Joachim Schlegel

The World of Steel

On the History, Production and Use of a Basic Material

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The most beautiful thing we can experience is the mysterious.

Albert Einstein

Foreward

The material steel, with its versatile properties and an almost incalculable wealth of applications, accompanies us all day long – and has done so for many generations.

As we read this, we may be stirring our coffee with a stainless steel spoon looking at the number combination 18/10 on its back. The exact designation is X5CrNi18-10. During manufacturing, it is listed the number 1.4301. In the workshop, it is named V2A. Directly, we find overselves in the middle of the world of steel, where "The World of Steel" accompanies us with an unmistakable and pleasant writing style. It shows that teaching about steel is not difficult to understand and is definitvely not as far away from us as we might think.

A great strength of this book is the successful mixture of technically well comprehensible contents combined with a huge amount of versatile, practical applications. Therefore, this book is suitable for many users: For basic teaching in the discipline of materials science and production technology as well as for technical postgraduate studies based on a business degree.

In addition to teaching the basics, author Dr Joachim Schlegel takes us back through the history of steel, covers the area up to the latest applications, and amazes us with the question "Did you know ...?".

The book "The World of Steel" will take its place linking theory and practice, especially for those who enjoy interesting, visual and practice-oriented learning and teaching.

I wish the author and his work all the best.

Prof. Dr.-Ing. Andreas Zilly
Professor of Materials Science at the Duale
University of Baden-Württemberg

Preface

A stainless steel sink in the modern kitchen is ubiquitous; so is the stainless steel cutlery and the often used steel wool to clean pots. On steel skates, the bobsleigh glides towards the target on the ice channel. It is fun to play boules, translated from French “balls”, which today are made of steel. Needles for knitting, weaving, felting, combing and sewing, whether for the housewife or for use in textile machines, are made of special steels. And if you want to build something in your own home, you will be pleased to have suitable tools made of durable tool steel, such as a spiral drill, a jigsaw, a chisel or hammer. Steel stamps emboss coins or form medicine into pills. A copper-plated steel wire is used in fireworks. Bowden cables on bicycles for operating the brakes up to suspension cables for suspension railways or suspension bridges are made of high-strength steel wire. Even if you can't see it, there is a lot of steel in modern concrete buildings. Steel rails for railways and trams secure our mobility. The power lines are attached to steel lattice masts. Steel beams carry loads, and modern cars consist of many different types of steel. No matter where we are and what we are doing, steel is always part of our lives, at work or in our leisure time, sometimes as a work of art. Steel is essential, recyclable and has a very special meaning: In our modern industrial society, steel is the basic material for all important industrial sectors, such as automotive and shipbuilding, aerospace industry, apparatus and machine construction, bridge and steel construction, energy and environmental technology, packaging industry, household and sports industry, medical technology, robotics and IT technology, etc. All the global megatrends of today, such as energy supply, mobility, healthcare, environmental and climate protection, cannot be solved and mastered without steel.

The large-scale production and processing of steel is state of the art today and the number of developed steels is impressive: Already over 2500 steel grades are listed in the European steel register. The over 5000 year long history of iron and steel production is rather impressive as well. The world of steel is constantly evolving and has become so diverse and complex in the meantime that it is not easy to overview it in practice. The reader should be brought closer to this world, from steel production, further processing with ingot and continuous casting, forming and machining to finishing, testing and packaging of the products, the processes and facilities used for this purpose, including the environmentally friendly recycling and disposal of waste. Interesting and new techniques and applications will also be pointed out.

Not high-scientific and all-encompassing, but informative and exciting, structured, above all understandable and with concrete practical examples, partly also with historical references - this is how an insight into the world of steel will be granted here. A timeline provides information on important milestones in iron and steel production in chronological alignment with social and technical events. And in a glossary, finally, terms and abbreviations from the practice of steel metallurgy, steel processing and material testing are explained in order to find one's way around the world of steel more quickly.

I would like to thank the shareholders of the BGH Edelstahl Group, in particular Messrs. Rüdiger and Sönke Winterhager, who promoted the creation of this book. The BGH Edelstahlwerke GmbH kindly provided some photos from production and approved the publication of photos that I took during my work in the companies of the BGH Group for training purposes.

I would like to thank Prof. Dr.-Ing. Andreas Zilly, Professor of Materials Science at the Duale University of Baden-Württemberg, Stuttgart, for his expert support in the preparation and review of the manuscript. Valuable hints on steel production and the chronology of iron production and processing were given by Dr.-Ing. habil. Bernd Lychatz, Institute of Iron and Steel Technology at the TU Bergakademie Freiberg. I would like to thank Mr. Frieder Kumm M.A., Senior Editor, Department of Civil Engineering of Springer Vieweg, for his motivation and support during the creation of the manuscript and the design of the book. Finally, Mr. Claus-Dieter Bachem, Project Coordinator at Springer Nature, and Mr. Georg Haller-Kaimann, Implementation Manager at Springer Nature, have contributed greatly to translating this with book into English with help of an automatic translation software using artificial intelligence.

