the further they are spaced from one another, the higher the temperatures which must be reached in order to completely transform the initial microstructure to Austenite and distribute the carbon uniformly. In practice, complete dissolution of all carbides is not always expedient, however.

Austenitization can also be accomplished by means of isothermal heating. TTA diagrams for isothermal austenitizing, as shown in **Figure 3.16** for the example of a 34CrMo4 steel, apply for this purpose.

Changes in microstructure at a specific temperature can be read off parallel to the time axis in this diagram. It is presupposed here that the particular temperature observed in each case has been reached extremely quickly. This assumption is, in principle, obvious in the case of **surface hardening**, in view of the extremely high-speed heating in this process.

The minimum holding time necessary for austenitization as a function of temperature can be read off from the TTA diagram for isothermal austenitization. It is also apparent that complete austenitization is not achieved even after a long period of retention at a temperature below the A_{c3} temperature. Even under isothermal heating, homogeneous distribution of carbon in the Austenite requires relatively high temperatures and a relatively long holding time.

It is important for austenitizing practice to note that the temperature in the interior of a workpiece rises more slowly than that on the surface and in the surface layer, or “case”. Differing rates of microstructural transformation must therefore be anticipated. The differences here are the greater, the more rapidly a workpiece is heated and the larger the cross-section to be heated is. In the case of workpieces heated in a furnace, this fact must correspondingly be taken into account by means of a soaking time. Significant temperature differences between the surface and the interior of the heated case must also be anticipated in surface hardening using an external heat source, with high heat-flux densities.

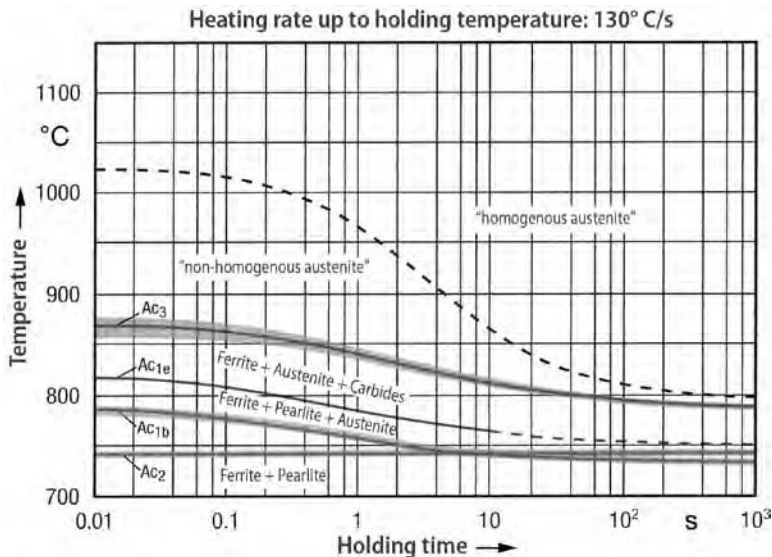


Figure 3.16: TTA diagram for isothermal austenitization of a 34CrMo4 steel [3.9]

It should also be noted that every TTA diagram relates to a highly specific steel composition and a specific initial microstructure. The boundaries for the start and end of Austenite formation shift both with increasing alloying-element contents and with differing initial microstructure. In accordance with the permissible scatter for carbon and alloying elements stipulated in the grade specifications for steels, more or less significant, but quantitatively unknown shifts in transformation must be anticipated, a fact which in no way diminishes the utility of these diagrams for case hardening practice.

Short-time austenitization

It would appear plausible from the deliberations above that heating rates and subsequent holding times exercise a definitive influence on austenitizing behavior. Lower limiting temperature A_{c3} is of particular importance for complete transformation in this context. Transformation temperatures move to higher values as heating rate increases. This is explained by way of example using the (simplified) continuous TTA diagram for a C45 steel (see **Figure 3.17**). For the sake of simplicity, only the heating rates of 0.05, 10 and 2,400 K/s are plotted in this diagram. A heating rate of 0.05 K/s equates approximately to heating in a furnace, 2,400 K/s to a surface-hardening treatment. As can be seen from the diagram, the transformation temperatures A_{c1} and A_{c3} known from the metastable Fe-Fe₃C diagram are not constant temperatures but are, instead, dependent on heating rates and shift toward higher values when heating rates increase. This means that an increasing heating rate will be accompanied by a rise in austenitization temperature ($T_A = A_{c3}$). At a heating rate of 0.05 K/s, for example, austenitization (A_{c1}) in this C45 steel commences at around 730 °C with the Ferrite, pearlite and Austenite three-phase region, and is completed at around 800 °C at the A_{c3} temperature. At this heating rate, homogenous Austenite is present from approx. 850 °C onward.

At a heating rate of 2,400 K/s, on the other hand, transformation (A_{c1}) starts only at a temperature of approx. 800 °C and is completed at around 920 °C. According to the continuous TTA diagram,

homogenous Austenite cannot be achieved at this heating rate without holding time. This circumstance results in the fact that the austenitization temperatures (hardening temperatures) must be selected around 50 to 100 K higher for short-time austenitization, as is customary for surface hardening treatments, than is usual in conventional (furnace) hardening.

If, as described, transformation governed by diffusion is assumed, this is, in the case of austenitization, (highly) dependent on temperature and time (or distance). The result is that the heat-treatment state, and thus the microstructure of the initial microstructure, have a significant influence on austenitization conditions. This correlation is clearly illustrated by **Figure 3.18**.

Not only heating rate, but also the heat-treatment state of the initial microstructure, has a decisive influence on the hardening success of short-time austenitization. This can be seen from the example of the TTA diagram for a 50CrMo4 steel shown in **Figure 3.18**. Here, the transformation

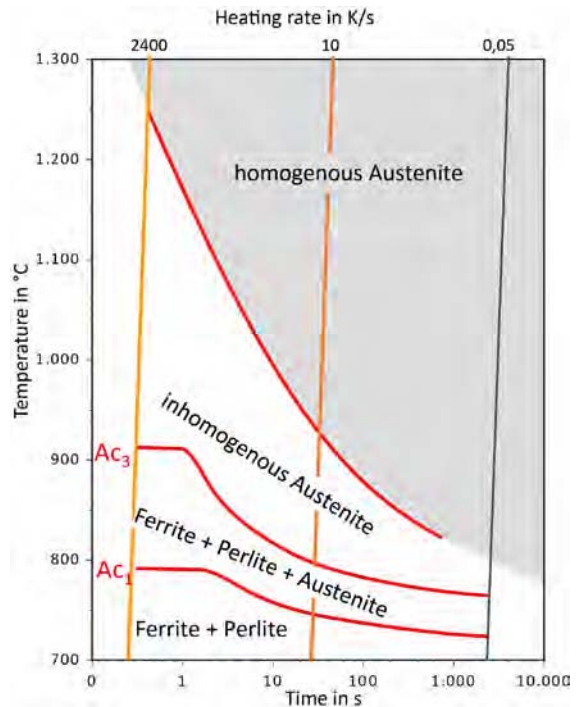


Figure 3.17: Continuous TTA diagram for C45 (simplified) [3.9]

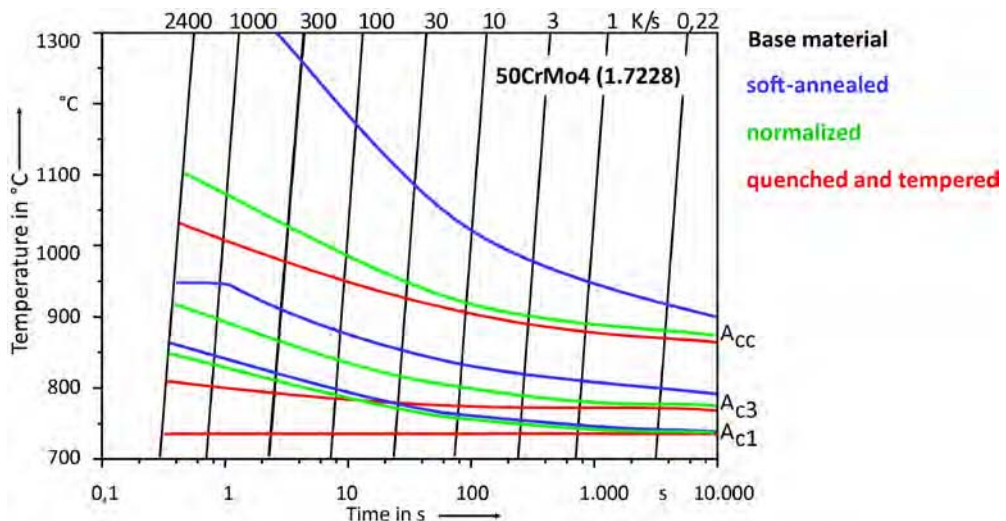
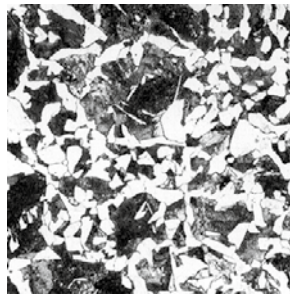


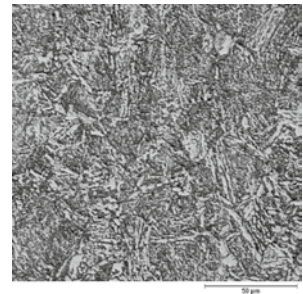
Figure 3.18: Continuous TTA diagram for 50CrMo4 as a function of initial microstructural state [3.9]



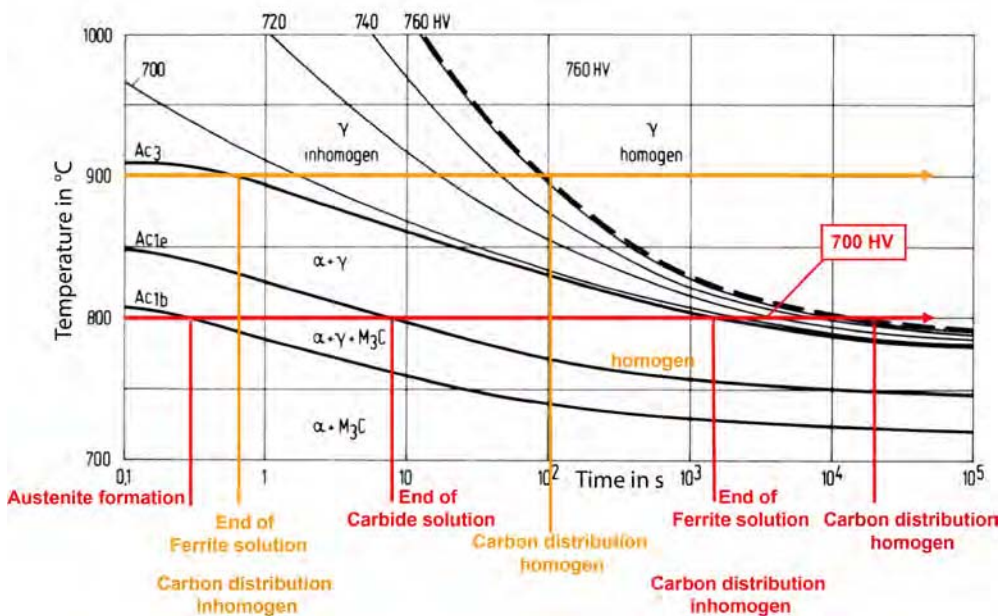
soft-annealed



normalized



quenched+tempered

Figure 3.19: Microstructural states of TTA diagram for 50CrMo4**Figure 3.20:** Isothermal TTA diagram for C45 (simplified) [3.9]

lines A_{c1} , A_{c3} and A_{cc} (carbide dissolution) are plotted for various initial microstructures (see **Figure 3.19**). It is apparent that significantly higher temperatures are necessary for austenitization in the case of the soft-annealed and thus coarse-grained state than are necessary for a martensitic or a quenched and tempered state. Located between these is the behavior of a normalized (pearlitic-Ferritic) initial microstructure.

Quite apart from this, it must also be remembered that alloyed steels require higher transformation temperatures and times than low- or non-alloyed steels.

In commercial short-time austenitization, holding times above the A_{c3} temperature, if only short ones, are always implemented after heating, a fact which raises the question of the holding times

needed for homogenous austenitization. This question is examined using the isothermal TTA diagram for the C45 steel (see **Figure 3.20**).

At an isothermal holding temperature of 800 °C, the transition from the Ferrite (α) and pearlite (α -SS + M_3C) two-phase region to the Austenite (γ) + Ferrite (α) + pearlite three-phase region is located at around 0.5 s. At this temperature, carbide dissolution is completed at around 9 s. The Ferrite is dissolved only at approx. $2 \cdot 10^3$ s (33 min.). Totally homogenous carbon distribution, and thus a homogenous Austenite, can be achieved only after an annealing time of approx. $3 \cdot 10^4$ s (8.3 h). It should be noted in this context that the isothermal diagram shown here was drafted for a heating rate of 130 K/s and a holding time of 0 s [3.9].

The three-phase region is nonexistent at a holding temperature of 900 °C, on the other hand. Instead, commencing from the Austenite + Ferrite two-phase region, the Ferrite is completely dissolved after approx. 0.8 s. Homogenous Austenite occurs at approx. 102 s (1.7 min.). Homogenous austenitization thus also occurs with short holding times, as a result of the higher austenitization temperatures in short-time austenitizing.

Microstructural modifications during cooling – the time-temperature-transformation (TTT) diagram

At a continuous low rate of cooling, the microstructural modifications are the reverse of those described for the heating process. Segregation results in zones of lower and higher carbon content in the Austenite. In hypoeutectoid iron/carbon alloys (< 0.80 % C by mass) Ferrite and, ultimately, Pearlite with a carbon concentration of 0.8 % by mass are generated from Austenite in the low-carbon zones. In hypereutectoid steels, transformation commences with the precipitation of cementite/carbides from the Austenite, and concludes with transformation to pearlite.

The time-temperature transformation (TTT) diagrams are used to describe the processes occurring in transformation of the Austenite. One must note that any TTT diagram applies only to a specific heat of steel, with a specific composition, and only for a specific austenitization condition. **Figure 3.21** shows an example of this for the C45E steel.

The existence ranges of the various microstructural states as a function of time and temperature, and also curves for cooling at differing rates, are plotted on this diagram. The cooling parameters for the 800 to 500 °C temperature range are plotted below the 500 °C temperature horizontal. Multiplication of these by 100 supplies the respective cooling time in seconds, sometimes also referred to as “ $t_{8/5}$ time”. The corresponding transformation processes can be read off along the cooling curves shown. Hardness in HV is stated in each case at the terminal point of the cooling curves.

The curves labeled with “20 K/min.” and “1.25 K/min.” on the far right of the diagram apply to slow cooling. This would equate to normalizing. The curves on the left of the diagram, along which transformation of Austenite to Ferrite, pearlite and/or bainite is avoided and Austenite is transformed directly to Martensite when temperature falls below the Martensite starting temperature M_s , are of importance for hardening, however. The cooling rate necessary for this is known as the “critical cooling rate for the Martensite region”. Here, the carbon atoms are, as a result of rapid cooling, no longer able to leave their places in the iron lattice and distort the cubic face-centered lattice of the Austenite into a tetragonal body-centered lattice.

A zone in which transformation to bainite occurs exists between the zones denoted as “Ferrite”/“Pearlite” and that denoted as “Martensite”. Transition through this region occurs in cases in which the cooling rate still to a certain extent permits diffusion of carbon atoms, and thus segregations in the Austenite. The Austenite is thus converted to a Ferrite with a higher carbon content, from which submicroscopically fine carbides are precipitated during further cooling.

Figure 3.22 shows the TTT diagram for continuous cooling of a 42CrMo4 steel. Comparison with the C45E steel reveals that the start and end of the transformations have shifted toward longer

times. This is the result of the alloying elements chromium and molybdenum; these make the steel slow-transforming, and thus impart to it a higher hardenability.

There are, in addition to TTT diagrams for continuous cooling, also such diagrams for isothermal transformation. These have no practical significance for case hardening, however, and are therefore not reproduced and discussed here.

Martensite formation

Martensite formation, alongside austenitization, is the second important stage in hardening. The following processes can be described, in simplified form, in Martensite formation:

1. Diffusion of the carbon atoms dissolved in the Austenite is not possible under rapid cooling from austenitization temperature.
2. The driving force for the transformation of the cubic face-centered lattice of the Austenite to the cubic body-centered lattice structure existing at room temperature increases greatly as temperature falls and undercooling thus rises. This transformation is greatly hindered by the carbon atoms dissolved in the Austenite. A diffusionless “distortion” of the Austenite ultimately occurs, as a result of the driving force.
3. The carbon atoms forcibly held in solution in the cubic lattice cause a strain in and tetragonal distortion of the originally cubic body-centered lattice.
4. These lattice strains cause the macroscopically observable high hardness of Martensite, and are a function of carbon content.

Martensite formation is a complex process. Unlike short-time austenitization, it does not, in surface hardening, differ from conventional hardening in a furnace, for which reason attention is drawn at this point to the relevant technical literature.

In low-carbon steels, the Martensite appears under the light microscope as an arrangement of lath-shaped crystals, for which reason this variety of Martensite is known as lath or massive Martensite. It changes as carbon content increases. The appearance of the Martensite changes to plate-like, for which reason this manifestation is referred to as plate or tetragonal Martensite. **Figure 3.23** shows Martensite forms generated as a function of carbon content.

As is apparent from Figure 3.23, however, the amount of Austenite not transformed to Martensite, so-called Retained Austenite, also increases as carbon content rises. This reduces maximum achievable hardness, as is discussed in the next chapter. It also has generally negative effects on component properties.

Hardenability

Hardenability is a material-specific property and denotes the ability of steels to take on a characteristic hardness as a result of hardening. Differentiation is made here between maximum attainable hardness and hardness penetration.

Maximum attainable hardness

The term “maximum attainable hardness” is used to describe the correlation between carbon content and maximum possible hardness. This is achieved only when the microstructure consists virtually 100 % of Martensite, and is determined by the quantity of carbon dissolved in the Austenite prior to quenching. This correlation is shown in **Figure 3.24**, while the topmost curve (continuous line) reflects this. It can be seen here that at a carbon content of, for example, 0.20 mass-%, a maximum hardness of 45 HRC can be achieved, and a maximum of 65 HRC at 0.60 mass-%.

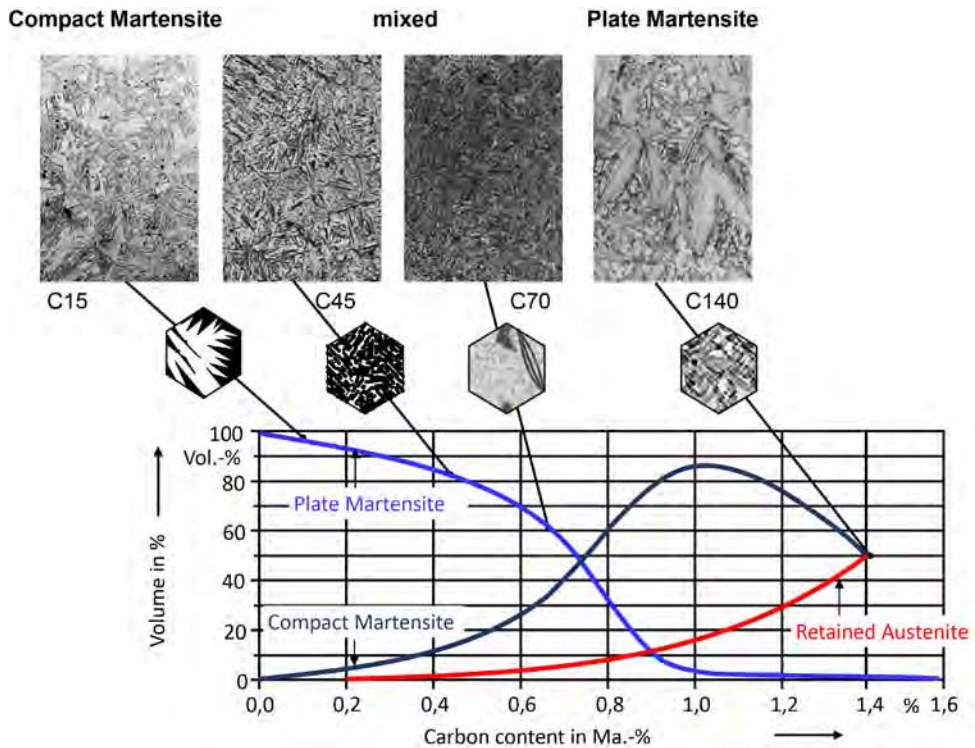


Figure 3.23: Manifestations of Martensite as a function of carbon content

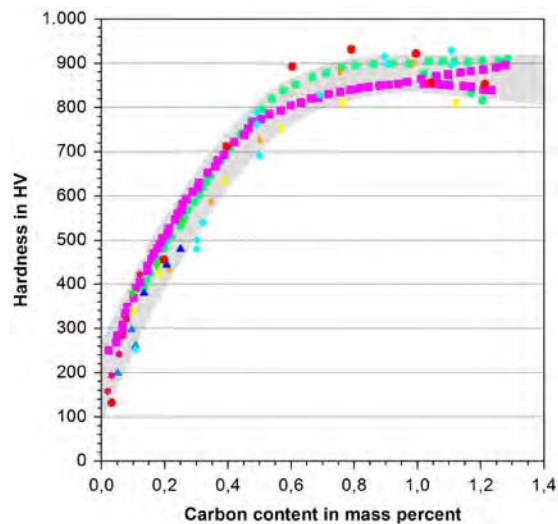


Figure 3.24: Correlation between carbon content and maximum achievable hardness as a function of Martensite content

Thanks to the virtually linear plot of the curve, intermediate values can be approximately calculated using the following equation:

$$\text{Hardness}_{\text{max.}} = 35 + 50 \text{ carbon content (mass-\%)} \pm 2 \text{ HRC} \quad (3.1)$$

This equation applies to carbon contents of between approx. 0.15 and 0.60 % by mass with virtually 100 % Martensite in the microstructure, and both to non-alloyed and alloyed steels.

The hatched line obeys the correlation:

$$\text{Maximum hardness} = 20 + 60 \cdot \sqrt{\text{carbon content (\% by mass) in HRC}} \quad (3.2)$$

These two equations supply hardness readings which differ by 1 to 3 HRC. Hardness values calculated using the latter equation tend to predominate in the case of case hardening.

3

Hardness penetration

Hardness penetration denotes the hardness achievable in the center of a workpiece and thus characterizes the transformation behavior of a steel in accordance with the differing cooling rates achieved in each case in the various zones of the workpiece. This, in accordance with the TTT diagram for the particular steel, causes differing results for Austenite transformation.

Maximum attainable hardness is directly dependent on carbon content, whereas hardness penetration derives from the type and the quantity of alloying elements which retard the transformation behavior of steels. Molybdenum, chromium and manganese are therefore used to systematically increase the hardness penetration of steels. Carbon also increases hardness penetration, however, if only slightly. Austenite-grain size also has a similar, but slighter, effect: hardenability increases with increasing grain size.

Due to the lower hardness penetration depth, particularly at values of less than 1.0 mm, hardness penetration is not of relevance in case hardening to the same extent as in hardening intended to modify the entire cross-section of a workpiece. Hardness penetration is predominantly of importance for any quenching/tempering applied prior to case hardening.

Quenching

Differentiation is made here between self-quenching and foreign-medium quenching, depending on the nature of cooling of the austenitized case for the attainment of a martensitically hardened case. In so-called self-quenching or volume quenching, cooling is accomplished by means of the conduction of heat into the interior of the workpiece. The quenching rates achievable in this process are sufficiently high, if the volume of the workpiece is sufficiently large in relation to the austenitized case. In foreign-medium quenching or “external quenching”, cooling takes place by means of transfer of heat from the heated case to a coolant surrounding the surface of the workpiece.

Various liquid quenching media, or “quenchant”, are used for foreign-medium quenching in induction hardening. **Table 3.1** shows an overview of the quenchants most widely used in industry.

Emulsions consisting of water and polyalkylene glycols (PAGs) as additives are primarily used in induction hardening. Variation of the type and concentration of the additive makes it possible to adjust the cooling characteristics of the quenchant systematically to match the particular material and/or particular workpiece. The concentration used varies between 4 and approx. 20 %.

The decisive advantage of the polymer solutions cannot necessarily be found only in a modified quenching action compared to that of water alone, but also in their property of reducing the risk of

Quenchant	Method	Remarks
Water / brine	Spraying turbulent immersion bath	• Not always reliable (steam bubbles) • Danger of cracking in alloyed steels • No corrosion protection
Polymer solutions		• Quenching rate can be selected • Slight corrosion protection
High-performance oils	Turbulente immersion bath Special case: Spraying	• Risk of cracking in high-alloy steels • Good corrosion protection
Compressed air	Air nozzles	• Thin components (low SHD) • For high-alloy steels with particular susceptibility to cracking • Problem: noise
Compressed air containing water	Special nozzles	• Little experience up to now

Table 3.1: Overview of widely used industrial quenchants

cracking. This is the result of the fact that a thin plastic film which suppresses the formation of small and ultra-small clusters of steam is immediately generated when the polymer meets the hot surface of the workpiece. The transition from film to nucleate boiling, with its extremely high rate of heat removal, occurs virtually simultaneously over the entire surface of the workpiece. The result is uniform removal of heat without any local delays throughout the quenching process. The film formed by the PAG polymers is heat-resistant and, at high temperatures, insoluble in water. At room temperature, however, it dissolves and disappears in the quenchant.

3.2.2 Hardening of steering racks

Dirk M. Schibisch, Martin Bröcking

“Power-on-demand”, maximum mileage, and more functionality – modern automotive steering systems need to offer all this while being maintenance-free and of low weight at the same time. Most vehicles already use electric power steering to assist the steering movement, allowing for easy maneuvering for parking or at low speeds. The core component of these complex steering systems is the steering rack which is heavily loaded during use. Induction hardening increases steering rack wear resistance and service life.

Induction hardening is done to improve **material properties**. As a result of the structural transformation that occurs during hardening, the wear resistance, fatigue strength and – linked to this – the static strength can be improved.

With racks, too, induction hardening is limited here to the particularly heavily loaded areas of the workpiece, **Figure 3.25**. These areas comprise the teeth and, depending on the type of rack, the shaft area, into which a recirculating ball screw is incorporated after

hardening. The areas to be hardened are subjected to an alternating electromagnetic field which in turn induces an electrical current in the target area of the rack. The current flow heats the metal to approximately 900 °C, after which it is quenched (i.e., rapidly cooled) directly using a special polymer emulsion and thereby hardened. The penetration depth of the induced current in the workpiece depends on the alternating current frequency and the material. For steering racks a hardening depth of just a few millimeters is usually required which can be attained with an operating frequency within the 3 – 20 kHz range.

In terms of the induction hardening process, two different methods have been developed. These are known as “scan hardening” and “single shot hardening”.

For scan hardening, as shown in **Figure 3.26** (also called progressive hardening or progressive radial hardening), heating and quenching take place at the same time, whereby a continuous relative movement between the fixed inductor spray head unit and the workpiece is required. With racks the inductor-quench-head unit is usually guided along the stationary clamped rack.

For single-shot hardening on the other hand, heating and quenching take place successively in one or more stations. Single-shot hardening is used for greater penetration depths and/or higher throughputs, **Figure 3.27**.

There are pros and cons to both methods which need to be weighed depending on the hardening task and throughput requirements, insofar as both methods are even technically interchangeable in the first place. With single shot hardening, in general, the higher power requirements are offset by much shorter process times, whereas with progressive hardening lower throughput rates can be achieved with less power. There are even applications where both methods can be used at different points of the workpiece.

The induction hardening of steering racks is often performed in a protective atmosphere. Scale forms at temperatures within the austenitization range as a result of oxygen in the environment. The scale would then have to be removed again from the racks at great cost and labor. Flooding the induction chamber with inert gas prevents scale formation, producing surfaces with virtually no scale residues.

With steering racks, the hardening process must be followed by a tempering process to reduce the hardening-induced stress within the rack. Tempering also reduces hardness somewhat which is acceptable because the not tempered surface hardness is usually higher than the final required hardness in the finished part. Tempering is done by reheating the rack to a temperature between 150 and 200 °C (300 and 390 °F). As an alternative to induction tempering, the rack can also be heated in an electrically heated tempering furnace. The tempering temperature and duration influence the



Figure 3.25: Section of induction-hardened teeth on a steering rack

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Figure 3.26: Scan-hardening of a vertically clamped rack (Source: SMS Elotherm)



Figure 3.27: Heating using the single-shot hardening method (Source: SMS Elotherm)

hardness reduction, e.g. high temperatures and short durations may have the same tempering effect as low temperatures and longer holding times.

Hardening machine types

The individual machining systems used for rack hardening are presented and explained in the sections below:

Scan hardening of racks with vertical workpiece positioning

Hardening machines with a feed axis are typically used for producing small batches. Machines with multiple vertical axes have been developed to increase productivity. The entire area to be hardened is 'scanned' progressively in the hardening station(s). Circumferential clamping of the workpieces, for example if the shaft and teeth need to be hardened, is not necessary.

The workpieces are clamped in position by means of a clamping device with a workpiece drive and a backstop. A rotation control device is fitted to the backstop so that the rotation of the workpieces can be monitored to ensure a safe and reliable process. The backstop is designed so that the steering rack can deflect freely, i.e. without any significant back pressure during the heating process in order to minimize distortion.

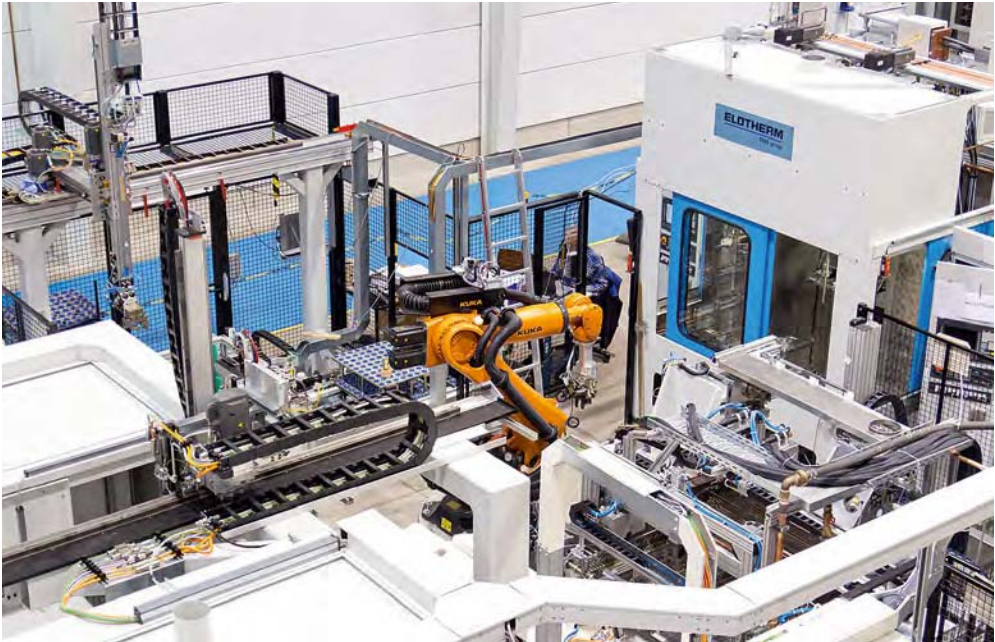
Since the tooth area is generally hardened without rotation, the rack needs to be clamped in the hardening machine with the correct orientation or the machine has to be equipped with a manual alignment aid or, alternatively, a fully automatic aligning unit. As an alternative to this, the workpiece may be aligned in an external station and guided into the hardening machine by means of an automated system, e.g. a robot. External alignment has the advantage that it occurs parallel to the process without increasing the hardening process cycle time.

Rack hardening can be performed using round or shape-adapted inductors which can be designed with one or several turns. The design of the inductor is finally determined by the hardening specifications and required throughput. As a rule, multiple-turn inductors can be used to attain greater feed rates as the area, in which power is induced in the workpiece, is longer than with a single-turn inductor.

Increasing the wear resistance and fatigue strength in the tooth area is essentially only required for the teeth. Hardening only the teeth and tooth base area, however, causes severe hardening distortion, increasing the time and labor involved for straightening the rack. In addition, there is an increased risk of cracks appearing in the hardening zone as result of straightening. The back of the rack in the area of the teeth is, therefore, also hardened in order to reduce distortion. To attain a consistent hardening pattern in this area, the rack must be able to be positioned in the inductor. For this it must be traversed horizontally. Therefore, each hardening station is equipped with an additional NC axis for adjusting the inductor horizontally. In this way, the hardening depth in the area of the teeth and in the back of the teeth can be precisely adjusted.

Hardening in the shaft area is done by rotating the workpieces. Roller burnishing for the ball screw assembly is applied in this area at a later point in time. For this the workpiece must be centered in the inductor. For shaft hardening it is not normally necessary to guide the inductors over the sensors as hardening distortion is minimal.

If the hardening machine is equipped with several hardening stations, the stations can be operated sequentially. The workpiece is changed on one station while hardening is performed on the other. The power supply to the stations is provided by using a common converter (power supply) which is switched alternately between the stations. If the processing times are considerably longer than the workpiece changing times, which is the case when hardening the shaft and teeth, a second converter can be used. This then allows for simultaneous hardening in parallel in the stations, whereby



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Figure 3.28: Integrated manufacturing cell (Source: SMS Elotherm)

the process parameters can be individually adjusted for each station. Since the stations operate independently, productivity is correspondingly high.

To ensure that the racks can be hardened with minimal scale formation, as described above, the inductor is installed in a casing that is closed off as close as possible to the workpiece. This casing is flooded with nitrogen gas to displace oxygen. Heating/hardening is, therefore, performed in an oxygen-reduced environment to minimize scale formation.

Interlinking of the vertical hardening machines is often done using a robot, facilitating sophisticated hardening cells in which several manufacturing operations can be performed, **Figure 3.28**.

Progressive hardening of racks with horizontal workpiece positioning

The assemblies described above for a vertical hardening machine can, in principle, also be integrated into a horizontal hardening machine. A key difference with the horizontal machine design is that these machines feature an internal workpiece transport system and can be integrated into a production line. With this machine concept, too, various manufacturing steps can be implemented in one cell. For example, the workpieces can be hardened in one station, tempered in the next station and straightened in a further station. Transportation of the workpieces between the individual units is performed by using a walking beam transport system. Loading and unloading of the walking beam is performed using a gantry crane.

One difference between the horizontal and the above-described vertical plant concept is the quenching liquid guidance system, **Figure 3.29**. Whereas with the vertical hardening process the lower part of the rack is cooled throughout the entire process cycle and the cooling time decreases relatively as the feed rate increases, the exposure time of the coolant across the whole hardening zone remains constant with a horizontal inductor quench head arrangement. As a result, a more consistent microstructure can be formed. On the other hand there is a risk that defective or incor-

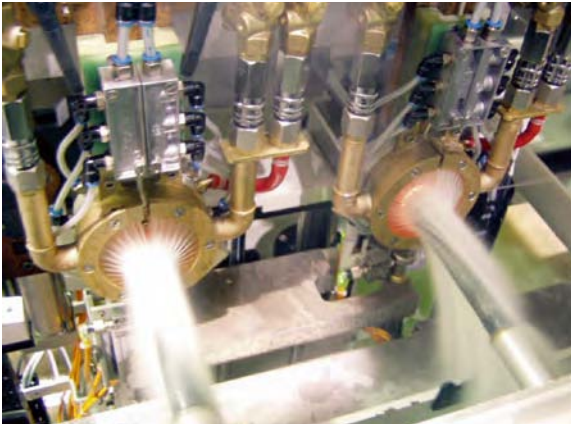


Figure 3.29: Inductor spray head arrangement in a horizontal twin station (Source: SMS Elotherm)

rectly arranged quench heads could allow quenching liquid to enter the inductor, causing inconsistent heating and soft spots.

The hardening process may also be performed in nitrogen atmosphere on these machines to minimize scale formation.

Single-shot hardening of toothed racks with indexing table transportation

In order to reduce production costs there are machine concepts available where the shaft area is hardened using the single-shot hardening method. Roller burnishing is applied in this area at a later point in time. To reduce handling times and ensure optimum capacity utilization, an indexing table for internal workpiece handling is used with this machine concept.

Loading and unloading takes place in one station while the shaft is single-shot hardened in the next station. The tooth section is scan-hardened in another station, as described above. There is also the option of setting up two additional stations for induction tempering on the indexing table, **Figure 3.30**.

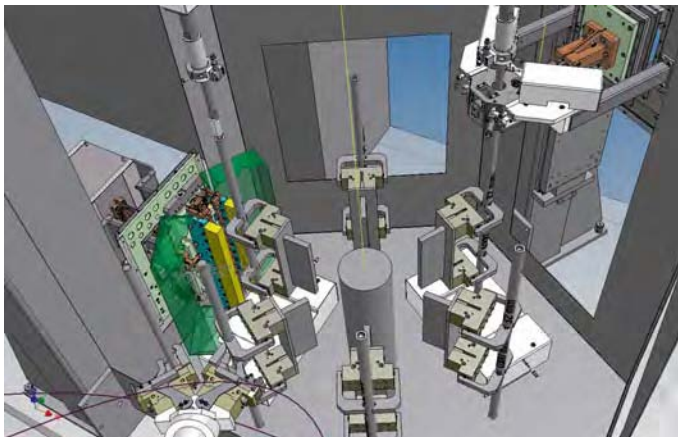


Figure 3.30: Indexing table hardening machine with two hardening stations; one for single-shot hardening and one for scan-hardening (Source: SMS Elotherm)

Single-shot hardening is well-suited for hardening the shaft area as the design is cylindrical here and the hardening distortion is correspondingly minimal. When clamping the steering rack any imbalance, which may occur when incorporating the teeth, must be offset.

With this modular machine design, internal workpiece handling and clamping in the hardening stations are performed separately. For operators this has the advantage that only one workpiece needs to be examined and evaluated for quality approval purposes. With conventional indexing table concepts, one workpiece per clamping unit needs to be examined and evaluated on the indexing table as the position of the workpiece is different in terms of the range of manufacturing tolerances in each clamping unit. The corresponding labor and costs associated with the quality approval are many times higher.

The single-shot hardening process can also be performed in a protective atmosphere. For this a split chamber is built around the inductor. The inductor is positioned horizontally with the chamber open. Then the chamber is closed and flooded with nitrogen during the hardening operation.

3.2.3 Hardening of gears – gear spin hardening

Hansjürg Stiele, Fabien Marquis

Gear hardening by induction represents one method of improving the utility of gears in a targeted manner, and case hardening is frequently used as a heat treatment method for this. Depending on the type of loading, heat treatment alone in induction hardening is one of the alternatives to this thermo-chemical method.

With regard to gear hardening by induction, there are several different methods which may be used. Initially, a difference can be made between the hardening process of the individual gear parts

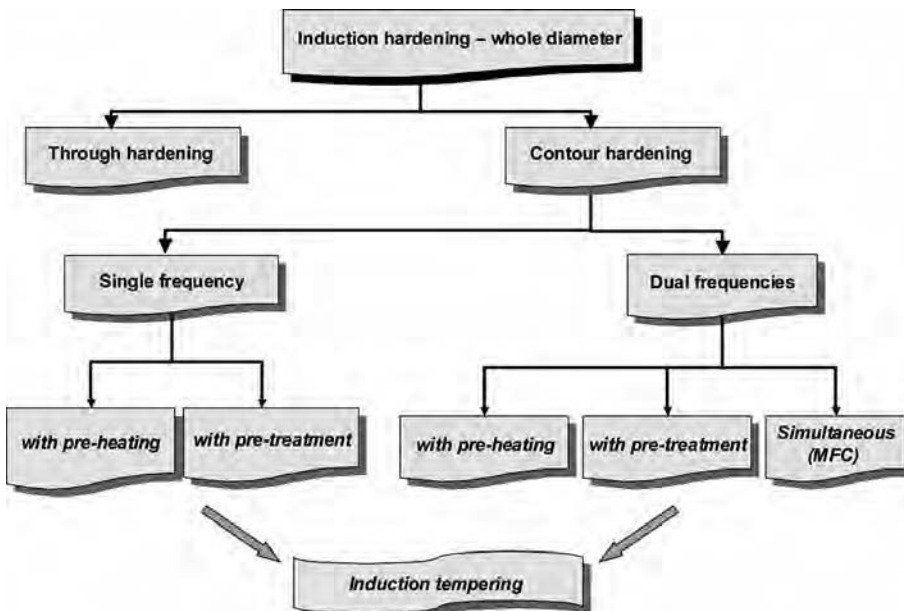


Figure 3.31: Classification of the different gear spin hardening methods



Figure 3.32: Micrograph of a submerged hardened gear

(tooth profiles and tooth spaces) and gear spin hardening, which affects the gear part in its entirety [3.10]. For economic reasons, the heat treatment of tooth profiles and tooth spaces is used for large gear dimensions, but in the case of smaller dimensions, the gear spin hardening method is becoming increasingly important.

In addition to gear dimensions (pitch diameter, module, tooth height etc.), which is one of the determining factors when selecting plant design, the module also represents an important criteria for the respective suitability of a certain method.

For hardening of gears with smaller modules ($m < 4$ mm) usually the single-shot hardening is applied. In this case the entire gear part is always brought up to hardening temperature via an inductor surrounding it, and subsequently quenched. In doing this it is possible to through harden the gear part down to the tooth root (in the same way as case hardening) or to harden in

the outer surface at either a uniform, or irregular distance to the face. There are different methods for contour hardening corresponding to different heating techniques. These methods for inductive gear spin hardening are summarized in **Figure 3.31**.

Through hardening of the gear tooth perimeter

For gears which are predominantly subject to wear (sprocket), the tooth is, most simply, through hardened with a relatively low specific power [3.11]. If the frequency is too low, there is the risk that beyond the Curie temperature the induced eddy current for the most part only flows in the root circle, and the temperature lags behind in the tooth. Quenching in through hardening can take place either by submersion or spraying (depending on the material) [3.12]. Depending on the situation with regards to factors from the module to the frequency, it is recommended to delay quenching in order to achieve a uniform temperature between the tooth and the root circle. Tempering after through hardening is essential for crack prevention. One example of a submerged hardened gear is shown in **Figure 3.32**.

Hardening of the gear tooth perimeter at either a uniform or irregular distance to the face

When hardening at an irregular distance to the tooth face or (ideally) at a uniform distance to the tooth face, a plant-specific differentiation can be made between the single frequency method, in which an oscillation at a specific frequency is used, and the dual frequency method (multi-frequency method) with separate oscillations.

Single Frequency Method

The inductor is fed from a single generator with a frequency selected according to the module. Heating (austenitizing) is effected either in a single heating or initially with a reduced power to approx. 550 – 750 °C as preheating (depending on the material) and subsequent final heating with a higher specific power to the hardening temperature. Preheating may also consist of several pulsed cycles. The purpose of preheating is to reach an adequately high austenitizing temperature in the root circle during final heating, without overheating the tooth tip. The schematic graph can be seen in **Figure 3.33**. In order to achieve hardening profiles at an irregular distance to the tooth face using a single frequency, short heating times combined with a high specific power is usually required. Both parameters (time and power) depend on the module of the gear to be hardened.

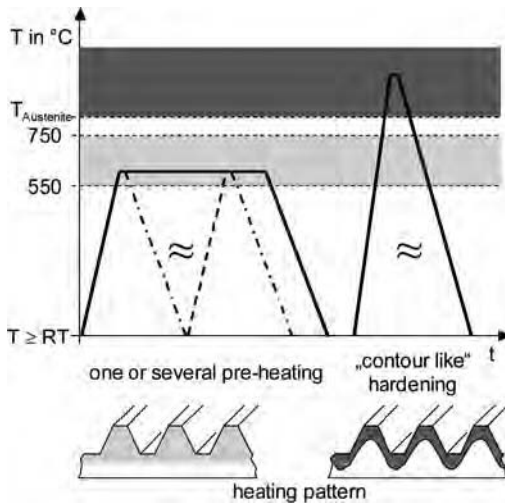


Figure 3.33: Single frequency contour hardening, preheated by induction (schematic time-temperature graph)



Figure 3.34: Micrograph of single frequency hardened gear

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In practice it cannot always be guaranteed that a generator with the suitable frequency will be available, or is able to be correspondingly adjusted. In case of doubt, better results can be achieved for contour hardening with a generator whose working frequency is higher rather than lower for the given module. If the generator frequency is higher than in the ideal case, it is possible to heat the root circle by thermoconduction during the preheating phase mentioned above in order to subsequently achieve hardening results at an irregular distance to the face with a final heating impulse using a high specific power (**Figure 3.34**).

If, on the other hand, the generator frequency is too low for a given module, the through hardening of the tooth or an inadequate austenitizing temperature of the tooth tip will be unavoidable for physical reasons.

In addition, if the initial microstructure is not suitable for gear hardening further improvement in the hardening result may be achieved by an inductive “pre quenching and tempering” operation before the actual hardening itself. For this, heating of the entire gear area to an austenitizing temperature corresponding to the material is carried out. Cooling by self quenching is then followed by a short inductive “tempering” of the entire gear part.