I would like to thank my brother, Dr.-Ing. Christian Schlegel, and my son, Dr. Peter Schlegel, for their help with proofreading the manuscript in German and in English, respectively. And I would also like to sincerely thank my dear wife Birgit for always having my back and also for her critical remarks on understandable formulations.

Dr.-Ing. Joachim Schlegel

Contents

Systematization of Materials

1

> The history of mankind is closely linked to the development and use of materials, which even shaped different periods in history such as the Stone Age, Bronze Age and Iron Age. It was a long, hard way: from the stone handaxe to the use of processed, solidified metals such as gold, silver and copper, the discovery of the first alloy (bronze) to today's targeted material development. Metallurgical processes and plants, processing technologies and usage concepts had to be developed and implemented. The driving force for this was the constantly increasing demand for materials associated with the progress of mankind.

"Materials made to measure" – durable, sustainable, light, but highly resilient, recyclable, and even intelligent – such materials can already be produced today. Yet the requirements continue to increase. The complex properties of a material must be considered for its future use, as shown for example in Fig. 1.1 (Weißbach et al., 2018), e.g.:"

- *State of the material*
- *Interactions with other materials*
- *Behavior under mechanical stress*
- *Behavior during manufacturing (forming, machining, coating, etc.)*
- *Behavior under environmental influences*

These complex requirements mean that materials have been mainly divided according into chemical groups, since these essentially also determine the characteristic properties of the material concerned (Briehl, 2014; Kutz, 2013). Today, materials are divided into the following main groups: metallic systems, semiconductors and non-metallic systems (Fig. 1.2).

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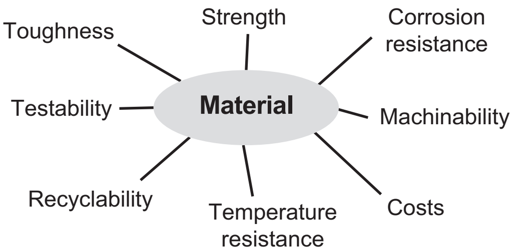


Fig. 1.1 General properties and requirements for materials

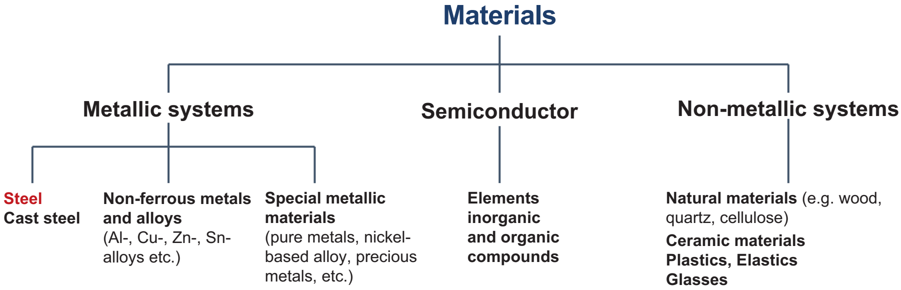


Fig. 1.2 Division of materials into main groups

The most important material groups are characterized below according to their properties.

Metals (75% of all chemical elements).
Metals have a metallic bond, are usually shiny, plastic, malleable, alloyable, meltable, ductile, hard or tough, weldable and recyclable.
Main materials:
Steels, cast iron, aluminum, copper, nickel and titanium alloys, pure metals, precious metals, special alloys, nickel-based alloys.
Examples:
Structural steel and metalwork, lightweight construction, toolmaking, machine and plant construction, vehicle construction, shipbuilding, medical engineering, textile machinery construction, electrical engineering, electronics, hydraulics / pneumatics, and many others.

Metals are to be found in all areas of our lives. For example Fig. 1.3 shows an interesting steel structure of the Sony Center at Potsdamer Platz in Berlin with fabric and 105 t of safety glass.

Semiconductor
These are materials of electrical engineering, electronics and information technology, which are conductive between the metallic conductors and the insulating ceramics or polymer materials. They are functional materials with a huge social impact on humanity.

Fig. 1.3 Steel roofing struture of the Sony Center at Potsdamer Platz, Berlin. (Photo: Schlegel, J.)

Main materials:
Silicon, germanium, gallium arsenide.
Examples:
Components for electrical engineering and electronics, optoelectronics, LED lighting technology, mobile radio technology, etc., produced using semiconductor materials. Figure 1.4 shows a monitor module with components made of semiconductor materials.

Plastics
Their properties depend on the manufacturing process, the additives and the temperature conditions: insulating, light, easily moldable, chemically resistant, low temperature resistant, colorable, transparent to opaque, rubbery to brittle, high thermal expansion, difficult to recycle, low strength and usually inexpensive.
Main materials:
Polyvinyl chloride, polyethylene, polypropylene, polystyrene, polyamide, polyethylene terephthalate.
Examples:
Plastic is omnipresent in our daily lives, and is a material for countless, indeed almost all, industrial sectors, for the areas of household, leisure, sports, etc. It is therefore superfluous to list all its applications; a fine example is shown in Fig. 1.5 in the form of a child's toy.

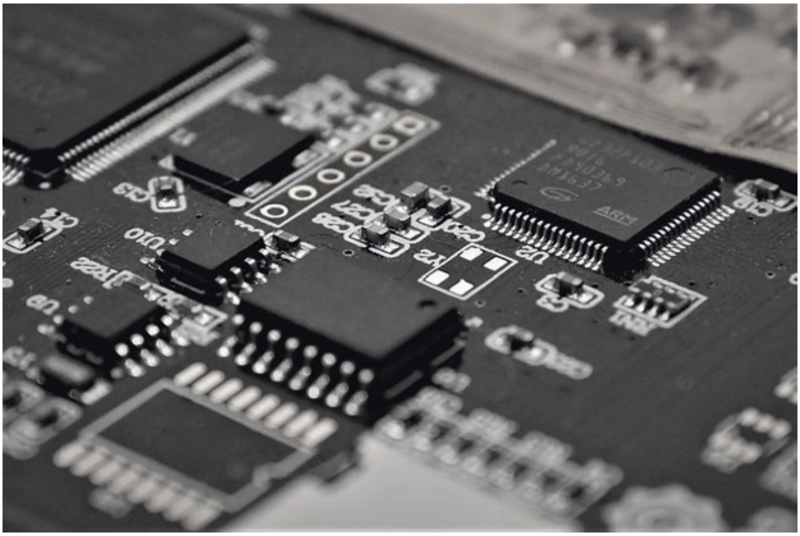


Fig. 1.4 View of a monitor module. (Photo: Schlegel, St.)

Glass and Ceramics

Glass and ceramics are usually mentioned together because they have similar properties: insulating, heavy, hard, wear-resistant, brittle, chemically resistant and temperature-resistant, transparent to opaque and non-toxic.

Main materials:

Clay minerals, silicides, oxides, carbides, nitrides, borides, hard materials

Examples of glass applications:

Glazing on buildings (windows, doors, facades, canopies, other glazing), automotive industry, household goods, beverage industry, works of art, etc. An example of a one-time and especially creative use of glass is the Hundertwasser toilet in Kawakawa on New Zealand's North Island. It has a glass-bottle wall, shown in Fig. 1.6. In the masonry, the famous artist *Friedensreich Hundertwasser* (1928–2000) set colorful glass bottles, a fanciful peculiarity that he cultivated in his architecture.

Examples of ceramic applications:

Cutting materials, parts and linings for plants and apparatus in the chemical industry, insulators, wearing parts, coatings and many other parts in electrical engineering/electronics. Ceramic ware is to be found in almost every household, e.g. in the form of dishes, vases and planters (Fig. 1.7).

Fig. 1.5 Fire truck turntable made of plastic. (Photo: Schlegel, J.)

Fig. 1.6 Detail of the glass-bottle wall of the Hundertwasser toilet in Kawakawa, New Zealand, built in 1999. (Photo: Schlegel, J.)

Fig. 1.7 Typical ceramic planters (Photo: Schlegel, J.)

Composite Materials

Custom-made structural materials with unusual, multifunctional property combinations are considered to be composite materials. They have high strength and stiffness, are light and durable, but usually expensive, difficult to repair and not recyclable.

Types of composite materials:

- Fiber-reinforced composites
- Particle-reinforced composites
- Layer (sandwich) composites

Figure 1.8 shows these three types of composite materials schematically.