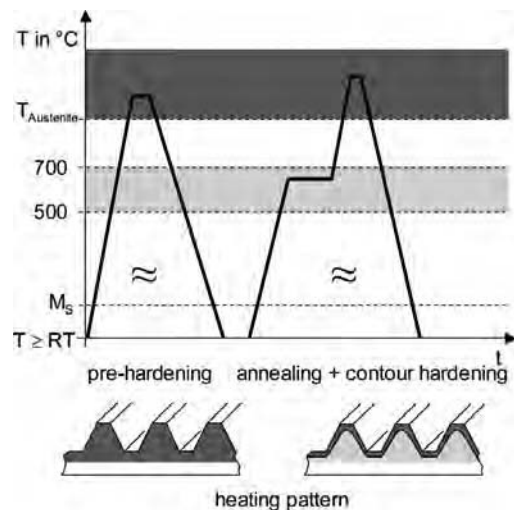


Figure 3.35: Single frequency contour hardening, pre quenched and tempered by induction (schematic time-temperature graph)

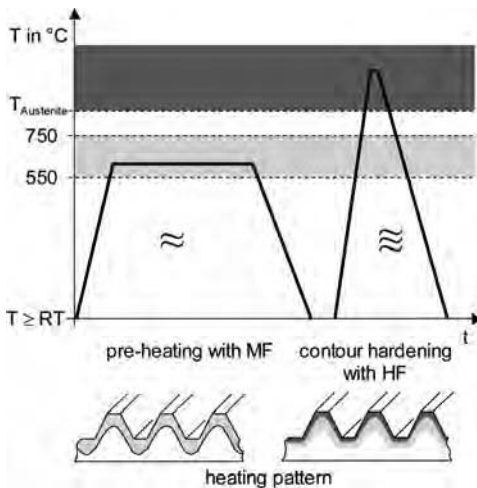


Figure 3.36: Dual frequency contour hardening, preheated by induction (schematic time-temperature graph)

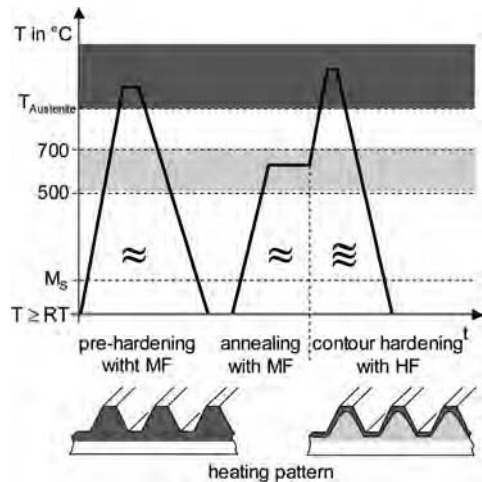


Figure 3.37: Dual frequency contour hardening, pre quenched and tempered by induction (schematic time-temperature graph)

The actual hardening zone, at an irregular distance to the face, is then generated by a short final heating. The schematic time-temperature graph for single frequency contour hardening, pre quenched and tempered by induction, is shown in **Figure 3.35**.

Dual Frequency Methods

Separate Frequencies

This process allows hardening profiles close to case hardening to be achieved. Two different frequencies, one after the other, are applied to the gear. The tooth part is preheated (depending on the material) using a low frequency and limited power to approx. 550 – 750 °C. The frequency should be such that the preheating preferably takes place in the root circle region. After a short delay, austenitizing using a higher frequency and higher specific power is effected. Heating times are measured in tenths of seconds or seconds (depending on the module) in this final heating phase and requires then a very accurate and fast monitoring system [3.13]. The schematic graph can be seen in **Figure 3.36**. Due to the high demands on the hardenability of the material in contour hardening, pre quenching and tempering by induction of the tooth area before hardening may be considered as an alternative process (just as in the case of the single frequency contour hardening process). The process diagram required for this is shown in **Figure 3.37**.

Simultaneous Frequencies

In this method a lower (MF) and a higher (HF) frequency are fed in the inductor via a special transistor generator at the same time. The preheating necessary in the normal dual frequency method with separate frequencies is, in this case, not used [3.14]. Simply stated, dual frequency contour hardening with simultaneous frequencies is effected by heating in the region of the root circle by means of the MF frequency, and in the tooth tip region using the HF frequency (**Figure 3.38**). The short heating times required in this process, however, place higher demands on the generator and machine engineering. One example of a hardening profile which can be achieved with this method is shown in **Figure 3.39**.

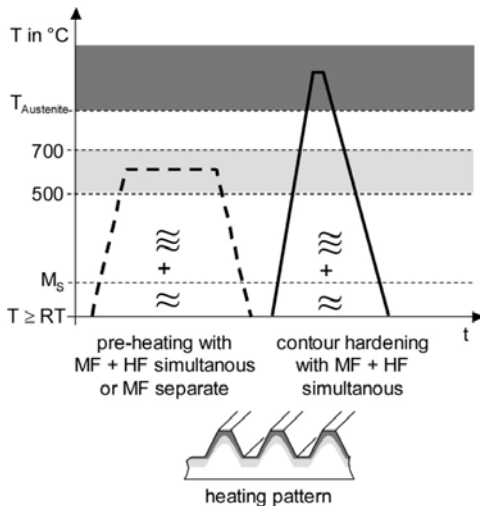


Figure 3.38: Simultaneous dual frequency contour hardening (schematic time-temperature graph)



Figure 3.39: Micrograph of simultaneous dual frequency hardened gear

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Quenching

Quenching from the austenitizing temperature can either be done using a spray head or by (turbulent) submerge quenching. The quenching agents are to be adapted the materials used in the process. Quenching has a considerable importance for perfect hardening results in gear spin hardening, at both a uniform or an irregular distance to the face. It should be effected directly after the final heating has finished with as little delay as possible (fast CNC axle for positioning the spray head, or quenching from the inductor via an integrated quenching circuit). During the quenching phase the rotational speed of the gear is decreased from approx. 600 – 800 rpm (the speed during the heating phase) below 50 rpm in order to avoid a “shadow effect” on the flank opposing the direction of rotation.

Factors Influencing the Hardening Result in Gear Spin Hardening

In addition to factors specific to the method (such as frequency and power) mentioned above, there are many other process relevant factors which influence the hardening result in the gear spin hardening of gears.

Materials and Initial Structure

In principle, all of the steels normally recommended for induction hardening can also be used for gears to be hardened by induction, although the carbon content should not be below 0.45 % for unalloyed qualities. Due to the short austenitizing times required for the method, the initial structure of the steel is also of considerable importance, having to be close-grained with a grain size index of ASTM 7 (6) or higher (= finer). A pre quenched and tempered (Q + T) structure offers the best starting point. Unsuitable are inhomogenous pearlite-ferrite initial structures. The smaller the module, the more importance the initial structure as well as the carbon content is, and thereby the required austenitizing temperature i.e. with unsuitable material parameters it is more likely that undesired through hardening will occur than with optimal qualities. If a somewhat increased



a) Symmetrical hardness profile at the centre of the gear

b) Asymmetrical hardness profile at the face of the gear

Figure 3.40: Micrographs of hardened parallel helical gear hardened with a single frequency

quenching distortion is acceptable, the above-described pre quenching and tempering by induction of the gear part can make a decisive improvement on the hardenability of critical structures using the same hardening plant, and before the contour hardening itself.

Gear Dimensions

The suitable module range is $(1.8) 2.2 < m \leq 5$ mm for the dual frequency method with simultaneous frequencies. The gear diameter suitable for this method should be limited to approx. $d \leq 250$ mm for economic reasons, as, in view of the short heating times, especially the MF power may be proportionally high (60 – 65 % of the total power). For modules where $m \leq 3.0$ mm, the separate dual frequency method with subsequent MF and HF energy application is, in part, better than the simultaneous dual frequency method, as here (assuming an adequate energy density) the best opportunity for a hardening at an irregular distance to the face is offered by HF final hardening alone. It is advantageous if the energy source permits adaptation of the final heating frequency for the size of the gear. If a slight loss of uniformity in the distance to the face is acceptable, for modules where $m \leq 3.0$ mm it is likewise possible to carry out the preheating with the same high frequency required for the final heating. The loss of middle frequency energy in this case has economic advantages. It is, however, very important to note that the specific power required to avoid through hardening significantly increases with ever smaller teeth. The single frequency method is almost exclusively used for internal ring gears with a module where $m \leq 1.25$ mm, such as those frequently used today in automotive automatic transmission systems. Despite using frequency $f > 150$ kHz, a complete through hardening of the gear occurs.

Gear form

Spur-toothed and helical spur gears and internal gears can be hardened at an irregular distance to the face. In the case of helical gearing, an asymmetrical hardening of the tooth flank at a depth of up to approx. 2 – 3 mm measured from the faces of the gear has to be accepted (the tip exit flank is hardened to a greater depth) [3.15]. This situation, however, is only more pronounced from a helix angle of $\beta \geq 28$ degrees (**Figure 3.40**). Patented coil solutions enhancing power distribution can limit this effect.

Gears which have functional zones to be hardened in addition to the teeth are, as a rule, less suited to inductive contour hardening (several inductors, mountings and working steps may be required, tempering of the initially hardened zone possible).

Quenching Distortion

As is the case with any heat treatment which has the goal of a martensitic case, inductive contour hardening causes dimensional changes to the workpiece regardless of heating time. Due to the usually low heated mass as opposed to the overall mass of the workpiece, however, usually only slight distortion is to be expected in comparison to furnace hardening. Should the gear body be favourably formed, processing of the workpiece can be completed.

In critical cases hardening trials on an adequate number of test pieces must be performed in order to determine the average expected distortion. Should the starting conditions remain the same (material composition, initial microstructure as well as internal stresses), the resulting quenching distortion when using induction hardening will be of the same nature with less variance.

3.2.4 Hardening of crank-shafts

Stefan Dappen, Farsad Amiri, Dirk M. Schibisch

Hardening, as a procedure for setting certain properties, is based on metallurgic conversions as the result of heat treatment specific to the materials. The hardening process is divided into four phases:

1. Heating, see **Figure 3.41**
2. Holding
3. Quenching, see **Figure 3.42**
4. Tempering.

An essential advantage of induction heat treatment lies in the fact that high power densities (typically $500 - 2,000 \text{ W/cm}^2$) are achieved within a short period of time ready to heat the layer close to the surface.

The actual formation of the tempered martensitic structure occurs once the heating and the quenching phase has ended. To this end, the austenite in the area to be hardened must be selectively quenched. The result of this process is



Figure 3.41: Inductor and cross-section of the crankshaft during heating procedure
(Source: SMS Elotherm)



Figure 3.42: Quenching of a crankshaft
(Source: SMS Elotherm)

a considerable increase of hardness of the surface of the material compared to its initial condition. Based on the structural changes of the microstructure at the required cooling rates, the formation of martensite is an extremely demanding process which, in order to be mastered reliably, requires equally high levels of process and engineering expertise.

Depending on the application, compressible and non-compressible fluids are used as quenching media (gases, water, oils etc.). The various media are distinct from one another by their different quenching effects. If quenching is too slow, the result is a bainitic final structure, while too quick quenching can result in the appearance of unacceptable distortion and the formation of cracks. It is, therefore, a matter of finding the balance between the required final hardness, structural quality of the micro-structure and the condition of the component after hardening.

The formation of martensite results in a massive increase in strength. However, at the same time, brittleness and mechanical stress also increase. In order to reduce undesirable mechanical stress on a component to an acceptable level, the workpiece concerned is often tempered immediately after the hardening process. This usually occurs at temperatures between 180 and 300 °C. Indeed, this procedure is accompanied by a reduction of hardness, but it does considerably increase bending fatigue strength.

Machine technology used for hardening crankshafts

There are various machine technology concepts available for hardening crankshafts. Important criteria for the design of a machine are as follows:

- Design of the crankshaft
- Hardness specifications
- Tempering
- Cycle time
- Production program
- Automation.

The hardening process requires perfect interaction between the mechanical movements monitored by control technology, the power supply for the induction process and the quenching medium. This results in various induction hardening solutions.

A significant feature of crankshaft hardening machines is the parallel oscillating circuit used to generate the necessary induction power. The advantage of the parallel oscillating circuit is the process control system which is dependent on the voltage. It prevents the material from overheating when the hardness temperature is reached; such overheating would cause the surface to melt.

Essential conditions for all machine types are reproducibility of results and availability. The following requirements of advanced engine manufacturers must be met:

- Constant operating parameters during operation
- Long-term stability of induction tools
- High wear resistance and rigidity of the mechanical machine part
- Monitoring of the energy induced in the workpiece by means of a patented process [3.16]
- Angular power control option (power pulsing).

The various applications of crankshafts, from small motors for garden equipment to automobile and truck engines, from diesel engines to generators and marine diesels, have led to the development of a correspondingly wide variety of sizes and designs.

Accordingly, there are various crankshaft hardening machines available which, thanks to their modular design, each cover a wide design range.

Figure 3.43 shows a typical example of a flexible induction hardening machine for automotive crankshafts of varying sizes. Offering flexibility in terms of the length and swing diameter of the



Figure 3.43: Flexible induction hardening unit for automotive crankshafts (Source: SMS Elotherm)



Figure 3.44: Induction hardening unit EloCrank™ for passenger car crankshafts (Source: SMS Elotherm)

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crankshaft, both the number of machining stations and the quantity of individual inductors can be chosen as a function of the number of units produced.

Therefore, this system is used for crankshafts in trucks. The main difference here – in addition to its ability to harden crankshafts up to 1,500 mm – is the linear traversing carriage with the clamped workpiece. It offers great flexibility in reacting to different unit volume requirements, as it can be operated with a minimum of inductors for the successive hardening process or with a full tool complement of 13 transformer-inductor units.

Another system is used for series production of passenger car crankshafts, **Figure 3.44**. The ability for automatic change-over to various workpieces, one machine with two hardening stations can harden 4-cylinder crankshafts within a cycle time of about 30 s, for example. Various tempering processes for reducing the residual stress are also possible, such as induction tempering or tempering by residual heat (autotempering).

The modular designed machine tool provides good visibility of the process with operator-friendly controls and adapts to various typical part handling concepts of the engine builders. Next to a walking beam transport, loading of the machine can be done with a shuttle or directly with a gantry.

A modular system of induction hardening machines is available for large crankshafts. Above all, its machine beds of varying lengths enable successive hardening of crankshafts with a length of up to 12 m and a weight of 8 tons. Therefore, crankshafts for marine propulsion systems, locomotives or stationary units, such as generators, compressors and pumps, for example, can be induction-hardened, **Figure 3.45**.

Depending on customer requirements, a choice of low-investment basic equipment or higher-level expansion stages for greatly reduced cycle times is possible. Assemblies with up to six transformer-inductor units are possible, as is the operation of two separate frequency converters – which supply the power for induction – for parallel hardening of two bearings, **Figure 3.46**.

The hardening process can be adjusted separately for all bearings and is fully automatic.

Component distortion and internal stress

Depending on the material, the induction process generates a growth in volume during the micro-structural change. This is an undesired reaction because the generated stress distorts the crankshaft. The type of expansion has several causes which are mainly due to the uneven distribution of mass along the crankshaft. In cases, where only the bearing surfaces are hardened, this is fairly



Figure 3.45: Induction hardening unit EloCrank™ XL for large crankshafts up to 10 meters
(Source: SMS Elotherm)



Figure 3.46: Assembly with four transformer-inductor units for parallel hardening of bearings
(Source: SMS Elotherm)

minor and almost always causes axial expansion. It can be easily compensated by pre-calculating length allowances.

It is more difficult in the case of fillet hardening. In this case, in addition to axial expansion, there is also volume growth in the area of the sidewalls. Due to the structure of the shaft, this can distort neighboring bearings. This distortion can only be compensated by specific counter-hardening.

However, the residual compressive stress close to the surface caused by the hardening process is not the only reason for the component's distortion. There is usually certain internal stress caused by previous manufacturing steps. Internal stress of the crankshaft is created during the casting or forging process [3.17]. The internal stress is partially released during the heating phase of the hardening process but later on overlaid with the stress caused by the micro-structural changes. The consequence is that undesirable distortion can occur in the component. Nowadays, manufacturers are using the distortion control option offered by the modern induction systems. To do this it is necessary to adjust the upstream processes in such a way that they guarantee reproducible and constant internal stress behavior of the components.

The design of the crankshaft also causes further distortion during the case hardening process. The major influencing variables are:

- Orientation of the bearings
- Overlap of main and pin bearings
- Thickness of the counter-weights.

Furthermore, the required hardness zone is an important influencing variable. Here the hardness distortion is defined in particular by the hardening depth, especially in the radius, and the height of the hardness zone at the sidewalls of the counter-weights.

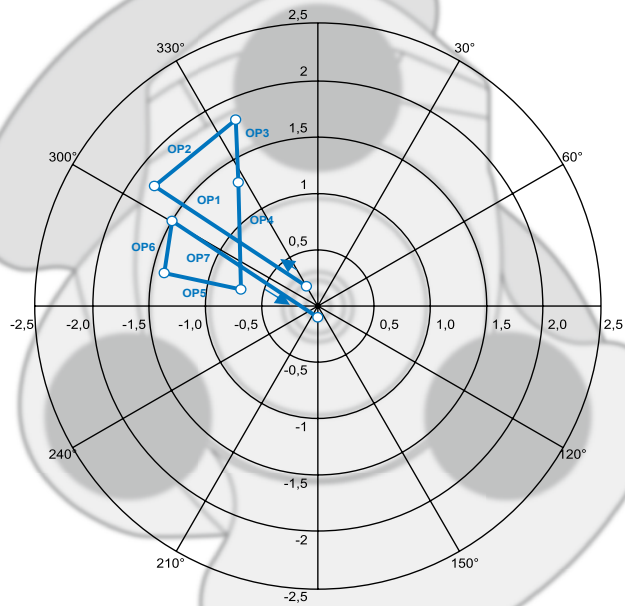
Minimal distortion induction hardening

The problems of hardness distortion can be solved by utilizing the appropriate hardening sequence and with the correct power control system. The process has proved in practice that the desired results are obtained despite a very wide variety of crank-shaft shapes.

Hardening sequence

The term 'hardening sequence' is understood to mean a sequence of hardening steps on single bearings or groups of bearings. Having analyzed the hardness specification, material expansion

Figure 3.47:
Hardening sequence
for a six-cylinder in-line
crankshaft
(Source: SMS Elotherm)



properties and the design dependencies, the sequence of hardening operations is verified on the component. An optimized hardening sequence is illustrated here taking the example of a six-cylinder in-line crankshaft, **Figure 3.47**.

Power control system

The power control system enables the induction hardening process to react to variable mass distributions on the perimeter of a bearing. The angular position of the workpiece is recorded continuously during the hardening process. By presetting the heating power according to the angle in the pre-set angle range, it is possible to control the run out. For pin bearings the power control is used to prevent overheating in the area of the top dead center, **Figure 3.48**. In the case of main bearings it is mostly used to control distortion. There, within the range

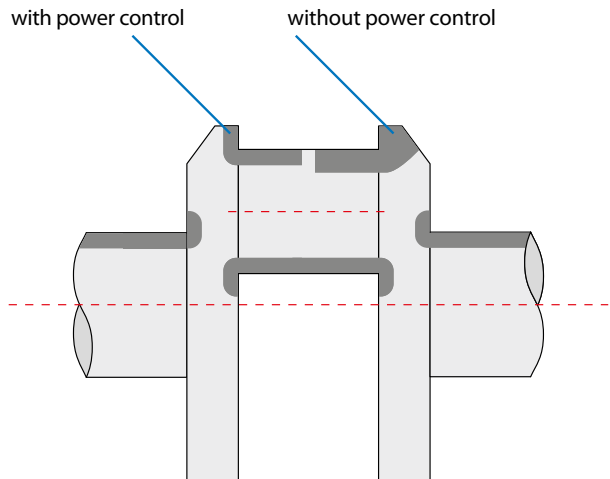


Figure 3.48: Power control system (Source: SMS Elotherm)

Figure 3.48. In the case of main bearings it is mostly used to control distortion. There, within the range

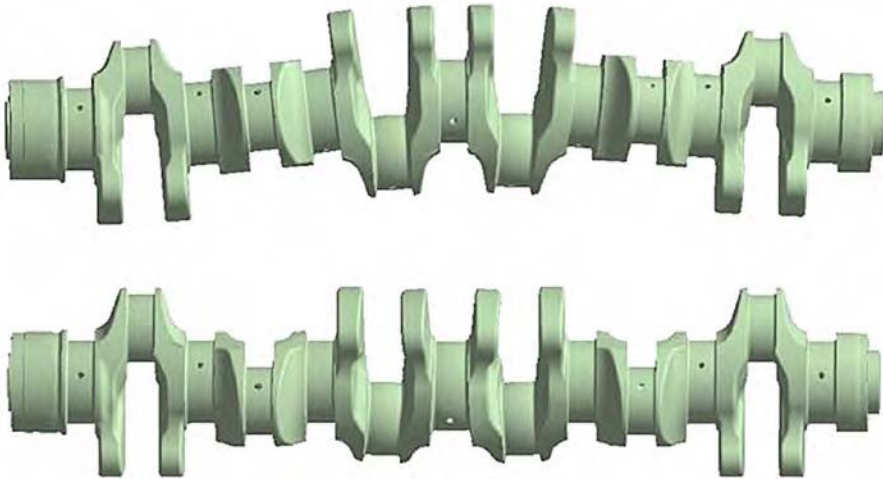


Figure 3.49: Distortion control in a six-cylinder crankshaft (distortion enlarged for better visibility)
(Source: SMS Elotherm)

of the angular overlap with the neighboring pin bearing, it is possible to effect the distortion positively.

Distortion simulation

For both engine manufacturers and machine builders the optimum hardening sequence and correct use of the power control system are fundamental. This requires a great deal of experience regarding the materials and the workpiece itself, combined with comprehensive process expertise. In recent times numeric distortion calculation systems offer excellent support – especially for complex workpieces. The direction of hardness distortion is determined on the basis of 3D modelling and a suitable hardening sequence and power control are selected. In **Figure 3.49** top it is possible to see the distortion in the shaft caused by simultaneous hardening of the pin bearings. The shaft clearly shows run out beginning at the central main bearing. The following hardening process with power control makes it possible to push it back thus achieving a distinct reduction in distortion, **Figure 3.49** bottom.

Chuck clamping configuration

It is possible to achieve a distinct reduction in distortion by using special design fixtures on the hardening machines. The specially designed and patented clamping chucks [3.18] allow the crankshaft to expand lengthwise. One of the clamping chucks works as a rotary drive, while the second clamping chuck monitors the rotation with a floating bearing. This means that no axial forces, which could result in distortion, will affect the crankshaft.

Advantages of rotational induction surface hardening

Rotational induction hardening has developed into the global standard for engine manufacturers. While it has been used and further developed in Europe for decades now, engine producers in Asia – China most of all – as well as the Americas have adopted this technique and integrated it into

many new plants. The increasing minimization of engine components worldwide, due to reduction of CO₂ emissions, is currently leading to a shift in the NAFTA countries. Whereas in the past NAFTA nations primarily used non-hardened crankshafts – which were nevertheless large in size – for large displacement motors, they are now increasingly using rotationally induction-hardened crankshafts with much smaller dimensions. The emerging supercharged 3- or 4-cylinder engines are every bit as good in terms of their performance as their larger predecessors.

This development stems from the obvious benefits offered by the rotational induction hardening process with which the crankshaft is clamped between the chuck and tip, a rotary motion is induced, the crankshaft is heated using half-shell inductors and then quenched with an integrated spray head.

With rotational hardening a car crankshaft is rotated at 30 – 60 rpm under a half-shell inductor, Figure 3.41. Therefore, the entire circumference of the bearing is brought to austenitizing temperature at the same reproducible depth – an essential prerequisite for the creation of an evenly shaped hardening zone. An angle at circumference of almost 360° (of which 180° is with forced quenching by spray head) is then available for the equally critical quenching process, thereby ensuring that the critical cooling rate for producing a homogeneous, martensitic structure is actually achieved.

A design feature of a crankshaft are the various mass ratios around the circumference of the bearings, especially the pin bearings. Whereas there is scarcely any material at the top dead center at the sides, the cheeks of the pin bearing are located at bottom dead center of the same bearing on both sides. Since with induction hardening, as described, the heat is generated in the component itself, the mass distribution in the vicinity of the heating zone results in a distinctive heat flow which necessarily produces various temperatures. To prevent this, rotational hardening allows for what is known as “power pulsing”. Here, the optimum amount of energy can always be supplied as a function of the crankshafts angle of rotation, ensuring that consistent conditions for heating are generated at all times. Accordingly, less energy is supplied at the top dead center of the pin bearing since less energy is able to dissipate into the surrounding areas. At the bottom dead center, however, more energy is supplied to level out the heat flow into the cheeks.

The above-described rotational machining process, which can be precisely controlled, not only guarantees a reproducible hardening result, it also minimizes the distortion of the crankshaft. This results from the local material growth in the heating zone, especially during hardening of the radii. Distortion is minimized by a combination of warp simulations, intelligent hardening sequences for the bearings, selective power pulsing and specific mechanical workpiece guides. The result is low-distortion crankshafts with precisely hardened surfaces and the desired microstructural properties [3.20].

Whereas for the quenching process the monitoring of the temperature, composition, cleanliness and flow of quenchant is used, for the heating process the workpiece effective power measurement system [3.16] is used, which reliably calculates the process energy required for austenitization of the workpiece.

This system monitors exactly what electric power is actually induced in the workpiece and, consequently, converted to thermal energy. The main feature of this system is that it takes into account the entire power loss between the energy supply and inductor with the result that the active energy is not only shown as a parameter for the quality of the heating process, it is also recorded. Compared to other systems, which only measure the converter output power, the workpiece-based recording of the active power enables a full check without the otherwise essential quality inspection where the workpiece is destroyed.

Hardening of large crankshafts

As a result, the specific stress of these types of crankshaft is increasing too so that more and more importance is being attached to induction hardening of the bearings. For process-related reasons, induction rotational hardening has been adopted by all engine builders as it allows them

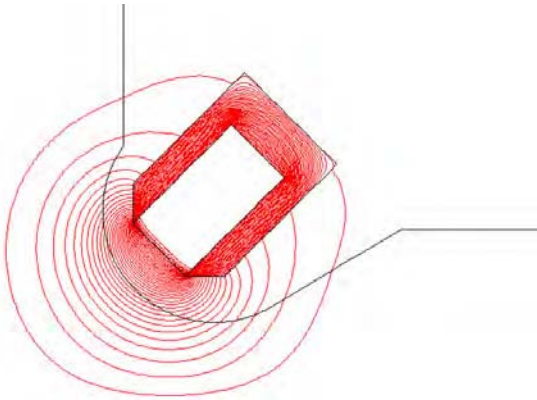


Figure 3.50: Example of magnetic field propagation in the undercut (Source: SMS Elotherm)

to achieve reproducible quality results in a cost-efficient manner. This is based essentially on the precisely controlled coordination of both sub-processes for producing a homogeneous martensitic material structure: austenitization of the bearings and selective quenching.

In addition to the variety of types of crankshaft for automotive use, more and more importance is being placed on large crankshafts for stationary and mobile applications on land and sea, as these heavy-duty engines are being used in many cases for the resource-efficient transportation of vast numbers of people and goods. In the future conventional 2-stroke diesel units in sea vessels will likely be replaced by modern gas engines which, in turn, will mean higher requirements being placed on the strength of the crankshafts due to the

specific ignition characteristics – something which can be achieved by induction rotational hardening.

A more detailed explanation of an induction hardening process for a large crankshaft with undercut radii and the specific characteristics of this system is given below.

The standard hardening process for many large crankshafts continues to be surface hardening. Here only the cylindrical exterior surface of the bearing is hardened. The inductors have copper heating loops, whereby the active part is made from a single section and is predominantly effective in the area of the transverse branches. The heat-affected zone is restricted to the bearing and does not affect the area of the bearing cheeks. Consequently, no significant warping of the crankshaft can occur during hardening. Surface hardening is essentially a method of wear hardening with added stabilization against torsional fatigue.

Hardening of the fillets together with the bearing face is the second method used to further strengthen the crankshaft, particularly against flexural fatigue. The inductors have to be better adapted to meet the additional hardness requirements in the fillets and feature complex copper heating loops, whereby the radius-side thermal conductor branches have field concentrators. Hardening of the fillets requires more power and may result in warpage of the shaft. When selecting a suitable hardening sequence, however, the amount of warpage can be reduced to a value below the grinding allowance.

Undercut hardening is a further development of hardening of the fillets. Typically, workpiece designs, which have been tried and tested for many years, have been used for large crankshafts. However, up to now these have usually been only quenched, tempered and partially nitrided. This is also an area where undercut hardening is applied.

As mechanical stresses on the crankshaft increases, the radii can become weak spots. However, further enlargement of the fillets to reduce excessive stress is often impossible due to the reduction in the useful bearing face with the result that the enlarged fillets are ‘cut in’ at the expense of the cheeks. If undercut hardening is required, the inductor has to penetrate into the undercut and heat up the radius there, **Figure 3.50**.



Figure 3.51a: Hardening zone with single-sided undercut (Source: SMS Elotherm)



Figure 3.51b: Hardening zone for two-sided undercut (Source: SMS Elotherm)

The available hardening results for undercut hardening were taken from a hardening machine for large crankshafts with an installed MF capacity of 1,200 kW. The power is supplied by two 600 kW converters which operate within a frequency range of 2.5 – 10 kHz. This power and frequency range allows for the hardening of a wide workpiece range and the adjustment to various hardening requirements.

The plant has four transformer-inductor units; two large fixed ratio transformers for good positional stability and high output and two disc-type transformers for smaller bearing dimensions and medium output levels.

The machine allows automatic operation with up to four different inductors so that fully automatic hardening can be performed for standard large crankshafts without changing the inductors. The crankshaft is held in a cardan chuck on one side and rests on up to four V blocks which are adjusted in line with the hardening position by motor-operated means using the program control system.

Figure 3.51a shows the hardening zone of a single-sided undercut hardening process whereby the inductor here is initially lowered onto the bearing and then axially into the undercut. Hardening on both sides, as shown in **Figure 3.51b**, requires a great deal more effort by comparison, as the thermal conductor needs to heat both undercuts.

Figure 3.52a and **Figure 3.52b** show the position of the inductor in a workpiece (cut in order to provide a better view) and the heating process. Here one can see the special design – allowing the area of the fillets to be penetrated – as well as the field concentrators for selective heating.



Figure 3.52a: Position of the inductor in the undercut (component cut for this purpose) (Source: SMS Elotherm)



Figure 3.52b: Heating pattern of the undercut inductor (Source: SMS Elotherm)

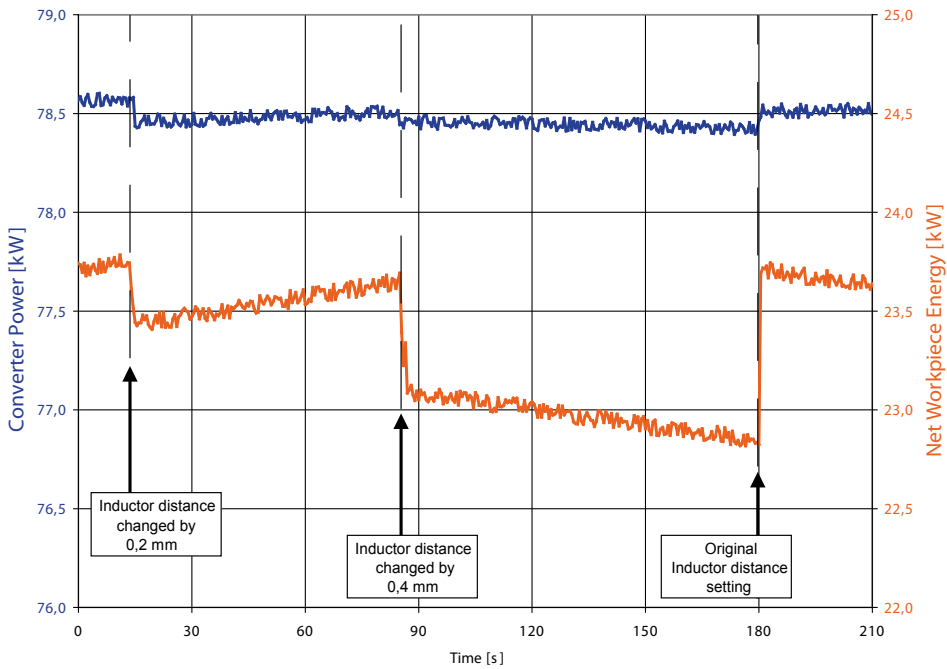


Figure 3.53: Working principle of the patented workpiece energy measurement (Source: SMS Elotherm)

3.2.5 Hardening large bearings for wind energy plants

Dirk M. Schibisch, Stefan Dappen, Otto Carsen

Large bearings are required to handle large axial and radial forces and their resulting torques. Typical applications include general machinery and construction equipment, as well as onshore and offshore energy technology.

These diverse applications have one thing in common: their components are highly stressed mechanically and are, therefore, induction-hardened to increase their dynamic strength and wear resistance. In the past, conventional progressive induction scan hardening necessarily left a small, not hardened zone in the bearing race. This soft zone compromised the bearing's load-bearing capacity and smoothness. The innovative and patented scan hardening with no residual soft zone is essential, specifically if systems do not allow any vibration (e.g. magnetic resonance imaging, or MRI technology), if extremely high mechanical stress needs to be considered (e.g. tunnel drilling machines), if continuous rotation is required or where challenging environmental conditions mandate maintenance-free systems with long service life (e.g. offshore technology such as wind turbines, tidal plants or oil platforms) [3.21].

Advantages of induction surface hardening of large bearings

Some conventional heat treatment shops use case hardening to harden rings up to three meters in diameter. This process suffers from five major problems. First, it requires long periods – sometimes several days – in the carburizing furnace. Second, it produces large workpiece distortions, which must

be corrected by expensive and time-consuming straightening operations. Third, larger workpieces cannot be hardened due to practical limits related to the size of the furnace. Fourth, carburizing necessarily treats the entire workpiece, including surfaces that should not be treated. Fifth, carburizing is energy-intensive with high emissions. Induction hardening overcomes all these problems.

In contrast to conventional carburizing, induction hardening is performed only on the highly loaded surfaces where it is needed, such as bearing races and gear teeth. Resulting advantages are faster process times (for example, about one hour for a ring with a diameter of several meters), substantially lower energy consumption, and better control of workpiece distortion.

Induction hardening benefits from a rapid and uniform workpiece heating. The inductors with integral quenching heads can be optimized for the application, producing well-defined and reproducible hardening results. For mission-critical components in offshore technology, maintenance or repair operations would be extraordinarily expensive or even technically infeasible. This is exactly the type of application where precise and accurate formation of hardened zone must be achieved and documented with online quality control.

This is another application area for the patented workpiece energy monitoring system [3.16], which continuously monitors the electrical power that contributes to net heating of the part. This system automatically accounts for the total energy loss between the system input power and the inductor. Furthermore, the remaining net workpiece energy is continuously monitored and recorded. Unlike other methods that simply measure the inverter output, the workpiece energy monitoring system provides 100 % online quality control of the hardening process without having to destroy the workpiece. Small changes in the inductor – workpiece gap distance – can lead to significant hardening zone variation. **Figure 3.53** illustrates how the workpiece energy measurement detects small

Surface hardening technologies			
Induction hardening	Flame hardening	Case hardening	Nitriding
• Uniform heating of the areas to be hardened • Short heating times (reduced scale buildup, no formation of large grain structures) • Little or no machining required after hardening (minimal part distortion) • Reliable control of heat input and part temperature • Partial hardening possible – even with complex part designs • Inductors adaptable to virtually all part designs • Very large and massive parts can be hardened • Easily integrated into new and existing production lines • Small equipment footprint • Simple, straightforward operation and high reliability • Environmentally friendly (reduced energy consumption and CO₂ emissions)	• Short heating times • Little or no machining required after hardening (minimal part distortion) • Partial hardening possible • Small equipment footprint • Simple, straightforward operation • Temperature errors due to variation in gas pressure and flame positioning • Poor hardening depth reproducibility • Different burners needed for individual parts	• Thin, but uniform hardening depth • Partial hardening possible • High operating costs, high energy consumption • Long annealing times • Prone to large part distortions • Shielding required for surfaces that should not be hardened • A centralized hardening facility is required (transport and logistic costs) • Post processing (part cleaning) is required • Hardness and hardness case depth decreases at the base of the tooth for large gears.	• Due to reduced hardening capabilities the suitability of nitriding for large ring hardening applications is limited

Table 3.2: Surface hardening technologies



Figure 3.54: Single tooth hardening
(Source: SMS Elotherm)

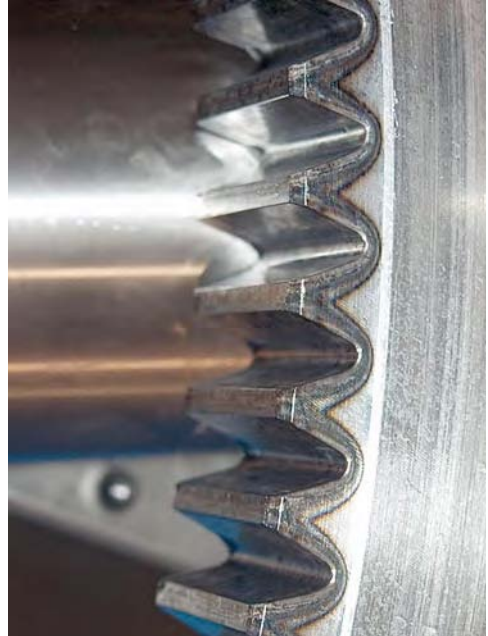


Figure 3.55: Hardened teeth
(Source: SMS Elotherm)

inductor position changes. In contrast, the conventional inverter power monitor (blue trace) is largely insensitive to this source of process variation.

For critical components, where induction hardening with no soft zones is required, the workpiece energy measurement gives the manufacturer a reliable system to fulfill the stringent requirements of modern quality control audits and part/process traceability.

Characteristics of various surface hardening techniques

Table 3.2 compares the attributes of the various surface hardening techniques used to improve the properties of large roller bearing rings.

The precise process control offered by modern induction systems ensures uniform and highly reproducible surface hardening.

Gear tooth hardening

Gear teeth on the inner or outer diameter of large roller bearing rings are also hardened by induction. Typically, the tooth base and flank are hardened and a “soft zone” (not hardened area) is maintained at the tooth tip. An induction frequency ranging between 4 and 30 kHz is selected to achieve the desired hardening depth. High throughput production systems are capable of processing multiple teeth simultaneously, **Figure 3.54** and **Figure 3.55**.



Figure 3.56: Induction hardening machine with horizontally positioned ring
(Source: SMS Elotherm)

Hardening of bearing raceways

Scan hardening with soft zone

Scan hardening with a remaining soft zone is the standard process for hardening single raceway and multi-raceway large bearings. Except for a linear axis to compensate for different workpiece diameters, the inductor/shower head assembly is stationary. The ring rotates with a low, constant tangential velocity past the inductor. A small soft zone (not hardened area) necessarily remains at the end of the scan path. With less than 100 kW of power a 3 m diameter bearing race can be hardened in less than one hour.

Figure 3.56 and **Figure 3.57** show two different induction scan hardening machines. Both machines are capable of hardening raceways and gear teeth on the inner and outer ring diameters. The machines differ in regard to the workpiece positioning to prepare the workpiece for optimal quench control for different hardening applications. For gear tooth hardening, a horizontal work piece is preferred. For raceway hardening, a tilted or vertical ring works well.

The flexible automatic tilt machine shown in **Figure 3.58** performs horizontal, vertical, and tilt- ed scan hardening. Industrial hardening



Figure 3.57: Induction hardening machine with 70° tilted ring in a fixed position
(Source: SMS Elotherm)



Figure 3.58: Induction hardening machine with pre-heater and 0-70° adjustable tilt table position
(Source: SMS Elotherm)

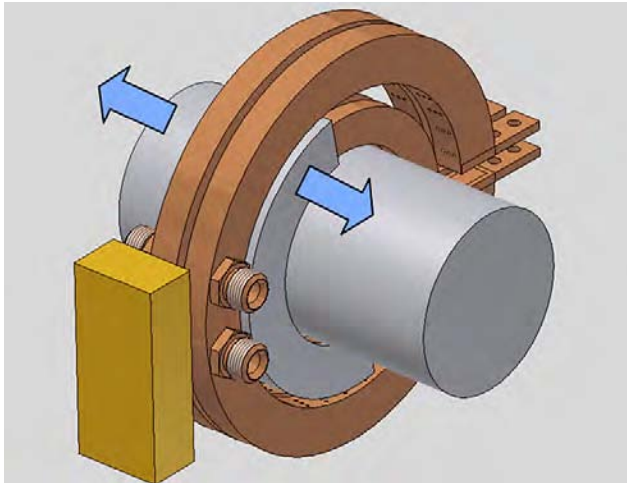


Figure 3.59: Illustration of the inductor setup with flux concentrators and shower heads during the starting sequence
(Source: SMS Elotherm)

machines for workpiece diameters up to 6 m (20 feet) and weights up to 20 tons are working reliably in high throughput production settings.

Complete surface hardening (single shot)

With single shot hardening the workpiece rotates past one or more stationary inductors or a complete 360° ring inductor interfaces with the entire workpiece. The ring is heated to the appropriate hardening temperature and then the entire workpiece is quenched. Quenching may be done by submerging the workpiece in a bath or by using spray nozzles that are integrated into the inductors and customized for the process requirements.

The single shot process is best suited for workpieces with a diameter less than 2 m. The electrical power requirement grows quadratically with increasing workpiece diameter. For example, single shot hardening of a 2 m diameter ring would require about 1.5 MW of power.

Compared to scan hardening, the single shot process with its high power is very fast, typically a few minutes.

Induction scan hardening with no soft zone

As previously described, traditional scan hardening is inadequate for mission-critical components with stringent requirements for smoothness and heavy loads due to the remaining soft zone.

Carburizing is limited as a process alternative by furnace size and long process times. Single shot induction hardening is impractical due to its high power requirement. A better hardening method is needed to efficiently and reliably harden large, high-value rings.

In response to this need, a process was developed and patented several years ago to scan harden arbitrarily large rings with no remaining soft zone [3.21]. This process differs from conventional scan hardening primarily at the start location and end location of the scan, where special shower heads and techniques completely quench the austenitized steel while avoiding unwanted tempering and changes in the hardened zone microstructure.

Comparing this process to single shot induction hardening, one finds that even a 6 m diameter ring can be processed with a 200 kW scanning system, which is about factor 7 – 8 times less power

than the single shot process would require. In contrast to carburizing, which would require several hundred hours in the furnace, the time required for the scan hardening process (less than two hours) is negligible. Moreover, the cost-intensive and time-consuming straightening operation to clean up the distortion caused by carburizing can be avoided altogether.

This induction hardening system is universal and modular. Thus, in addition to scan hardening with no soft zone, conventional scan hardening and tooth hardening on both inside and outside diameters of the workpiece can be done on the same machine. Manufacturers of large ring bearings with small production runs appreciate this flexibility and the freedom to process diverse workpieces while keeping equipment costs at a minimum.

Characteristics of induction scan hardening with no soft zone

The patented process for scan hardening with no soft zone requires only two inductor assemblies, each comprised of an inductor and a shower head. This differs from competitive three inductor systems which require more complex mechanical and control systems. The inductors are narrow to create a compact hardening zone. Flux concentrators focus on the magnetic field for one-sided hardening. Each inductor is accompanied by an independently positioned shower head. A single stationary shower head completes the assembly, **Figure 3.59**.

3

Start sequence

The inductor assemblies are brought together back- to-back and then energized with independent power supplies. Both assemblies move side-by-side in the same direction for a short distance. One of the assemblies reverses directions. Thus, the inductor assemblies move in opposite direction, each accompanied by its shower head. This technique avoids the formation of a soft zone at the start location.