The most important composite materials known today are:

- fiber-reinforced plastics
- carbon fiber-reinforced plastics
- metal matrix composites
- new material combinations

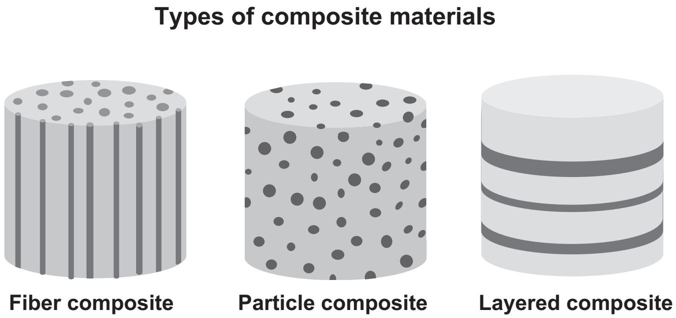


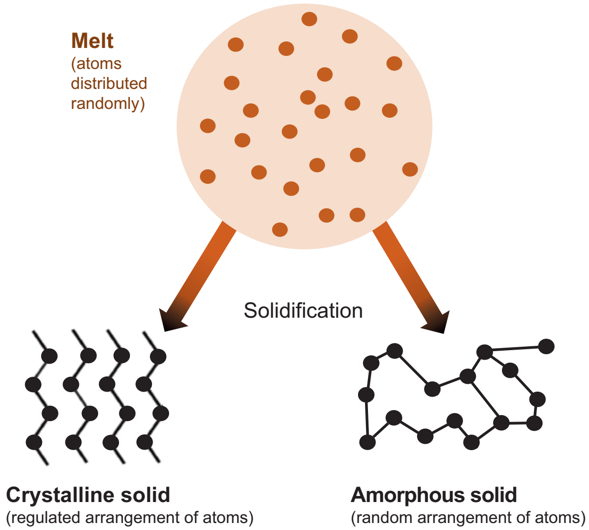
Fig. 1.8 Schematic representation of the structure of composite materials

Examples:
Parts (mostly lightweight) for the automotive, aerospace and shipbuilding industry, space technology, motorsport, model making, sports equipment, medical technology, and many more.

If you also add natural materials, such as leather, you quickly come to a product that combines all of the above-mentioned material groups into a form of outstanding engineering, which is beautiful and very mobile, and more or less sustainable: our automobile ("self-propelled", motor vehicle).

The materials mentioned, metals, plastics, glass and ceramics, have two different solid states, see Fig. 1.9. These depend on the conditions during solidification, i.e. on the temperature gradient during the transition from the liquid to the solid state (Hornbogen et al., 2019).

Fig. 1.9 Representation of the material states crystalline and amorphous



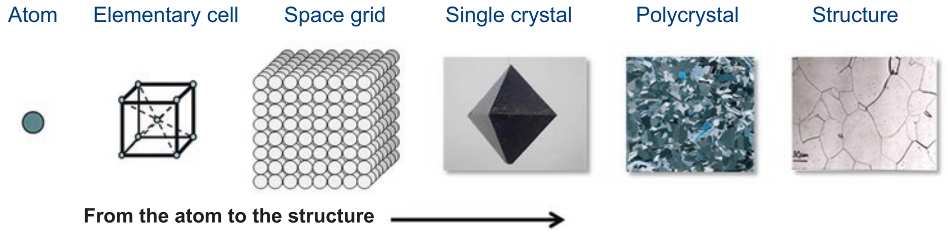


Fig. 1.10 From the atom, the smallest building block, to the polycrystalline structure of a steel

The crystalline state Metals, crystalline ceramics, semi-crystalline plastics.
In the crystalline state there is a regular arrangement of the building blocks (atoms), and it is a stable state. Solidification takes place abruptly with a phase transition at a defined melting point (temperature of the liquid – solid transformation).

The amorphous state glass, plastics, metallic glass
An amorphous state is to be understood as a "supercooled melt" (e.g. as in glass). The atoms are in an irregular arrangement. The density of this state is lower than in the crystalline state.

Technical Metals are almost exclusively *polycrystalline* (Eisenkolb, 1958 ff.). They form in the solid state crystals, which in turn consist of atoms in different spatial arrangements (lattice). The crystals are also called grains and their association structure. An interesting look inside a metal (Fig. 1.10): From the structure of a usable object, such as a drill, a crankshaft or a connecting rod, down to the smallest building blocks, namely the atoms.

Note

The following explanations only apply to the material ***steel***; namely steel as the "forgeable", malleable iron with less than 2.06% carbon content (i.e. not cast iron).

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The Material Steel

2

Steels always fascinate with their many, often also extraordinary properties, with a great potential for application and increasing production worldwide.

- What characterizes the material steel?
- How are steels classified or differentiated?
- What are steels composed of?
- What properties do steels have and how can they be influenced?
- Where are steels mainly used?

The following section provides an orientation with explanations of the basics of the material steel, the possibilities of classifying steels as well as short portraits of selected steel grades.

2.1 What is Steel?

Steel is malleable, forgeable iron with a carbon content of less than 2.06 mass-% (usually with <1 mass-% carbon). At carbon contents above 2.06 mass-%, one speaks of cast iron. Therefore steel is an iron-carbon compound. This is mixed with other metallic and non-metallic elements (alloyed) to obtain steels with different properties (Berns & Helmreich, 1980).