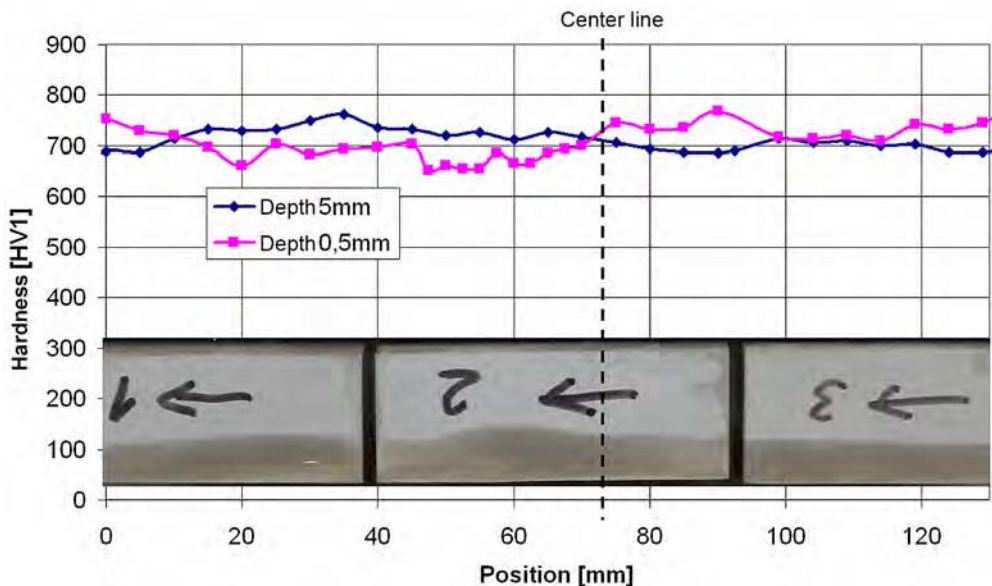


Figure 3.60: Polished section and hardening depth of a ring segment after the starting sequence show uniform hardening with no soft zone (Source: SMS Elotherm)

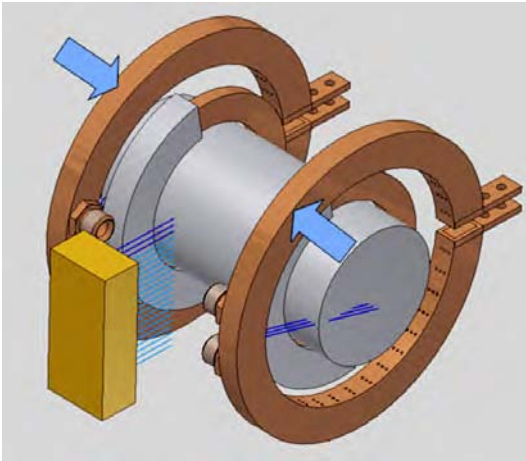


Figure 3.61: Inductor movement and shower setup during the end sequence of induction hardening (Source: SMS Elotherm)

Figure 3.60 depicts the hardening result with the etched case (below) and with two hardening passes along the workpiece axis at 0.5 and 5 mm depths after tempering. The start location is still recognizable and one can see that the entire area has been hardened with a relatively constant depth. With this special process technique for the inductors and showers, one creates uniform hardening with no soft zone at the start location. The next critical process is at the end location where the two inductor assemblies come together.

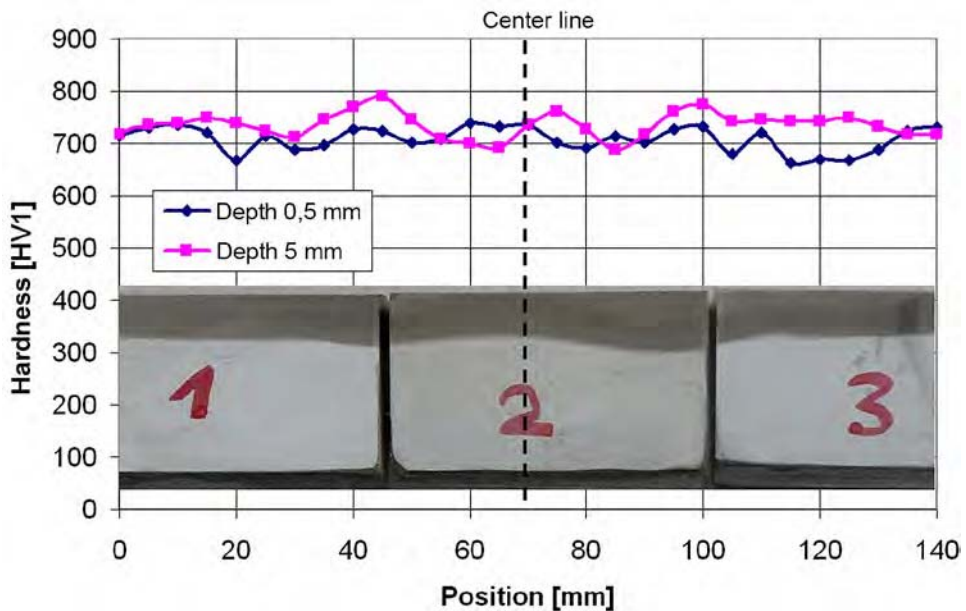


Figure 3.62: The result of the end sequence of induction hardening is uniform hardening with no soft zone (Source: SMS Elotherm)

End sequence

After initial heating at a common start position, both heads move along the workpiece surface in opposite directions, heating and then quenching the surface as they move. At the opposite side of the workpiece, the two hot zones come together, **Figure 3.61** and are quenched with a stationary shower head, producing an induction hardened workpiece with no soft zone.

Like the start sequence, the end sequence relies on precise control of the quenching heads and tight motion control of the inductors and showers to achieve a uniform depth with no soft zone at the end location, **Figure 3.62**.

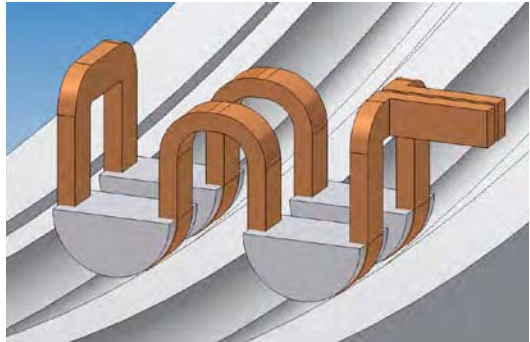


Figure 3.63: Twin inductor for hardening of double row ball bearings (example) (Source: SMS Elotherm)

3

Double row ball raceway hardening

For hardening double row ball and roller raceways, for example in large slewing rings, the use of a twin inductor is particularly interesting as the hardening process productivity is essentially doubled. If coupled with a suitable power supply, the twin inductor scan hardens both raceways simultaneously. **Figure 3.63** illustrates a typical twin inductor design.

With single head induction hardening there is always a risk that the previously hardened raceway will be softened (annealed) when the adjacent raceway is hardened. The twin inductor process eliminates this risk.

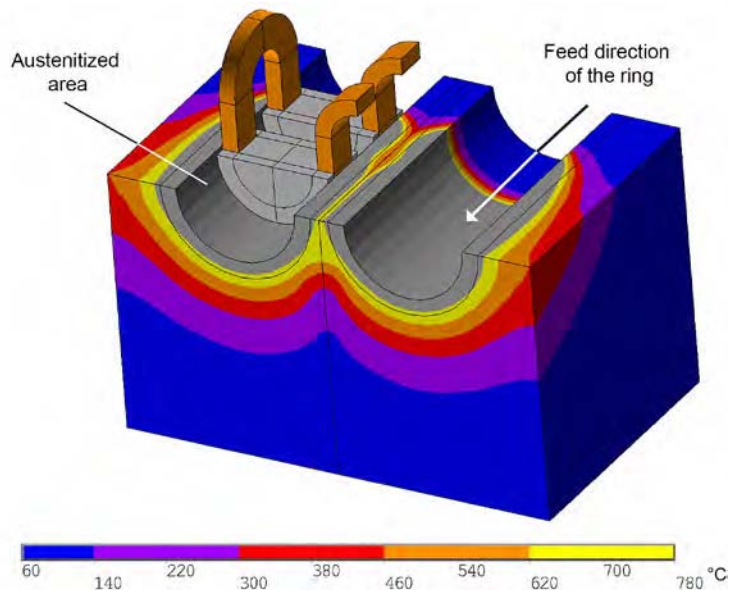


Figure 3.64: Finite element temperature model for a twin inductor (Source: SMS Elotherm)

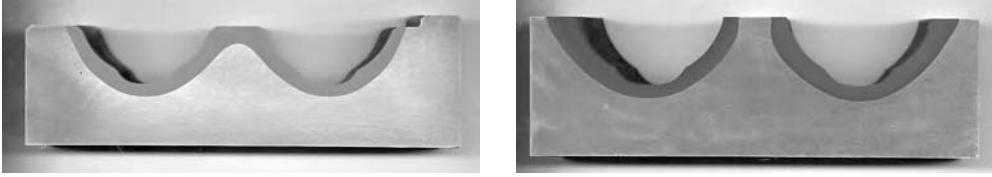


Figure 3.65: Optimized twin inductor raceway hardening for thin, double-row slewing rings (Source: SMS Elotherm)

Moreover, the trend toward compact (thin) slewing rings with increased hardness depths leads to narrowed shoulders between the raceways. The narrowed shoulder designs are prone to complete through-hardening which is usually an undesired side effect of traditional hardening methods.

Figure 3.64 shows the numerical simulation for the formation of the austenitized region (gray area). Unwanted through-hardening of the raceway shoulder is avoided.

With supplemental shoulder cooling, the twin inductor can be used for high throughput hardening of very thin shoulder double row rings, **Figure 3.65**.

3.2.6 Hardening of drive train components

Dirk M. Schibisch, Jochen C. Huljus

Power train and suspension components require toughness to handle the worst of everyday driving and also high-precision mechanical characteristics to accurately transmit road conditions and driving dynamics to the driver. This paradox can be resolved with induction hardened modern automotive components.

The manufacturing of these high-performance components is accomplished by a sophisticated induction hardening machine with the flexibility to harden a variety of different parts.



Figure 3.66: Induction hardening machine for manual loading of two double-heating stations (Source: SMS Elotherm)



Figure 3.67: Examples of drive shaft components (solid and tubular design)

Essential machine performance requirements include:

- A good price/performance ratio
- Fast and reliable setup
- Short machine delivery times
- Simple and quick installation and commissioning on the production floor
- Optimal, appropriate solutions for each application.

Induction hardening machines meet these diverse requirements by incorporating modular machine designs, where a base system can be configured with various modules for fast and easy adaptation to a variety of hardening jobs. Standard hardware and software interfaces facilitate a plug-n-play approach to the machine configuration process, streamlining the engineering, manufacturing, installation, and commissioning of these machines. Depending on the requirements, machines are available with both manual and automated loading and unloading with one or more workstations for hardening and tempering.

Figure 3.66 shows a manual machine with two double workstations for hardening drive shafts with a length up to 1,000 mm, **Figure 3.67**. In each station two shafts are hardened simultaneously while the other station is unloaded and reloaded. Both stations are supplied by a single power supply. Thus, the time for loading and unloading does not increase the cycle time.

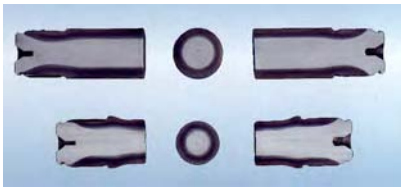


Figure 3.68: Hardening depths on longitudinal sections of induction hardened drive shafts



Figure 3.69: Interlinked and automatic hardening machine with one heating station
(Source: SMS Elotherm)



Figure 3.70: Various inner races and VL outer races



Figure 3.71: Hardening depths on sections of VL outer race (left) and inner race (right)



Figure 3.72: Interlinked and automatic hardening machine with two heating stations
(Source: SMS Elotherm)



Figure 3.73: Various sizes and design variations of outer races



Figure 3.75: Polished section of an outer race

◀ **Figure 3.74:** Polished section of a tulip

Depending on customer requirements, hardening depths in a range from 3 to 8 mm can be achieved by adjusting the relevant parameters such as power, feed rate, and frequency, **Figure 3.68**.

Figure 3.69 shows an automatically-chained machine with one workstation for hardening ball hubs, jointed parts (see **Figure 3.70** and **Figure 3.71**) or similar workpieces with one hardening zone. The hardening can be performed in a single shot or alternatively in the scanning process. The workpieces go into the machine by way of a plate conveyor with a separating device. From there the machine transports them to the hardening station and (if needed) to cooling and/or blow-off stations before they are placed on a plate conveyor again at the machine outlet.

Figure 3.72 shows an automatically-chained machine with two workstations for hardening workpieces with two hardening zones, e.g. outer races or tulips, **Figure 3.73**, **Figure 3.74** and **Figure 3.75**.

For these workpieces usually a shaft and the tracks (contact surfaces) are hardened in the bell or in the tulip. These areas can be hardened with a single shot or a scanning process. Optionally, the two stations can be used for hardening and subsequent tempering. Here as well, the intermediate positions are available for cooling and/or blow-off.

3.3 Annealing

Dirk M. Schibisch, Gerd Ommer

3.3.1 Induction heating of strips

Induction heating during the metallic and non-metallic coating process for tubes, profiles and sheets is gaining importance for the continuous process due to its high cost-effectiveness. While the production volume of metallically coated sheet/strip has risen steadily worldwide since the early 1990s, the production of tinplate has stagnated with a downward trend. The market for organically coated strips or sheets, on the other hand, has developed positively in recent years.

The need for weight savings, particularly in the automotive industry, has driven the demand for higher quality sheet steel. "Coated sheets" are galvanized, aluminized and coil-coated sheet steel and tinplate.

The thinner the sheets used, for example in the automotive industry, the higher the requirements regarding quality of the corrosion protection and, hence, also coating. Sheet thicknesses under 0.5 mm require improved production processes and generally new production facilities. Particular importance has to be linked to reliable process control and continuous quality assurance right down the line. In order to ensure a stable process, the lines have to run continuously. The infeed method is expediently chosen for the metallic coating of strips – and induction heating is particularly suited for this process.

During induction heating the heat necessary to increase the temperature of the workpiece is generated directly in the workpiece and not applied via the strip surface as in classic heating methods. Induction coils with single-layer windings of water-cooled copper tube cast in refractory, polyurethane or epoxy resin compound are used to apply the necessary heating power, **Figure 3.76**.

The electricity flowing through the coil induces eddy currents in the strip which, depending on the selected frequency, heat the surface layer of the strip to differing depths. The strip thicknesses lie between 0.2 and 3.5 mm. The working frequency range of this system type, therefore, typically lies between 10 and 200 kHz. In the heating coil the current density is so high that water cooling has to be applied to dissipate heat losses.

Although the principle of induction strip heating using the longitudinal flux or transversal flux method is well-known, it was necessary particularly for metallically coated strips to adapt both the quality and the cost-effectiveness of the process control to meet the market trends outlined above.

On galvanizing lines an important role is played by the division and control of the induction heating section. In vertical, gas-tight induction heating furnaces the coil distance is expediently divided into three sections – namely the ascending inlet section, the center section with the strip return and the descending outlet section.

Each of these sections has its own easily controlled energy source with digitized IGBT (Insulated-gate bipolar transistor) frequency converters. The inlet and outlet section is designed in such a way that the majority of the heating is applied there. The center section is controlled and, thus, adapts itself to fluctuations in throughput.

The energy consumption decreases with narrower strips. In order that a constant strip throughput is possible even in this area, the power supply to the center section can be infinitely regulated. The reactive power component is covered by activating capacitors. The total power of the induction furnace is controlled in proportion to the throughput. With uniform strip dimensions, speed changes lead to a proportional power correction. With the same strip thickness and speed, changes in the strip width effect a change in power consumption in relation to the width but require less voltage correction. A change in strip thickness with constant speed, on the other hand, results in a sharp



Figure 3.76: Typical heating system for varnish and lacquer drying (Source: SMS Elotherm)

change in the line throughput and, hence, in the power requirement which can only be adjusted by means of a change in voltage. The different control functions for strip width and strip thickness changes are known and are reliably implemented with the frequency converters available today which can react to a sudden change in the voltage/power set point within ≤ 300 ms.

The entire process monitoring of the induction furnace and the evaluation and control of the system is handled by a PLC. Visualization and networking of the system controller and frequency converter via Ethernet (TCP/IP) for integration into the customer's Intranet, as well as teleservice access via Internet or telephone ISDN line with the integration e.g. of cameras, are indispensable parts of the overall concept today.

3.3.2 Inline seam annealing and normalizing

Modern process-optimized tube seam annealing systems, **Figure 3.77**, enable inline induction annealing of high-frequency welded tubes with wall thicknesses of up to 25 mm. Calculation programs enable a process-orientated system design in the project engineering phase which usually avoids the need for inductor changes. The basic requirements here are the right frequency, heating conductor width, orbital inductor tracking, **Figure 3.78**, and inductor zones with sufficient length.

The induced power is individually calculated and controlled by multi-zone technology with L-LC converters (from the circuit architecture: L for pre-choke and LC for parallel resonant circuit). In contrast to existing single-converter technology with the same power modules, this enables maximum power induction in every heating phase without surface overheating. It is, therefore, important to ensure for every material specification that the inner seam is reliably heated at least in the width of the wall thickness to the end of austenite formation at approximately 785 °C.



◀ **Figure 3.77:** Seam annealing for API tubes with NC-controlled positioning axis
(Source: SMS Elotherm)



Figure 3.78: Tube seam annealing with pilot line for orbital correction of the inductor position
(Source: SMS Elotherm)

L-LC converters offer a constant high power factor ($\cos \varphi > 0.95$) regardless of load conditions, including partial load operation. Mains harmonics are distinctly reduced by using 12-pulse L-LC converters.

Double annealing with quenching station

Heat treatment of the high-frequency welded seam region is necessary in order to match its mechanical properties to those of the tube.

In the past, single-stage induction seam annealing was followed by normalizing in a continuous furnace.

Multi-stage induction annealing with water quenching, also known as double annealing, yields a fine grain structure and, therefore, high impact strength, **Figure 3.79**. Multi-stage annealing provides a high statistical confidence level in the event that tube manufacturers are held liable due to possible annealing defects.

Repeating the alpha-gamma transformation process (alpha-gamma transformation starts at approximately 723 °C and ends at approximately 785 °C) in multi-stage annealing with water quenching greatly improves the quality of the seam.

In order to achieve the toughness properties of the parent metal in the weld area, the heated seam region must be water-quenched at higher than the critical cooling rate after annealing and then reheated above A_{C3} .

The demand for higher notch impact strength can be met in practice only with the fine grain structure achieved by double annealing with intermediate cooling.

In induction double annealing with water quenching after the first annealing stage, fine carbide precipitates in a fine crystalline matrix and generates the desired favorable combination of strength and toughness.

Hardness values above 300 HV can be achieved after normalization. After the double annealing process, the hardness between the inside and outside surfaces in the seam region is approximately 180 to 200 HV which corresponds to the hardness of the parent metal.

No yield strength loss occurs in thermo-mechanically treated steels after induction double annealing of the seam region, unlike the situation with furnace annealing of tubes.

Dual annealing with cooling section

There is increasing demand for weld seam and full body annealing to achieve homogeneous material properties. The newly launched “dual annealing with cooling” system combines induction full body annealing with and seam annealing.

Modern internal scraper systems with coolant return are an essential element here. Even with tubes under 30 mm in diameter, it is now possible to reliably achieve a uniformly annealed structure both in the weld seam and over the tube cross-section, with full body heating of tubes without internal liquids. Full body heating is used for tubes with outside diameters up to approximately 40 mm, while induction seam annealing is used for larger diameters to save energy. Converters, preferably with L-LC technology, are used as the energy source for both annealing processes.

The dual annealing system is designed to be used with either round coils or linear inductors with field concentrators matched to the weld seam.

An energy source with a common cooling water system for induction full body and seam annealing enables a cost-effective system design with a small footprint and optimal adaptation to individual annealing requirements in the temperature range extending from 500°C for recrystallization annealing to 1,200°C for diffusion annealing.

Annealing processes in an inert gas atmosphere

Inline tube annealing processes are performed in a nitrogen atmosphere to prevent scale formation, while bright annealing requires a reducing hydrogen/argon atmosphere.

For the manufacture of brake pipes, the tubing is sized to a final diameter of 8.0, 6.35 or 4.75 mm after HF welding at a rate of approximately 100 m/min. The sized tubes are induction-annealed in a nitrogen atmosphere at temperatures above A_{C3} and subsequently chilled to below 100°C in double-walled, water-cooled chilling tubes.

Inline bright annealing of tubes is normally applied for tubes made of austenitic stainless steels, duplex steels, nickel alloys and titanium due to the limited welding rate of TIG and laser welding systems (up to 20 m/min). The range of wall thicknesses is 0.5 to 6.0 mm, especially for tube diameters from 5.0 to 114 mm. For economic reasons induction annealing is no longer used for larger tube diameters due to high gas consumption.

Inline bright annealing is integrated in continuous tube production processes and, as an independent unit, can be retrofitted in existing tube production lines.

Bright annealing creates a corrosion-resistant seam while retaining the bright surface of the tube. The process requires a bright tube at the inlet of the induction zone. If necessary, a washing unit



Figure 3.79: Weld on a longitudinally welded pipe with subsequent double-annealing (micro-section etched in order to show the ferrite line)
(Source: SMS Elotherm)

with a tank containing a suitable, heated solution must be used. This removes dirt, oil and grease from the tube surface as well as dries it.

It is essential that the tube transport system keeps the tube in equilibrium throughout the entire annealing process, i.e. the same compressive and tensile forces must be present when the tube is fed into the heating zone and when it is removed from the annealing and cooling zone in order to prevent tube compression, tapering or tearing at annealing temperatures between 1,100 and 1,300°C.

In the inert gas chamber the metallic bright tube passes through controlled induction heating and soaking zones. Heating to the required annealing temperature takes place in the chambers with the exclusion of oxygen and a reducing atmosphere.

Argon, hydrogen or a mixture of these gases can be used as inert gas. Hydrogen gas is burned off upon leaving the chamber. Argon, an inert gas used for welding, is used inside the tube to protect the inner surface against oxidation in the annealed area.

After a short soaking zone, the red-hot tube is rapidly cooled below the oxidation threshold by special cooling elements in three stages. This cooling process also takes place with the exclusion of oxygen. Residual cooling of the tube to room temperature is done in a water spray chamber.

3.4 Induction heat treatment of tube and bar material

Dirk M. Schibisch, Stefan Dappen

Induction heat treatment for tubular and bar material, called quench and temper, has by now become established mainly in those application areas where precise, fast, flexible and reproducible heat treatment for long products is required.

At first induction hardening was used only for automobile components, such as stabilizers, in which consistent hardness and microstructure are required in the workpiece for the cold bending process.

After induction hardening of bar steel gradually became established in the industry, the process was also developed for tube products, e.g. for seamless tubes and tubes with induction welded longitudinal seam. Because the results were so convincing in comparison to conventional processes in furnaces and also because of the booming market in the area of OCTG products (Oil Country Tubular Goods) for oil and gas exploration, the induction hardening process for tube material has become completely established in the last few years. Processes have also been developed for tubes that are slightly upset on one end and, thus, involve special requirements for the induction heating process.

3.4.1 Basic structure of a quenching & tempering system

A typical quenching and tempering induction system is generally designed for a throughput of 1 to 20 tons per hour, **Figure 3.80**. The flexibility of the process also allows for smaller partial throughputs or even less tonnage.

In principle, a quenching and tempering induction system consists of the following components:

- A separating and loading table on which the bundles are placed and separated and the individual bars or tubes are supplied to the following roller way.
- A system made of several specifically designed roller ways that are designed so that the tubes / bars are transported through all the heat treatment steps.

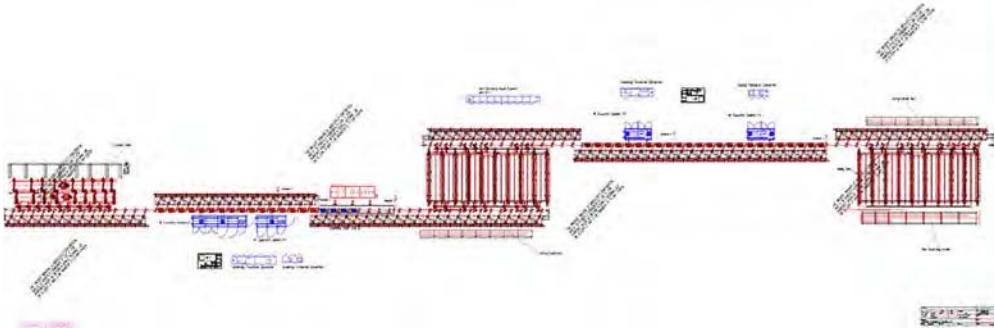


Figure 3.80: Layout of a typical Q & T induction line for long products (source: SMS Elotherm)

- Several IGBT (insulated-gate bipolar transistor) converters which supply the electrical power at the required frequencies for the austenitizing, tempering and soaking zones. The IGBT is a cross between a conventional Bipolar Junction Transistor and a Field Effect Transistor (MOS-FET) making it ideal as a semiconductor switching device. It takes the best parts of these two types of transistors, the high input impedance and high switching speeds of a MOSFET with the low saturation voltage of a bipolar transistor and combines them together to produce another type of transistor switching device that is capable of handling large collector-emitter currents with virtually zero gate current drive. There are several inductor lines, each consisting of individual heating coils through which the tubes/bars run in order to be brought to the austenitizing, tempering and soaking temperature.
- A quenching station with specifically designed spray heads for quenching the material from austenitizing temperature to ambient temperature.
- In case of quench and temper tubular goods, there is a draining table between the quenching and the tempering section.
- A cooling bed with subsequent collecting bed to cool the workpieces coming from the tempering or soaking zone by natural convection and to bundle them in an appropriate way after that.

3.4.2 Advantages of induction heat treatment

Induction hardening of long products is advantageous for the operator in many ways in comparison to conventional methods in furnaces with fossil-fuel firing. The important differences, which effect ongoing savings in production, are described briefly below:

Flexibility

In modern integrated tube plants current demands for reducing stock material and the large number of different materials lead to a flexible just-in-time manufacturing strategy with small charges of 30 to 50 tons.

In many cases this means that several charges daily of different material dimensions and grades have to be heat treated at different tempering temperatures. Here the limits of combustion furnaces are quickly reached since these cannot react flexibly to different lot sizes and temperature adjustments can only be achieved very slowly.

The advantages of induction technology are especially clearly recognizable if flexible manufacturing lots are involved. During a change of charges the entire induction system is run clear within a few minutes and the next charge is set up within short time. For this purpose fast change tool systems are available to the operator that ensure that a changeover can be made to energy-efficient heating coils with suitable diameters quickly.

In this context, another advantage of induction is the fast and simple determination of heat treatment recipes for new materials or component geometries. This means test productions or quality verifications can be performed for customers at minimal costs which in turn give them a competitive advantage.

Constant throughput for all dimensions

In a fossil-fuel fired chamber furnace or fossil-fuel fired continuous furnace the entire furnace chamber has to be brought to the proper temperature and, thus, good efficiency is only achieved with full loads. An induction quenching and tempering system reacts flexibly to different lot sizes and dimensions.

An induction quenching and tempering system, which is designed for a throughput of, for example, 13 t/h and can process workpieces with outer diameters of 3 to 9 inches, is able to achieve 13 t/h with 3-inch tubes or with 9-inch tubes.

This is possible because induction generates the heat directly in the workpiece and it does not have to be supplied from outside. In this process the long material runs through the induction coils at a speed adjusted to the respective diameter and, thus, is heated thoroughly and/or brought to the material-specific austenitizing or tempering temperature in a few seconds.

Only induction hardening makes it possible for the operator to always use its system optimally since production can occur with maximum throughput independent of the material dimensions in most cases.

Nonetheless, if partial throughputs have to be run because the production lot is small, mature converter technology with the Elotherm zone technology iZone™ also allows specific coil lines to be switched off. Because of this only the required minimal energy for heating a defined material quantity is consumed which is seen not only directly by the reduction of production costs but also by the reduction of CO₂ emissions.

It is just these last two points that clearly differentiate induction technology from fossil-fuel fired furnaces which must always be kept at the maximum temperature no matter what the charge size or the furnace fill and, furthermore, cannot be switched on and off easily depending on requirements.

Homogeneity of material hardness and microstructure

An induction heat-treated workpiece is distinguished by very homogeneous microstructure and hardness.

Evaluation of the Rockwell hardness over the entire cross-section and across the entire long product generally reveals a small variance only. **Figure 3.81** shows such an example of a very homogeneous microstructure after induction heat treatment.

However, these results are not actually based exclusively on the induction principle alone but rather basically on the combination of process technology with mechanical and electrical design of the induction system adapted to it.

Regarding the induction hardening technology described here, the product to be heat-treated runs sequentially through the entire process consisting of austenitizing, tempering and possibly also

soaking. In this process each incremental cross-section of the long product experiences identical heating and quenching conditions since the throughput speed is constant over the entire process. This effects the appropriately high homogeneity related to the hardness and microstructure of the material.

Strength and notch impact strength – even with nickel-chrome steel

In fossil-fuel fired systems, the tempering process takes place within a temperature range of 400 to 600 °C over a long period of time in order to achieve a decrease in hardness and/or tensile strength because of the structure conversion after a soaking.

However, an undesirable side effect is the so-called “tempering brittleness” which greatly reduces notch impact strength. This effect occurs due to the separation and recrystallization of carbides at the grain boundaries during the conversion of the microstructure, especially with nickel-chrome steels that are susceptible to this.

In contrast to this there is the induction quenching & tempering process. Here the critical temperature range between 400 and 600 °C can be run through so quickly that the described tempering brittleness cannot occur. The separation of carbides does not occur; the material maintains its good strength characteristics and notch impact strength without becoming brittle.

Therefore, for example, safety-relevant elements on offshore platforms for oil and natural gas production are heat-treated with the described induction technology.

Heat treatment without edge decarburization

Due to the long dwell time of the heat-treated product at high temperatures, in fossil-fuel fired furnaces normally an undesirable edge decarburization of the heat-treated product occurs. This negative effect weakens the workpiece in the area close to the surface and leads to an inhomogeneous hardness over the entire cross-section of the material.

Such decarburization does not occur during induction hardening since the material remains at high temperature for only a very short period of time. The two micrographs below serve as an example, **Figure 3.82**.

Figure 3.82 (left) shows a cold-drawn bar out of 41Cr4 steel. On the surface there are white areas (ferrite accumulations) which developed due to edge decarburization during the rolling process.

Figure 3.82 (right), having the same 160 x enlargement, shows the same bar after running through the induction quenching and tempering process. It is obvious that the martensitic microstructure created by heat treatment does not contribute to further decarburization of the edge area but, on the contrary, it even reduces the ferrite accumulations.

Because of the short heating and dwell time at austenitizing temperature, scale formation during heating is also minimized. This not only makes the material yield higher overall; mainly it extends the service life of the roller ways. In conventional heat treatment systems these transport units are

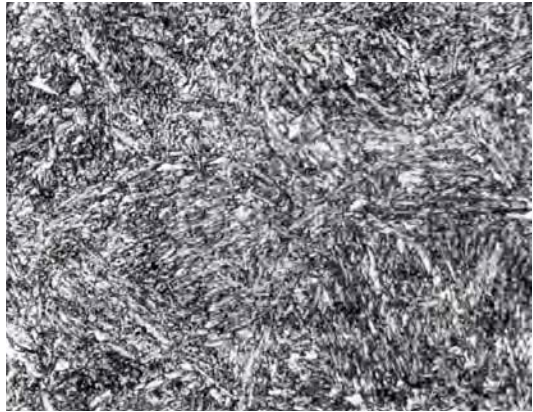


Figure 3.81: Microstructure of a bar steel out of 41Cr4 after quenching and tempering (1,000 x enlargement)

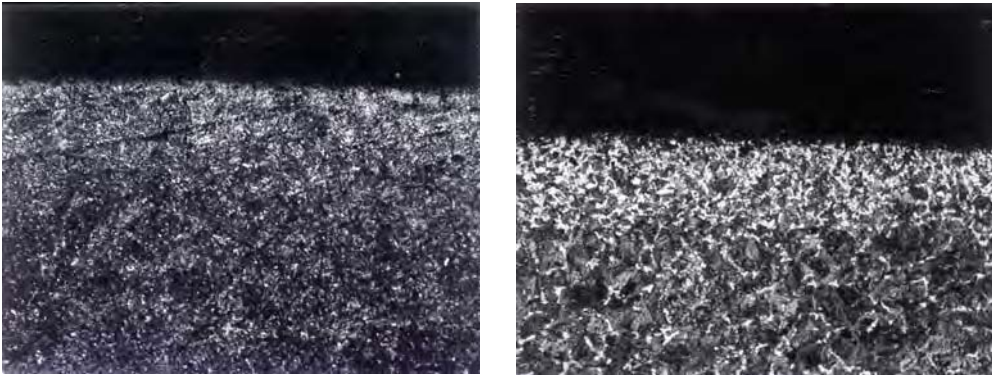


Figure 3.82: Microstructure of a cold-drawn rough bar out of 41Cr4 (160 x enlargement), left before and right after induction heat treatment

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greatly stressed by the intensive abrasive effect of the hard brittle scale and they wear quickly. Thus, the rollers have to be reworked and/or replaced often.

Minimal maintenance costs

In comparison to fossil-fuel fired furnaces, which are continuously exposed to very high temperatures and, thus, subject to intensive maintenance, in induction hardening systems all components are water-cooled that come into the area of the product to be heated. This means both the copper heating coils, the rollers of the transport unit, the electrical components of the converter and/or of the capacitor unit are water-cooled and, thus, protected from thermal stress.

The repair effort is minimal and the system is characterized by very high availability.

The installation effort for the induction system is already very low since no complicated preparations of the set-up location or foundation work are necessary. After that, a brief process-related initial start-up of the system occurs. This means that a customer can already produce commercially-viable, heat-treated products six weeks after delivery.

3.4.3 Innovative solutions for new products

Since in the last few years more and more fossil-fuel fired heat treatment systems for bar steel and tube material have been replaced by induction technology and the operators have been able to realize the production cost savings described, there is now a search for solutions that can transfer the advantages of induction to more complex components as well.

Recently, induction solutions have been developed which make it possible to heat seamless tubes with slightly upset ends so that homogeneous heating can create the desired material properties.

Tubes with upset ends

The special challenge for the induction process is the weight difference between the straight tube elements and the upset ends.



Figure 3.83: Seamless, thick wall tubes after induction heat treatment



Figure 3.84: The result of the quenching & tempering process of tubes with upset ends

In order to have a uniform austenitizing temperature and homogeneous hardness and microstructure conditions after the tempering, additional heating of the upset ends is necessary.

For this purpose induction preheating coils are arranged in front of the actual austenitizing system. These induction coils are supplied with power by separate IGBT converters that provide an average working frequency adjusted to the upset ends and, thus, the upset material is induction preheated.

Using an integrated position control, the position of the upset ends is detected precisely although the tubes are transported through the entire system without gaps. This ensures that in the preheating units only the actually upset, i.e. thicker, tube areas are heated and the rest of the tube body remains approximately at ambient temperature. The preheating temperature can be adjusted flexibly according to the upset tube end.

After being preheated this way, the tube runs into the actual austenitizing area and is then heated uniformly to the conversion temperature over its entire cross-section.

The subsequent quenching process and tempering with the subsequent cooling in air on special cooling beds are very similar to the process already described. **Figure 3.83.**

Again, the result of this special induction hardening process is a product with very good mechanical properties and homogeneous hardness and microstructure – along the entire tube and over the different cross-sections, **Figure 3.84.**

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4. Joining and cutting

4. Joining and cutting

This chapter describes several methods for joining and cutting of materials. The focus is on the areas of inductive soldering and brazing, induction heating in bonding technology, induction heating for shrinking and various induction methods for welding. Among the latter are the since many years in practice well-established longitudinal seam welding of pipes, a relatively new method for laser welding with inductive assistance, a method for welding with inductive preheating and a new inductive heating method of pressure welding (Predox welding).

4.1 Inductive soldering and brazing

Roland Waitz, Hans Windsheimer, Branko Petric, Horst Linn

One of the most important methods of joining parts made of the same or different materials is brazing (brazing temperatures $> 450^{\circ}\text{C}$) or soldering (soldering temperatures $< 450^{\circ}\text{C}$). The possibility to create a soldering connection is not only limited to metals. Even connections between glass/glass, glass/metal, ceramics/ceramics, graphite/metal or hard metal/diamond can be realized with suitable solders. In contrast to welding, the connection is made by a third component with a melting point lower than the melting point of the materials to be joined. Such connections are solid. However, in most cases it is possible to separate the soldered parts again by heating.

Inductive heating is possible in most soldering processes when one component is electrically conductive and the soldering area can be surrounded to largest extent by the induction coil. Depending on material and used frequency, every component should have a certain thickness in order to be able to absorb and evenly spread the induction power. Another limitation can be electronic components near the soldering point as they can be damaged due to induced currents.

The main advantages compared to furnace brazing are:

- Good automation
- The process can be easily adapted to continuous production processes
- Only one or few workpiece carriers are needed
- It is not necessary to heat up the complete workpiece.

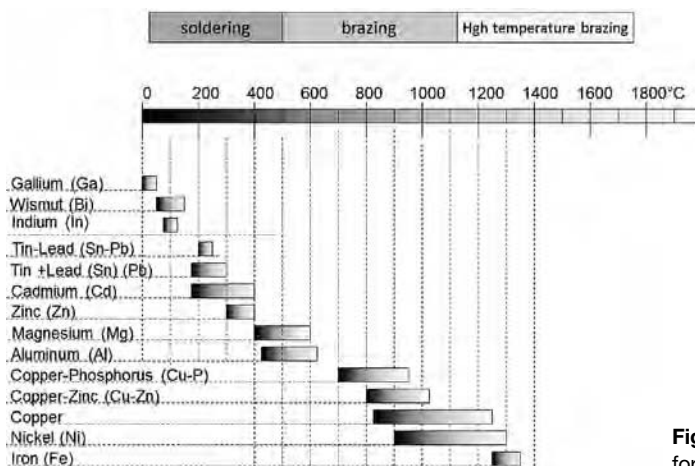


Figure 4.1: Solder/brazing alloys for various temperature ranges

For selection of the solder and the adequate flux, the same rules are valid as in case of furnace or flame brazing. Despite a higher price, use of silver-containing braze mostly offers advantages compared to copper braze due to the low melting point as time, generator power and energy are saved. **Figure 4.1** shows an overview of common brazing solders.

The basis for professional inductive brazing already has to be established in the construction of the component to be soldered. Form and width of the brazing fit, brazing depot as well as surface condition are decisive.

Inductive flux-free brazing can be realized by protective gas showers respectively protective gas or vacuum chambers.

4.1.1 Particular features in case of inductive brazing

In case of inductive brazing, the following special characteristics are valid:

- The design of cross section and form needs to enable good approach of the induction coil to the brazing point.
- Heating is effected in very short time from outside. In case of brazing of concentric parts, the brazing gap is widened as the outer part is heated up earlier and expands automatically while the inner part is only heated decisively with the capillary penetration of the solder through heat conductivity.
- When using brazing rings, they should be interrupted as they otherwise heat up too fast due to high induced currents before the basic material is heated sufficiently.

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4.1.2 Brazing gap and solder materials

The form of a soldering connection and the size of the soldering gap have great influence on the quality of an inductively soldered product. In principle, there is a better soldering connection when the gap is very narrow. However, there has to be a minimum gap size in order to enable the flow of the solder. In **Table 4.1** you can find the necessary gap sizes.

The brazing gap should have a uniform thickness or should narrow in flow direction of the braze (**Figure 4.2**). The different thermal expansion of the metals has to be considered when calculating the size of the soldering gap. In case of extremely differing thermal expansion, e.g. pairing of hard metal ($5 \cdot 10^{-6} - 7 \cdot 10^{-6} \text{ K}^{-1}$) with steel ($11 \cdot 10^{-6} - 14 \cdot 10^{-6} \text{ K}^{-1}$), it is advantageous to increase the gap width and to use sandwich alloys based on silver with low melting point.

Solder	Material of the parts to be connected				
	Copper	Copper-alloys	C-steels	Stainless steels	Al and Al-alloys
Cu	–	–	0.01 ... 0.05	0.02 ... 0.07	–
MS	0.08 ... 0.04	0.08 ... 0.4	0.08 ... 0.3	0.1 ... 0.35	–
Cu-P	0.05 ... 0.2	0.08 ... 0.3	–	–	–
Ag	0.05 ... 0.25	0.05 ... 0.25	0.05 ... 0.3	0.08 ... 0.25	–
Al					0.1 ... 0.6
*Flux-free soldering mostly enables smaller soldering gaps					

Table 4.1: Recommended gap width for soldering with soldering flux* in mm for different materials

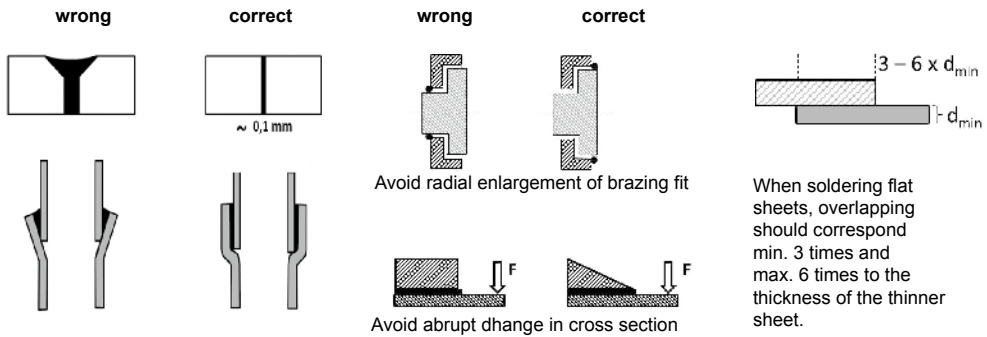


Figure 4.2: Recommendation for design of soldering/brazing gaps

The solder quantity needs to be calculated so that the complete soldering gap can be filled. In case of soldering of concentric objects with soldering wire, the cross section of the soldering wire has to correspond to the product regarding gap width b and soldering point depth t .

$$b \cdot t = \pi \cdot \frac{d^2}{4} \quad (4.1)$$

This is valid for round soldering wire. The diameter d can be calculated easily:

$$d = 2 \cdot \left(\frac{b \cdot r}{\pi} \right)^{\frac{1}{2}} \quad (4.2)$$

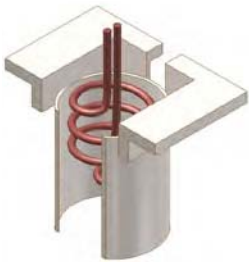
Main alloy proportion of hard solders	Copper (Cu)	Silver (Ag)	Nickel (Ni)	Cobalt (Co)	Aluminium (Al)
Soldering temperature in °C	705-1,150	620-980	927-1,205	1,175-1,245	570-620
Max. application temperature in °C	370	370	980*	1,040	150
Application	High alloyed steels, stainless steels, tool steels, unalloyed steels, cast iron, Cu-/Ni-alloys	High alloyed steels, stainless steels, tool steels, steel, cast iron, Cu-/Ni-alloys	High alloyed steels, unalloyed steels, stainless steels, tool steels, Cu-/Ni-/Co-alloys	Co-alloys	Al-alloys
Atmosphere in case of protective gas resp. vacuum soldering	Cracked ammonia gas, hydrogen, endo-/exogas, Argon, Nitrogen, vacuum	Cracked ammonia gas, hydrogen, endo-/exogas, Argon, Nitrogen, vacuum	Cracked ammonia gas, hydrogen, Argon, Nitrogen, vacuum	hydrogen, Argon, nitrogen, vacuum	vacuum
* Max. application temperature of the nickel braze with highest heat resistance					

Table 4.2: The most important brazes (according to main alloy element) and their application [4.2]

The strength of the soldering points depends on the following factors:

- strength of basic metal
- strength of soldering material
- width of soldering gap
- size of soldering area
- stress optimized design of soldering connection
- perfect connection between solder and basic material.

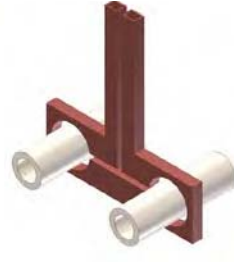
The last point depends on the surface condition – clean and oxide free – as well as on the selection of the correct solder. In **Table 4.2**, the characteristics of the most important brazes are listed. The surface can be cleaned mechanically, chemically or by ultrasound before soldering process. Soldering points can be kept oxide-free by soldering fluxes or by suitable protective gas atmospheres respectively vacuum.



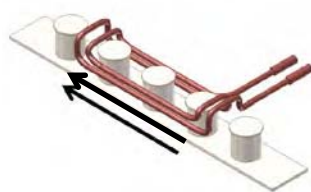
Inside inductor



*Inductor for double heating
solder lid on housing*



*One-winded inductor for
simultaneous soldering of
two workpieces*



*Inductor for continuous
heating in passage*



*Flat inductor "pancake coil" for
surface heating*



*Inductor for soldering of
hard metal*



Inductor for extensive heating



*One-winded inductor for specific
heating of a soldered seam*



*Inductor for soldering of
hard metal*

Figure 4.3: Inductor shapes often used for soldering and brazing

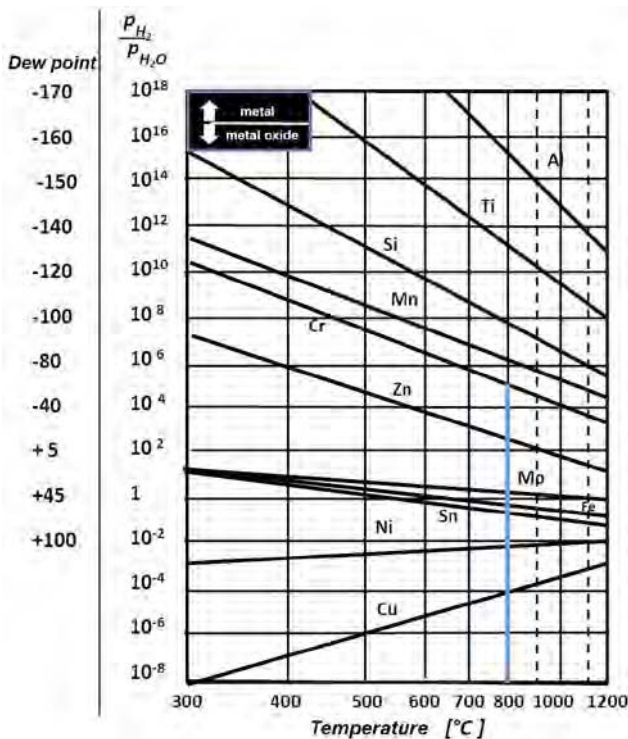


Figure 4.4: Oxidation/ reduction of selected metals in hydrogen atmosphere depending on dew point resp. H_2/H_2O -ratio (modified Ellingham-diagram [4.1])

4.1.3 Inductors for soldering/brazing

Inductive heating is always local heating. This results in uneven expansion which, in turn, results in deformation which might render the workpiece unusable. Therefore, the inductors have to be designed such that the area around the soldering point is heated as uniformly as possible regarding space and time.

In case of uneven heating, two cases principally might occur. If one section is too cold, the solder only melts partly or the cold section is not wetted by the solder. If one part is too warm, alloy components of the solder can evaporate and the solder might flow uncontrolled. Moreover, it might be that the workpiece deforms due to increased thermal stresses. **Figure 4.3** shows various induction coil designs which are characteristic for inductive soldering/brazing.

4.1.4 Soldering and brazing in protective gas and vacuum

In order to receive blank parts after the soldering process, vacuum or protective gas atmospheres are used instead of a soldering flux. Depending on filler and basic material, protective gases with purity 99.99 % (gas quality N4) or 99.999 % (gas quality N5) are used. The purity requirement increases with decreasing soldering temperature. Soldering of stainless steel with a soldering temperature of 800 °C requires hydrogen gas with a purity of min. 99.999 % (quality N5, dew point -60 °C). In case of 1,000 °C, gas with a purity of 99.99 % (dew point von -40 °C, quality N4) would be sufficient. **Figure 4.4** shows the oxidation/ reduction of selected metals in hydrogen atmosphere depending on dew point resp. H_2/H_2O -ratio.

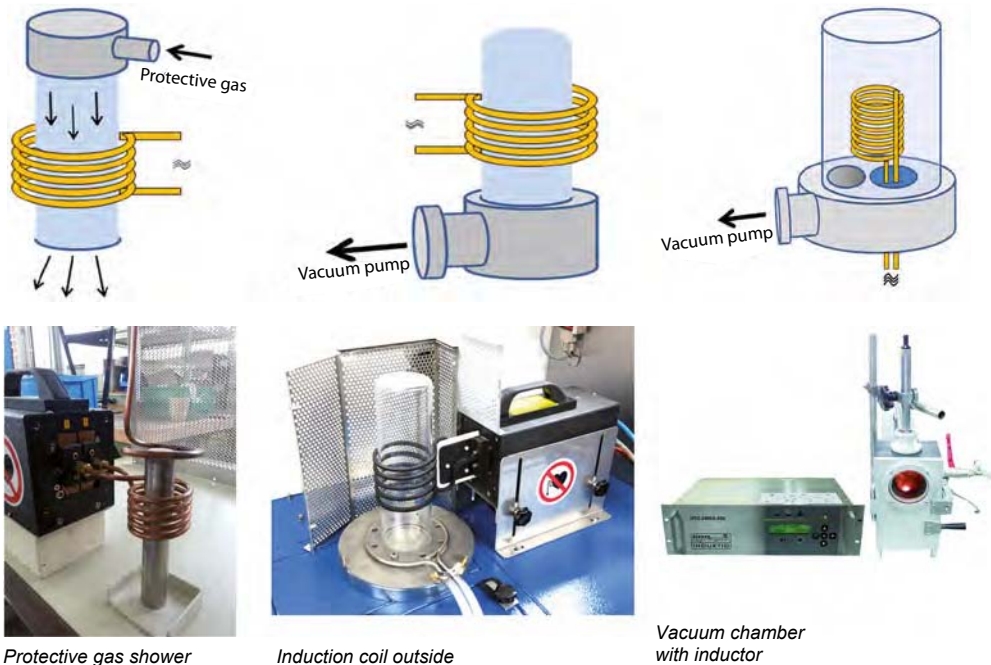


Figure 4.5: Schematic diagram as well as real designs for creation of a protective gas atmosphere or vacuum in case of inductive soldering

In the simplest case, a protective gas atmosphere can be created by a protective gas shower. The equipment requirement is not very complex, however, protective gas consumption is substantial.

For vacuum applications as well as for reduced protective gas requirement, a “hood” made of borosilicate or quartz glass is appropriate. It is advantageous to install the coil outside of the hood as the volume which has to be evacuated is minimized.

If the inductor has to be installed inside of the vacuum vessel, it makes sense to connect the inductor via the bottom plate and to equally use a non-metallic hood. In case of a chamber consisting exclusively of metal, the wall distance to the inductor has to be adequate. If the induction coil is installed in the vacuum vessel, the coil should be cooled with tempered water (water temperature > room temperature) which prevents that in case of opened hood condensed water sets down on the coil which evaporates during vacuum operation and has to be removed as gas (1 g water in case of 10^{-4} mbar corresponds to a water vapour volume of app. 12,500 m³ which has to be removed!).

Figure 4.5 shows various principle solutions for the application of vacuum and protective gas.

The evacuation time to 10^{-4} mbar for a clean, dry chamber made of stainless steel (electropolished) or quartz glass with a volume of 5 l is approximately 10 s when using a modern vacuum pump stand consisting of a pre-pump with a nominal suction capacity of 32 m³/h and a turbo pump with a nominal suction capacity of 200 l/s.

In case of components which have to be evacuated later on, the vacuum can be created already during the brazing process. Pre-evacuation even makes sense in case of protective gas operation as the purging gas quantity can be decreased by factor 6 – 10 depending on required purity (see **Table 4.3**).

Purging factor*	Residual oxygen in %	Dew point in °C	Vacuum in mbar	Gas quality
0	21	+61	1,031	
1	7.7	+40	378	
2	2.8	+23	137	
4	0.38	−5	18	
6	0.05	−26	2.4	N3
8	0.007	−45	3×10^{-1}	N4
10	0.0009	−61	5×10^{-2}	N5
16	0.00006	−80	3×10^{-4}	N6

* The purging factor is the ratio (purging gas volume current x purging time)/container volume

Table 4.3: Comparison of achievable residual oxygen content by purging or by evacuation as well as the corresponding dew points and gas qualities

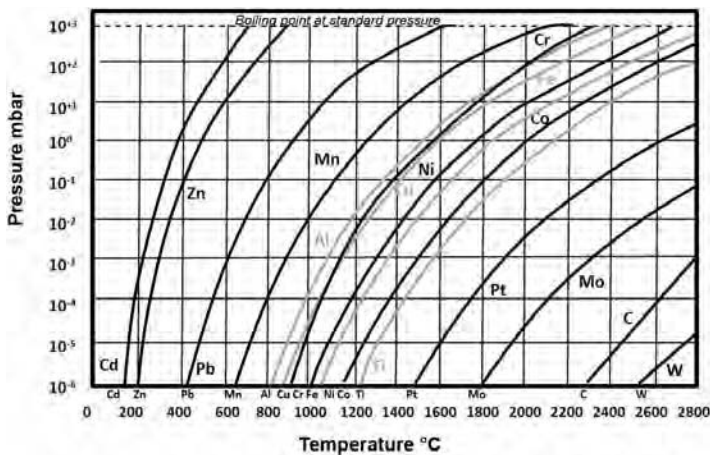


Figure 4.6: Vapour pressures of selected metals depending on temperature [4.2]

In case of vacuum atmosphere, special emphasis has to be put on the selection of the braze. At brazing temperature, the vapour pressure of single alloy elements may not or only be slightly higher than the applied vacuum which results in strong evaporation. **Figure 4.6** shows the vapour pressures of some metals depending on temperature. The diagram shows that, for instance, zinc containing solders cannot be used with vacuum.

Another undesired effect may be ignition of plasma. Paschen's law (**Figure 4.7**) shows the relation between the breakdown voltage U and the product of the gas pressure p and the distance d of the components acting as electrodes, whereby a pronounced minimum exists. Practically, this relation means for inductive soldering furnaces with higher induction coil voltages ($> 250 - 400$ V) that a vacuum range of 10^{-1} to 10^{-3} mbar should be avoided.

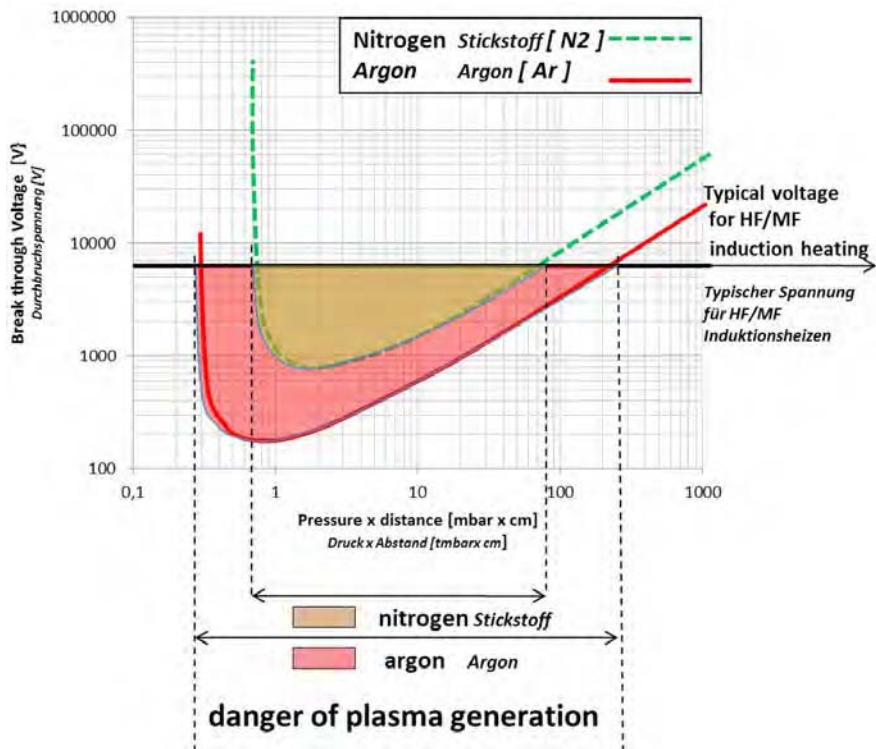


Figure 4.7: Paschen's law for description of electric break-throughs, according to [4.3]



Figure 4.8: Inductive brazing with two frequencies of parts for automotive air-conditioning

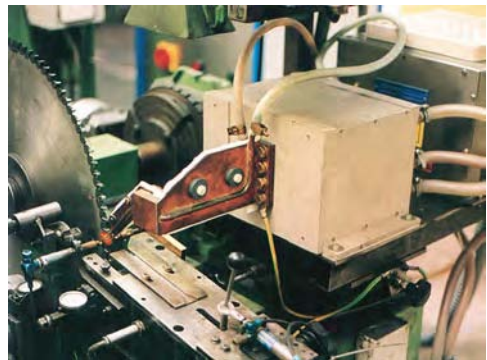


Figure 4.9: Induction brazing unit for soldering of small diamond plates on masonry saws

4.1.5 Applications

Inductive brazing has many applications in modern production. The most important advantages compared to other processes are in the mass production of soldering parts such as automotive applications like air-conditioning (**Figure 4.8**), in case of hard metal and diamond tools production, core bits, masonry saws (**Figure 4.9**), freezers and armatures (**Figure 4.10**). The coil shown in Figure 4.8 consists of several areas with different diameters as well as winding numbers and simultaneously realizes two different working frequencies in the workpieces to be treated.



Figure 4.10: Mixer tap for water armatures

4.2 Induction in bonding technology

Christian Lammel

4.2.1 Introduction

Bonding as a technology for joining parts is gaining increasing importance in important industrial sectors in Germany. Bonding has become established in the key industry automotive engineering in particular and is the only technology for joining parts that can consistently implement the desired lightweight design, both in relation to the materials and in relation to the design of the components. However, in automotive body assembly it is mostly necessary to combine a second spot joining process with the bonding so that the cycle time can be met; this combination is necessary due to the protracted curing process of structural adhesives. On many production lines with high volumes, the usage of liquid adhesives causes process-related problems. These limitations can be eliminated with the aid of induction technology.

In addition, it is described in the following how this heating process can be used to make the repair of structurally bonded vehicles quicker and cheaper in future.

4.2.2 Fast bonding using induction

To be able to integrate bonding as a technology for joining parts straightforwardly and safely into series-production processes, it is necessary that the bonded joints reach handling strength within the cycle time. Some types of adhesive such as cyanoacrylates ("superglues") or pressure-sensitive adhesives meet this requirement – however they are not suitable for every application.

If the specification requires the usage of structural (force-transmitting) liquid adhesives, their curing speed is mostly not high enough to fix the components within the cycle time. Such chemically reacting adhesives could be accelerated, however, this action would degrade the storage conditions (shorter shelf life, lower storage temperatures) and make processing difficult if not almost impossible – particularly at the heat of summer – due to the increased reactivity.

For this reason bonding systems are needed that can be stored and processed easily, and that can be made to cure as quickly as possible at the required time using an external switch. Inductive heating can undertake this task perfectly.

Either a non-conductive adhesive layer is doped with suitable fillers and heated directly (**Figure 4.11, right**) or the adherends are heated and conduct the heat to the adhesive. Typically, adherend heating is preferred, as the heating of the adhesive layer requires adherends that cannot be heated by induction, the efficiency of the heating is very low and temperature control can only be implemented with difficulty, because the temperature of the adhesive layer of adhesive between the adherends cannot be measured easily.

For this reason – depending on the thickness of the adhesive layer – either one or both adherends must be heated inductively to be able to accelerate the curing of the bond line. This technique works very well, as most adherend materials that are of interest technically can be heated straightforwardly and quickly using induction. The following are used

1. Ferromagnetic metals (steel)
2. All other metals (aluminium, magnesium ...)
3. CFRP parts (can be heated due to the electrically conductive carbon fibre component)
4. Non-conductive materials doped with suitable particles (nanoferrites).

Here 1 can be heated excellently, 2 can be heated well to moderately well, 3 can be heated moderately well and 4 can be heated relatively poorly. The efficiency drops from 75 % for ferromagnetic steel to less than 1 % for particle-doped layers of adhesive.

The acceleration of the cross-linking of chemically reacting adhesives is based on faster chemical reactions at elevated temperatures due to the greater particle movement. The Noble Prize winner Svante Arrhenius identified this relationship in 1889 and represented it mathematically in the Arrhenius equation named after him (4.3), where k expresses the rate constant of the reaction.

$$k = Ae^{\frac{-Ea}{RT}} \quad (4.3)$$

Ea stands for the activation energy; R stands for the universal gas constant (8.314 J/mol K), T stands for the absolute temperature in Kelvin, A stands for the pre-exponential factor or frequency factor. It is valid for

$$A = p \cdot Z,$$

where Z represents the collision frequency and p a steric factor. Z is found to be only weakly dependently on the reaction temperature. Therefore the frequency factor represents a constant for the related reaction.

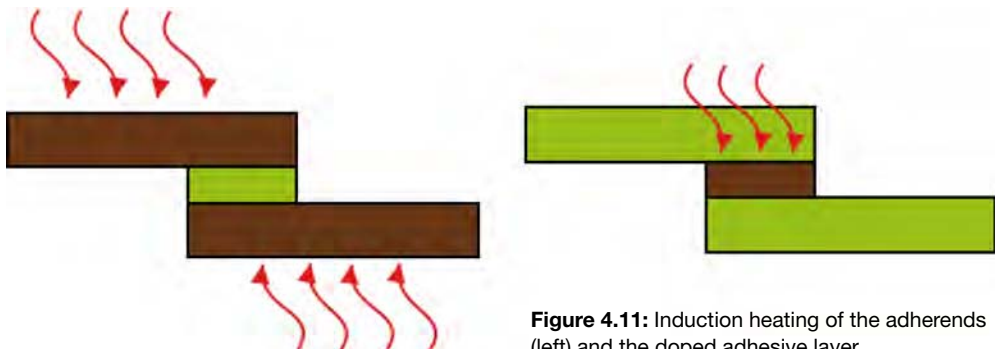


Figure 4.11: Induction heating of the adherends (left) and the doped adhesive layer

As this formula is a little difficult to use, a helpful rule of thumb has been developed for practical use, this is:

A temperature increase of 10 °C doubles the rate of reaction!

To calculate the acceleration that can be obtained by specific heating (rate of constant of the reaction rate k) the following formula can therefore be used:

$$k = 2^n \quad (4.4)$$

(n corresponds to the number of 10-degree steps)

For example, this formula means that with a temperature increase of 80 °C, the reaction will be 2^8 that is 256-times (!) faster than at the initial temperature. This situation has the consequence that, on heating the layer of adhesive to 100 °C, the cross-linking time reduces from 20 min to barely 5 s, while the working time and storage time of the adhesive remain the same – an unbelievably effective process advantage.

Qualification of adhesives

In principle, the process works for all heat-curing structural adhesives; the greatest benefit is obtained with two-component adhesives that cure only due to mixing the components without further heating. Here the inductive heat not only results in the acceleration of the curing reaction, but also better adhesion to the heated adherends.

However, it must be noted that a heating rate of 20 K per second should not be exceeded for standard adhesives, as this can cause the formation of bubbles in the adhesive due to volatile substances or overheating in the event of exothermic reactions during cross-linking. **Figure 4.12** shows a laboratory unit with integrated induction heating with this apparatus bonded specimens can be produced for testing according to DIN EN 1465 using different heating parameters. In this way, the optimal curing conditions can be found and the adhesives and the bonding processes can be optimised for fast inductive bonding.

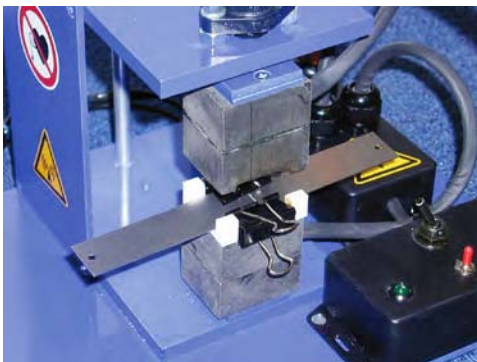


Figure 4.12: Induction apparatus for the qualification of adhesives



Figure 4.13: Industrial usage of fast bonding technology using induction

Once it has been demonstrated that the adhesive to be used can be inductively accelerated without degrading its properties such as crash stability or ageing resistance, the process is implemented in practice.

Figure 4.13 shows an industrial bonding workstation with an application from the electronics industry. This integral unit contains the adhesive application system (two control units and two application nozzles) and the inductive curing unit as a 19" generator (red ellipse). Also shown are the movable induction coil (small red ellipse) and the pyrometer (orange ellipse) for measuring the temperature.

4.2.3 Debonding of structural bonded joints using induction

Current separation methods for bonded joints

The current repair methods in the automotive sector can be divided into the categories mechanical separation for elastic thick film bonding (e.g. windscreen bonding) using an oscillating knife or wire and thermal-mechanical separation using a hot-air gun and chisel for structural bonding.

Cutting polyurethane beads for windscreen bonding works if undertaken properly, as the layer of adhesive is rubbery and a few millimetres thick.

For structural bonding comprising strong epoxy resin adhesives that are only a few tenths of a millimetre thick the current separation method (heating to weaken temporarily the adhesion and prising open using a chisel) is rather inadequate. It is also to some extent considerably more time consuming and causes significantly greater expense, as the components left on vehicle during the repair are damaged unnecessarily on opening the layer of adhesive and therefore need to be reworked.

Description of inductive debonding

To avoid this additional effort, an inductive separation process has been developed especially for structural thin film bonding; this process is based on the extreme heating rates that induction technology can offer.

To implement this method a hand-held inductor adapted to automotive flanges was developed; this inductor is supplied from a portable workshop generator (**Figure 4.14**).

Using this inductor, the bonded flange to be separated is sequentially heated (not at adjacent positions but at the positions marked in colour to prevent the build-up of heat) to around 250 to 300 °C using one-second heating processes, and that only on the side facing the inductor (**Figure 4.15**).

Figure 4.14: Fully encapsulated hand-held inductor and workshop generator



The adhesive layer and the metal sheet behind remain sufficiently cold that the adhesive does not discolour (and is definitely not pyrolised), and the paint finish on the component remaining on the vehicle is also not damaged.

The separation of the high-strength bonding is, as mentioned above, not based on burning the organic adhesive layer, but on the very significant thermal expansion of the heated metal sheet in fractions of a second. This expansion causes a very high shear stress in the adhesive layer and, as a consequence, the bonding strength of the adhesive is exceeded. This separation is supported by the heating of the metal sheet that causes heating and therefore weakening of the directly adjacent adhesion layer.

Accordingly, the inductive separation process causes thermally induced adhesive failure of the structural bonding. **Figure 4.16** shows this type of failure, which is optimal for the repair process. This type of failure is optimal because the component remaining on the vehicle is protected to the maximum and the effort for the next work steps is minimised. The straightening of parts that resulted with the previous repairing method is no longer required at all.

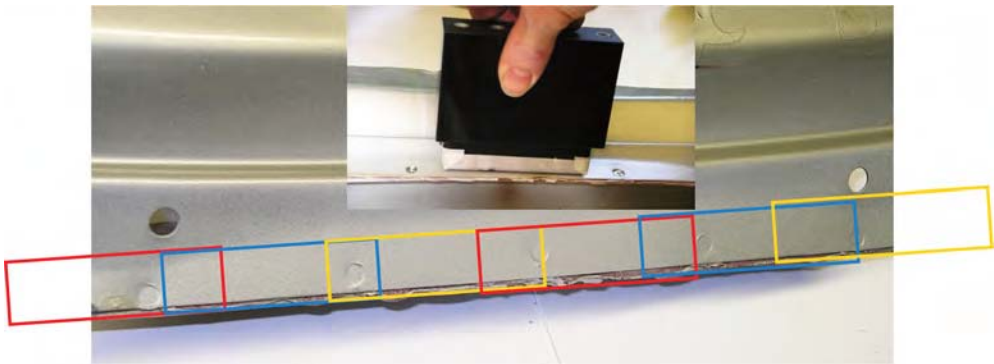


Figure 4.15: Inductor positions for opening the bonded flange



Figure 4.16: Separation of a structural bonding without adhesive pyrolysis

4.2.4 Summary

The work presented above is clear evidence that induction technology can be used to excellent effect to eliminate weaknesses in the processes for bonding technology – whether for the fast curing of series-production bonding that must reach initial strength in seconds, or for the quick separation of modern lightweight vehicle components during repair without damaging other components.

Particularly the separation of structural bonded joints is only possible using induction technology, as only in this way can the necessary local heating of the automotive bodywork be achieved in extremely short times.

These examples show that the special induction technology is an excellent process aid. With this technology, the usability and attractiveness of bonding as a technology for joining parts can be increased demonstrably.

4.3 Induction heating for shrinking

Wilfried Goy

Heat shrinking, as for instance heat shrinking combined with prior induction heating, is counted amongst the group of so-called “force-fit” connections. This means that the mutual force (friction) between the two surfaces to be connected is so large that it is usually able to prevent reciprocal displacement. The adhesion between the two components is usually larger than any tangential displacement force likely to occur.

The heat shrinking process is based on the principle of heat expansion. This means that a component (usually the outer component) is heated until it has expanded so far as to enable problem-free joining. The outside component contracts upon cooling and shrinks on with force-fit.

In principle, it is possible that two components connected by heat shrinking may be separated again by a reverse process. The problem is that the crimped connection of two components also promotes heat transfer via the joining surfaces, which heats the inner component also. Therefore, heat shrinking falls into the category of permanent connections.

4.3.1 Calculation formula

The length-increase of an expanded body is represented by the following formula:

$$\Delta L = \alpha \cdot L \cdot \Delta T \quad (4.5)$$

where α represents a material-specific parameter which describes the linear expansion behaviour (within a certain temperature range).

Rearranging the equation to

$$\alpha = \frac{\Delta L}{L} \cdot \frac{1}{\Delta T} \quad (4.6)$$

demonstrates that ΔL represents the relative length alteration in relation to the original length (or initial length) L .

Designation	α [10^{-6} 1/K]	Designation	α [10^{-6} 1/K]
Aluminium	23.1	Nickel	13.4
Lead	28.9	Platinum	8.8
Chrome	4.9	Quartz glass	0.6
Iron	11.8	Silver	18.9
Glass	8.61	Silicon	2.6
Gold	14.2	Steel	11.9
Graphite	1.9–2.9	Titanium	8.6
Table salt	40	Wolfram	4.5
Copper	16.5	Zinc	30.2
Magnesium	24.8	Tin	22
Manganese	21.7		

Table 4.4: Expansion coefficients of selected materials

The unit of the length expansion coefficients amounts to 1/K, corresponding to the temperature change $1/\Delta T$.

Table 4.4 shows the expansion coefficients of selected materials in the range of 20 to 100 °C.

4.3.2 Example for a car flywheel

In this example, heat shrinking of a hardened sprocket on a cast flywheel (**Figure 4.17 left** and detail **Figure 4.17 right**), the inside diameter of the gearing to be shrunk on amounts to approx. 250 mm.

Prerequisite to safe heat shrinking with a force-fit connection is that the inside diameter of the component to be shrunk on is smaller than the exterior diameter onto which the heat shrinking is to be performed. Cooling produces plastic deformation of the sprocket. In this example, the inside diameter of the sprocket was 0.3 to 0.4 mm smaller than the shrink-on nominal diameter. The heat shrinking process was performed accordingly with heating of 160 to max. 200 °C.



Figure 4.17: Car flywheel – flywheel connection

As the sprocket was already hardened, it was necessary to determine the lowest possible temperature increase and set it reliably, as the decrease in hardness resulting from the inherent tempering effect was not to amount to more than 1 HRC.

4.3.3 Assembled camshaft

Conventional camshafts are usually cast, only rarely forged, or may, for special applications be also made of solid material. In any case, a subsequent heat treatment consisting of hardening and tempering is to follow. To this very day, the market is dominated by camshafts produced in this way.

The “assembled camshaft” has gained ever greater significance since about the mid-1990s, initially in the car, but meanwhile also in the lorry and truck sector.

Assembled camshafts consist of multiple materials and components. The carrier shafts are not solid, but are made of a torsion-resistant precision steel pipe, which alone effects an overall weight-reduction of approx. 40 %. A further significant advantage is that the material can be selected according to the individual function elements and adapted to the respective loading cases. The production process can also be selected to match the component.

Normally, individually-produced cams (usually made of the material 100Cr6) are subjected to inductive surface hardening and then directly afterwards, to inductive tempering. **Figure 4.18** shows such a single cam for a lorry camshaft with a case hardening depth of approx. 3 mm.

The individually-produced components must be joined together: the individual cams must be “threaded” onto the support pipe and positioned with the highest possible precision and angle-accuracy. One of the joining procedures consists of warming the individual cams inductively in an annular coil and then joining over the support pipe in an expanded state, sliding it into the corresponding position and cooling it there, developing a force-fit joint between pipe and cam.

The expansion amounts to 0.1 mm at a typical process temperature of approx. 150 °C. Admittedly, the reheating causes renewed tempering with low-level loss of hardness, but the low temperature and the short-term process permit this to be tolerated. Performing the shrink-on process in this way brings the advantage of an equal cam fastening in a (secure) elastic area.

Figure 4.19 shows the production of a camshaft in a heat shrinking machine. **Figure 4.20** shows multiple inductively hardened and heat shrunk “assembled” camshafts.

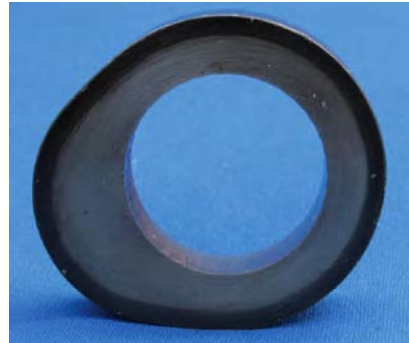


Figure 4.18: Inductively hardened single cam made of 100Cr6

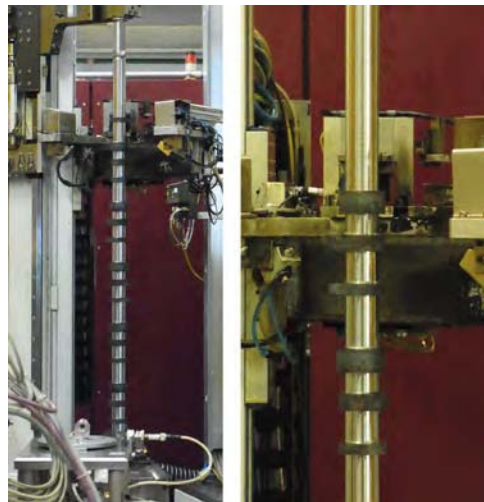


Figure 4.19: The production of a camshaft in a heat shrinking machine (Source: Daimler AG, Mercedes Benz Mannheim plant)



Figure 4.20: “Assembled” camshafts produced using heat shrinking
(Source: ThyssenKrupp Presta Camshafts)

4.3.4 Summary

Further usual processes for inductive heat shrinking include:

- Starter sprockets on fly wheels
- Various gear wheels on shafts
- Heat shrinking of steel cores, gear wheels and drive wheels
- Stainless steel rings on different pipe diameters

In summary, it can be concluded that inductive heating for heat-shrinking applications and joints of different components is perfectly suited for use in semi- or fully automatic production lines and also for the integration in so-called “one-piece-flow” process lines.

4.4 Induction heating for welding

4.4.1 Induction longitudinal seam welding of tubes

Dirk M. Schibisch, Gerd Ommer

Induction tube welding is performed almost exclusively using high-frequency (HF) technology.

All around the world induction coils (HFI process, **Figure 4.21** and **Figure 4.22a**) are the preferred technology chosen for this purpose. The strip to be welded is usually fed in automatically from strip accumulators. This guarantees a continuous, cost-efficient process with welding rates of over 200 m/min.

For contact welding (HFC method, **Figure 4.22b**) the energy is transferred via sliding contacts on the open-seam tube. These contacts are wear parts and are, therefore, subject to wear depending on the surface condition of the tube to be welded. As a rule, the contacts need to be replaced during one working shift, which in turn results not only in relatively high costs for the contacts but in production stoppages, too. Even more troublesome, contact abrasion beside the weld seam often

gets into the tube surface. Modern dual HF generators offer the possibility of choosing between both methods by simply preselecting the program and using coils or a contact unit with replaceable contacts without the need for modifications.

There are numerous applications for which the HFC method provides the right technical solutions, such as, for example, the manufacture of corrugated cooling tubes, tailored tubes or tube sections which do not allow impellers to be used in the tube section for space-related reasons.

Induction welding processes at frequencies below 30 kHz, that means medium-frequency applications (MFI and MFC), can also be used for joining pipes, among other things. However, these are not further examined in here.

HF-welded tubes, manufactured by the continuous mill process, are primarily used as structural tubes, precision pipes for the automotive industry, cooling pipes, exhaust pipes, spacers for multiple glazing systems, line pipes and steel oil-field pipes for transporting gas, oil and water as well as other oil country tubular goods (OCTG).

In such cases conventional international standards, for example DIN, EN, API and ASME are applied.

To achieve perfect weld seam grades within the 10 to 660 mm diameter range and wall thicknesses between 0.12 and 25 mm, a wide frequency band is now available for a huge variety of materials.

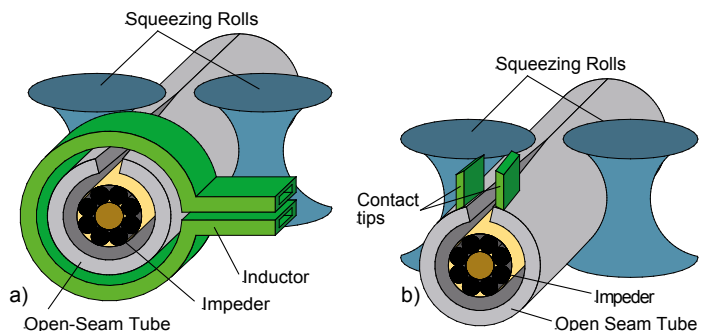
Figure 4.23 lists the key components of a plant used for HF-welding:

- HF section with generator, flexible HF feeder line and external oscillating circuit
- Inductor adaptor with terminal connection for inductor or contact unit
- Control, operation and visual display systems
- Control hardware, depending on requirements and possible applications for feed rate, temperature, voltage, capacity and energy input
- One to three-way positioning table for program-controlled, reproducible positioning of the inductor for the welding point



Figure 4.21: HFI welding process
(Source: SMS Elotherm)

Figure 4.22:
Schematic diagrams
of the HF welding
procedures:
a) HF induction welding;
b) HF contact welding
(Source: SMS Elotherm)



- Water/water re-cooling system with process water flow control
- Inductors and contacts, impeder
- Outside flash trimmer and inside scarfer with integrated impeder.

Generators with high-frequency tubes were used for decades throughout the industry for pipe and tube welding. In the mid-1980s the first HF pipe welding machines with MOSFET transistors, which were based on current-controlled parallel tuned converters with a capacity of up to 500 kW, were developed in Germany for series production and successfully used in pipe welding lines.

A further decisive step towards voltage-controlled HF series resonant converters for pipe welding applications with modern IGBT modules came ten years later.

This innovative development, which offers welding capacities between 600 and 2,400 kW and is now reliably used in production processes, originated in Germany.

Modern HF transistor pipe welding machines are available in cost-effective modular designs for welding rates of between 50 and 2,000 kW. They run with low operating voltages and frequencies within the 60 to 600 kHz range – ideal for a wide variety of applications – and guarantee perfect HF welding results (**Figure 4.24**).

In conjunction with today's PLC/PC control systems, as well as process visual display and fault tracking capabilities, its incorporation into an integrated welding line via a bus connection is now



Figure 4.23: HFI welding facility for integration into the pipe shaping line (Source: SMS Elotherm)

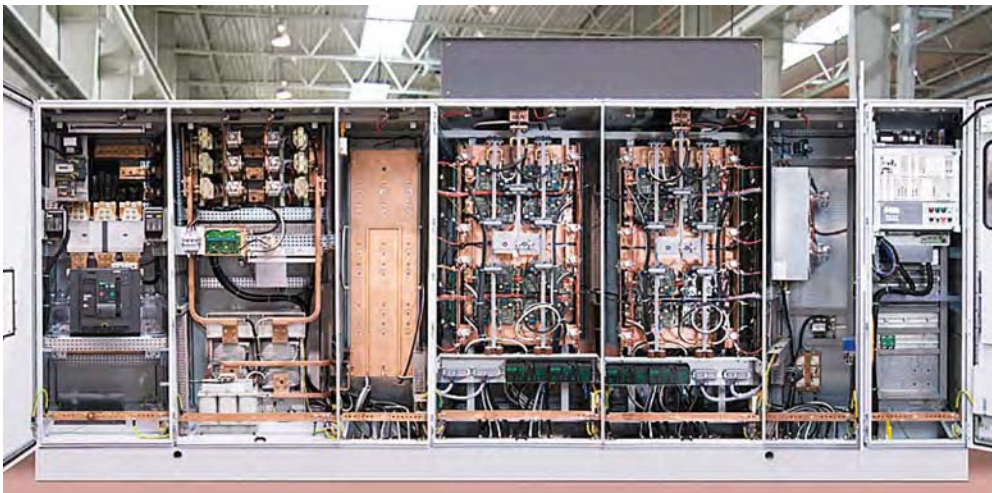


Figure 4.24: Series resonant converters with a 1,600 kW capacity and IGBT technology (Source: SMS Elotherm)

common practice. Furthermore, control systems, based on power, speed and welding temperature, ensure the process can be managed with stable, reproducible results.

The inductor or contact can be positioned in up to three axes, either manually, by electric motor or reproducibly by NC control via an adjustable slide.

Impressive features of well-designed modular transistor welding machines are their compact dimensions, adjustable and pre-selectable frequencies and high level of reliability, efficiency and operational safety.

They are particularly suitable for welding cold rolled strip, hot rolled black strip, thick-walled tubes (**Figure 4.25**) and a variety of various materials and grades, including:

- Steel and bright, galvanized, aluminized and aluminium-plated steel
- Carbon steel St 32 – St 52
- Steel as per DIN 2393/94, 17172, EN 10219 1&2
- API 5L to X-80, EN L555 NB, EN L555 MB
- ASME SA 516 16-60, ASTM 500, A501, CSA G4021
- JIS G3444, JIS G3466
- Special steel:

Austenitic:	[1.4301 AISI 304, 1.4828 AISI 309, 1.4541 AISI 321]
ferritic:	[1.4512 AISI 409]
- Zinc
- Aluminium:

High-grade aluminium
Wrought alloy: hardened
Wrought alloy: not hardened
- Brass and copper.

The welding frequency has a major influence on the structure of the weld seam. The specific load on the strip edges, which is important for the longitudinal seam welding of tubes and pipes, depends on a variety of parameters in terms of its absolute magnitude (**Figure 4.26** and **Table 4.5**).

The impeder position, ferrite material and dimension, welding angle, coil/welding point distance, coupling distance and frequency, for example, play an important role.

Looking at the influence of the frequency on the power converted in the gap, which itself is determined by the heat source and temperature distribution above and below the Curie point in the gap, in theory an increase in the frequency results in a slight decrease in the requisite gap output at a constant throughput.

The current to be fed into the coil at a given throughput level decreases due to the effective resistance of the gap which increases with the frequency, for example by about 10 % if the frequency is

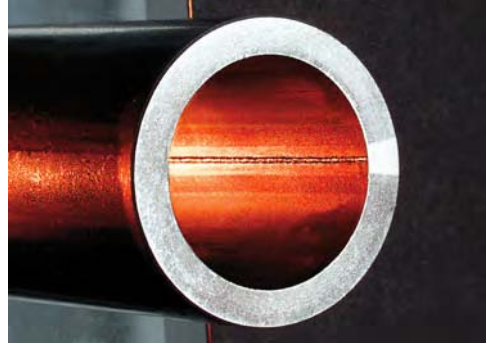


Figure 4.25: HFI-welded, thick-walled precision tube (Source: SMS Elotherm)

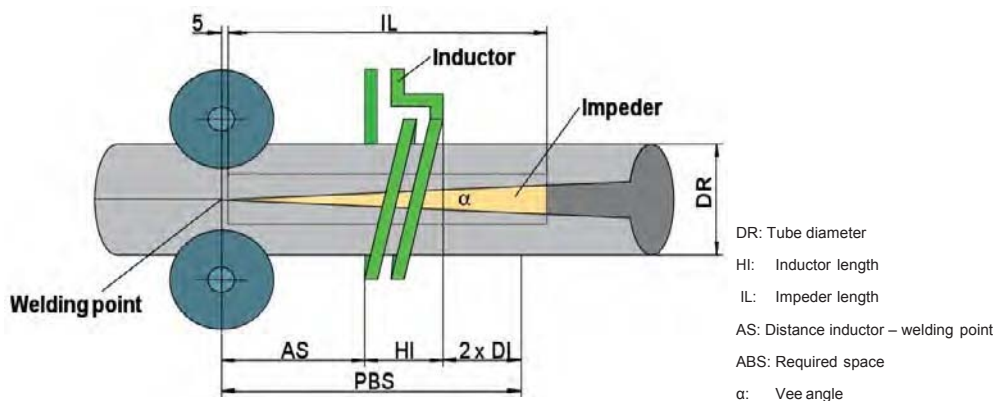


Figure 4.26: Conditions for HFI tube welding (part 1)

Material	Entry angle α	Inductor width HI	Impeder length IL	Dist. inductor- welding point AS
Ferritic steel	$2^\circ - 3^\circ$	$\approx DR$	$\approx 3 \times DR$	$< DR$
Austenitic steel	$4^\circ - 7^\circ$	$\approx DR$	$\approx 3 \times DR$	$< DR$
Aluminium	$5^\circ - 10^\circ$	$\approx DR$	$\approx 3 \times DR$	$< DR$

Table 4.5: Conditions for HFI tube welding (part 2)

doubled, whereby the total output and, thus, the efficiency “line to coil” is largely determined by all system components.

By contrast, a higher operating frequency for the purpose of improving the gap output necessarily results in a loss of efficiency in the converter and is, therefore, not recommended.

In terms of an assessment of the quality of the weld seam, frequencies which are far lower than those usually used in the past, i.e. up to about 150 kHz, should preferably be used for wall thicknesses which are over 4 mm and pipe diameters above 80 mm.

The characteristics used for assessing the quality of a weld seam in test procedures performed parallel to the production process are essentially the formation of the ferrite line, edging line progression, width of the zone affected by heat, position of the neutral zone, flash formation and cleanliness of the weld seam.

The design of the weld seam differs in terms of the formation of the middle section if frequencies for thick-walled tubes are set below 150 kHz. While a joint welded using a relatively high frequency displays a narrow zone affected by heat with considerable necking in the center, a seam produced at low frequency is wider in the zone affected by heat with less necking. The heating process is the cause of this formation; at lower frequencies it is more concentrated on the edges of the open-seam tube at the beginning and, therefore, prevents uniform temperature rise to welding temperature, whereas if heating at a lower frequency there is no overheating of the edge. Moreover, the structure displays small grain sizes with clear transition zones between the individual structural components. The balanced hardening progression curve clearly confirms this. The flash is small and is not off center. Therefore, the service life of the seam scrapers are improved considerably as a result.

4.4.2 Induction assisted laser and hybrid-welding processes

Jörg Neumeyer, Holger Schülbe, Bernard Nacke

For powerful welding of high-strength steels nowadays often laser welding processes are applied. The intense focusing of the laser beam proposes very high power densities onto a small area of the commodity that has to be jointed and thus leads to a distinctive deep-weld effect. Though, the high power density of the laser welding process causes very high temperature gradients within and beside the weld seam. These temperature gradients involve a fast cooling subsequent to the joining process and thereby an inadmissible beam hardening and brittleness at the seam. The principle of the electromagnetic induction is excellently suited for fast and controlled insertion of thermal energy. **Figure 4.27** shows the schematic experimental arrangement of a hybrid laser-induction process with a preheating inductor and appropriate measuring devices [4.4]. The length of the inductor and the scanning speed v_{ind} determine the heating duration. Simultaneously the electromagnetic penetration depth can be influenced by the frequency of the inductor current. Finally, both the heating duration and the frequency define the temperature profile within the workpiece. The additional implemented thermal energy provides for lower temperature gradients subsequent to the welding process and for lower necessary temperature raise to achieve the welding temperature. So, a laser with a reduced output power or the same laser at a higher scanning speed can be applied. The inductor and the laser are integrated in a single process head together.

Beside the setup with a preheating inductor also a following inductor can be implemented that brings additional thermal energy subsequent to the welding process into the workpiece. **Figure 4.28** shows the calculation results of several simulations and exemplifies the effects of supplementary inductors on the $t_{8/5}$ -time – the cooling time between 800 °C and 500 °C – that allows conclusions about the beam hardening of the material. The shown process simulations are done with a workpiece thickness of 6 mm. With a single laser welding process the $t_{8/5}$ -time is merely 2.3 s. The assistance of a preheating inductor increases the $t_{8/5}$ -time to 9.8 s. At the temperature profiles a temperature drop over two seconds shortly before the welding process can be seen. This phenomenon can be explained by the necessary safe distance between the inductor and the laser beam. To avoid a damage of the inductor a distance of about 30 mm should be observed. By the here used speed of 1 m/min a period of 1.8 s results for the safety distance. Compared to a preheating inductor a following reheating inductor achieves a $t_{8/5}$ -time of 12.1 s. But in this case the laser has to supply the full necessary thermal energy to achieve the welding temperature. At this

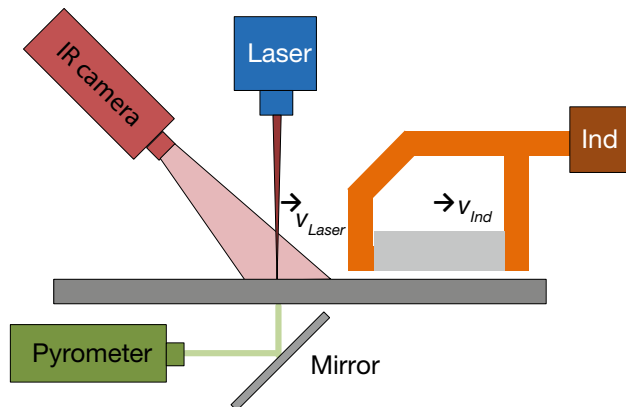


Figure 4.27: Schematic experimental arrangement of a hybrid laser-induction process

comparison it has to be taken into account that the temperature profiles are shown for the area of the weld seam that is faced towards the inductors and is therefore positioned inside the electromagnetic penetration depth. The launching thermal conduction effects lead to a wide spreading of the heat in the whole workpiece whereby the temperature at this surface-located point decreases and the application with a preheating inductor results in a lower $t_{8/5}$ -time. The inversed effect occurs considering the point at the seam root. The combination of a preheating and a following inductor with an adaption of the distance between laser and reheating enables a $t_{8/5}$ -time of actually 26.3 s.