Density of steel: approx. 7.85 to 7.87 g/cm^3.

Melting point (iron/steel): depending on the chemical composition up to 1536 °C.

The material steel is polycrystalline, that is, it is made up of individual crystal lattices. Their modifications are determined by the *base element iron*. Iron as the main component of steel occurs in two types, namely as a space-centered cubic and a face-centered cubic crystal lattice (Bleck, 2010).

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The space-centered cubic lattice (α-iron)

In this type of lattice, there is one iron atom at each of the eight vertices, and a ninth iron atom exactly in the center of the cube (Fig. 2.1).

In such an α-iron, which exists at temperatures up to 911 °C, a maximum of 0.018 mass-% of carbon can be dissolved. This resulting crystal consisting of iron and carbon atoms, that is, of different atoms, is called a mixed crystal. Since the iron in this case is in the form of a body-centered cubic lattice (α-iron), this mixed crystal is called α-mixed crystal and is also referred to as a *ferrite* (lat. "Ferrum", the "iron").

The face-centred cubic lattice (γ-iron)

There are atoms at the eight corners of the cube lattice. However, the center of the cube remains free. More atoms are arranged in the center of each of the six cube faces, as shown in Fig. 2.2.

In this γ-iron, which only occurs in the temperature range from 911 to 1398 °C, a maximum of 2.1 mass% carbon is dissolved. This γ-mixed crystal is called *austenite*,

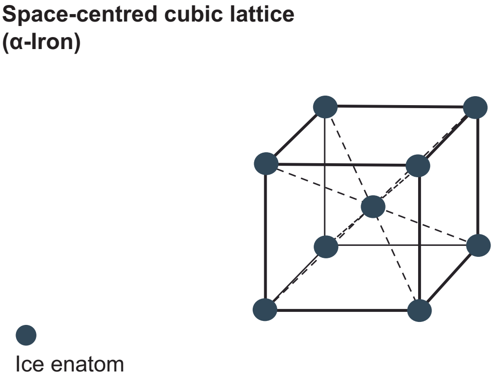


Fig. 2.1 The space-centered cubic lattice

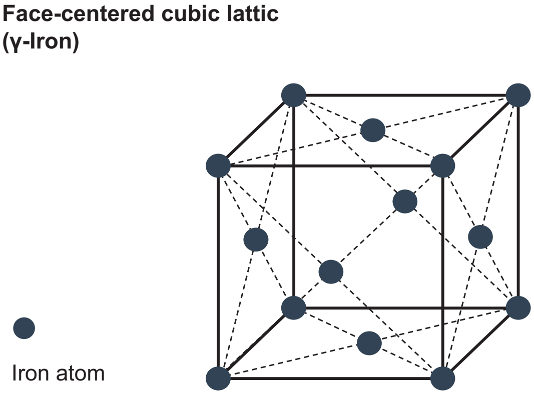


Fig. 2.2 The cubic-centered cubic lattice (cubic close-packed)

after Sir *William Chandler Roberts-Austen* (1843–1902). He was a British metallurgist who studied the physical properties of metals.

In iron-carbon alloys, the carbon is stored on interstitial sites in the iron crystal lattice. This results in so-called mixed crystals. These contain atoms of different alloying elements in the lattice structure. Depending on the crystal structure, the carbon is only slightly soluble in the iron lattices. When heated and cooled slowly, the iron atoms migrate, and a lattice transformation (phase transformation α into γ or γ into α) takes place. This process is deliberately used during heat treatment to create certain microstructures and thus corresponding properties of the steels.

▶ **Note** There is a variety of steels that have a lattice transformation, but also steels such as ferritic and austenitic steels that do not show such a transformation.

2.2 The Iron-Carbon Diagram

The most important alloying element in steel is carbon (C). This is present as a compound (cementite – Fe_3C). In general, the higher the carbon content, the harder the steel, but also the more brittle. With the well-known iron-carbon diagram, as shown in Fig. 2.3, the phase composition of steel is described as a function of carbon content and temperature.

The mass percentages of carbon content are plotted on the x-axis below, and the temperature in °C is plotted on the y-axis upwards. For technical use, the pure two-substance system iron-carbon is only considered up to a maximum of 6.67 mass-% carbon (cementite – Fe_3C) and at normal pressure. It is assumed that the cooling takes place very slowly with complete transformation processes.

The iron-carbon diagram therefore only provides information on equilibrium conditions. In this way, the expected state of an unalloyed steel with a certain carbon content at a specific temperature can be determined. The microstructural changes taking place during temperature changes can also be predicted (Klemm, 1973). Therefore, the iron-carbon diagram is also the most important basis for the heat treatment of steel.