Beside the exclusive usage of a laser welding process meanwhile combinations of conventional arc welding and laser welding processes in so-called hybrid welding processes are established. This kind of welding was firstly executed by Prof. Steen et al. in the seventies of the last century to support the at this time weak laser processes to achieve higher welding power [4.5]. Generally synergy-effects will occur while combining these two methods that exceed the simple summation of the single advantages of both procedures. The eminent gapbridging and the wider heat impact of an arc welding method reduce the necessary effort of the weld preparation and therefore it also reduces the resulting temperature gradients that lead to a very high brittleness of the welded area when using a single laser process. Equally the deep weld effect and the high welding velocities of a laser-beam enable a reduced workpiece distortion and can perfectly support the comparatively cheap arc-welding process.

The technological progress facilitates the application of more powerful lasers for which reason the raised welding power of a hybrid process is ideally suited for joining of thick metal sheets. The higher mass and therefore the higher heat capacity of such thick sheets increases the heat conductance from the welding area towards the inner material wherefore the $t_{8/5}$ -time diminishes and the hardness of the seam may get inadmissible high values. The wide temperature effect by the arc welding process cares for a damping of the cooling rate but does not allow a direct inducement of the temperature profile and of the resulting crystalline structure. Simultaneously, at welding procedures of thick metal sheets by hybrid welding processes so-called middle rip defects occur that can only be avoided by productivity-degrading and energy-intensive multiple layer methods or by adjusted temperature control. Middle rip defects are solidification cracks that mainly arise in the areas where the metal-arcwelding process has the dominating contribution of the whole welding power.

In the framework of a research project [4.6] the possibility of a welding process of thick-walled butt-welded workpieces (16 – 32 mm) with induction assistance had been investigated. Considered materials were a typical pipeline steel (X65) and a fine grained structural steel (S690). By use

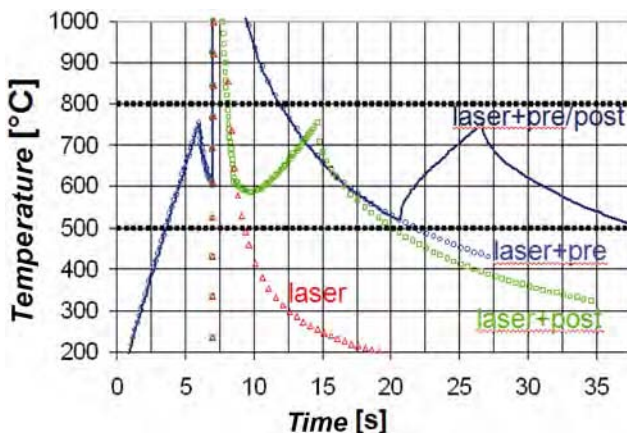


Figure 4.28: Effects of supplementary induction heating on the $t_{8/5}$ -time

Figure 4.29: Induction assisted orbital welding of tubes



of a comparatively low frequency of 3 kHz und a preheating time of 6 s and also 6 s heating by the following induction process the $t_{8/5}$ -time at the seam root was increased to 10.65 s due to the large electromagnetic penetration depth and heat conductance. **Figure 4.29** shows the application above the heated seam of the pipe. The middle region between both inductors that are each orientated along the weld seam is arranged for the process head of the hybrid welding process.

Figure 4.30 shows the transient temperature profile at discrete points of the metal sheets over the whole process time. The red painted curve “T_root” is the most important value. The temperature at this point should be held above 500 °C over a time-period of at least 10 s. Simultaneously the maximum temperature in the workpiece mustn’t exceed 900 °C (dark-blue curve). The other temperature profiles show the transient temperature behavior at locations near to the weld seam. Though the demand of a $t_{8/5}$ -time larger than 10 s can be full-filled by use of induction assistance with both a preheating inductor and a following inductor this principle leads to a relatively high energy input per unit length and low thermal efficiency rates. Even thicker workpieces account for enhancements of the residence time and therefore prolongations of the line inductors due to electromagnetic effects of the penetration depth and the heat conduction effects.

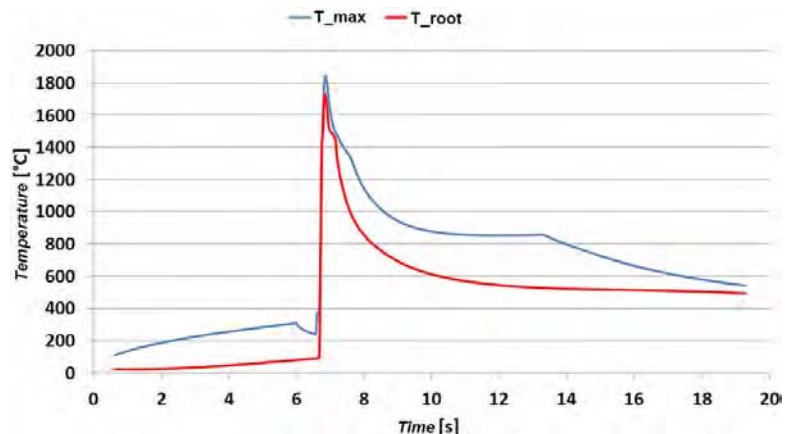


Figure 4.30: Effects of supplementary induction heating on the $t_{8/5}$ -time for metal sheets with thicknesses of 16 mm

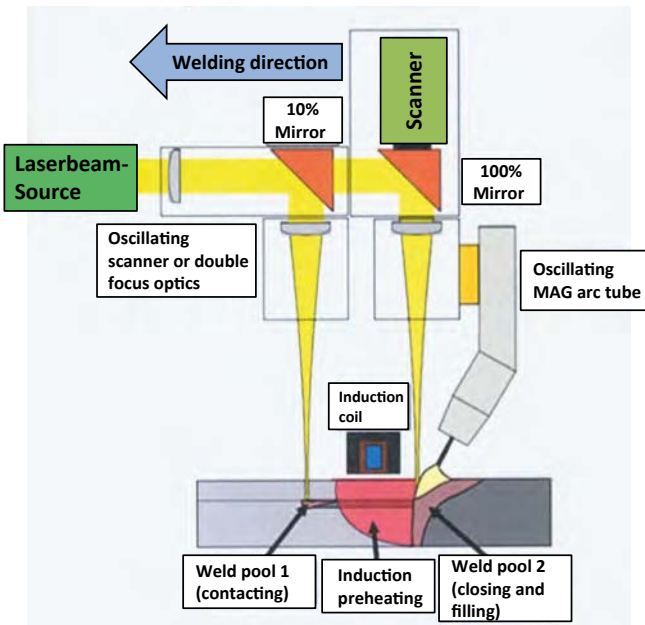


Figure 4.31: Process with bifid beam source and induction assistance [4.7]

In the framework of further research projects [4.7] a process with a bifid beam source and induction assistance was investigated. For welding of primarily thick-walled sheets a hybrid process head is applied with a laser beam and an arc-welding process that are working in combination on a single weld bath. To avoid middle rip defects an inductor was developed that allows an adjusted temperature regime and that is focused to achieve a preheating only at the weld seam region. In this connection the inductor was – converse to so far investigated inductors – arranged perpendicular to the scanning direction. With an extraction of the laser energy in the first instance a small weld seam is established that realizes a mechanic and therefore also an electric connection between both sheets **Figure 4.31**. This joint is built to enable a current flow that is driven by the electromagnetic field of the inductor along the weld flanks.

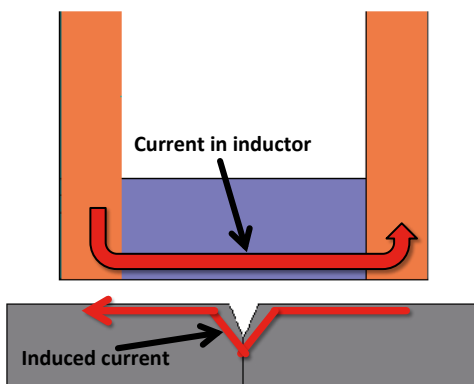


Figure 4.32: Inductor current and the induced current in the workpiece with transverse positioned inductor [4.7]

Figure 4.32 shows the characteristics of the inductor current and the induced current in the workpiece. The current within the workpiece flows along the weld flanks und generates Joule Heat in this region. The complete material that is relevant for the welding process can be preheated perfectly by this application. Subsequent to the induction heating the full-power hybrid process will accomplish the filling and completion of the weld seam.

In first feasibility studies that were done by use of FEA-simulations and physical heating experiments the principal functionality of the induced

Figure 4.33: Practical feasibility study of heat generation at the weld flank

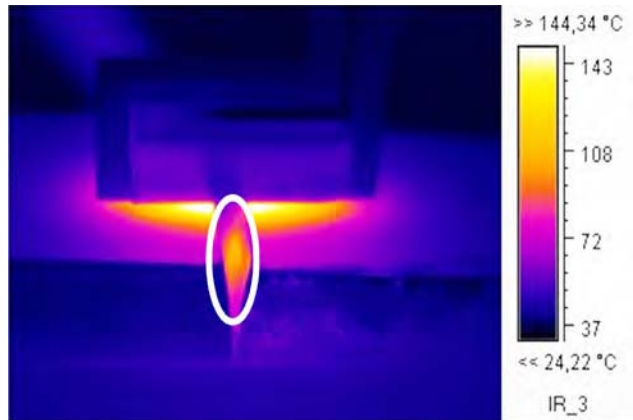
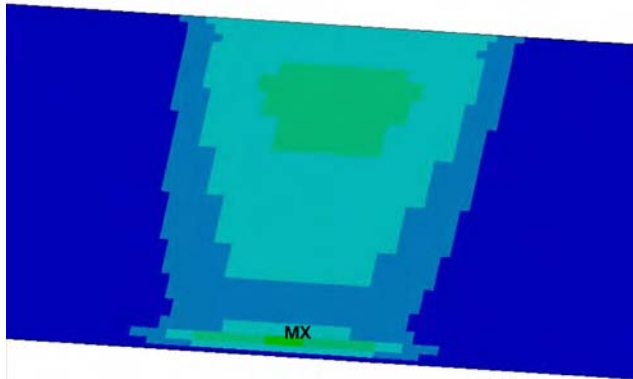


Figure 4.34: Numerical feasibility study of heat generation at the weld flank (view directly to the flank)



currents along the weld flanks could be confirmed. **Figure 4.33** shows the picture that was taken by a thermal camera at the surface and at the weld flanks of the region that shall be heated up. The white oval points out the higher heat generation at the flanks that were confirmed by FEA-simulations. **Figure 4.34** shows the calculated Joule heat generation at the weld flanks.

By means of further numerical parameter studies and additional developed analytical correlations the optimal geometric parameters of the inductor regarding the preheating process were estimated. In this case a special focus was set to the inductor length and the inductor width. From electromagnetic studies that were executed by FEA simulations the adjusted electric values of the frequency and the electric power were identified. Afterwards the simulation results were verified by a comparison with the measurements at the experimental rig.

Investigations of the resulting crystalline structure by grinding patterns, radiographic examinations and hardness analyses demonstrate for a thermo mechanical rolled fine grained steel S700MC with a thickness of 10 mm that the hardness profile in the matrix, the heat affected zone and the welding area can be influenced with induction assistance. By oversized induction power large excess penetrations occur at a thermal mechanical rolled X70-Pipeline steel with a thickness of 13.2 mm. These parasitic effects can be eliminated by an increase in productivity due to a raise of the scanning velocity. Via an added content of manganese at the welding filler and with an operation of induction assistance the considered sheets can be welded without middle rip defects.

Induction heating is an excellent method to achieve higher qualities at the weld seam resulting from beam welding processes and to raise the productivity. Numerical simulations permit the analysis of electromagnetic values and a holistic consideration of the temperature values at each point at every time step of the process. So, in the forefront of the experimental tests and production the geometric and the electric design of the induction unit can be determined and optimized excellently by use of FEA-simulations.

4.4.3 Induction pre-heating for welding processes

Hans Windsheimer, Horst Linn

Recently, different welding processes such as friction or diffusion welding have been applied to a number of materials and material combinations such as steels or titanium respectively titanium alloys [4.8].

Due to compact units and efficient heat transfer on the product, inductive pre-heating of the product is reasonable in case of this welding process. TiAl-alloys, for example, can only be connected permanently if the workpieces are heated to temperatures above the brittle-ductile transition range (550 – 800 °C) before the welding process [4.9, 4.10]. Only then the mechanical forces, which are necessary for the connection, can effect joining of the materials without development of micro-structure defects.

As such welding methods are typically characterized by high throughput rates with short cycle times (minute range), pre-heating of the components has to be adjusted to the cycle time. Here the energy input of inductive heating directly affects the workpiece which enables extremely short heating up times. In addition, the penetration depth respectively the heat penetration zone can be adjusted specifically and reproducibly by proper selection of the working frequency of the generator.

Figure 4.35 shows an example of an inductive pre-heating unit with a maximum power of 120 kW at a working frequency of 2 – 5 kHz. Due to the power output of the generator in combination with a well-adapted one-winded inductor, very high pre-heating temperatures of up to 1,350 °C at cycle times of approximately 2 min can be reached.

Figure 4.36 shows typical converters for this application field. Due to its compact design, the generators are especially suitable for retrofitting of existing units.

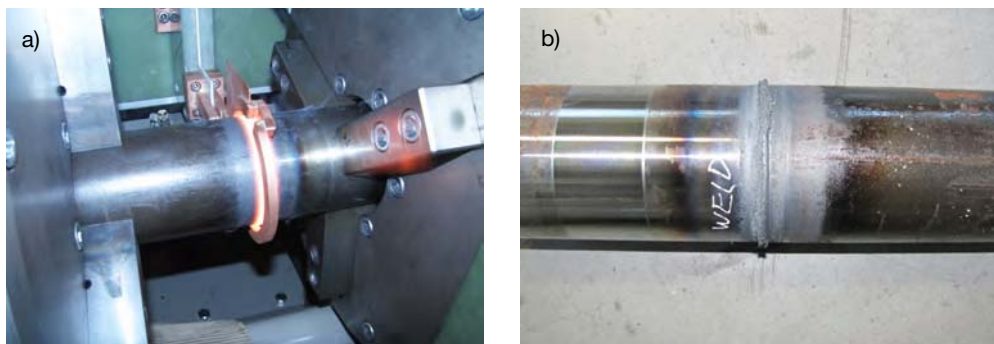


Figure 4.35: Inductive pre-heating in case of diffusion welding of steel;
(a) pre-heating step on the welding point, (b) welding seam after cooling down



Figure 4.36: (a) Semi-conductor high frequency generator with outside resonant circuit ($P_{max} = 1,2\text{--}10\text{ kW}$, $f = 150\text{--}450\text{ kHz}$),
 (b) typical medium frequency inverter ($P_{max} = 10\text{--}1000\text{ kW}$, $f = 10\text{--}80\text{ kHz}$) [4.11]

4.4.4 Inductive Predox welding

Thomas Stange

To improve axle housing manufacture in competitive terms and as part of a strategy project, the Daimler AG plant in Kassel [4.12] developed the Inductive Predox Welding Procedure (IPS) for a rectangular cross section when manufacturing axle housings.

The major components in the new axle housing design (**Figure 4.37**) consist of a center section, also known as the banjo, and two ends, also known as stubs.

Here, the banjo itself is a welded structure made of molded parts. Fine-grained construction steel with steel grade E460N is a suitable material for this application case. This material distinguishes itself through excellent ductility and welding suitability.

The geometry means that the stubs are designed as casting parts. A GJS-600-3 (GJS = NCI) is selected as the material in this case.

Because of the forming technology involved here, the joint (**Figure 4.38**) between the parts can only be made in the form of a rectangular hollow section.

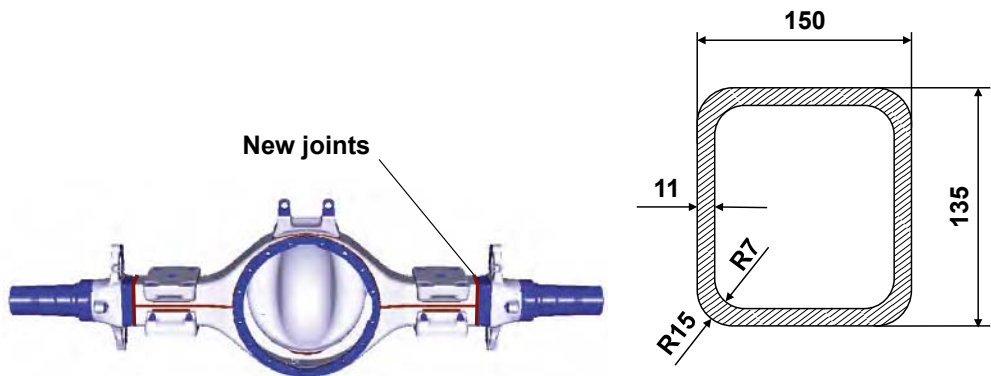


Figure 4.37: New three-piece axle housing design

Figure 4.38: Weld seam cross section

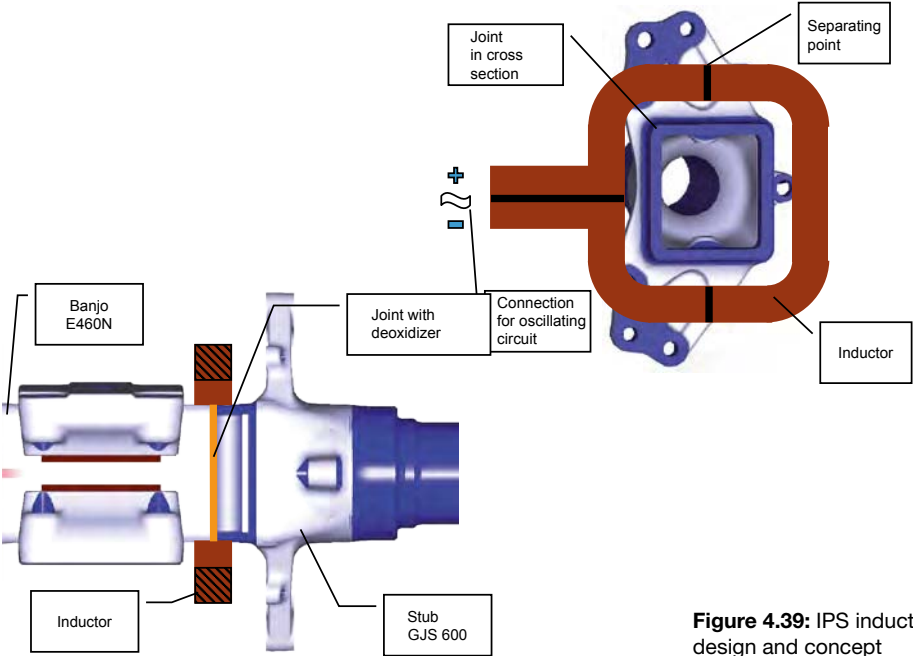


Figure 4.39: IPS inductor design and concept

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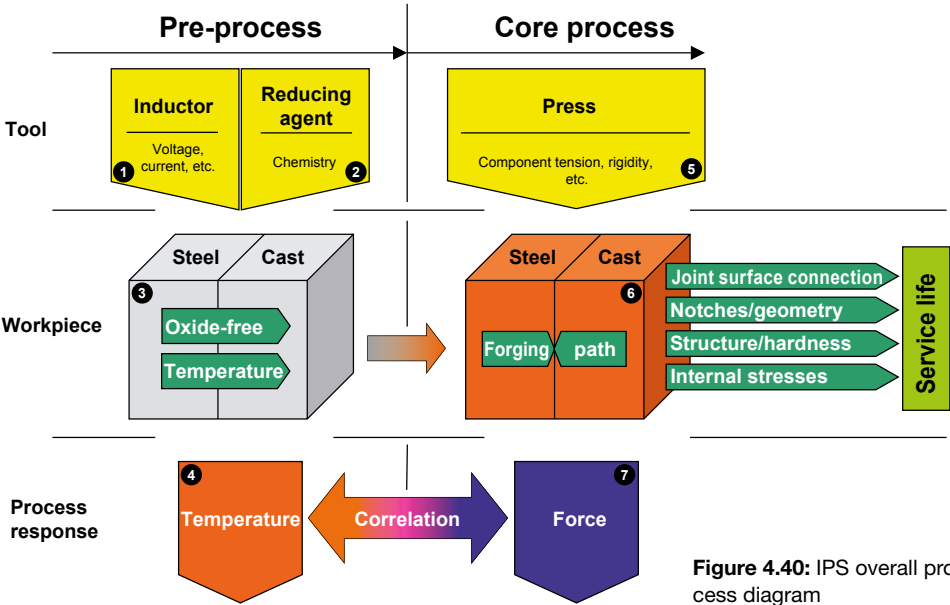


Figure 4.40: IPS overall process diagram

In the IPS procedure the joint is heated by means of induction. The potential of this heating option, along with the “low-cost” design of the magnetic field, means that the joint can be heated quickly and uniformly.

As shown in **Figure 4.39**, the inductor in this particular joining instance is positioned directly around the joint. The coupling of the magnetic field in the component is contingent on coupling distances in an area that requires a separated inductor. This is why the inductor is designed so that it can be separated after the welding procedure.

The IPS welding process (**Figure 4.40**) is a two-stage process.

The first process stage, known here as the “pre-process”, has two target variables. On the one hand, the joint is to be heated to a uniform temperature below the casting material melting temperature. On the other hand, both joint surfaces have to be deoxidized. The tools available here are the inductor and a reducing substance. The component temperature can be read out as a response to the pre-process.

In the second process stage, known here as the “core process”, the input parameters for the forging path, forging speed and the forging acceleration are important. The tool available here for the process is the press, which is used to clamp the components. The force required for forging the parts can be measured as a response to the core process.

Under the same boundary conditions, a good correlation exists between the responses for the two process stages, temperature and force.

The result of the overall process is determined to be the 4 service-life-related weld seam properties – connection of joint surfaces, notches due to the weld seam geometry, structure with hardness traverses and, last but not least, the internal stresses.

To understand the joining process, an inductive heating simulation was conducted in cooperation with the Leibniz Universität Hannover (ETP) Institute of Electrotechnology. When designing the simulation model, it was expedient to introduce simplifications at certain stages, to significantly reduce the amount of CPU time involved and, consequently, the costs. Because the component in the joint cross section is symmetrical both horizontally and vertically, the model can then be simplified to the extent that only one quadrant (**Figure 4.41**) of the component and inductor is simulated.

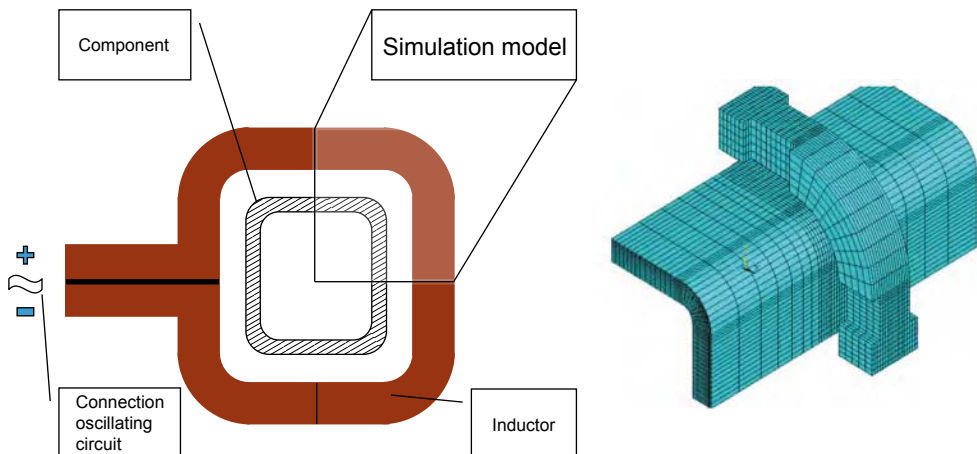


Figure 4.41: Simulation quadrant and cross-linking

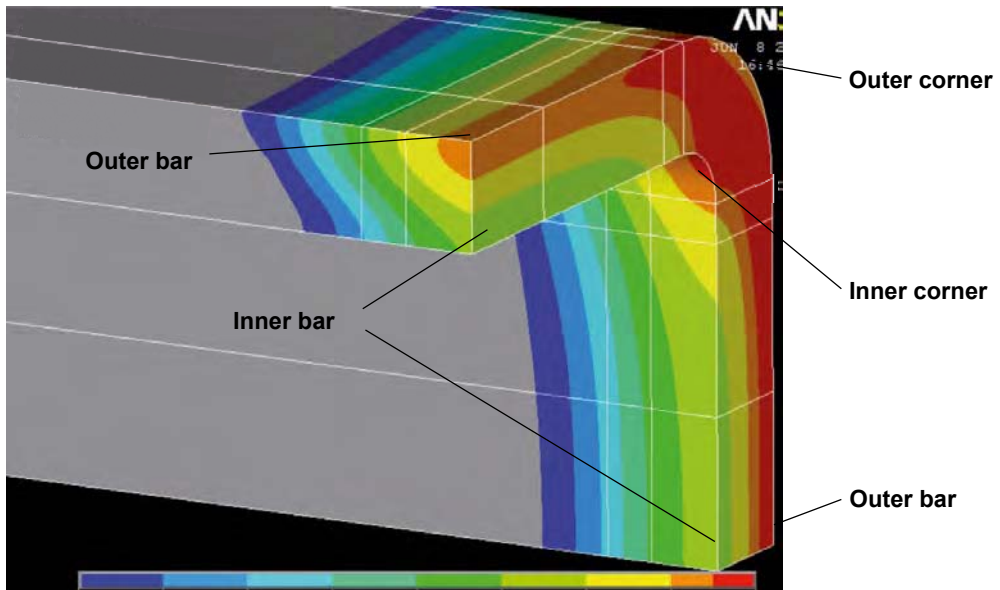


Figure 4.42: Simulated temperature distribution

Mutual influence of the quadrants is ruled out here. Any effects generated by the contact point as well as the inductor connection on the oscillating circuit can be neglected here.

A further simplification has been made for bonding part modeling (Figure 4.41). The geometries adjacent to the joint are not mapped in the model.

Heat transfer between the components requires ideal contact, so that heat can flow over the joint between the bonding parts through thermal conduction.

Material data for the steel used are available in the customary literature. Material data for the casting material are determined through thermophysical measurements.

Figure 4.42 depicts the three-dimensional temperature distribution in the welding level. The displayed simulation result shows the casting component. The display of the simulated steel component shows an analog temperature distribution result. As there is a difference in temperature of approx. 300 K between the melting points for castings and steel, the steel side cannot be melted. Consequently, the temperature in the casting component is very important here.

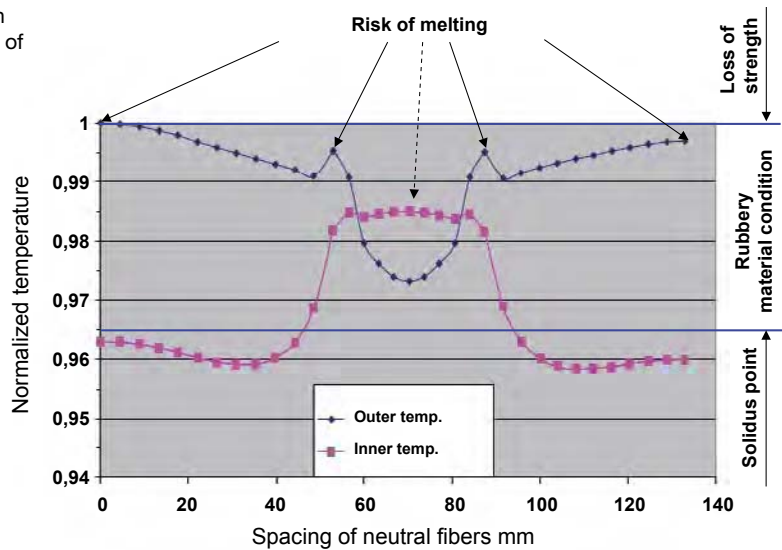
As can be seen here, the bonding temperatures result in an unequal distribution across the bonding level.

The systematic temperature distribution in the bonding level can be divided up into three areas: long side, short side and corner.

The temperature distribution classification in the sides is similar. By contrast, the temperature level differentiation here is negligible.

The distribution of temperatures in the outer sides drops only minimally towards the end of the side. By contrast, on the inside the temperature drop is very strong. This distribution is exhibited

Figure 4.43: RTD with bonding zones at risk of melting



two-dimensionally in the bonding level as a cold “lens” in the center of the bar. If the third dimension is incorporated, the temperature pattern can be described as onion-skin distribution, as it recalls the skin-type structure of an onion. The temperature-distribution characteristic in the corner is the opposite.

In the interior of the corners the temperatures are higher than at the outer corner. Here, the turbulence – irrespective of the indentation depth and frequency – takes the shortest path around the corner and heats it up, in particular, on the inside.

As the temperatures in the bonding level, when vertical to the seam, generate a maximum value or minimum value at the edge or close to the edge, a mainly constantly falling or rising temperature pattern is then the result. It is advisable here to display the edge temperatures in the form of the diagram in **Figure 4.43**. The maximum and the minimum temperature and their spread across the

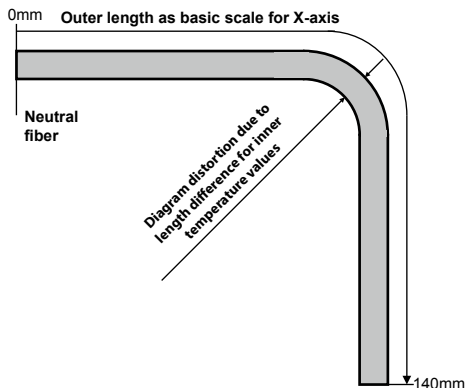


Figure 4.44: X-axis explanation of RTD



Figure 4.45: Inner corner melting

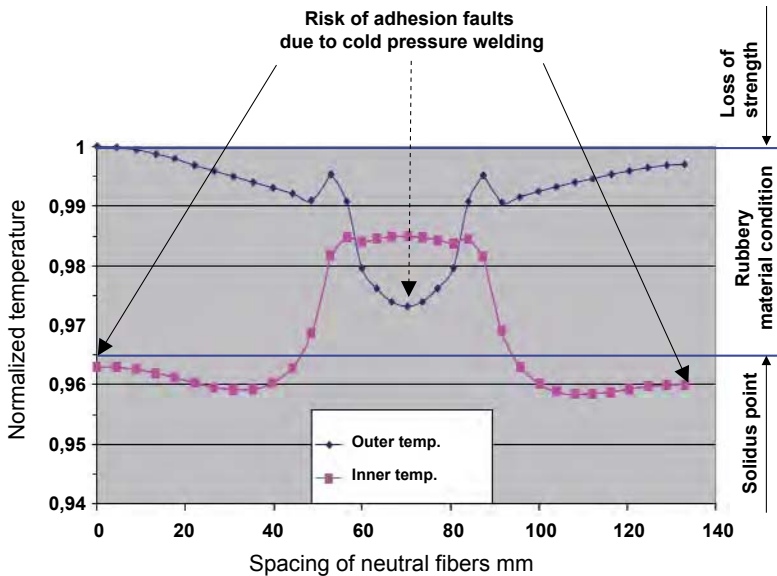


Figure 4.46: RTD with bonding zones at risk of cold pressure welding

bonding level can be read off at any position in the RTD (*Rand-Temperature Diagram*). The X-axis scale mapped in the RTD refers to the outer edge of the component (**Figure 4.44**). As the length of the inner edge is shorter, even though a comparison of the temperature patterns is to be made in a diagram, the temperatures of the corner area (inner edge) are shown in elongated form.

Too hot joint:

When the temperature limit is reached (loss of strength) melting may occur, particularly in the outer edge of the weld seam. The centers of the bars are the most endangered areas here for melting. Furthermore, in the transitions from the outer edges to the bars, there are always areas that are at risk of melting. In the inner area, the maximum temperatures are expected in the corners.

In a real component that has been welded when too hot, this effect is exhibited in the form of melting in the bonding area. As shown by way of an example in **Figure 4.45**, the inner corner also exhibits melting of the casting material, similar to the simulation results.

Too cold joint:

As shown in **Figure 4.46**, joint areas that are too cold are expected inside the component and in the centers of the bars. In the outer area of the component, the radii may exhibit a lack of adhesion because of the too cold temperatures involved.



Figure 4.47: Lack of adhesion faults on bonding surface through cold pressure welding

In a real component that has been welded when too cold, this effect is exhibited in the form of cold pressure welding in the bonding area (**Figure 4.47**). Cold pressure welding refers to lack of adhesion faults that lead ultimately to a significant reduction in service life.

Structure at optimum welding temperature

Inductive heating of the joint results in the basic temperature-distribution characteristics shown in Figure 4.43 and Figure 4.46. This can be influenced in terms of spread by the frequency, inductor positioning, heating time schedule, forming of magnetic field and, last but not least, component tolerances. If favorable influencing parameters are selected, the spread can be reduced far enough to ensure that a weld seam does not exhibit any melting or cold pressure welding.

Figure 4.48 shows the bonding zone for “good” welding. The upper part of the picture shows the casting material. This differs from the base material on account of a higher pearlite content. The ball-shaped spherulites are enclosed by ferritic islands. Reshaping the material does not flatten the spherulites, which would mean a reduction in the service life due to the higher notch effect. No signs of ledeburite were detected in the casting material.

The steel structure (lower section of image) shows not only a fine-grained, ferritic/pearlitic structure, but also parts of the cellular pearlitic structure as known from the feed stock. There are no signs of martensitic structures.

The new weld junction created during bonding is made of purely pearlitic material.

The IPS weld seam exhibits excellent fatigue strength under vibratory stresses. The procedure features this property and thereby makes it an interesting one for manufacturing casting steel joints that have static and dynamic loads applied to them.

Some important IPS procedure properties:

- The IPS procedure provides an option to join rectangular cross sections of different types of material in a large-scale industrial process. The weldability for casting steel joint wall thicknesses of up to 13 mm has been proven. Following estimates, and depending on the application case in question, wall thicknesses of up to approx. 16 mm can be welded as rectangular casting steel joints.
- The IPS procedure offers an extremely high level of accuracy for weld joints in terms of position and angular position of the joint partners.
- The weld seam does not need to undergo thermal re-treatment.
- The internal seam excels on account of the lack of any weld spatter and no requirement for mechanical re-treatment.

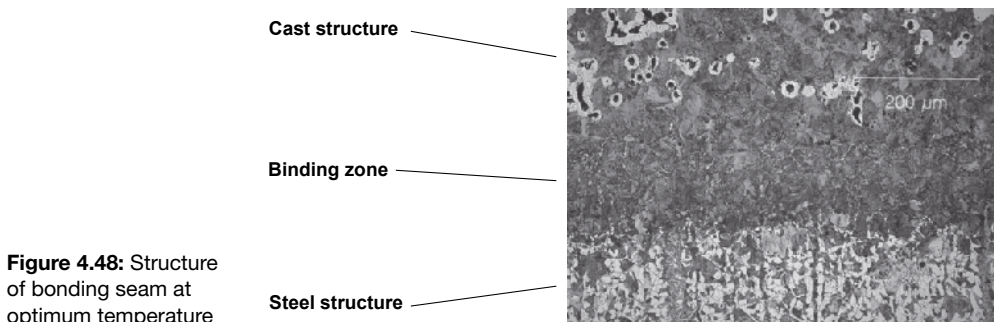


Figure 4.48: Structure of bonding seam at optimum temperature



Figure 4.49: IPS welder (built by Daimler AG Kassel plant)

- The geometry and generated notches are primarily influenced by the temperature and the forging path. The cast is badly deformed and it shifts over the steel to match the forging path. Any ledeburite generated in the joint seam is pushed out of the joint seam and it collects in the notch of the casting material pushed over it. This effect means that the outer area of the welding burr has to undergo mechanical processing to prevent any negative effect on the fatigue strength.
- The two-dimensional joint surface is generated by a low temperature spread, the correct temperature level, a low surface roughness, a low angular error of the joint surfaces and a defined pressure. The special challenge here is founded in the various properties involved in both steel and casting materials.
- Inductive heating of the joint results in a basic temperature-distribution characteristic in the component that has been proven through experiments and a 3D simulation model. The magnetic field indentation depth means that the temperature in the bars is higher on the outside than inside. In the corners, the opposite temperature characteristic can be observed. Here, the inner corner exhibits the highest temperature, which drops off towards the outer corner.
- A deoxidizer is used to remove the oxide from the surface. Deoxidation takes place so quickly that a special deoxidizer does not have to be integrated into the process.
- The force generated when compression molding the components is solely dependent on the forging path and the bonding temperature for identical components and compression molding



◀ **Figure 4.50:** IPS inner weld seam

Figure 4.51: IPS outer weld seam



rigidities. For process-consistent manufacturing of the weld seam, the force in relation to the temperature, can be referred to as important information for assessment of the weld seam quality. A correlation exists between the temperature, forging path and forging force. It is not linear.

- The casting material in a perfectly welded bonding zone is differentiated by the higher pearlite content of the base material. The spherulites are enclosed by ferritic islands. No signs of ledeburite were detected in the casting material. The steel structure shows not only a fine-grained, ferritic/pearlitic structure, but also parts of the cellular pearlitic structure as known from the feed stock. There are no signs of martensitic structures. The new weld junction created during bonding is made of purely pearlitic material and has a width of approximately 200 μm .
- Progression of the hardening process shows that at a distance of 20 mm next to the seam, the hardness of the base material has already been reached. The hardness increases from the base material (200 HV30) to a maximum value of only 300.

New-generation axle housings are made with the aid of the IPS welding procedure in the Mercedes Benz plant in Kassel under series production conditions. The plant technology required for this **Figure 4.49** was developed and built at the same time as part of the project. Where process limits are complied with, an internal seam, as shown in **Figure 4.50** can be made without any melting. By contrast, the outer seam can be mechanically processed as seen in **Figure 4.51**. The new procedure enables steel/casting joints that were previously not weldable to now be produced on a large-scale industrial process.

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5. Special Processes

5. Special Processes

This chapter describes various special procedures used in the field of induction heating. The examples provided show the range of uses for induction heating in thermal process technology. These processes are not restricted to metals; induction heating is often used in innovative applications with semiconductor materials, carbon materials and glasses.

5.1 Press hardening

Wilfried Goy

With growing environmental requirements and the development of increasingly energy-efficient vehicles comes the necessity to develop ever lighter vehicle components. With the rise of light-weight design, security requirements must not be neglected. The resilience of a passenger cabin is especially important in this respect.

In recent years, a thermo-mechanical process for the hot forming of complex structure components has been established to fulfil these requirements.

This process aims at saving weight in the manufacture of structure components, whilst hardening sections of these structures so as to produce zones of both resilience and a softer consistency, the structure of which is thereby able to absorb and reduce deformation energy in a customized targeted fashion. **Figure 5.1** shows an example of the various structure areas in an Audi B-pillar.

This is achieved through the use of modern high-performance steels (e.g. 22MnB5), which permit the production of key structure components from ever thinner panels. The high level of resilience which these panels exhibit results from the quench hardening of pre-punched and heat-hardened panels (called blanks) in a form press. This quench hardening is performed indirectly via individually-controllable cooling channel circuits under the surface of the press-hardening die. The various settable quenching characteristics make it possible to define individual areas to different hardnesses in accordance with requirements regarding stiffness. The steel quality specified above (22MnB5) means that the upper critical cooling rate amounts to approx. 27 K/s, which is to be exceeded or undercut as required. Where appropriate, also Bainite joint structures can become possible.

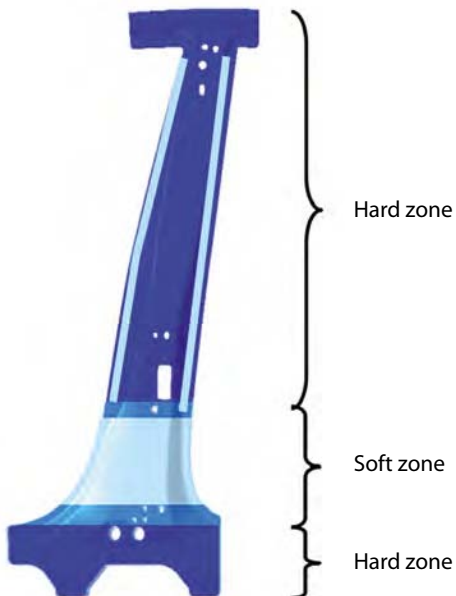
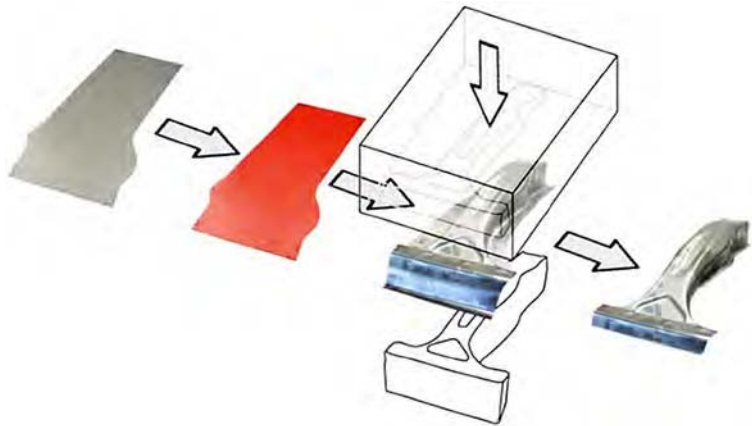


Figure 5.1: AUDI B-Pillar [5.1]

5.1.1 Production lines for structure components

A typical production line for structural components is depicted schematically in **Figure 5.2**. The first step sees the blank punched from a flat blank. It is already shaped in the rough exterior contour of the finished component, taking into account the final three-dimensional form.

Figure 5.2: Production lines for structure components [5.2].



The blank can also be provided with the necessary drill-holes or other blanking features to save weight and / or fulfil other design requirements. The next stage is the heating to hardening temperature. This is conventionally performed using a gas-heated through-type roller furnace in which as homogeneous a temperature distribution should be administered to the blank as is possible. The following steps serve to allow hot forming in a hardening press, the negative shaped die of which form the component. After quenching in the pressed state, the component is released, after which it receives its final processing, essentially through final cutting with a laser beam and the formation of the necessary openings and drill-holes.

5.1.2 Alternative induction heating

The heating time requirements and the usually demanded short cycle times mean that the gas-heated ovens necessitate large dimensions. Today, the length of usual heating lines can be 40 m or more. Even the currently developed two-story through-type roller furnaces require considerable space. A further disadvantage is the level of energy-efficiency, as even at optimal operating grade, both gas heating and indirect heating via electrical resistance heating achieve energy-efficiency levels of only about 55 %. This explains current attempts to convert conventional heating to induction heating. In principle, three different inductor types can be used to heat up the blanks schematically shown in **Figure 5.3**.

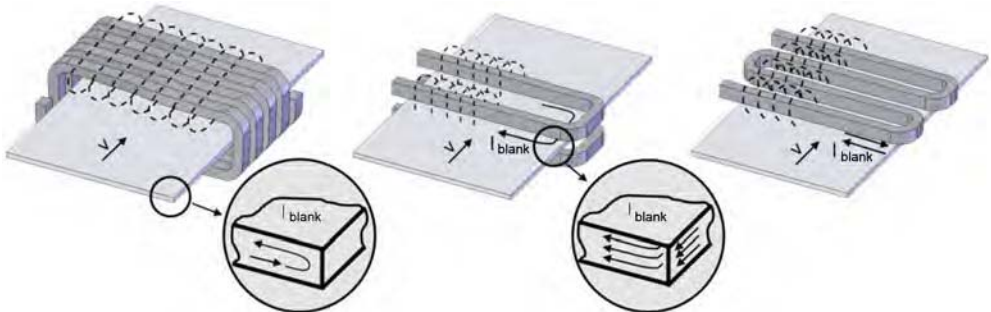


Figure 5.3: Possible inductor types for blank heating [5.3]

1. Longitudinal field inductor

The inductor consists of a multi-turn coil enclosing the work piece. The longitudinal field of the coil generates an induction current in the blank which connects along the cross-section of the exterior diameter. The thickness of the blank must match the electromagnetic penetration to allow current flow – see chapter 1.4.

2. Transverse field inductor

The inductor consists of a minimum of two heating loops, one located above and one below the blank. As a result of the identical orientation of the direction of the current in both inductor loops the magnetic field connects through the workpiece and the induction current is generated inside the sheets in plane loops parallel to the surfaces. This type of heating is largely independent of the depth of electromagnetic penetration, as the induction current connects according to the inductor loop in the surface of the blank.

With versions 1 and 2, it may be relevant to take into account that any necessary transport systems may require a larger coupling distance between the inductor and the workpiece, which may influence the efficiency.

3. Transverse flux field inductor

The direction of action of this type of inductor is the same as with version 2; nevertheless, the inductor consists only of a single heating conductor which heats the workpiece from one side (from above). The efficiency is correspondingly lower. Such inductors are usually fitted with field amplification elements which effect a certain increase in efficiency, but which are also prone to malfunction and can result in a lower inductor service life. This inductor type is largely independent of the electromagnetic penetration.

In practice, a two-stage heating process is recommended:

The first heating stage uses a longitudinal field inductor (Figure 5.3, version 1). As the workpiece is heated from room temperature, and the steel is magnetic, the penetration depth at 10 kHz (as a usual process frequency) amounts to only a few tenths of a millimeter (approx. 0.3 mm). This means that the induction current can flow (with sufficient penetration depth) in a closed loop inside the blank given a panel thickness of approx. 1.5 mm. When the temperature approaches Curie point (approx. 760 °C, depending on the steel type) at which the steel loses its magnetic properties, the penetration depth increases with increasing specific resistance until the induction current is unable to flow, as a sufficient “conductor” cross section is no longer given.

This characteristic can be used for self-regulation, as the current is depressed / reduced when approaching the Curie point. With very good levels of efficiency, approx. 85 %, the heating can be performed very quickly and with a high level of energy. In the areas reaching the Curie range first the induction current will be limited first, thereby preventing over-heating. There may be smaller areas that – due to contours – may remain colder because of insufficient current flow.

In this case, the operating frequency could theoretically be used as a control parameter; the large inductor cross-section and the mechanically-necessary relatively large coupling gap renders this impractical and economically unsound.

The second heating stage brings the workpiece to hardening temperature, i.e. this stage must generate the missing 200–250 K. Due to the physical conditions outlined above only inductor versions 2 and 3 are eligible. The lower efficiencies produced by these versions must be accepted.

It should be noted, though, that these versions can produce significant temperature inhomogeneities, as the induction current must be adapted to the contour. The changing edge contours in the feed (in the induction area) may entail, in addition to areas of overheating, also areas of lower temperatures. The possibility of employing a suitably adapted inductor must be examined on a case-by-case basis [5.4]

Should it prove difficult to perform the second heating stage in production or should it only be possible with a wide range of inductors, the lacking 200–250 °C can always be heated subsequently in the conventional manner, taking into account the reduced production rate and the resulting space requirements.

5.2 Fixture hardening

Wilfried Goy

Usually, changes in dimension and form of the workpieces occur with heat treatment. Although the distortion produced by inductive surface layer hardening is indeed not as great as with conventional heat treatment that heats and then quenches the entire workpiece, ever increasing levels of exactness are being demanded from workpieces in order to e.g. minimize distraction of switching cycles and noise development and the increase of running smoothness.

The significant causes of dimension and form alteration are described below [5.5, 5.6].

5.2.1 Distortion due to heat expansion

With a tension-balanced cuboid workpiece of equal side lengths, the temperature increase subjects the corners to the highest level of heating; as a result, they expand first (**Figure 5.4**) [5.7]. The core initially remains cold. With increasing heating time the temperature of the core raises. When heated completely, the resulting expansion causes a slightly spherical form. At high temperatures, the surface tensions are largely reduced by the lowered yield strength. If one starts the quenching process now, as before, the corners will be the first to cool. The surface also becomes cold and tightens around a still expanded hot core. Tensile stresses will accordingly develop on the surface of the cube. Eventually, also the cooling core will shrink.

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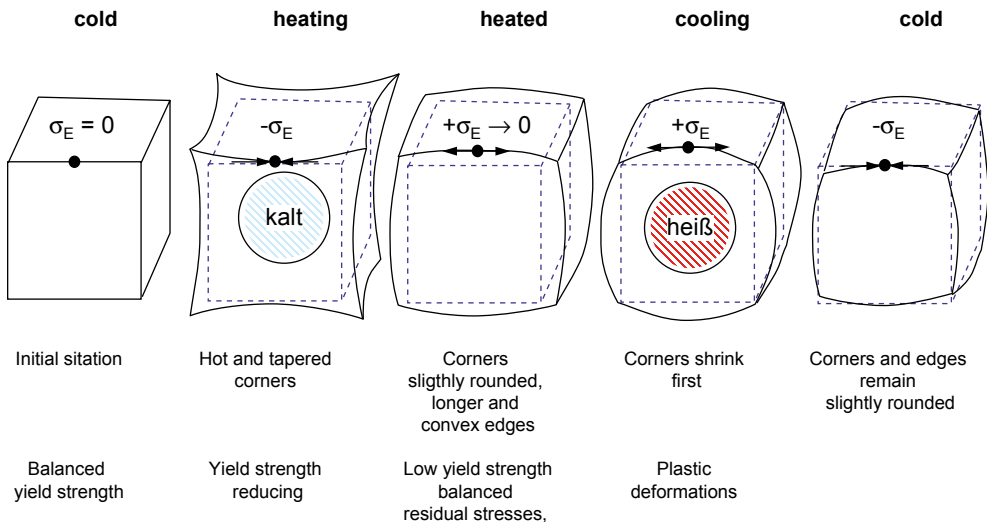


Figure 5.4: Temperature-conditioned distortion of a cube (schematically)

As the already solidified surface tends to follow the inner volume reduction by further shrinkage (radial inward tensile forces), the near-surface tension transforms into (compactively acting) compressive stresses that will finally persist [5.8].

5.2.2 Distortion resulting from phase transformation and volume changes

Also this potential for distortion is described originating from room temperature (point A). A workpiece will first expand approximately linearly with increasing heating – the example shows the lengthwise dilatometer curve of a rod (**Figure 5.5**). The microstructure is a cubic body-centred grid. Once the austenitizing temperature (point B) has been reached, the grid changes into a cubic face-centred structure, the greater compactness of which even results in a slight length reduction. A further temperature increase leads to an expansion of the austenitic structure until the target temperature for complete austenitization has been reached (point C). If necessary, this could be followed by a short transformation time (material-related) at constant temperature.

The subsequent quenching process – given a rate of cooling fast enough to avoid undesired microstructure components – will also produce an initial linear volume reduction. Until the so-called “martensite starting temperature” has been reached, the austenitic structure – with its reduced volume – is present (point D). This even leads to a reduced overall length in comparison to the initial state. If the austenite transforms now into the bulky and more voluminous hardened structure (martensite), the volume will again begin to increase erratically. Finally, once the room temperature has been reached again, a workpiece retains a slightly larger volume (point E in comparison to point A – Figure 5.5).

Of course, all distortion potentials caused by thermal and transformation processes will overlap.

In case of an asymmetric workpiece contour or one-sided heat treatment, the formation of asymmetric tensions is obvious. These conditions require additional dimensional and form changes.

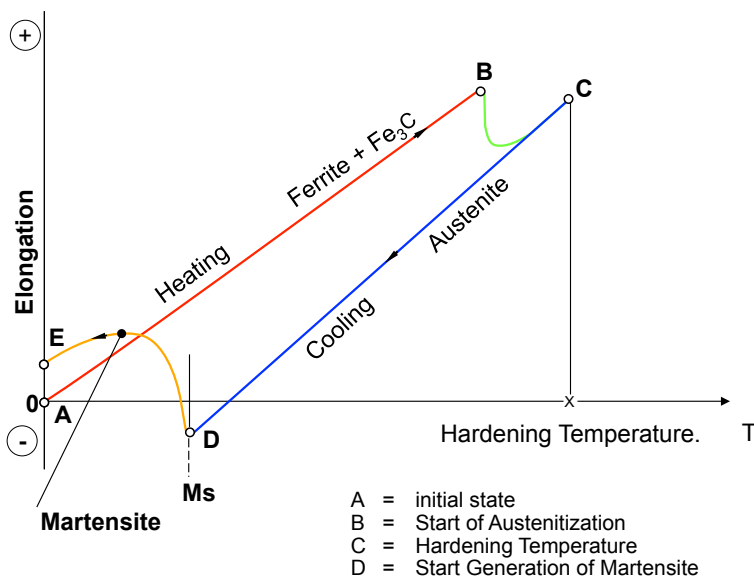


Figure 5.5: Dilatometer curve of a steel rod

5.2.3 Distortion resulting from pre-treatment of the workpiece

An often ignored potential for distortion is introduced through the soft machining steps and processes preceding heat treatment. The fast modern manufacturing machines preferred today – which, in addition, often still work without cooling – generate quite substantial potential for tensions, which may also be released during the hardening process. As the resistance against deformation of a material reduces with increasing heating, the workpiece is no longer able to withstand those tensions so that already on those grounds distortions are possible.

The latter potential for distortion, due to production and pre-treatment of so-called “green” parts, is often underestimated and/or ignored, although its effects may exceed even dimensional and form changes caused by thermal treatment and transformation.

The common stress-relief annealing process does not represent a solution, as on the one hand it does not make sense to reduce the tension before hardening in order to then harden a stress-free but distorted workpiece, and on the other hand this process would also represent an additional production step.

It is important to note that all the tensions mentioned beforehand are released during hardening and lead to undesired dimensional and form changes – especially if the workpiece is thin-walled and/or asymmetric. To achieve the desired exactness of a heat-treated final workpiece, it is often necessary to perform long, difficult and expensive subsequent operations on the already hardened surfaces, especially straightening and grinding. As the grinding of hardened surfaces represents one of the most expensive manufacturing processes, it is already a great advantage if the workpiece has almost near-net-shape dimensions after heat treatment. Even if it may be impossible to avoid the re-grinding altogether, a significant reduction in final processing might be achieved.

If a workpiece to be subject to inductive heat treatment is made of case-hardening steels of lower carbon content and thus requires carburization prior to induction hardening, the carburizing depth can be considerably reduced by means of a near-net-shape fixture hardening process that not only saves carburization time but also involves considerable cost reduction.

5.2.4 The principle of fixture hardening

The fixture hardening process, also known as press-hardening, aims to harden a workpiece and at the same time, produce final dimensions which are as close to the final contours as possible and exhibit the lowest possible dimensional tolerances.

The prerequisite for this is that the dimensions of soft-machining manufacturing processes be matched to the dimensions of the mandrel, the fixture and the desired end dimensions as closely as possible already during production of the still unhardened “green part”. This usually means that the manufacturing dimensions must deviate from the final contour by a few hundredths of a millimetre, as the surface is subject to plastic deformation during fixture hardening of the workpiece. The difference of these dimension-offsets must not be too great, as the final product must, of course, be crack-free.

With regard to a workpiece which is to be hardened on a mandrel for the calibration of the interior diameter (e.g. a sliding sleeve **Figure 5.6**) this means that the interior diameter of the still unhardened green part should be about 2–4 hundredths of a millimetre smaller than the desired final diameter, assuming usual final tolerances of approx. 5 hundredths of a millimetre. Characteristically, the workpiece sliding sleeve will have a slightly larger diameter after hardening than the green part.

The force generated during plastic deformation is primarily responsible for setting the dimensional tolerances (of course, unavoidable in this process, too). In the case of mandrel calibration of an interior diameter, this is the force which eventually effects the widening (expansion) of the broached internal diameter. If the manufactured diameter selected for the “green part” is too large,

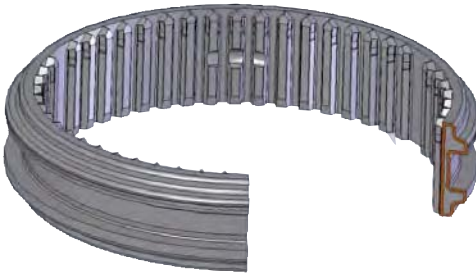


Figure 5.6: Depiction of a sliding sleeve

insufficient deformation force is exerted during the shrinking on the mandrel and the tolerances disperse across a possibly impermissible range. With a still larger start diameter, the workpiece may even not shrink on at all.

In contrast, an insufficient production diameter entails the risk of cracking from undesired surface tension on the workpiece.

Should a component also require hardening on the bottom in addition to its interior broached diameter (if necessary, a flat and plane surface) and on an upper contoured area, a small plastic deformation must also be possible. One contour parameter must, of course, be “free” and able to “take up” the material displacement and volume change associated with the press-hardening. In this case, it is the outer diameter.

Compliance of the tolerances is set with the press force of the upper, moveable fixture punch. The forming pressure is usually generated hydraulically and is determined by tests. The maximum limit of the press force is prescribed by the need to prevent pressure marks of the punch on the surface.

In addition to the dimensions predetermined by the fixtures (calibration mandrel, resting surface and press punch), further parameters can be used during inductive fixture hardening to set the final contour: the quenching conditions.

If usual practice involves the homogeneous quenching of a component, it may be appropriate, when quenching asymmetric component contours, to set different quenching conditions for different areas of a workpiece. As asymmetrical mass distributions have different properties with regard to energy storage and result in different volume changes from the martensite structure (especially with carburized components), it is highly advantageous if a component can be quenched in a partially varied way. This range of quenching behaviour can be effected by the use of multiple individually-controllable quenches working independently of each other.

In the inductive fixture-hardening machine for crown wheels depicted in **Figure 5.7** and **Figure 5.8**, these quenches are integrated through drill-holes in the lower fixture surface and the upper hydraulically-moveable punch. In addition, it is possible to quench the interior through drill-holes of the mandrel. Additional quenching options are possible by means of exterior quenches. As all four of these quenching options can be controlled independently, it is possible to determine both the moment of activation of the individual quenches and the flow rate of the quenching medium for each circuit.

The advantage becomes evident with the workpiece sliding sleeve. The sliding sleeve depicted in Figure 5.6 has two exterior rings which are distributed fairly symmetrically for height. Mostly, however, both ribs will either display various thicknesses and/or be unevenly distributed in terms of height, e.g. in the form of the letter “F”.

Inductive press-hardening of a crown wheel

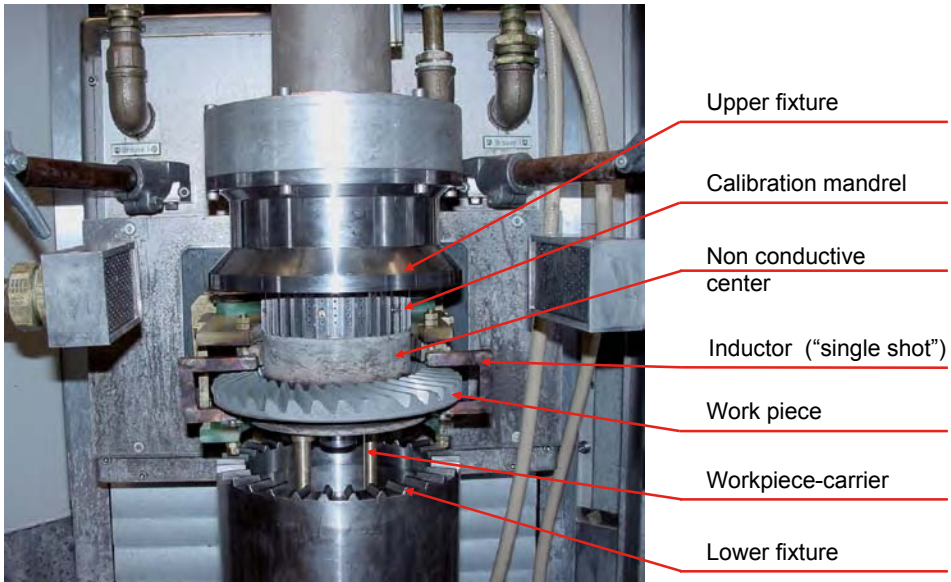


Figure 5.7: Press-hardening machine for crown wheels

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Four individually controllable quenches

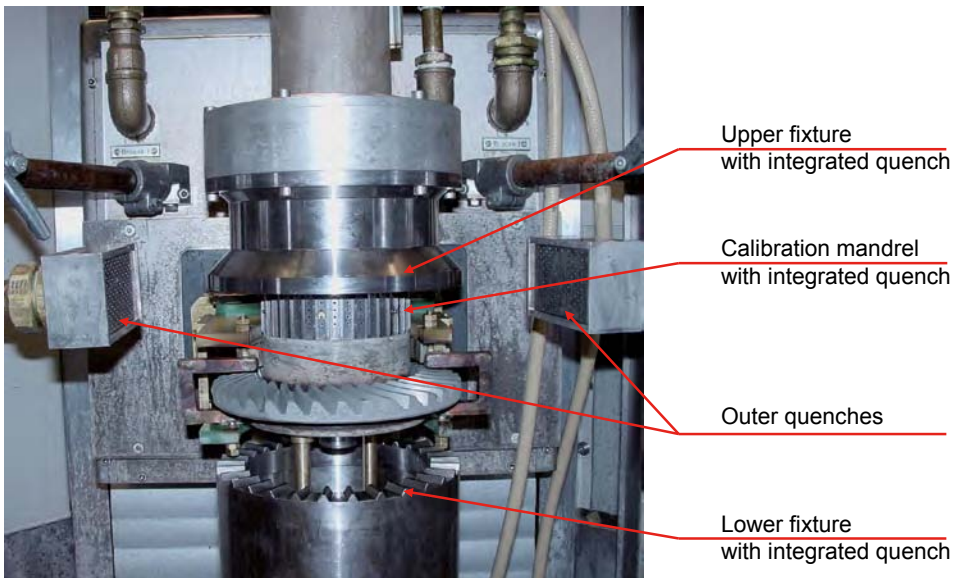


Figure 5.8: Four individually-controllable quenches of a press-hardening machine for crown wheels.

In order to retain the ability to quench the design-conditioned variety of mass distributions with thermo-technical homogeneous characteristics and thereby prevent conicity of the interior diameter, the upper quenching option is e.g. activated somewhat earlier and the workpiece shrinks on in the upper area, whilst still able to yield in the other still warm areas.

For crown wheels with toothing on their upper section these individually settable quenching circuits are also advantageous.

As a matter of course, components can and should rotate during the entire fixture hardening process.

5.2.5 The sequence of a fixture hardening process

Hardening procedure

An inductive fixture hardening process is described using the example of a carburized crown wheel (16MnCrS5) and the following scheme (Figure 5.9).

First, the crown wheel (red) is placed (at the correct height and centrally) between the two press punches (both light green) using a non-electrically conductive centre device (grey). Then the inductor is moved into the working position at the workpiece and the power is switched on; the workpiece begins to warm up (step 1). Naturally, care must be taken that neither the fixtures (light green) nor the calibration mandrel (olive green) are able to couple to the electromagnetic field.

As the workpiece is carburized, it can be heated evenly and as homogeneously as possible. Only those surface areas become hardened during quenching, into which sufficient carbon was diffused during the carburization process. As a rule, the entire surface is carburized. The hardening depth is also predefined by the carburization.

In this example, the crown wheel is heated, as it had initially been cold when placed in the fixture. If the workpiece is already hot and is directly delivered from the carburization process with sufficient hardening temperature, the heating phase can be omitted. If necessary, e.g. in case of transportation losses, the workpiece may also be re-heated to make sure the desired hardening temperature is set.

Cold delivery usually occurs if the component has been left uninsulated and exposed to the air for a long period during transport from the location of carburization to the press and/or surface oxidation (scaling) must be avoided.

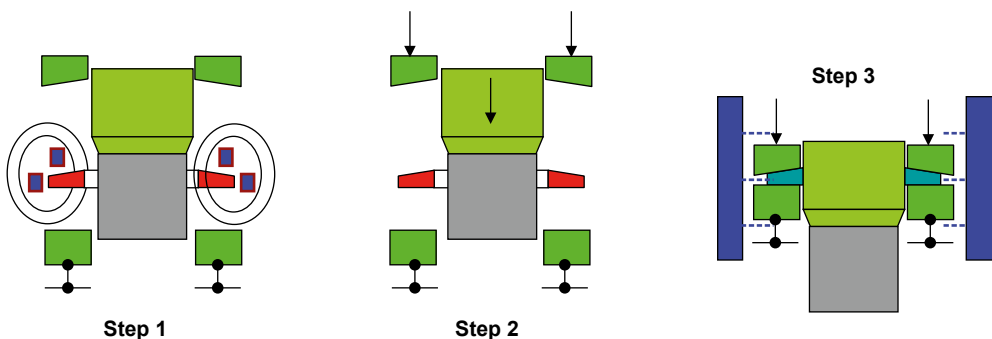


Figure 5.9: Scheme: Inductive fixture hardening

The component expands with increasing heating and the diameter grows. Once the hardening temperature has been reached, the interior diameter of the workpiece should be a little larger than the exterior diameter of the calibration mandrel.

Upon reaching the austenitization temperature and a homogeneous temperature distribution within the workpiece, the inductor is retracted in order to clear the way for the upper pressing punch (step 2).

The upper fixture moves down at the same time as the calibration mandrel enters into the interior diameter of the workpiece. In this (pressed) state, the workpiece is quenched down to room temperature – controllable via the four individual quenching options described above. Induction hardening will normally use a polymer solution as the quenching medium.

At the end of the quenching procedure, the workpiece has been hardened and calibrated; it fits exactly on the corresponding surfaces of mandrel and fixtures.

The upper fixture can now be moved up so that the workpiece is “free” again, but still shrunk onto the calibration mandrel. The hardening and calibration procedure has been completed.

Tempering

There are, essentially, three methods of continuing the process:

1. The workpiece is withdrawn in cold state. It can deform at maximum within the range of physical elasticity. The subsequent tempering can be performed in a separate processing station either inductively or in a conventionally-heated oven.
2. If an expanding mandrel was used the retaining elements are retracted, and the workpiece is released. With this method, too, a component can only deform within the bounds of physical elasticity. The subsequent tempering can be performed in a separate processing station either inductively or in a conventionally-heated oven.
3. The third possibility is depicted in **Figure 5.10**. The inductor is returned to the heating position (step 4) in order to warm up the workpiece. The target temperature has been selected on the basis that the low heat expansion which now begins forms a small gap between the workpiece and the calibration mandrel (step 5) which allows the workpiece to be withdrawn from the calibration mandrel without excessive force and without significant wear. The temperature remains below the tempering temperature for short-term tempering, which is comparable with the temperature used for the heat-shrinking procedure – i.e. approx. 140–150 °C. The further tempering can be performed as with method 1 or inductively in the withdrawal station, provided the

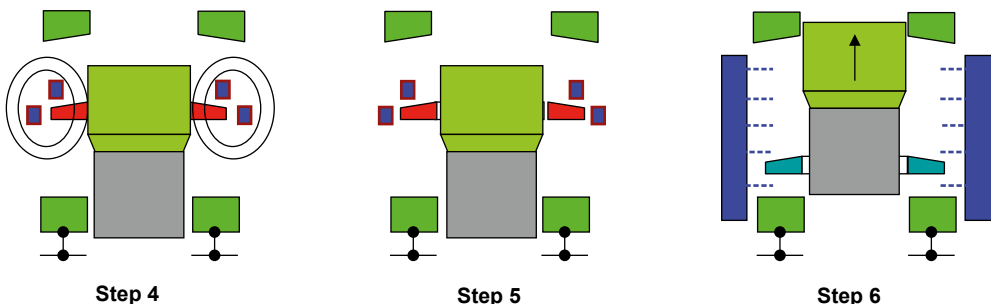


Figure 5.10: Scheme: Removal of inductively heated workpiece in combination with inductive tempering

presence of sufficient cycle time. Subsequently, the component may be cooled or not, depending on the requirements of following production steps (step 6).

The depicted process combines the advantages of inductive tempering with those of inductive hardening. This results in hardened and at the same time calibrated workpieces with near net-shape dimensions so that re-working can either be omitted or minimized. The procedure is suitable for all workpieces requiring high accuracy, especially for gear and transmission components.

5.3 Impulse Induction Heating

Andreas Seitzer

In this chapter some examples of short-time induction heating processes are presented. “Short-time” can have different meanings in this extent:

- The workpiece is not moved or only slowly moved. The duration of the induction heating impulse is determined by the controls of the high frequency power supply. This duration is typically within a range of several milliseconds through some seconds. Such kind of processes are usually controlled by optical temperature measuring devices like pyrometers, which monitor the target surface temperature.
- The workpiece is moved in high transition speed through an induction heating device, which lead to only short times of electro-magnetic coupling between the inductor and the workpiece. The workpiece itself triggers the heating impulse by its own transition speed. The power supply is constantly switched on and must be able to provide the preset amount of heating energy to the process as soon as the workpiece is in proximity of the inductor.

Characteristic for short-time heating applications is a small area of the heat affected zone. This can be either because of the size of the workpiece itself or because only a very limited heating zone is demanded by the process. The following examples will show both possibilities. In any case, the frequency converter must be able to follow the fast transient phases when either the output power is being switched on and off in a range of milliseconds or when permanent changes on the load side of the resonant circuit occur due to the rapid changes of the inductor being filled with material and being empty.

5.3.1 Pulsed induction heating in fastener production

In the fastener industry the incoming material – in many cases round-shaped wire – typically is shaped by cold and warm forming processes. Depending on the size of the incoming material and the dimensions of the final product, the production machines like multi-head-presses or rolling lines operate in combination with fully-integrated induction heating.

Due to the fast cycle times especially at the production of smaller fasteners like bolts and screws the heating operation is a critical part of the overall efficiency of the production process. While in some applications the induction heating device is in a permanent mode of “HighFrequency-Power ON”, in other applications the induction heating power output is synchronized with the pace of the forming machine.

Depending on the design of the forming machine, the space for integrating an induction heating coil within the machine, can be a challenging detail. Since modern forming machines show a tendency of decreasing foot-print, the choice of the ideal location for an integrated resonant circuit including the inductor in the forming machine is a true inter-disciplinary subject: mechanical engineering, metallurgy and induction heating specialists need to work together before the entire mechanical engineering phase and the simulated forming operations are finalized.

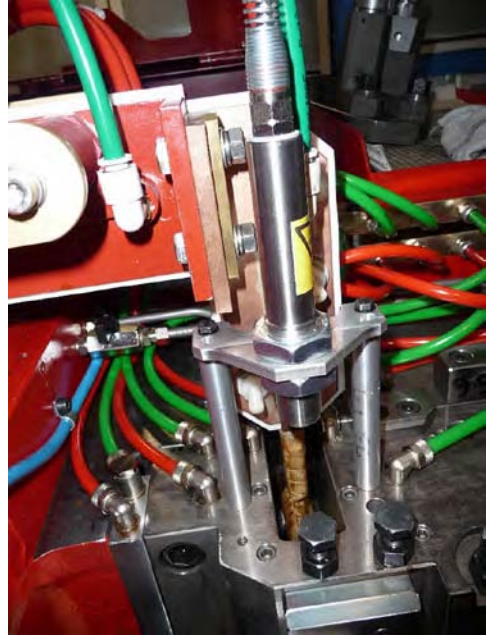
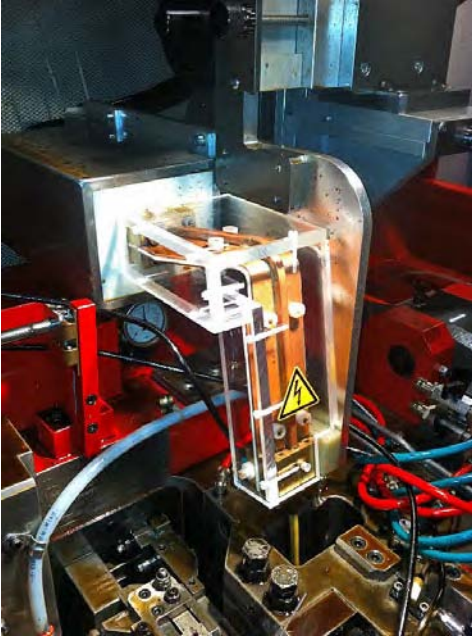


Figure 5.11: Typical limitations and space restrictions for integrated induction heating in a multi-head press environment (Source: Geisser Thermoprecision)

Figure 5.11 shows the limitations in available space in a typical induction heating set-up in a multi-head-press for fastener production. In the given example the induction heating coil is placed between feed roll and shear knife. A closed inductor design is chosen because of its smaller stray-field compared with u-shaped open inductors. Thus, the parasitic heating effect of the inductor-vicinity is kept within a smaller range and helps to improve both energy efficiency and mechanical tolerances of the machine.

The general design of the inductor and the external resonant circuit in the machine-environment is shown in **Figure 5.12**. The placement of the heating coil is as close as possible to the shear knife in order to keep heat losses during transportation of the material as low as possible. Since presses in the fastener production need to be very versatile in terms of different fastener dimensions (see impression on **Figure 5.13**), the position of the heating coil is adjustable in one or more dimensions.

For reasons of both process feasibility and energy efficiency the heating of the wire is happening not continuously, but synchronized with the movement of the wire.

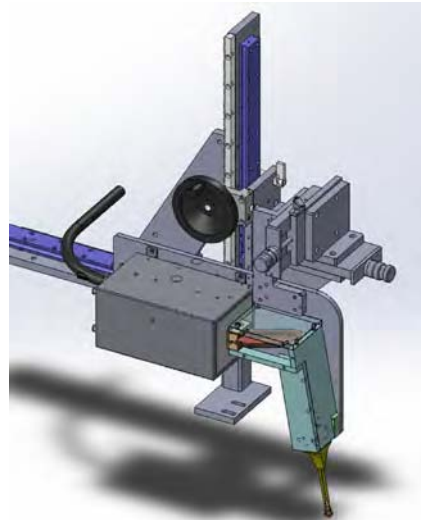


Figure 5.12: General design of integrated induction heating in a multi-head press (Source: Geisser Thermoprecision)



Figure 5.13: Impression of variety in the fastener production (Source: Himmelwerk)

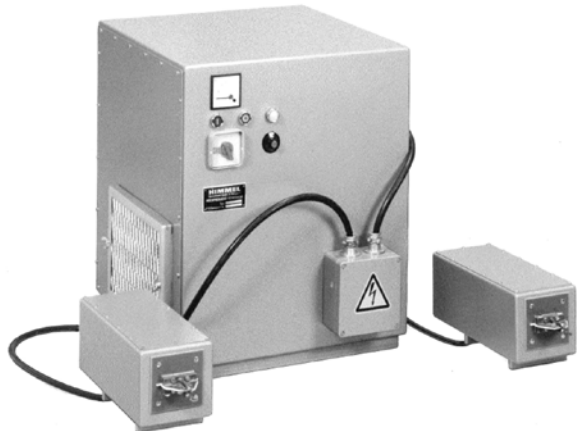


Figure 5.14: Vacuum-tube based HF-generator with two external resonant circuits (Source: Himmelwerk)

The length of the heating zone corresponds with the length of the following forming operation (header length). By heating only a part of the wire, also the risk of wire getting stuck in the shear bush is substantially reduced. Some forming processes like large forming grades, high alloy steels or non-cubic crystal structures can only be realized with synchronized and pulsed induction heating.

The high-frequency generator power ranges typically from below 1 kW up to 50 kW depending on the workpiece dimensions and the production rate. The operating frequency is in a range of 100 kHz to 2 MHz, whereas higher frequencies are linked to smaller workpieces and faster processes. Typical heating times can range from 100 milliseconds to several seconds.

5.3.2 High frequency induction heating for the optical industry

In the optical industry there is a multitude of brazing, soldering and welding operations when manufacturing spectacle frames. In times back when spectacle frames were mostly metal frames the high frequency heating processes were established with vacuum tube based HF generators. The generator is connected by HF-cables with one or more external resonant circuits, which are basically consisting of HF capacitors and the workpiece-related inductor. **Figure 5.14** shows a typical example of a vacuum tube based HF generator with two external resonant circuits (appr. 1980).

HF induction heating has come to be the preferred method with respect to other soldering techniques. The following advantages are of particular importance:

- The heat is not transmitted from the outside, but is produced within the workpiece itself, exactly where and when it is needed.
- The energy is transmitted from the energy source to the heating joint without contact. No surface damage is produced as it can occur when performing e.g. resistance soldering.
- The induction heating technique employs the highest possible concentration of energy. The development of heat is thus confined to the smallest area possible. The areas adjacent to the soldering joint are not affected, i.e. the spectacles' strength and elasticity – even in the immediate vicinity of the soldering joint – are preserved in their entirety.
- The quantum of heat which shall be applied to the process can be dosed quite exactly. The joints thus have a greater degree of uniformity and a more "impeccable" appearance.

Figure 5.15: Spectacle frame and typical soldering spots (Source: H. Michalet, Himmel France)

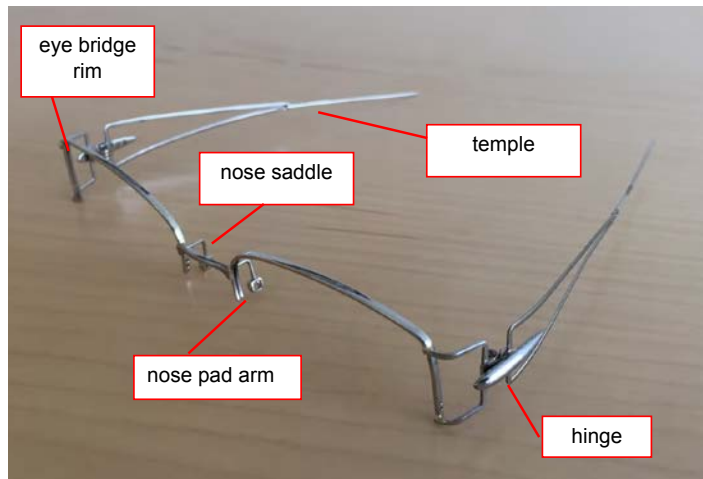


Figure 5.16: Compact Design Solid State High Frequency Converter with external resonant circuit and temperature control device (Source: Himmelwerk)



- Induction heating exploits the capillary effect. This effect causes the solder to always be drawn into the solder-crevice which forms between the two pieces. So-called “cold” soldering joints can thus be avoided.
- The heating spot is easily accessible during the heating operation.

In today’s optical industry spectacle frames are both metallic and non-metallic. But even with non-metallic frames, several heating operations still are necessary and also performed by high frequency induction heating. **Figure 5.15** shows a contemporary spectacle frame and the typical heating operations on it.

The power supplies for this heating process are no longer vacuum-tube based generators, but solid state frequency converters as shown in **Figure 5.16**. A compact design is needed because these converters need to be integrated in work-benches where the spectacle frames are assembled and where space is very limited. Typical operating frequencies range between 0,5 – 2 MHz. The rated power of the converters is in a range of 1–3 kW. The heating time typically between 1 and 2 seconds.



Figure 5.17: Example of medical metal-plastic-components (Source: Himmelwerk)

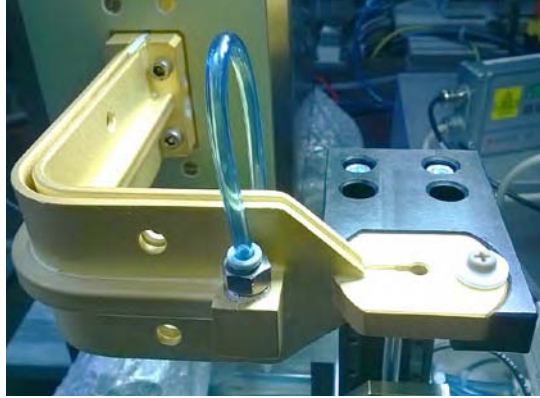


Figure 5.18: Example of an induction heating coil for medical applications (Source: Geisser Thermoprecision)

5.3.3 Short-time induction heating for material bonding in medical industry

In the medical industry when manufacturing syringe and dose needles or similar products often a bonding process is used for jointing the metal cannula with plastic components (see example in **Figure 5.17**).

Metal cannula and plastic cartridge are precisely placed as assembly group in a high frequency inductor. The induced heat in the metal cannula is melting the plastic surrounding and by this the plastic material is bonding with the surface of the metal material. The positioning of the bonding joint can be done very precisely by the appropriate design of the inductor.

High frequency induction heating is a preferred heating method. Since no atmospheric or contact heating is used by induction, no contamination of the sterile components “metal” and “plastic” will happen during the heating process. The components can be prepared and delivered with sterile conditions and are still under the same sterile condition after being bonded by induction heating.

Other advantages of induction heating over adhesive jointing is the shorter process time and the increased mechanical strength properties at lower values of the statistical mean variation.

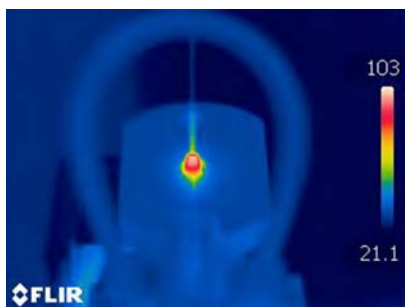


Figure 5.19: Infrared shot during the heating of an injection needle by induction (Source: Himmelwerk)

Besides the clean working environment, an additional technical challenge is to operate only components like HF-converters, capacitor and inductor without water-cooling. Water cooling could lead to leaks which would represent a risk for the sterile condition of the medical components. Therefore, no water cooling of the induction heating components is permissible. **Figure 5.18** shows the design of an induction heating coil for the medial bonding process. **Figure 5.19** shows an infrared picture taken during the heating process. The narrow heat affected zone can be seen in this picture.

Typical operating frequencies range between 1,5 MHz and 4 MHz with rated power values of up to 5 kW. Heating duration can be between 500 milliseconds up to 10 seconds depending on material dimensions and choice of the bonding reaction partners “metal/plastic”.

5.4 Induction sealing

Elmar Wrona, Torge Behrens, Jens-Uwe Mohring

5.4.1 Inductive squeeze-tube welding

Induction heating is used for welding of squeeze tubes when the tube material is coated aluminium. Tubes are filled from the side opposite to the closure and are then welded closed by flattening the tubular container. This takes place between the jaws of two linear inductors which provide not only the induction current, but also the necessary friction locking between the halves of the tube. The fact that there is no seam which could interrupt the flow of current makes this procedure particularly efficient and extremely automatable. The inductors are usually supplied with current via stranded-wire cables with no active cooling arrangement. This preserves mobility. The inductors themselves generally take the form of single-turn coils, of which one element is embedded in a field-amplifying material. This element presses onto the tube surface and is thus at the smallest possible coupling distance from the layer of aluminium. The inductors are water-cooled and are supplied separately. Motion is accomplished by means of pneumatic systems, on which the inductors are mounted. Generators with working frequencies of several hundred kilohertz are usually used as the energy source. Tube generators have been in use since the 1980s, but have been gradually replaced by modern semiconductor generators during the last around ten years. Generator outputs are, typically, 5 kW. Ultra-short heating times of some 200 to 400 ms are used in industrial mass production. Typical applications include pharmaceutical and drugstore products.

5.4.2 Induction welding of cartons

The type of weld used on cartons can differ greatly. In certain types, closure is accomplished by means of folding and welding, similarly to squeeze-tube welding. On other cartons, tops or bottoms consisting of a different material are welded in. In cartons, the layer of aluminium is embedded between two layers of an electrically insulating material. The cartons often feature a longitudinal seam, the result of the production technology used, with the consequence that the layer of aluminium is interrupted at this point. It is therefore not possible to induce a current which could flow around the entire periphery of the container, as is the case in squeeze-tube welding. Special inductor geometries are needed to permit welding of the longitudinal seam area to the base with the necessary quality. Due to the anomaly of conductivity along the periphery, field-amplifying materials are used in many cases only locally.

Unlike those used in squeeze-tube welding, the inductors used here are not movable. The necessary contact pressure is generated by a special arrangement on the opposite side of the inductor, and thus presses the carton against the live conductor. The foodstuffs industry is the main user of this technology.

5.4.3 Induction sealing of bottles, jars and cans

The principle of induction sealing of containers by means of a screw closure is shown in **Figure 5.20**. These containers are geometrically stable and are filled from the end at which the product is also subsequently dispensed. A wax-coated aluminium foil is generally used as the sealing medium. This is inserted into the cap and pressed against the rim of the container during screwing closed. The term “package” is used in this context. Not only a constant torque during screwing closed is needed for successful sealing using this process – the correct combination of container material, foil thickness and coating material is also decisive. Differentiation is made in the case of the foils between peelable types and foils which are destroyed when the container is opened. Such

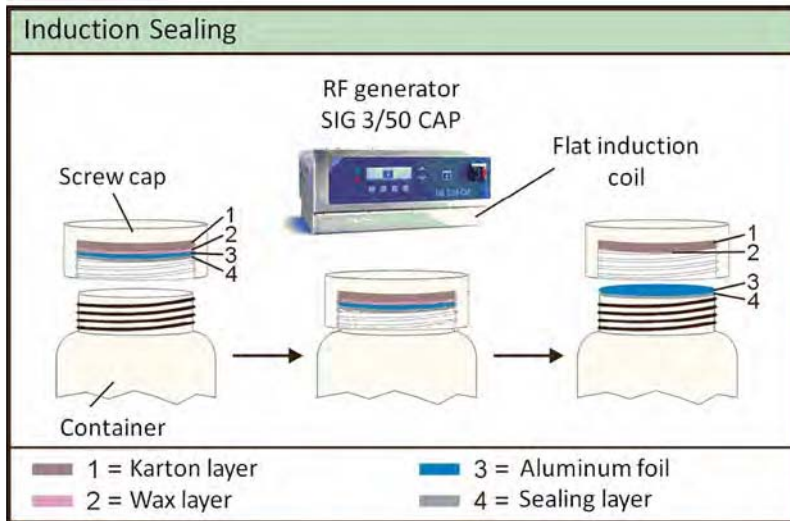


Figure 5.20: The principle of induction sealing
(Source: TRUMPF Hüttinger)

foils generally consist of two different layers, these being separated from one another only when the container is opened for the first time. This is accompanied by the familiar clicking sound. The layer which remains in the cap serves after removal of the sealing foil as a seal against liquid products, or as an aroma seal, as in the case, for example, of ground coffee. This procedure is also excellently automatable and can usually be operated continuously. Such systems are generally air-cooled, in view of the high cleanliness standards necessary in the foodstuffs industry. The inductors take the form of flat-wound coils consisting of stranded copper wires, below and past which the containers are moved on a conveyor. Modern systems are equipped with a foil-detection system which issues an error message if the foil is missing, with the result that the bottle affected can be rejected. The generators usually operate in the range between 40 and 60 kHz. Outputs of 5 kW make it possible to operate at throughput speeds of up to 30 m/min.. Certain forms of closure require an excessively large coupling distance between the inductor and the foil, however. So-called tunnel inductors, which are mounted to the side, next to the foil, are used in such cases. Homogeneous sealing across the circumference is then achieved by means of an additional rotation of the container.

5.4.4 The benefits of induction sealing over conventional methods

The use of induction sealing or welding of containers can make it possible to benefit, due to the typical properties of induction heating, from many advantages compared to non-electric methods. One extremely important aspect is the fact that the energy is always fed only into the conductive aluminium layer. There are thus no harmful thermal effects on the product itself. The quantity of energy necessary for production of the joint can be metered with high accuracy, with the result that, even after sealing, no surplus heat can flow away into the product. Thanks to non-contact energy transfer, many products are ready for packing immediately after the sealing process, and require no further finishing treatment or assembly operations. The achievable transferable power densities permit ultra-short heating times, and thus extremely high production rates. Further important benefits include a high degree of automatability and the above averagely high repeatability of this process.

5.5 Induction heating of plastics injection molds

Elmar Wrona, Torge Behrens, Jens-Uwe Mohring

5.5.1 Introduction

Processes in which the mold for injection-molding is heated prior to injection of the plastic, and then cooled again, are coming increasingly frequently into use for injection-molding of plastics. This “variothermal” process improves the surface quality of the plastic injection molding, and permits modeling of microstructures and ultra-small moldings. Conventional methods of heating, using hot oil or hot water, for example, entail the disadvantage that heating and cooling take place only very slowly, in view of the only low transferable energy densities. Processing times increase significantly compared to non-heated processes, and productivity drops.

Induction heating methods permit transfer of high power densities into precisely defined zones. Processing times are only insignificantly longer than without heating. Induction heating can, in addition, also save costs. The surface qualities achievable are equivalent to those of painted and polished components, but with costs lower by a factor 50.

5.5.2 Design of the heating and cooling system

The heating and cooling system in the injection-molding mold is designed by means of numeric simulations. The aim of induction heating is that of achieving in the shortest possible time a homogenous temperature profile on the surface of the mold. To this end, inductor geometry is repeatedly modified, and a new simulation iteration started, until the optimum has been achieved. The same procedure is used for the cooling system.