Explanations of the iron-carbon diagram

Line ACD: *Liquidus line*

Above this line, the alloy is liquid. Below this line, solidification begins. (Primary crystallization) of the melt.

Line AECF: *Solidus line*

Below this line, the alloy is completely solidified.

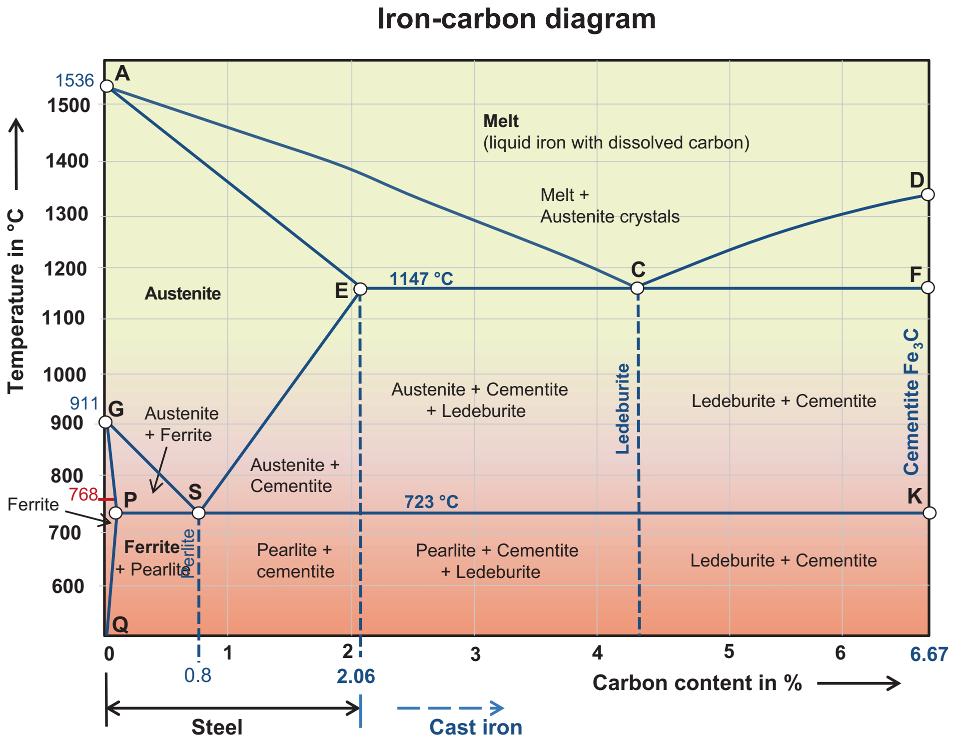


Fig. 2.3 Simplified representation of the iron-carbon diagram

ECF line:

Above this line, liquid and solid phases exist side by side.

Line PSK:

This line describes the constant temperature of 723 °C. Below this line, the Austenite mixed crystals have completely disintegrated.

Line SE:

At carbon contents between 0.8 and 2.06 mass-%, the carbon in excess of solution as secondary cementite (Fe_3C) is precipitated during cooling.

GPQ line: It delimits the single-phase region of ferrite.
768 °C: *Curie temperature* (magnetic transformation) Up to this temperature, iron is ferromagnetic, above this temperature paramagnetic (non-magnetic).
Ferrite: α-mixed crystal (max. 0.018 mass-% carbon).
Austenite: γ-mixed crystal (max. 2.06 mass-% carbon).

Perlite and Ledeburite:

They are special phase mixtures (structures) that only occur during slow cooling. If cooling takes place quickly, e.g. by quenching in water, the austenite becomes a hard and brittle structure, *martensite*.

Cementite Fe_3C:
It is a microstructure phase with 6.67 mass-% carbon, which can occur in three different forms at the same composition:

They are special phase mixtures (microstructures) that only occur during slow cooling. If cooling is rapid, e.g. by quenching in water, a hard and brittle microstructure, called martensite, *Martensit* is formed from austenite.

Primary cementite: primary crystallization from the melt, line CD

Secondary cementite: precipitation from austenite, line ES

Tertiary cementite: precipitation from ferrite, line PQ

Example
The change in microstructure for pure iron and a 1 mass-% carbon steel during heating and cooling is shown in Figs. 2.4 and 2.5.

2.3 Designation System and Classification of Steels

▶ As numerous and diverse as the steels, so are the names: steel type, steel grade, steel quality, steel name, steel brand, material number, brand name. Finding your way around in steel practice is not quite easy. For the identification and assignment of steels, rules are laid down in DIN EN 10027-1 for the designation by means of short names as well as in DIN EN 10027-2 for a numbering system. This designation system is described in detail, for example, in the Steel Key Pocket Book (Wegst & Wegst, 2019). Based on this, Fig. 2.6 shows a simplified representation of the steel designation system with examples of different steel grades.