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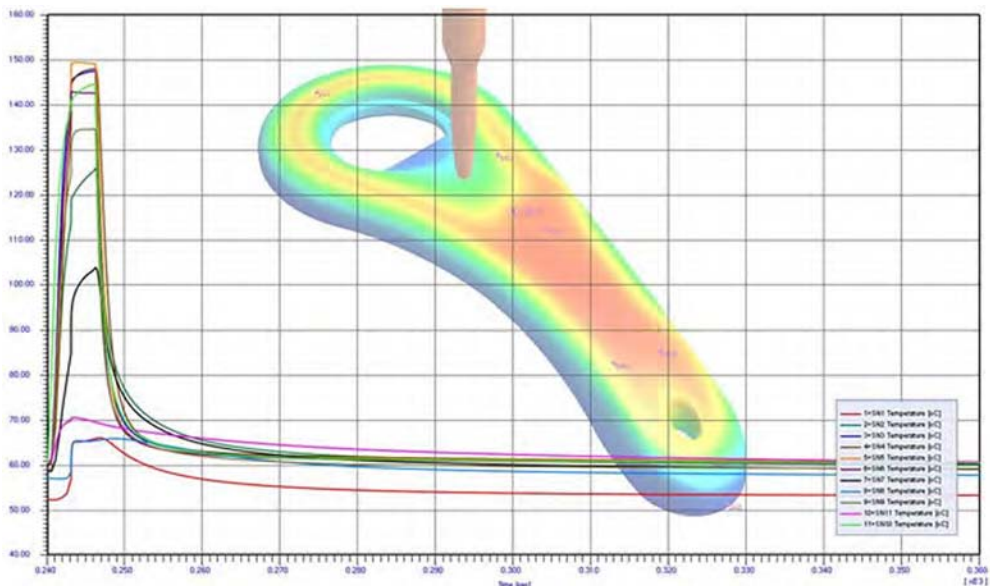


Figure 5.21: Temperature distribution on the surface after completion of heating
(Source: Kunststoffinstitut Lüdenscheld)



Figure 5.22: Grip of bottle opener, showing surface defects
(Source: Kunststoffinstitut Lüdenscheld)

The result of a numeric simulation is shown in **Figure 5.21**. The temperature profile on the surface of the injection mold is apparent, on the one hand. The plot against time at defined points in the surface of the mold is also shown, on the other hand. It is apparent that the lower grip area of the bottle opener is significantly cooler than the middle grip zone. This results in surface defects, as can be seen from **Figure 5.22**.

5.5.3 System concept

The induction coil normally consists of a copper wire or copper strand recessed into milled channels in the mold. This is known as the INDUMOLD® process. The ends of the coil carry a special connector which is connected to a medium-frequency (MF) power supply.

Power supplies with parallel oscillating circuits are typically used. The power supply is controlled by means of a higher-level control system. An A/D or Profibus interface, for example, is used. The injection-molding machine's control system generates a start signal. The power unit then supplies the necessary process energy for a defined period (integrated timer).

The power needed depends on the length of the inductor and the mass to be heated. Typical outputs range is between 20 and 40 kW. Frequencies of 70 to 100 kHz are used, since only thin layers are to be heated, in order to keep cooling time as short as possible, and to assure high productivity. Heating times generally vary between 2 and 7 s. Process temperatures between 120 and 180 °C are achieved in these times.

5.5.4 Summary

Induction heating is an innovative technology in injection molding. It permits high surface qualities combined simultaneously with high productivity and low costs. Numeric simulations are used to determine the optimum inductor geometry. The injection-molding machines must interact optimally with the heating system to assure successful industrial-scale use.

5.6 Induction heating of carbon-fiber-reinforced plastics

Elmar Wrona, Torge Behrens, Jens-Uwe Mohring

5.6.1 Introduction

The informal term “carbon” actually signifies a carbon-fiber-reinforced plastic (also known as CFRP), from which components and sections of the most diverse type are produced (see **Figure 5.23**). In CFRP, carbon fibers are generally embedded in a number of layers, to provide stiffening in a plastic matrix. Unlike quasi-isotropic metals, such as aluminium or steel, which can be equally exposed to loads in all geometric directions, carbon fiber is anisotropic. Complete layers of carbon fiber are in many cases incorporated in a range of different configurations, in order to extend the stiffness properties which these fibers impart into multiple directions (multi-axial layer). Typical mechanical characteristics, such as tensile strength, and modulus of elasticity normal to and perpendicular to the fiber direction, are shown in **Table 5.1**.

Tensile strength	650 [N/mm ²]
Modulus of elasticity in the fiber orientation	75,000 [N/mm ²]
Modulus of elasticity perpendicular to the fiber orientation	3,500 [N/mm ²]

Table 5.1: Typical characteristics of CFRP with a fiber content by volume of approx. 50 %



Figure 5.23: CFRP profile

CFRP, like a number of other materials, can be inductively heated. There are certain preconditions for the application of an alternating electromagnetic field, however, signifying that CFRP components must in all cases be checked in advance for their suitability for induction heating.

5.6.2 Heating mechanism

The heating pattern shown in **Figure 5.24** becomes apparent when a CFRP sheet is penetrated by an electromagnetic field. A grid-like plot of temperature – symmetrical to the fiber orientation – is apparent. It can be concluded from this that the orientation of the carbon fibers is definitive for heating behavior. Thanks to their electric conductivity, the alternating magnetic field can induce in the fibers a voltage, which generates a flow of current. The fibers, for their part, pass on the heat thus generated to the matrix system.

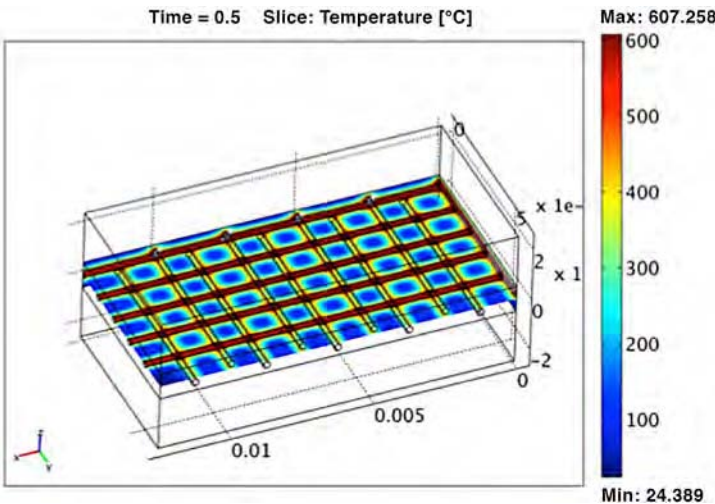


Figure 5.24: Heating pattern in a CFRP sheet

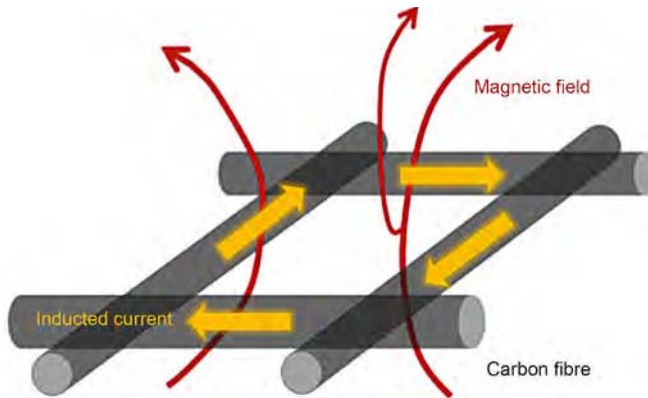


Figure 5.25: Conductor loop consisting of carbon fibers

An annular arrangement of the fibers is, in addition, necessary for heating. The structure must be arranged in such a way that a circular fiber structure similar to the windings of a coil results within the magnetic field, in order that the fibers act as conductors and, all together, make up a conductor loop (Figure 5.25). There must, for this purpose, be sufficient points of contact between the fibers. The contact resistances between fibers of differing orientation must also not be too great. They can be reduced by means of “com-

paction”. Flat-area heating thus presupposes multi-directional fiber orientation and good electric contact between the layers of carbon.

The possibility of treating CFRP using heat is equally dependent on the matrix component, since this exerts a great influence on softening behavior. Due to their insoluble cross-linking, fully cured thermosets cannot be remelted, whereas thermoplastics are reversible and can be heated infinitely frequently. They are heated, for example, in order to weld, form or reform them. Thermoplastic carbon-fiber composite materials combine the properties of carbon fibers, such as high stiffness plus low weight, with typical workability advantages of the thermoplastics.

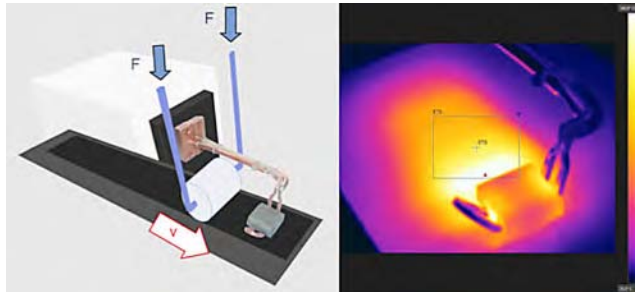
5.6.3 Practical examples of induction of CFRP

- Forming after heating
- Joining of moldings by means of melting of the thermoplastic matrix system: Induction welding
- Joining of moldings by means of an adhesive/weld-filler material
- Curing during the production process for thermoset CFRP, since heat accelerates the cross-linking reaction
- Flexible making of three-dimensional joints by means of a robotic arm
- Inductive preforming
- Recycling of CFRP components: recovery of high-cost carbon fibers
- Hybridization: Joining of CFRP to other materials
- Variothermal mold temperature control
- Joining of two thermoplastic-coated CF thermosets

5.6.4 Practical example of induction welding

In induction welding of CFRP, sheets are heated using a flat inductor while being fed, and pressed together by means of a roller (see Figure 5.26). The materials are thus welded. The frequencies used are typically between 200 and 600 kHz.

Figure 5.26: Diagram in principle and heating profile for induction welding of CFRP sheets
(Source: TRUMPF Hüttinger)



5.7 Heat treatment of carbon materials

Hans Windsheimer, Horst Linn

Due to their high electrical conductivity and mechanical load at simultaneous low density, carbon as well as carbon composite materials become more and more important in automotive, electrical and in aviation and aerospace industry. Promising applications are electrode materials for batteries of electric cars as well as structural or bodywork components.

Many of these new carbon materials are produced by suitable heat treatment processes of precursors at temperatures of up to 1,000 °C. In case of precursors, there is a range from synthetic polymers such as polyacrylonitrile (PAN) up to renewable raw materials [5.9, 5.10, 5.11]. This heat treatment step typically yields microstructures with carbon atoms in disordered form.

In principle, a graphitization step at temperatures of up to 3,000 °C follows for adjustment of desired characteristics such as elasticity and tensile strength of carbon fibers or electrical conductivity of electrode materials. During this process, the atomic arrangement of the carbon atoms is more and more organized with increasing temperature until there is a more and more layered graphite structure at temperatures starting from 2,000 K. This structure obtains the desired mechanical as well as electrical characteristics (**Figure 5.27**).

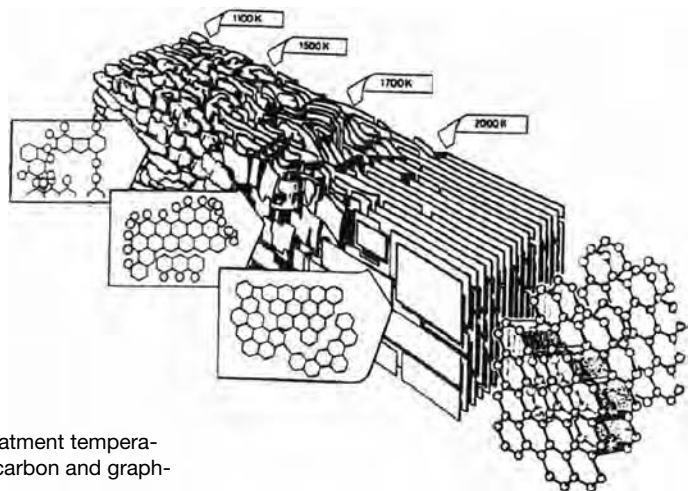


Figure 5.27: Influence of the treatment temperature on arrangement degree of carbon and graphite materials [5.12].

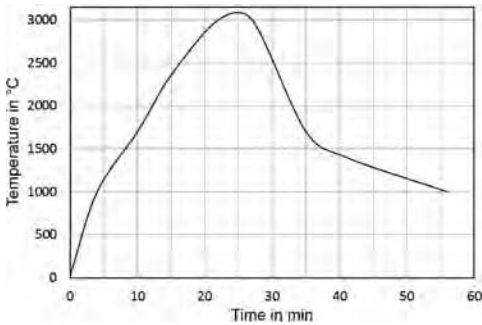


Figure 5.28: Exemplary temperature profile in case of inductive graphitization of carbon materials

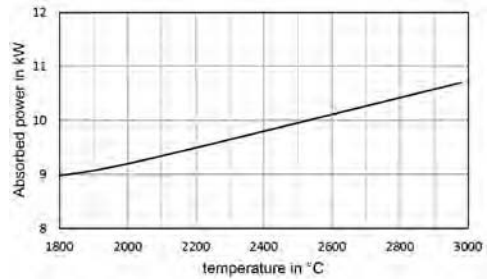


Figure 5.29: Absorbed power depending on temperature in case of inductive graphitization of carbon materials (exemplary)

Due to the necessary high temperatures and good electrical conductivity of the materials, inductive heating is recommended. In case of inductive heating, temperatures above 3,000°C can be reached within short time by direct heating of the material or by using suitable graphite susceptors (**Figure 5.28**).

Due to temperature increasing electrical conductivity of the carbon material, the induced power of the workpiece rises which, in turn, generally makes the process more efficient (**Figure 5.29**).

Such units (example **Figure 5.30**) are especially characterized by a compact design as well as low energy requirement. An advantage is a high heating rate up to app. 150 K/min at simultaneously low maintenance and operating costs.



Figure 5.30: Medium frequency induction unit for graphitization of semi-finished products and components made of carbon; $f = 8\text{--}12\text{ kHz}$, $P_{\text{max}} = 30\text{ kW}$

5.8 Inductive pre-heating in case of welding processes

Hans Windsheimer, Horst Linn

Recently, different welding processes such as friction or diffusion welding have been applied to a number of materials and material combinations such as steels or titanium respectively titanium alloys [5.13].

Due to compact units and efficient heat transfer on the product, inductive pre-heating of the product is reasonable in case of this welding process. TiAl-alloys, for example, can only be connected permanently if the workpieces are heated to temperatures above the brittle-ductile transition range (550 – 800 °C) before the welding process [5.14, 5.15]. Only then the mechanical forces, which are necessary for the connection, can effect joining of the materials without development of micro-structure defects.

As such welding methods are typically characterized by high throughput rates with short cycle times (minute range), pre-heating of the components has to be adjusted to the cycle time. Here the energy

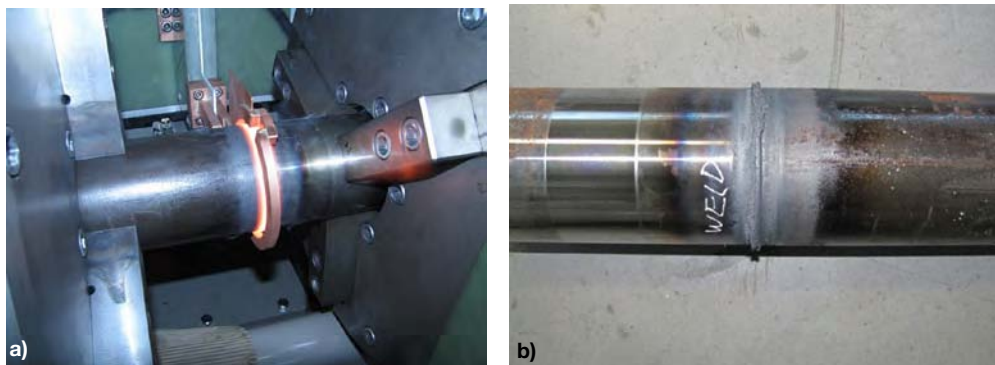


Figure 5.31: Inductive pre-heating in case of diffusion welding of steel; (a) pre-heating step on the welding point, (b) welding seam after cooling down.



Figure 5.32: (a) Semi-conductor high frequency generator with outside resonant circuit ($P_{max} = 1,2 - 10$ kW, $f = 150 - 450$ kHz), (b) typical medium frequency inverter ($P_{max} = 10 - 1000$ kW, $f = 10 - 80$ kHz) [5.16].

input of inductive heating directly affects the workpiece which enables extremely short heating up times. In addition, the penetration depth respectively the heat penetration zone can be adjusted specifically and reproducibly by proper selection of the working frequency of the generator.

Figure 5.31 shows an example of an inductive pre-heating unit with a maximum power of 120 kW at a working frequency of 2–5 kHz. Due to the power output of the generator in combination with a well-adapted one-winded inductor, very high pre-heating temperatures of up to 1,350 °C at cycle times of approx. 2 minutes can be reached.

Figure 5.32 shows typical converters for this application field. Due to its compact design, the generators are especially suitable for retrofitting of existing units.

5.9 Inductive methods for crystal-growing processes

Elmar Wrona, Torge Behrens, Jens-Uwe Mohring

5.9.1 Introduction

Humanity has always been fascinated by the synthetic production of crystals. The focus of industrial interest is, in particular, on growing single-crystals (monocrystals) from semiconductor materials, such as high-purity silicon, and oxidic materials, such as sapphire. Such crystals are used, for example, for the production of wafers and substrates destined, primarily, for the semiconductor and solar markets.

The most important of the crystal-growing processes are the Czochralski and floating-zone processes. Both technologies very frequently make use of induction heating systems.

5.9.2 The Czochralski (CZ) process

The CZ process is the most frequently used technology for the growing of monocrystals (supplying around 85 % of market demand for monocrystalline silicon). Here, a monocrystalline seed crystal is dipped from above into a melt (**Figure 5.33**). Due to the temperature gradient, the melt material

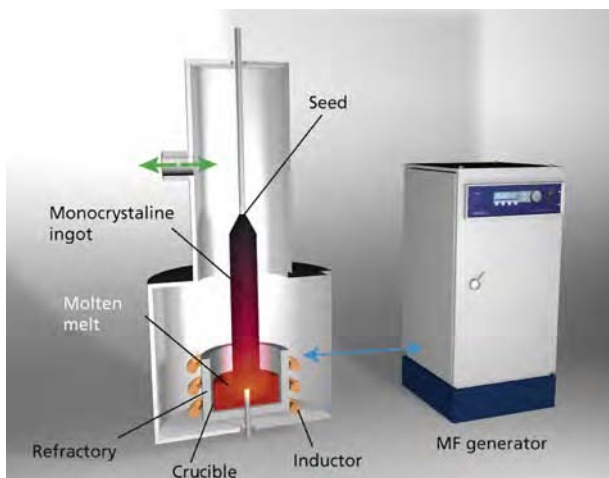


Figure 5.33: Schematic diagram of the Czochralski process
(Source: TRUMPF Hüttinger)



Figure 5.35: The melt zone in the FZ process

FZ silicon is used primarily for the production of power semiconductors. Here, not only purity, but also uniform distribution of resistance across the crystal diameter, plays a decisive role. If this were not the case, the current distribution in the power semiconductor would not be uniform, and would result in failure.

FZ silicon is also used in solar technology. Solar cells with ultra-high efficiencies of up to 25 % can be produced in this way. They are used, inter alia, in aerospace applications.

Induction performs several functions in the FZ process: it supplies the energy needed for remelting, generates the electromagnetic forces necessary to

support the melt, and causes the flow of melt needed for the crystal-growing process.

Induction generators of various outputs are used in the FZ process, depending on the required crystal diameter. The production of slim rods requires an output of 5 to 15 kW, whereas generator outputs of up to 120 kW are needed for monocrystals with a diameter of 200 mm. Silicon's relatively low electric conductivity, and the small radius of the melt, mean that the generator must operate dependably at frequencies of between 2 and 3 MHz. Only tube generators are therefore used in industrial applications. Such generators permit high frequencies while simultaneously supplying high voltages and power outputs, features currently not yet available in transistor technology. Tube generators are, in addition, also designed to supply the FZ process with process current reliably and without interruption for many hours or even days. A generator failure would make the crystal unusable, and cause a loss of several thousand euros.

5.10 Inductive susceptor heating in epitaxy processes

Elmar Wrona, Torge Behrens, Jens-Uwe Mohring

5.10.1 Introduction

The term "epitaxy" is used to denote a process in the semiconductor industry in which monocrystalline layers of a semiconductor material grow on a substrate. This method is used for the

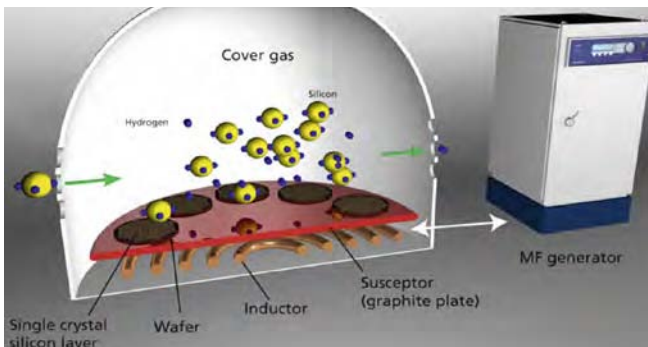


Figure 5.36: View in principle of an epitaxy process
(Source: TRUMPF Hüttinger)

production of light-emitting diodes (LEDs). **Figure 5.36** shows schematically the structure of a reaction chamber into which silane, a silicon-containing gas, is fed. The silicon is precipitated under precisely defined process conditions and deposited on to the monocrystalline silicon wafers. These wafers are located on a graphite susceptor material. The graphite is heated to a temperature of over 1,000 °C. In **Figure 5.36**, heating is accomplished inductively, by means of the coil positioned below the inductor. Heating can also be effected conductively, depending on the particular system design.

5.10.2 System concept

Inductively heated so-called planetary reactors (see **Figure 5.37**) are generally used. These essentially consist of a water-cooled stainless-steel chamber and a replaceable graphite susceptor. The susceptor serves as a platform for the rotating “carrier wafers” (the so-called “satellites”), on which the wafers, with the substrate, are located.



Figure 5.37: A planetary reactor
(Source: Aixtron)

5.10.3 The heating system

Great demands are made on the heating system here. It must, firstly, supply the necessary process energy dependably for years, in order to assure high productivity. It must, in addition, also be possible to set the process temperature of approx. 1,100 °C with great accuracy. Above all, homogeneity of around ± 5 K must be achieved in the zones containing the substrate. The induction coil must also be perfectly matched to the power supply, in order to assure high heating-up rates and high efficiencies.

The power supply consists of a medium-frequency generator typically operating in the 20 to 50 kHz frequency range and supplying outputs of 100 to 150 kW.

5.11 Inductive heating of float glasses

Hans Windsheimer, Horst Linn

The demand for more and more lighter and robust devices in consumer and household electronics as well as in the sectors automotive, sensors and MEMS simultaneously implies the demand for new, light-weight, high-strength, unbreakable and cheap materials for casings as well as their production processes. A new innovative method enables homogeneous heating of float glass by inductive heating of a graphite form in inert gas above the softening point in minute intervals (**Figure 5.38**) as well as to bring them into shape by subsequent creation of a differential pressure. Hereby, a broad variety of geometries can be realized, **Figure 5.39**. Housings for car shift consoles, housings for sensors, carriers for MEMS devices can be fabricated from float glass by this method.

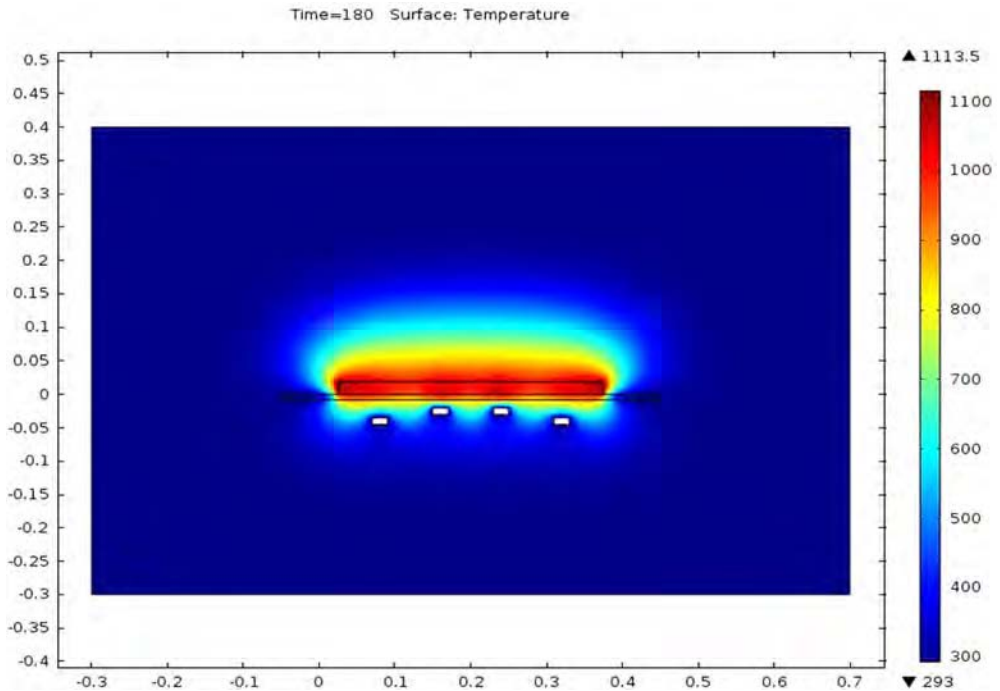


Figure 5.38: Simulated temperature distribution of a graphite form in case of thermal glass moulding



Figure 5.39: Geometries realized by thermal glass bending

5.12 Inductively-coupled plasma (ICP)

Elmar Wrona, Torge Behrens, Jens-Uwe Mohring

5.12.1 Introduction

Inductively coupled plasma (ICP) is used in an extremely diverse range of applications. It is, for example, an important ionization source in mass-spectrometric analysis of material specimens. A mass spectrometer incorporating ICP makes it possible to identify traces of atoms and their isotopes and to analyze them quantitatively with a high resolution.

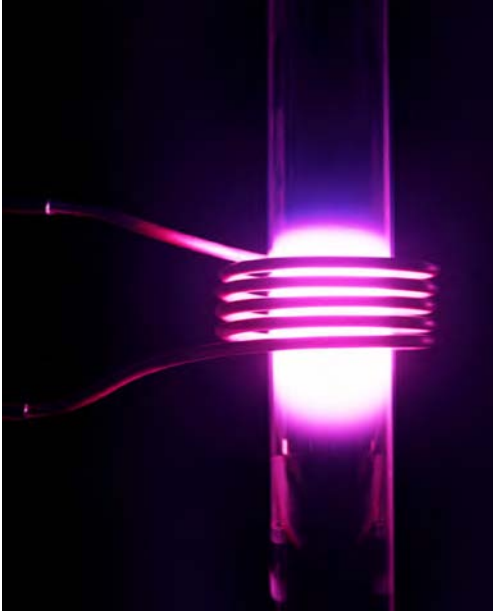


Figure 5.40: Inductively coupled plasma



Figure 5.41: Example of a tube generator (Source: TRUMPF Hüttinger)

ICP is also used in treatment of powders (spheroidization and chemical conversion) and in coating technology (plasma spraying). In this process, the feed material is passed in powder form directly through a plasma flame.

A more recent application is the combustion of impurities on the surface of a silicon melt. This procedure is also referred to as “PHOTOSIL”.

5.12.2 How is an ICP generated?

The simplest apparatus can be described as follows: a multi-turn induction coil is positioned around a number of centrally arranged quartz-glass tubes, through which specific process gases are fed. As in induction heating of metals, the electromagnetic field generated by the coil induces eddy currents in the plasma. Plasma temperatures of up to 10,000°C – as in the case of argon plasma, for example (**Figure 5.40**) – are generated. Absolutely any material can be melted at such high temperatures.

5.12.3 Requirements for the HF power supply

High-frequency (HF) generators operating at frequencies of around 2 to 3 MHz in an output range normally of 30 to 60 kW are suitable for the power supply here. Vacuum tube generators (**Figure 5.41**), inter alia, meet such requirements. Such high outputs are generally needed in powder treatment and in plasma spraying.

Semiconductor generators, which operate at significantly higher frequencies – usually at 27.12 or 40.68 MHz – are nowadays used for extremely small outputs of 1 to 5 kW. Such semiconductor generators are correspondingly known for their high efficiency. Such generators are very frequently used in spectrometry.

5.12.4 The benefits of ICP over DC plasma (DCP)

ICP permits the generation of significantly larger plasma volumes which, under atmospheric conditions, result in significantly smaller flow rates. Powder particles, for example, thus remain very much longer in the heating zone in plasma spraying, also making it possible to use large particles.

Thanks to the absence of electrodes, there are, in addition, no impurities in the plasma. Not only inert gases, such as argon, but also reactive gases, like oxygen, can be used.

5.13 Induction heating of magnetic nanostructured particles

Elmar Wrona, Torge Behrens, Jens-Uwe Mohring

Intensified activity in research into heating of magnetic nanostructured particles has been observable in recent years. The aim here is that of generating a method for non-contact heating of electrically nonconductive materials. Up to now, this has been possible only using indirect heating methods, such as thermal radiation or thermal conduction, for example, in which it is necessary to transfer the energy via the surface of the material to be heated. In the case of polar and polarizable materials, it is also possible to achieve an increase in temperature by means of dielectric or microwave heating. The development of paramagnetic, superparamagnetic and ferromagnetic nanostructured particles has now opened up another potential for heating of electrically insulating materials.

5.13.1 Physical principle

Substances which exhibit magnetic hysteresis are subject in an alternating magnetic field of Flux Density B and Frequency f to continuous magnetic reversal, which can result in three types of magnetization losses: eddy-current losses, hysteresis losses and remanence losses. The occurrence of these losses results in heating of the magnetic material. In nanostructured particles, eddy-current losses can be virtually excluded, due to their small size, since depth of electromagnetic penetration is much greater than the diameter of the particles, and no current eddies can thus be generated within a particle. Heating thus occurs as a result of hysteresis losses and remanence losses. A detailed description of the physical principles of these phenomena can be found in [5.17].

The heat generated in the particles is yielded via thermal conduction to the surrounding material and heats it. Since the particles make up only a certain percentage of the structure of the material, the mass of material to be indirectly heated is significantly larger, with retardation of heating-up rate as a result. Increasing the concentration of the particles above a certain level cannot be considered as an alternative, since this would, on the one hand, result in an ever more unstable material matrix and is, on the other hand, on economic criteria not acceptable for industrial use. It is therefore of the greatest importance for efficient heating to a) generate a high specific coefficient of energy transfer in the particles and b) achieve the most homogenous possible distribution of the particles in the material.

5.13.2 Practical implementation

An alternating magnetic field is characterized by its magnetic flux density and the frequency of its reversal against time. It can most easily be generated using an induction coil connected to a

medium- or high-frequency generator (semiconductor or vacuum tube technology) and through which an AC current is passed. Here, the flux density generated by the inductor is directly proportional to the inductor current. Inductor geometry also has a great influence on the intensity of the magnetic field, however. The larger the inductor the lower the magnetic flux density that can be generated. The material to be heated is either completely enclosed by the inductor (induction coil) or may be located at a certain distance from it (flat inductor), with the result that it is permeated by the inductor's magnetic field. Induction coils used in continuous processes are particularly efficient. Such inductors generate flux densities of an order of magnitude of up to 100 mT at several hundred kilohertz when connected to generators of an output power level of approx. 10 kW.

The specific power loss in the nanostructured particles must be maximized, in order to achieve a high heating-up rate. As a result of the nature of energy conversion here, this is attained via the combination of the highest possible flux density with a high alternating field frequency. This, in practice, is a great challenge, however, since the suppliable inductor current, and thus flux density, decline as frequency increases. Parameter studies under laboratory conditions have shown that it is necessary to determine these values specifically for the particles used, and that corresponding adaptation of the inductor is then necessary. It must be noted here that the achievable inductor efficiency (the ratio of thermal energy generated in the material to the effective power at the terminals) is extremely low ($< 10\%$) when compared to inductive heating of metals, since the losses, as a result of eddy currents in the nanostructured particles, are completely absent, and the mass of particles contained in the material is also, in practice, below 10% .

5.13.3 Industrial application

Inductive heating of magnetic nanostructured particles has up to now not yet achieved widespread industrial use. There are several reasons for this, predominantly of a technical nature, but also with an economic background. One application in which a breakthrough in the use of this process could occur is the production of extruded sections from elastomers and polymers requiring thermal cross-linking, for the most diverse range of applications. The nanostructured particles can be incorporated extremely easily in the form of powder (**Figure 5.42**) or masterbatches prior to extrusion. A certain temperature “lift” is needed after the extrusion process, in order that the section can be thermally cross-linked, and has, up to now, been provided by means of tunnel furnaces, autoclaves or salt baths. These classical heating methods are characterized by the fact that the heat is applied via the surface, and must then flow inward. The applicable power density is restricted, due to the poor thermal conductivity of elastomers and polymers. A relatively long heating line is necessary, to prevent hot-spots on the exterior and achieve thorough heating internally. This length can be reduced significantly when the inductive heating process is used, since the heat is then generated directly in the interior of the elastomer or polymer. It is sometimes necessary for this purpose to array several inductors/generators in sequence, in order to attain the high throughput rates needed for industrial production. Generators with outputs of 10 kW are typically used, and permit the achievement of flux densities of up to 100 mT at 500 kHz.



Figure 5.42: MAGSILICA®. These ferromagnetic nanostructured particles consist of various iron oxides (FeO) located in an insulating shell of SiO₂. The particles are for this reason particularly chemically stable and have a low reactivity (image courtesy of Evonik Industries AG)

5.14 Thermographic crack detection in components

Elmar Wrona, Torge Behrens, Jens-Uwe Mohring

5.13.1 Introduction

Thermography is an imaging process, using which the surface temperature of objects can be depicted. It also permits nondestructive crack-inspection of metal components, an increasingly frequent requirement in the automotive and aviation industries.

In active thermography, energy is fed into the component, and a flow of heat thus generated. Where material defects are present, the flow of heat causes characteristic anomalies in the temperature distribution on the component surfaces. Input of energy into, or “excitation” of, the component can be accomplished in various ways, by means, for example, of air excitation, laser excitation, using ultrasound and, of course, also by means of induction.

5.14.2 Inductively excited thermography

Sub-surface eddy currents are induced in the component using an induction system consisting of a generator and an induction coil. The otherwise uniformly distributed eddy-current flow is locally distorted if a crack, for example, or other discontinuities are present in the material. This results in elevated current densities at the ends of the crack (**Figure 5.43**) and, ultimately, in points of elevated temperature, so-called hotspots.

Small pulses of energy, i.e., short heating times, are used, in order that thermal equalization is not completed before the actual temperature measurement can be made. The surface of the material is thus inductively excited and the change in the temperature distribution recorded using a thermal-imaging camera.

This is a non-contact procedure and also has a large number of other benefits. The high energy densities make it possible to detect even ultra-small discontinuities in the material. Even visually hidden cracks can be detected, using the appropriate working frequency. The measuring results are, in addition, repeatable.



Figure 5.43: The effect of a crack on the flow of current in the workpiece at high (left) and low (right) frequencies



Figure 5.44: Example of a high-frequency generator with an output of 10 kW and a frequency of 50 to 800 kHz (Source: TRUMPF Hüttinger)

Only the fact that inductively excited thermography can be applied only to electrically conductive materials and that differing induction coils may be necessary for differing component geometries can be stated as limitations.

This procedure can be used not only on steels, but also on other materials, including aluminium, for example.

5.14.3 Requirements for the power supplies

The power requirement for thermal analysis is generally 5 to a maximum of 10 kW, since the temperature increase needed is relatively small, at only a few tens of degrees Celsius. Much more important is an adequately high frequency, which should be between 200 and 600 kHz. Penetration depth is significantly slighter at high frequencies, with the result that even ultra-small cracks on the surface are detected. Short heating times (< 150 ms) should also be repeatably achieved. Modern high-frequency generators are used as the power supply here (see **Figure 5.44**).

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6. Power supply

6. Power supply

6.1 Principles of frequency converters for induction heating

Edmund Zok

Frequency converters are electronic devices or systems that convert electric power with specified parameters (voltage, current, frequency, phases) into electric power with other parameters, required for example for induction heating. In addition to power these other parameters are voltage and frequency suitable for the heating process.

For induction heating, resonant converters are primarily used. The designation resonant converter is derived from the configuration of the connected load circuits which are usually designed as a series or parallel oscillating circuit.

Induction heating occurs by transferring the energy from the inductor into the workpiece to be heated by means of an alternating magnetic field. In the most basic case, the inductor is designed as a cylindrical coil in which the workpiece is located. When an alternating current flows through the inductor, it generates an alternating magnetic field in its vicinity that in turn induces an alternating voltage in the workpiece. This voltage creates so-called eddy currents in the volume of the material that causes the material to heat up.

The arrangement of the inductor and workpiece approximately equates to a transformer with a short-circuited secondary winding. In the equivalent circuit diagram, this arrangement can be simplified plotted as a series or parallel connection of inductance and resistance. For the following consideration a parallel connection of the components is chosen. In order to compensate the usually high reactive current of the inductor, a capacitor is switched in parallel to the inductor. The resulting circuit is generally known as a damped parallel oscillating circuit, refer to **Figure 6.1**.

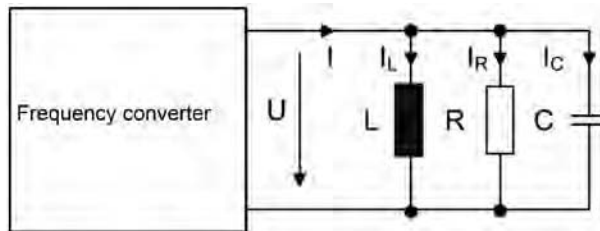


Figure 6.1: Parallel oscillating circuit connected to a frequency converter

The characteristic values of an oscillating circuit can be calculated as follows [6.1]:

$$\omega_0 = \frac{1}{\sqrt{L \cdot C}} \quad \text{Angular resonance frequency} \quad (6.1)$$

$$d = \frac{R}{2L \cdot \omega_0} \quad \text{Attenuation} \quad (6.2)$$

$$\omega_e = \omega_0 \cdot \sqrt{1 - d^2} \quad \text{Angular resonance frequency with damping} \quad (6.3)$$

If the output frequency of the converter is exactly matched to the resonance frequency of the oscillating circuit, the reactive current of the inductor is fully compensated by the reactive current of the capacitor, refer to **Figure 6.2**, and does not load the converter. In this case, the frequency converter must only supply the active power transformed into the workpiece and the energy losses in the oscillating circuit. Due to the described behavior, resonant converters have been the preferred devices used for induction heating for many years.

Resonant converters have means for the recognition and continuous tracking of the resonance frequency of the connected oscillating circuit. The attenuation and the resonance frequency change during the heating process because the material characteristics drastically change with the temperature. Therefore, continuous regulation of the operating frequency is absolutely necessary.

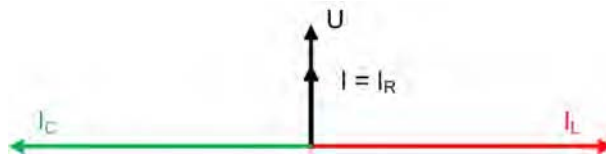


Figure 6.2: Vector diagram for a parallel oscillating circuit. Resonance of the currents

Frequency converters for induction heating are predominantly designed as so-called indirect a.c.-converters, refer to **Figure 6.3**. In such system, the input rectifier and the output inverter are separated by inductive or capacitive DC-link circuit. An inductive DC-link, also known as current source circuit, is used in the parallel resonant converters. It gives the inverter the characteristics of a current source. A capacitive DC-link, also known as voltage source circuit, is used in the series resonant converters and in the L-LC frequency converters. The inverters of such converters have the characteristics of a voltage source.

The inverters of the resonant converters operate predominantly in load commutated mode. This means that the frequency of the inverter always follows the resonance frequency of the load and the load also supports the commutation process. All resonant converters have a phase control loop, which continuously adjusts the phase shift at the output of the inverter.

The resonant inverter could operate load commutated or self-commutated if switched valve devices are used. Load commutation provides some advantages even in case of switched valve devices, because it enables soft switching of the inverter transistors and thus a reduction of the switching losses. This technology is a condition to achieve high operating frequencies. Multiple technologies have been developed for the optimum control of the resonant inverters [6.2].

IGBTs, MOSFETs and frequency thyristors can be used as switches in the parallel and series resonant inverters. Today, IGBTs are the most common devices and replace the MOSFETs, even at higher frequencies. Frequency thyristors are now only used for low frequencies (below 2 kHz) and in high power converters (several MW). The topology of the resonant converters is suitable for medium and high frequency applications.

There has been a trend over the last few years towards modular design of the frequency converters. The reason is a functional division of the heating machine in multiple zones, supplied by converters that can be independently controlled. This procedure provides diverse options for optimization of the heating process, taking into consideration technological and energetic points of view. Modular converters support this technology and, thus, provide cost-effective solutions. However, the basic topology of the module remains a resonant converter.

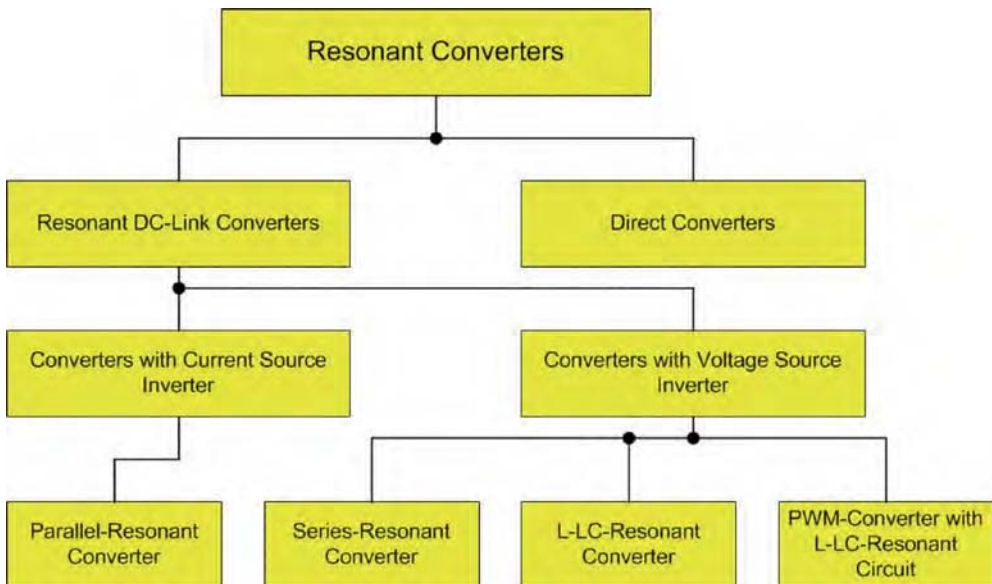


Figure 6.3: Resonant converters for induction heating (Source: SMS Elotherm)

In the last few years, a considerable increase of the installed power of frequency converters has resulted in increasing loading of the power supply networks with reactive power and current harmonics. Therefore, the reduction of power line disturbances from converters is increasingly important, also for frequency converters for induction heating. Rectifiers with Power Factor Correction (PFC) are increasingly becoming the focal point of interest. However, the high cost of the PFC rectifiers restricts their coming in the front-end section of the frequency converters for induction heating. As an alternative, active filter could be used and these can even be retrofitted into older existing systems.

6.2 Line frequency power supply

Johann Muras

6.2.1 Line frequency switchgears in conventional technology

The line frequency (LF) induction coils (billet heating, crucible furnaces or channel inductors) normally feature a low power factor. In order to improve this, the coils are operated using capacitors connected parallel (parallel compensation). Power control is carried out using the adjustable supply voltage to the coil (regulation transformer). Induction coils used as 1-phase consumers are usually designed for high power. Thus, it is necessary to uniformly distribute the high 1-phase power requirement to three phases of the supply network. In this case, a balancing inductor with balancing capacitors in Steinmetzcircuit.

Figure 6.4 shows the principle design of a system of this type. The connecting point of the balancing inductor and balancing capacitors form the third, simulated phase. In order to prevent possible

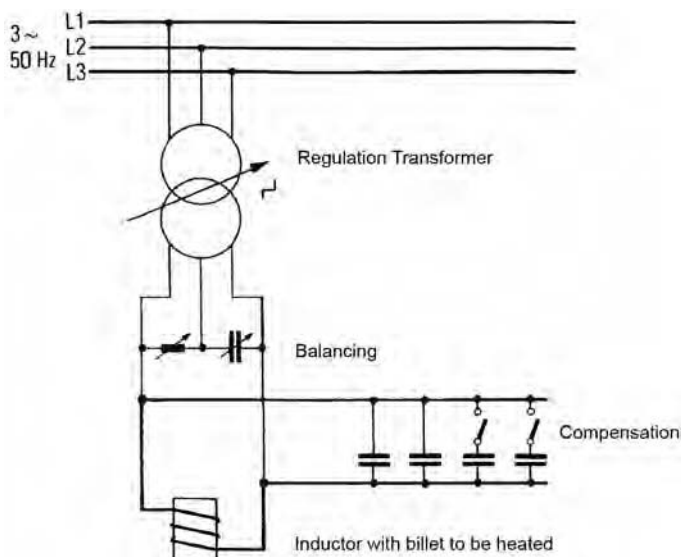


Figure 6.4: Principle construction of a net frequency system with conventional design [6.3]

excess voltage at the capacitors during switching, this phase must always be switched on first (“leading” contact of the capacitor contactor). Upon switching off, this phase must be switched off last. For greater power, damping resistances (dimensioned to ED 5 %) are used in order to reduce the currents when switching on. For a switching operation with damping resistances, this is bridged after approx. 0.5 – 1 s.

Crucible furnaces or channel-type furnaces loads change their electrical parameters in the course of a furnace campaign: (channel inductor) or the operating cycle (crucible furnace: sintering, operated with sump, full-load smelting). Therefore, the reactive power of the components installed (balancing inductor, balancing capacitors, compensation) must be permanently adapted in order to maintain uniform power distribution in the 3 phases.

Included in the more simple systems, which can uniformly load the three-phase mains supply, is the so-called “V-circuit” where the induction coils are compensated to $\cos\varphi = 0.866$ inductive and 0.866 capacitive by parallel compensation and the “Scott circuit”. However, these circuits require a load with two identical induction coils that must be simultaneously operated. A channel inductor in “Scott connection” is provided as an example here.

For multiple zone mains, frequency billet heating coils (billet heating systems for extrusion presses – primarily for aluminium and its alloys) are specifically designed switchgears (**Figure 6.5**). The three-phase current can be uniformly loaded using three or six zones. The switchgears are of modular design and enable the zones of the coil, electrically isolated from each other, to switch. The supply voltage can be achieved in each zone with the aid of a step autotransformer.

This circuit requires the use of a shifting transformer with two under-voltage systems, electrically deviated by 30° , e.g. using a vector group Dy5d6. The individual zones are switched with the aid of thyristor controllers, free of wear.

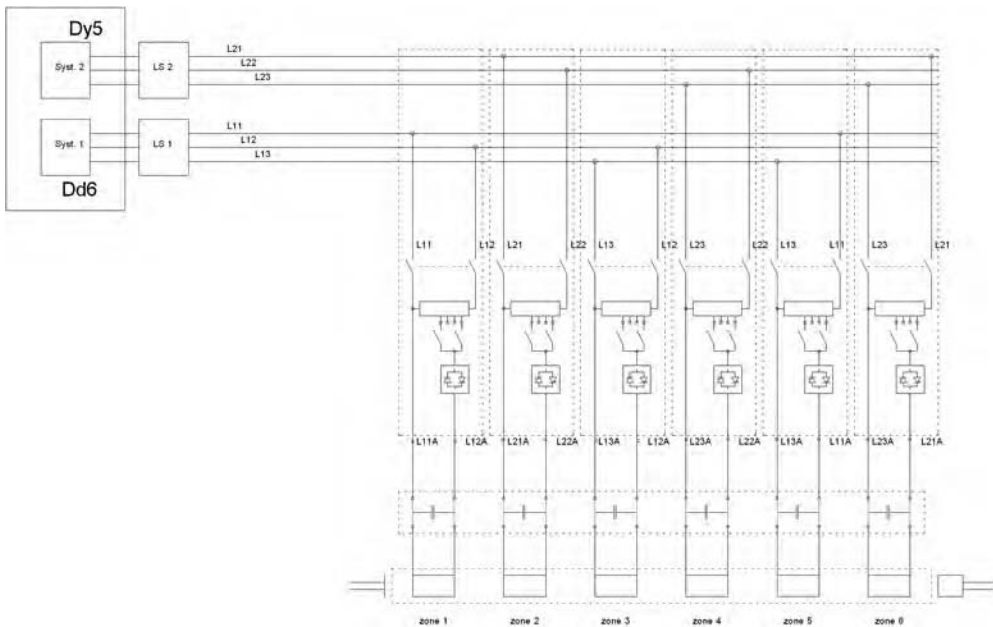


Figure 6.5: Simplified diagram of a net frequency system for a multi-zone billet heating coil

6.2.2 LF converter technology

The modern semi-conductor technology enables high power to be provided economically that normally requires a “mains frequency-induction coil” of a crucible furnace or billet heating system.

An example of a load-controlled thyristor converter, with an induction coil in a serial or parallel compensated induction coil, is shown in **Figure 6.6**.

The converter comprises a fully-controlled, three-phase rectifier in a bridge circuit, an indirect circuit (with smoothing choke and capacitors) and an inverter (thyristor “H-bridge”). The principle of converting AC-DC-AC enables a single-phase load to be uniformly distributed across three phases. Due to the controllable rectifier, the power can be simultaneously variably adjusted at the user. The thyristors of the inverter are switched in synchronous harmony with the resonance frequency of the load circuit – the operating frequency adapts to the resonance frequency. Greater efficiency and design power in this topology is possible up to several MW [6.3]. However, the fully controlled rectifier loads the mains supply with harmonics. The smaller the power input (degree of control of the thyristors), the greater the relative harmonic loading of the mains supply. Here assistance is provided by using 12, 24 and more rectifier pulse systems.

The further development and cost reduction of power transistors (IGBT) in the last few years has made it possible to build the modern transistor converters. In contrast to the thyristors, the transistor can be fully controlled. It can be switched on and off with relatively low switching loss. This characteristic of the IGBTs enables the inverter H-bridge to be controlled with an arbitrary switching pattern.

Figure 6.7 shows a principle circuit for a transistor converter with voltage indirect circuit. The principle of converting AC-DC-AC is retained.

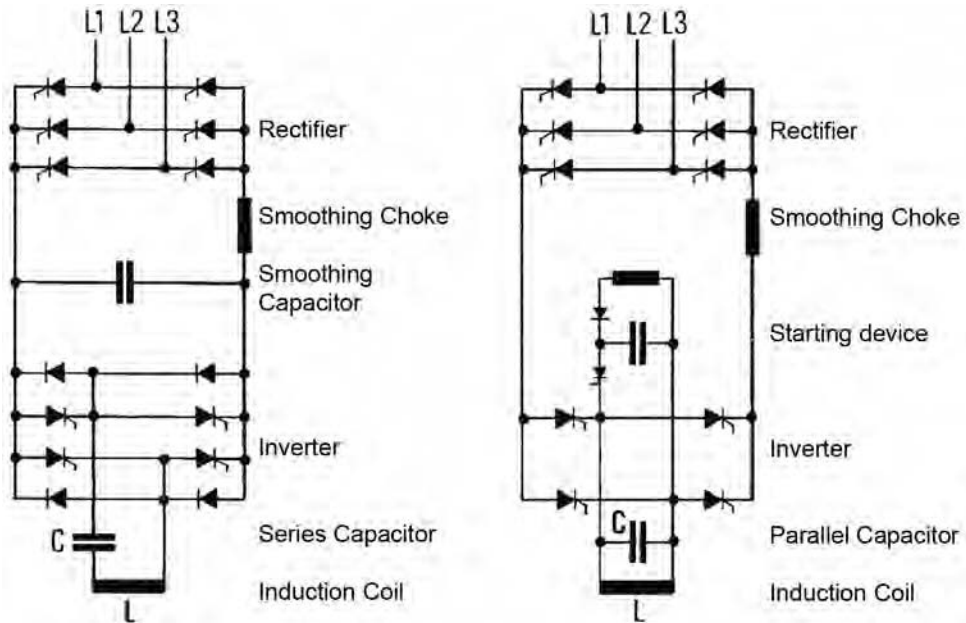


Figure 6.6: Static, load controlled thyristor converter (Oscillating circuit converter) [6.3]

The diode rectifier is not controlled. The indirect circuit comprises a smoothing choke and the capacitor bank (energy accumulator). It is charged to a constant voltage during operation (depending on the voltage of the mains supply). Thus, the mains supply only views the uncontrolled rectifier with smoothing choke. For non-intermittent rectifier current, the power factor on the mains side is practically independent of the decrease in power and high (B6-bridge approx. 0.95, B12-bridge 0.97). There is a filter choke at the output of the inverter through which the load circuit, comprising an induction coil with compensation capacitor switched in parallel, is provided with power. Full controllability of the IGBTs in the inverter enables variable regulation of the effective value of the output voltage. Here, the Pulse-Width-Modulation (PWM) procedure is applied. Examples are

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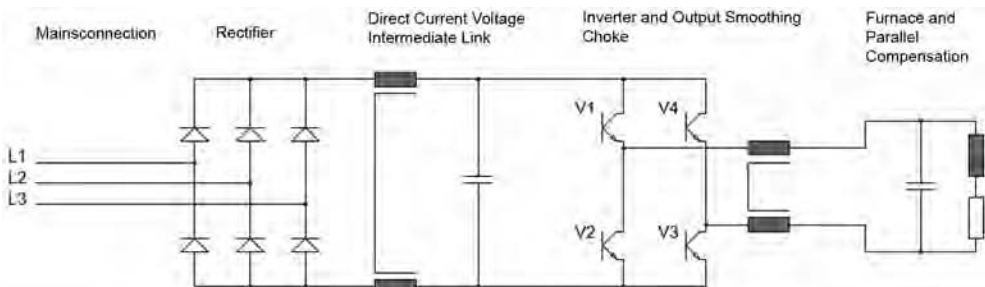


Figure 6.7: Principle circuit for a transistor converter with voltage indirect circuit (Source: IAS GmbH)

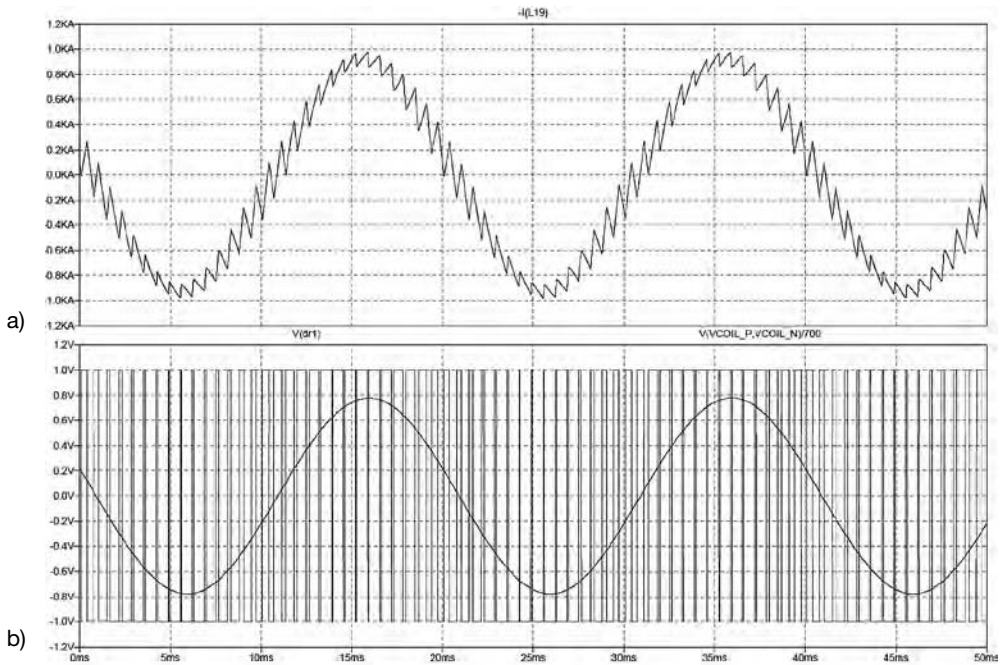


Figure 6.8: PWM with sinus modulation, full wave control: a) output current of inverter b) output voltage before and after the AC choke (Source: IAS GmbH)

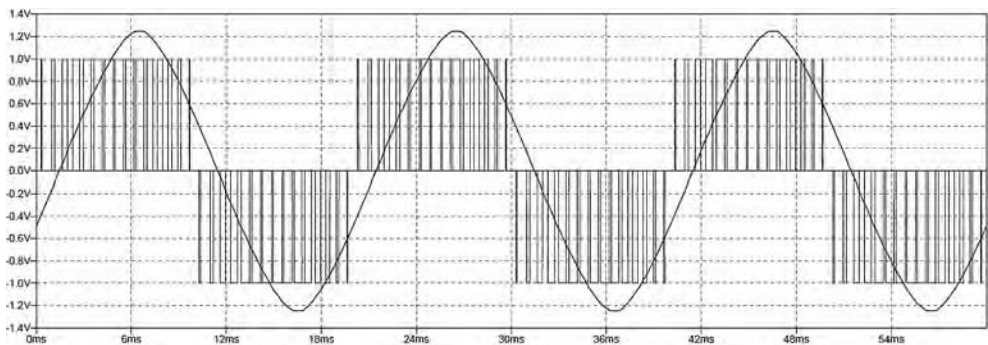


Figure 6.9: PWM with sinus modulation, half-wave control: output voltage before and after the AC choke (Source: IAS GmbH)

shown in **Figure 6.8**, **Figure 6.9** and **Figure 6.10**. The PWM procedure with sinus modulation makes the IGBT converter particularly effective up to 200 Hz due to the reduced loss in the AC choke [6.4]. The inverter can be operated using a fixed frequency as well as with resonance frequency of the load circuit. Due to the capacitor bank, it can also supply reactive power to the load.

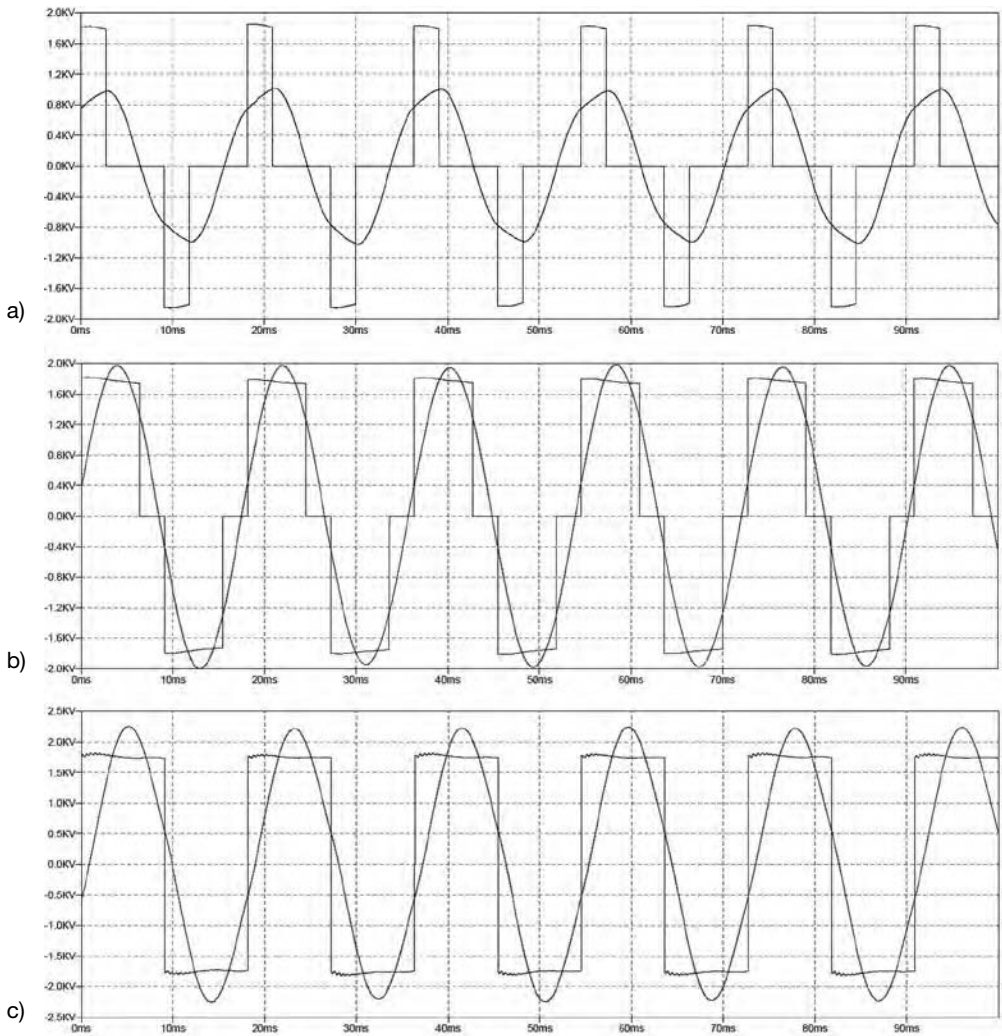


Figure 6.10: PWM with 30, 70 and 100 % fill factor: a) rectangular output voltage directly at the inverter 1,400 kW/40-57 Hz, b) in the background c) quasi sinusoidal voltage curve at the load (Source: IAS GmbH)

Particularly interesting is the application of the IGBT inverter with an indirect voltage circuit in modular design as a power supply to a multiple zone coil (**Figure 6.11**).

The coil segments (zones), electrically isolated from each other, are supplied with power by an inverter. The indirect voltage circuit can also be used together for all inverters. Due to the synchronization of

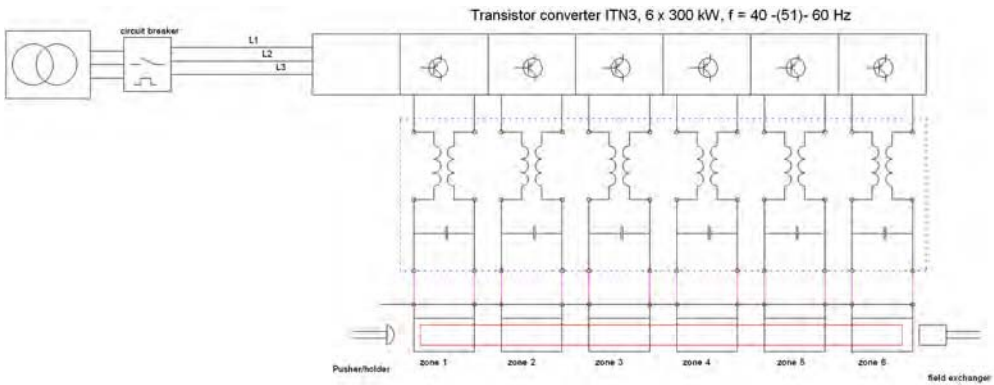


Figure 6.11: Transistor converter with voltage indirect circuit with modular design for feeding a multi-zone coil (Source: IAS GmbH)

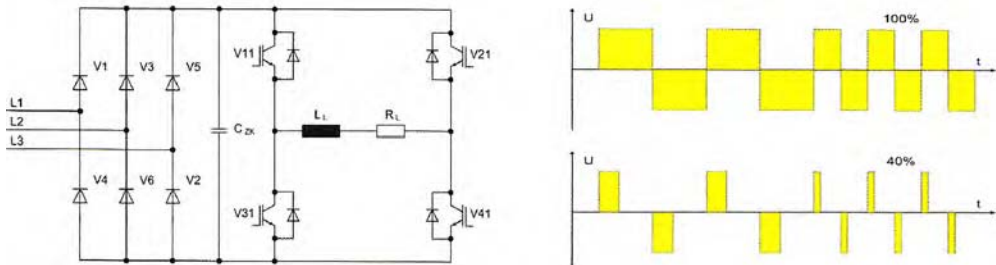


Figure 6.12: Direct converter with PWM [6.4]

all modules (same frequency and phase of the voltage in each zone), the block can be uniformly heated as if it had been heated in a continuous spiral coil. There are no power losses (temperature profile deformation) at the transitions of zones. Variable power regulation in each zone enables accurate temperature control in each zone and, thus, very good reproducibility of the temperature field for every block.

For relatively small power, “direct converters” (**Figure 6.12**), where load not compensated is directly connected to the inverter, are used as a source of AC voltage for mains-frequency channel inductors. In this case, the transistors of the coil current not compensated must switch which significantly restricts the design power of the converter.

6.3 Medium frequency converters

Edmund Zok

Today, different types of parallel and series resonant converters are used in medium frequency (MF) systems for induction heating. In the last few years, more complex topologies, such as the L-LC converter [6.5], have gained importance and are replacing the traditional converters for some applications.

6.3.1 Parallel resonant converter

The fundamental parts of a parallel resonant converter [6.5] are a controlled, line-commutated rectifier, an inductive DC-link circuit and the inverter. **Figure 6.13** shows a parallel resonant converter with an IGBT inverter.

The inverter supplies square wave current to the connected parallel oscillating circuit. Sinusoidal voltage is generated at the oscillating circuit because the high frequency current harmonics are filtered by the capacitor of the oscillating circuit and they only marginally influence the voltage waveform. The current in the inductor is also sinusoidal.

Reverse blocking semiconductor switches must be used in the parallel resonant inverter. If transistors are used as switches, fast diode must be connected in series to each IGBT. If thyristors are used, only one thyristor per inverter branch is required.

The output voltage and the power of the parallel resonant converter are controlled by the rectifier. The power factor on the mains side deteriorates with smaller output voltages.

The inverter operates most commonly in a load commutated mode. **Figure 6.14** shows the upper commutation circuit of the parallel resonant inverter. The parasitic inductances have been summarized as L_S . The commutation equations are derived under the assumption of sinusoidal voltage at the oscillating circuit:

$$u_L(t) = \sqrt{2} \cdot U_L \cdot \sin \omega t \quad (6.4)$$

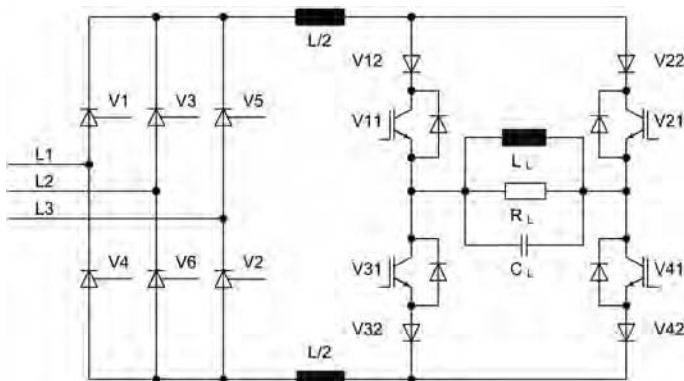


Figure 6.13: Parallel resonant converter with an IGBT inverter

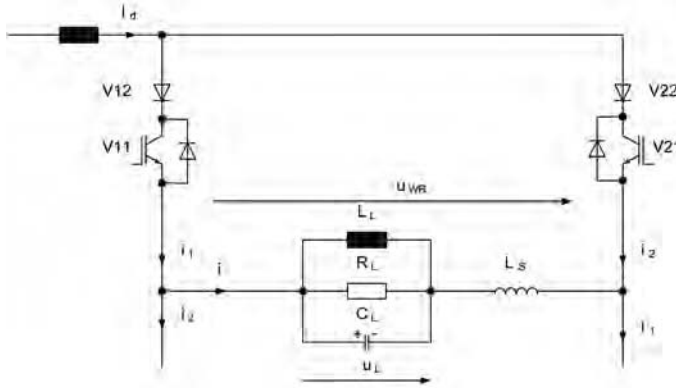


Figure 6.14: Commutation circuit in the parallel resonant inverter

Assumed the IGBT V11 is switched on before commutation, the V21 is switched off. Commutation is initiated by switching the transistor V21 on before the zero crossing of the load voltage u_L as shown in **Figure 6.15**, at the polarity specified at C_L . The transistor V11 is switched off at the end of commutation. The commutating voltage (and energy) is drawn from the load capacitor.

With the assumptions made, the following equations describe the currents during the commutation:

$$i_1(t) = I_d + \frac{U_L}{\sqrt{2} \cdot \omega \cdot L_S} \cdot (\cos \omega t + \cos \gamma) \quad (6.5)$$

$$i_2(t) = -\frac{U_L}{\sqrt{2} \cdot \omega \cdot L_S} \cdot (\cos \omega t + \cos \gamma) \quad (6.6)$$

$$i(t) = I_d + \frac{\sqrt{2} \cdot U_L}{\omega \cdot L_S} \cdot (\cos \omega t + \cos \gamma) \quad (6.7)$$

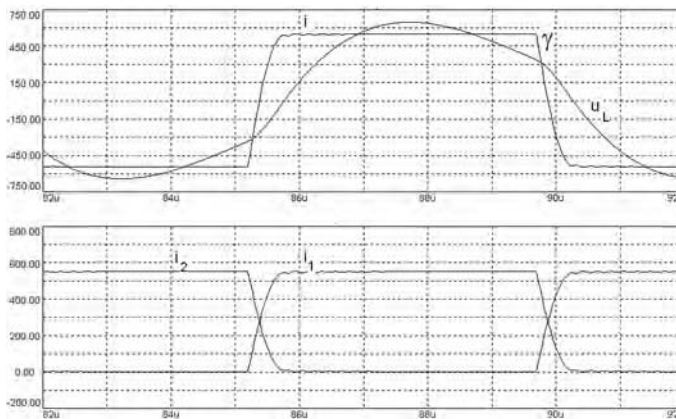


Figure 6.15: Commutation in the parallel resonant inverter



Figure 6.16: Parallel resonant converter EM22PI, 800 kW, 1,000 V, 10 kHz (Source: SMS Elotherm)

whereby

$$\gamma = \pi - \varphi_k \quad (6.8)$$

with φ_k equal to the phase angle of the load voltage u_L at the beginning of commutation. The current and voltage waveforms calculated in a simulation are presented in Figure 6.15.

Optimum commutation [6.8] is attained, if the falling current i_l reaches zero value exactly in the zero crossing of the voltage u_L . The transistor V11 can then be currentless switched off.

In case of optimum commutation no switching overvoltages occur at transistors V11 and V21. The diodes V12 and V22 are not loaded with reverse currents. The condition for optimum commutation in the parallel resonant converter can be described as follows:

$$\cos \gamma_{opt} = 1 - \frac{\sqrt{2} \cdot I_d \cdot \omega \cdot L_s}{U_L} \quad (6.9)$$

The optimum commutation can only be attained if the operating frequency of the inverter is higher than the resonance frequency of the load. Because the optimum switching points vary with the operating values of the converter, a complex controller must be used to ensure continuous optimum commutation [6.2].

Figure 6.16 shows a parallel resonant converter of the middle rating class.

6.3.2 Series resonant converter

The series resonant converter can be considered as a dual system to the parallel resonant converter. The load inductor L_L , capacitor C_L and the equivalent resistance R_L are switched in series. The converter has a capacitive DC-link circuit and has the characteristics of a voltage source. **Figure 6.17** shows a series resonant converter with an IGBT inverter.

The inverter of the series resonant converter operates also in load commutated mode. The output power can be controlled either by changing the operating frequency [6.6], by the pulse width modulation of the inverter or by changing the DC-link voltage. For MF converters pulse width modulation, refer to **Figure 6.18**, is preferred, because in this case uncontrolled rectifiers can be used.

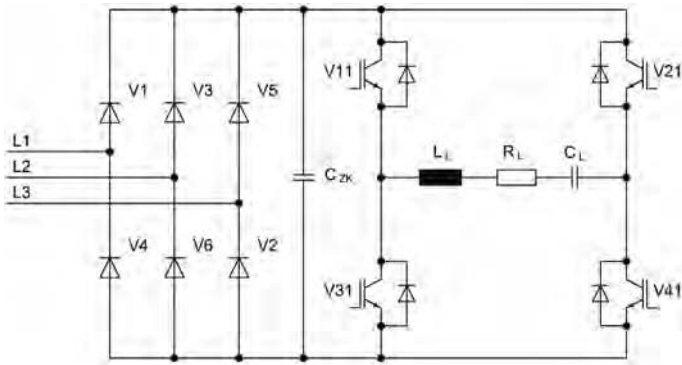


Figure 6.17: Series resonant converter with IGBT inverter

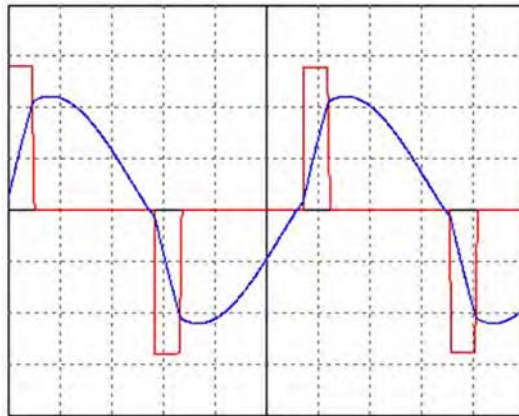


Figure 6.18: Series resonant converter. Modulation of the inverter voltage

The series resonant converter is well suitable for many applications and can be used in a large frequency range. An output transformer is often necessary to match the load impedance and/or to adapt the voltage at the inductor.

The application of series resonant converters is particularly beneficial if high inductor voltages are required, for example for induction melting, inductive heating of strips or for the welding of large-caliber pipes.

6.3.3 Converter with L-LC load circuit

IGBTs can be operated more efficiently in converters with a capacitive DC-link circuit. On the other hand parallel oscillating circuits can be often handled more conveniently than series resonant circuits. Unfortunately, a converter with a DC-voltage link cannot be directly connected to a parallel oscillating circuit.

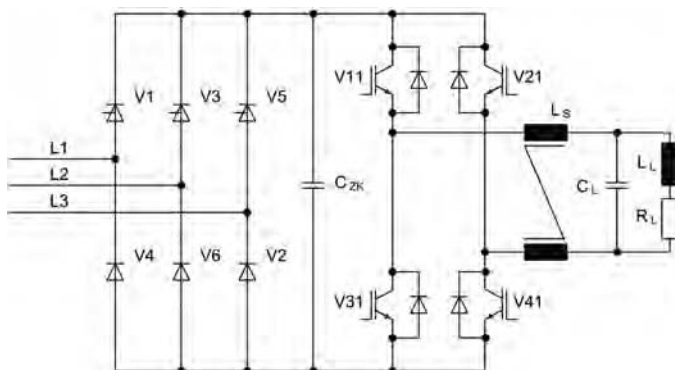


Figure 6.19: Converter with a L-LC load circuit

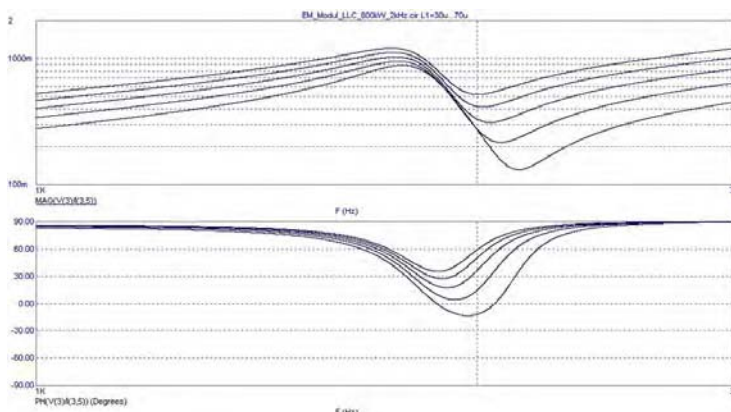


Figure 6.20: Frequency plot of the L-LC circuit

In order to optimally utilize the advantages of the IGBT technology and the parallel oscillating circuit, the L-LC topology [6.7] has been developed, refer to **Figure 6.19**. A coupling inductor L_S is switched in a L-LC converter between the output of the inverter and the parallel oscillating circuit.

The frequency characteristics of the L-LC oscillating circuit, refer to **Figure 6.20**, is more complex than that of a parallel or series oscillating circuit. The circuit has a parallel and a series resonance frequency. Both resonance frequencies can be used to operate the converter. In MF systems, the parallel resonance is preferably used.

In an L-LC converter both the frequency and the output power can be controlled by the inverter. The control of the inverter is rather complex and the available frequency range is relatively small in comparison to the frequency range of a parallel or series resonant converters. Nevertheless, the L-LC circuit is often used because it optimally combines the advantages of the IGBT technology and parallel oscillating circuit.

6.4 High frequency converters

Edmund Zok

High frequency (HF) converters are used for longitudinal inductive heating of thin strips, for inductive pipe welding and for inductive hardening. Traditionally, the boundary between the MF and HF systems is drawn at 100 kHz.

The circuits covered in the section about the medium frequency (MF) converters are also used for frequencies of more than 100 kHz. Both MOSFET and IGBT can be used in the inverters. Frequency thyristors are not suitable for this application. The design of the inverter must be optimized for high frequencies, refer to **Figure 6.21**. In order to increase the efficiency of the power semiconductors at high switching frequencies, the timing of the transistor control must be accurately adjusted. New control methods were also developed and introduced, such as sequential switching of paralleled IGBTs in one inverter branch [6.9].

Electronic tube generators, former standard appliances for HF induction systems, have no significance today. The decisive disadvantages of these appliances are their poor efficiency as well as a relatively short lifetime of the highly stressed electronic tubes.

6.4.1 Series resonant converter for HF applications

In the series resonant converter for HF applications, the commutation is significantly determined by the parasitic capacitances of the output busbars CP and the parasitic capacitance of the IGBT CCE. **Figure 6.22** shows the commutation circuit in the series resonant converter.



Figure 6.21: HF converter EM50PM, 700 kW, 450 V, 300 kHz, MOSFET technology
(Source: SMS Elotherm)

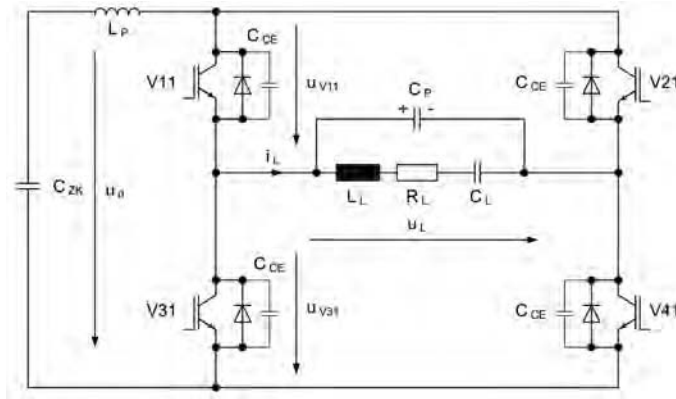


Figure 6.22: Commutation circuit in the series resonant inverter

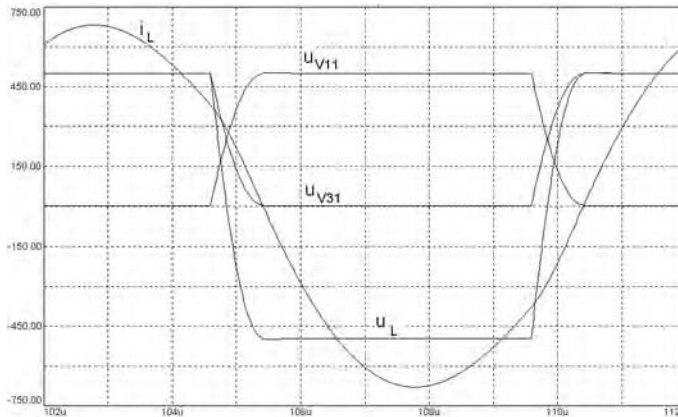


Figure 6.23: Commutation in the series resonant inverter

With the valves V11 and V41 switched on, the commutation is initiated by switching off the current-carrying valves before zero crossing of the output current. Subsequently, all transistors of the inverter are switched off during a defined dead time.

During the dead time, the parasitic capacitances C_P and C_{CE} are charged by the load current, refer to **Figure 6.23**. The transistors V21 and V31 are switched on after complete recharging of these capacitances and after the load current has commutated in the freewheeling diodes.

The condition for optimum commutation in the series resonant converter [6.8] is (without derivation):

$$\cos \gamma_{opt} = 1 - \frac{\sqrt{2} \cdot U_d \cdot \omega \cdot (C_P + C_{CE})}{I_L} \quad (6.10)$$

whereby:

$$\gamma = \pi - \varphi_s \quad (6.11)$$



Figure 6.24: HF converter EM70PI 2,400 kW, 800 V, 150 kHz, IGBT technology (Source: SMS Elotherm)

φ_s is the phase angle of the current i_L at the start time of the commutation.

Today, HF converters are available for frequencies up to 1 MHz and for very high power up to 4 MW, for example for inductive heating of strips. However the frequency of the highest power HF converters is limited to approximately 200 kHz.

Figure 6.24 shows a series HF resonant converter.

Silicon carbide (SiC) components offer new features for further development of the HF converters [6.10]. This wideband semiconductor material features many advantageous properties and there are already components available that appear suitable for the HF resonant converters. One obstacle existing in the past was the relatively high cost of the components. However these costs drop very fast.

For standard applications, however, IGBTs based on Si-wafer material will remain the modules of choice for some time to come.

6.5 Multi-frequency generators

Harry Krötz, Holger Haupt

6.5.1 Multi-frequency Process Fundamentals

The technical implementation of the multi-frequency process is the result of one decade of research and development. The potential of this method for process development had been recognized as early as in the 1940s. Even back then engineers were aware of the fact that heating of toothed components with currents of different frequencies would heat different tooth areas. However, there was not yet a technically feasible solution available to mix multi-frequency currents in an inductor. Today the process is mainly used to contour-harden toothed wheels and toothed components such as gear shafts and racks. This is done by applying multiple inverter currents with different

frequencies and amplitudes simultaneously to the same inductor. The different frequency-dependent hardening depths of the magnetic fields lead to the desired hardness contour of the components.

In practical use the process is generally limited to two frequencies that differ by a factor of about 10 to 40. Mixing, for example, three or more currents of different frequencies did not yet yield any benefits in terms of the desired technical application. The contour-hardening process is therefore often also referred to as Dual Frequency Hardening.

The first installations of dual frequency induction were technically limited and not easily scalable to process requirements arising from component geometry and the desired hardening contour. Recent advances in power electronics and converter technology improved the process performance and scalability, making it easier to adjust them to the requirements of the heated component. Today the application of the dual frequency process is no longer limited to toothed components. Even components with complex geometries are processed this way to achieve the required hardness profile.

To ensure that the heat energy remains within in the outer areas of the component at the time of quenching, it is necessary to minimize transfer of energy into the inner component areas until quenching takes place. This is achieved by heating the component for a short heating time with high power density, resulting in identical overall energy input, but lower heat transfer into the inner component parts. The heating times in the dual frequency contour hardening process often range between 100 and 500 ms.

6.5.2 Circuit Topology of a Dual Frequency Generator

The dual frequency generator basically consists of two independently controlled frequency converters. The inductor is their only point of electrical connection. **Figure 6.25** shows a schematic of the converter topology used for industrial applications under the trade name SDF® (Simultaneous Dual Frequency).

For the dual frequency process the powering generator must be capable to create alternating currents of different frequencies in the work piece. In the SDF® process, this is achieved by coupling a medium frequency and a high frequency converter to a common load.

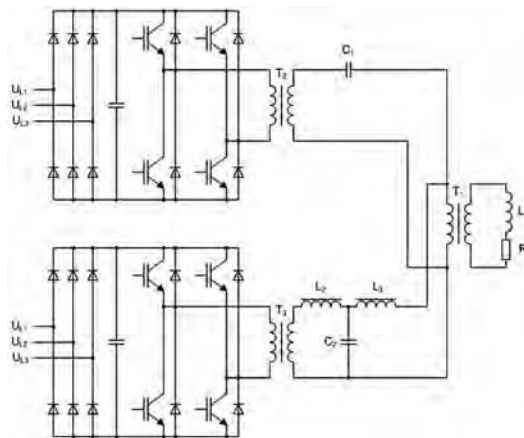


Figure 6.25: Simplified view of the SDF® generator topology

The frequency converters consist of a DC link fed via a three-phase bridge rectifier connected to the mains and a single-phase full bridge inverter. The inverter transforms the DC voltage into a square-wave voltage of desired frequency.

The load consists of the inductor and the work piece connected via inductive coupling. In a simplified model, the topology can be represented as a serial connection of the inductance L_1 and the resistor R .

Connecting the load to further reactive elements creates resonant circuits the converter uses to feed the load. The capacitor C_1 and the inductance L_1 form a series resonant circuit for the HF converter. The inductors L_2 , L_3 and the capacitor C_2 are connected to inductance L_1 to form an LCL-circuit used by the MF converter to provide the load current.

The resonant circuits within the SDF[®] topology serve multiple purposes. They provide the required voltage for the inductor using resonance rise, and therefore reduce the required converters' output voltage. Furthermore they correct the phase shift between output voltage and current of the converters when resonance occurs, thus reducing switching losses by zero current switching (zcs). The difference in frequency response between the individual resonant circuit impedances results in a decoupling effect between the converters. The series resonant circuit of the HF converter has a high impedance for frequencies below its resonance frequency. The same applies to the LCL-circuit of the MF converter for frequencies above the operating frequency range. This design prevents the converter from being unnecessarily loaded with current from the other converter.

Transformers match the impedances between load, resonant circuit and converter. Transformer T_1 serves as an output transformer for the SDF generator. It increases the low impedance of the load



Figure 6.26: 450 kW SDF[®] generator in an electrical cabinet (Source: eldec)



Figure 6.27: Converter and resonant circuit of a 300 kW SDF[®] generator (Source: eldec)

to a level more suitable for the oscillating circuits. The transformers T_2 and T_3 match the impedances of the HF and MF resonant circuit to the correspondent converter.

6.5.3 Power Output and Control

The dual frequency generator uses individual converters for each frequency. It is therefore possible to freely adjust the power distribution between medium and high frequency. The component to be treated usually requires very similar MF and HF power outputs. Thus, a 300 kW SDF® generator could be equipped with a MF/HF ratio of 100/200 kW, 150/150 kW or 200/100 kW.

Figure 6.26 and **Figure 6.27** show modern SDF® generators.

A power rating of 15 to 1,500 kW is feasible for both the MF and HF range. In order to use the generator in conventional hardening applications as well, either the MF or HF component can be switched off for single-frequency operation.

The current strength in the inductor depends on converter power, inductor design, component geometry and the material to be heated. Actual converters allow for HF currents of up to 8,000 A and MF currents of up to 30,000 A in the inductor. Such high currents are required to generate the alternating electro-magnetic field used for coupling the high power densities required for contour hardening to the work piece. Inductor currents of 1,500 A HF or 8,000 A MF are generally sufficient for components with smaller dimensions or higher tolerances in their hardness profile.

The converters can be either power-controlled or current-controlled and are protected against overload in both operating modes. Pulse width modulation, a technology tried and tested for years,

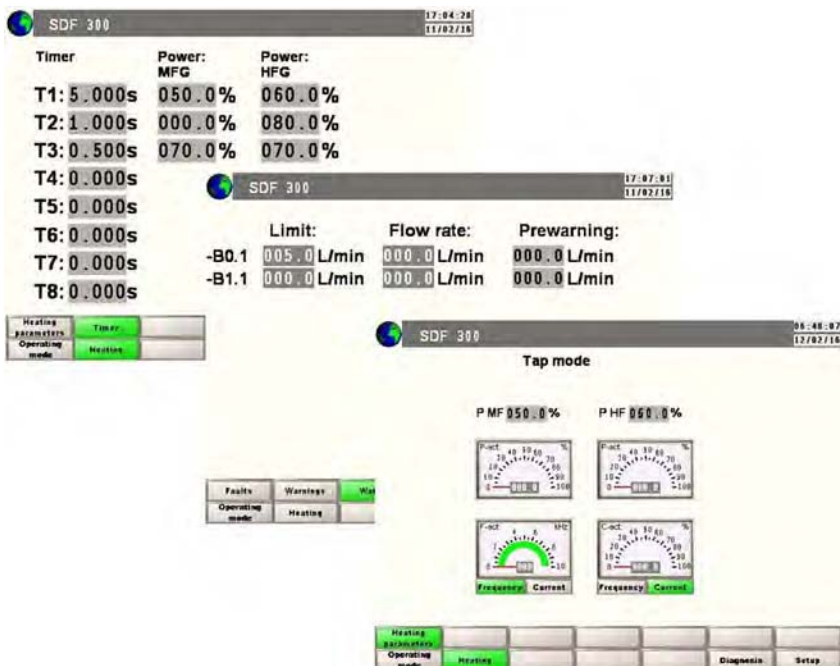


Figure 6.28: Input dialogs of a 300 kW SDF® generator



Figure 6.29: Hardening system with integrated 300 kW SDF® generator (on the left) (Source: eldec)

is used for voltage regulation of MF converters. HF converters are controlled using the widely used burst control, to minimize switching losses in the converter.

6.5.4 Adjustments, Activation and Process Monitoring

Since a multi-frequency generator comprises individual converters for each frequency, the user interface needs to be much more versatile than for conventional MF or HF generators. Using dual frequency generators allows the operator to adjust the desired values for power per frequency, heating times, inductor flow limits or cooling water temperature (see **Figure 6.28**).

The heating process can either be started manually or via an external control unit, for example, via Profinet. The Profinet handles all communications to the generator, making it easy to integrate these generators into appliances or machines (see **Figure 6.29**).

During the heating process the relevant converter and generator data will be recorded and shown on the display. Using a process data recording system allows the data to be saved every 10 ms. Even with very short heating times the operator will be able to observe and analyze value changes over the process cycle. The most important process data are converter current and voltage, frequency, output power and the so-called energy value calculated over current and time for each work piece at the end of the heating cycle. The energy value can have a defined upper and lower limit, guaranteeing a highly reproducible hardening result.

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