Steel short names
They give indications of the use, the mechanical and physical properties or the chemical composition of the steels. The steel short names consist of main and additional symbols, which can be letters (e.g. chemical symbols) or numbers (for the content of the alloying elements) respectively. These specifications differ for unalloyed, alloyed and highly alloyed steels as well as for high-speed steels (Langehenke, 2007).

Unalloyed steels (quality steels) are indicated by the letter C for carbon, followed by the carbon content. The number given for the carbon content is always multiplied by 100. I.e. in order to recognize the actual content, this number must be divided by 100.

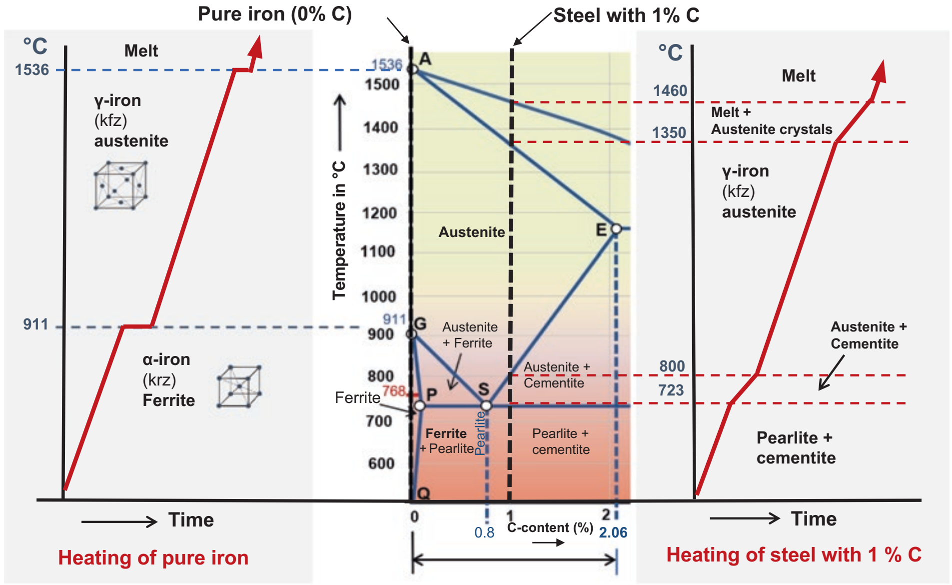


Fig. 2.4 Change in microstructure during heating of pure iron (0% carbon) and a 1 mass-% carbon steel

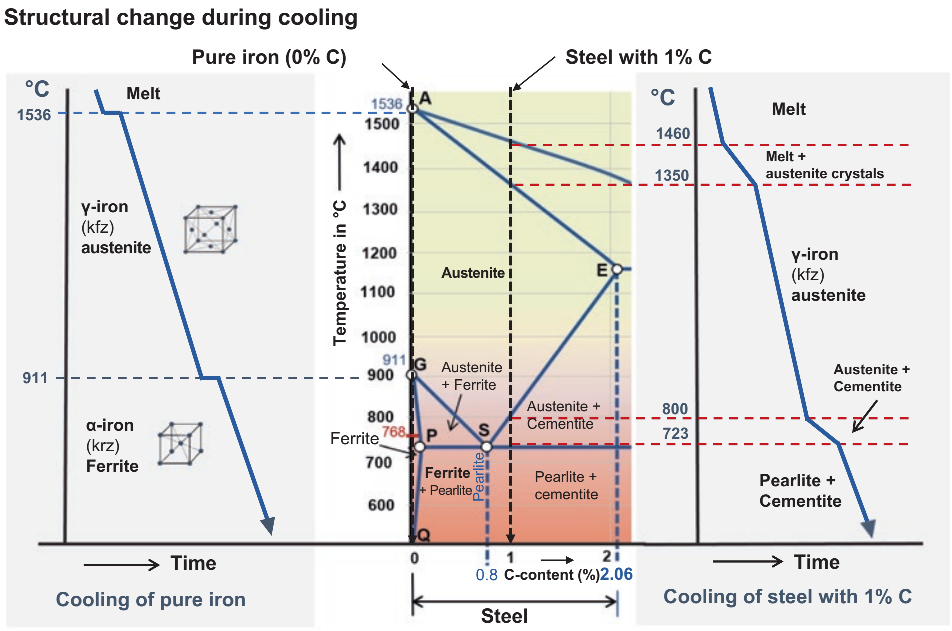
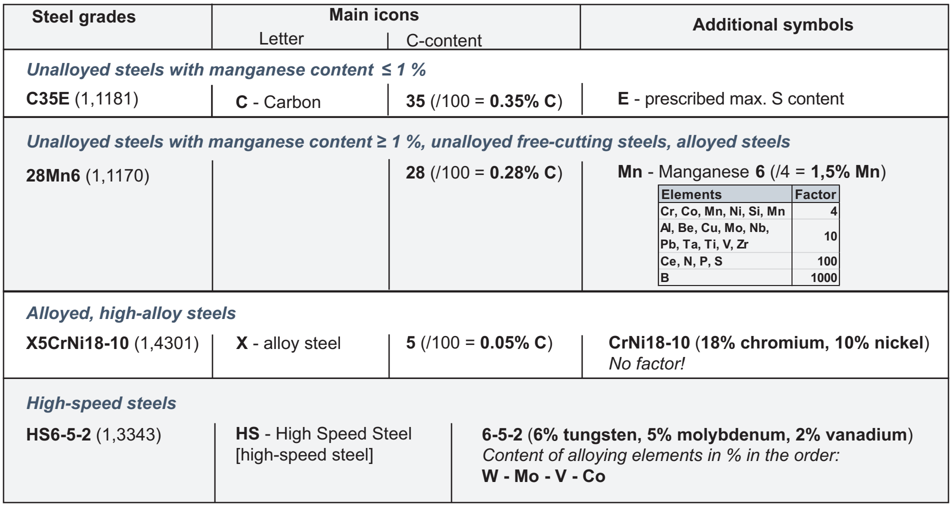


Fig. 2.5 Progression of microstructure changes during cooling of pure iron (0% carbon) and of a steel with 1 mass-% carbon



Steel grades	Main icons		Additional symbols
	Letter	C-content	
Unalloyed steels with manganese content ≤ 1 %			
C35E (1,1181)	**C** - Carbon	**35** (/100 = **0.35% C**)	**E** - prescribed max. S content
Unalloyed steels with manganese content ≥ 1 %, unalloyed free-cutting steels, alloyed steels			
28Mn6 (1,1170)		**28** (/100 = **0.28% C**)	**Mn** - Manganese **6** (/4 = **1,5% Mn**)
Alloyed, high-alloy steels			
X5CrNi18-10 (1,4301)	**X** - alloy steel	**5** (/100 = **0.05% C**)	**CrNi18-10** (**18% chromium, 10% nickel**) *No factor!*
High-speed steels			
HS6-5-2 (1,3343)	**HS** - High Speed Steel [high-speed steel]	**6-5-2** (**6% tungsten, 5% molybdenum, 2% vanadium**) *Content of alloying elements in % in the order:* **W - Mo - V - Co**	

Elements	Factor
Cr, Co, Mn, Ni, Si, Mn	4
Al, Be, Cu, Mo, Nb, Pb, Ta, Ti, V, Zr	10
Ce, N, P, S	100
B	1000

Fig. 2.6 Overview of the steel designation system

Example:
C15 – an unalloyed steel with 15/100 = 0.15 mass-% carbon.

In *unalloyed steels with manganese content ≥ 1 mass-%* the carbon content is given in first place, also multiplied by the factor 100 and in contrast to unalloyed steels with manganese content ≤ 1 mass-% always without the letter C. This is followed by the chemical symbols for the alloying elements and their mass content. It should be noted that these mass contents have always been multiplied by different factors. These multipliers for the individual alloying elements are as follows:

Factor 4: Chromium (Cr), Cobalt (Co), Manganese (Mn), Nickel (Ni), Silicon (Si), Tungsten (W)
Factor 10: Aluminium (Al), Beryllium (Be), Copper (Cu), Molybdenum (Mo), Niobium (Nb), Lead (Pb), Tantal (Ta), Titanium (Ti), Vanadium (V), Zirconium (Zr)
Factor 100: Cer (Ce), Nitrogen (N), Phosphorus (P), Sulfer (S), Carbon (C)
Factor 1000: Bor (B)

In order to recognize the actual alloy contents, the numbers given in the steel short name must be divided by the corresponding multipliers.
Example:
28Mn6 – an alloyed steel with 28/100 = 0.28 mass-% carbon and 6/factor 4 = 1.5 mass-% manganese.

High-alloy steels always have a mass fraction of various alloying elements of a total of at least 5 mass-%. These steels are characterized by an X at the beginning of the short name. This is followed by the carbon content, again multiplied by the factor 100 in principle, and the other alloying elements with their chemical symbols. The indication of the alloying elements takes place in the order starting with the highest content. This is followed by the respective mass fractions belonging to the alloying elements. However, these are not multiplied by a factor (typical for high-alloy steels!).
Example:
X5CrNi18-10 – a high-alloy, austenitic, non-corrosive stainless steel with 0.05 mass-% carbon, approx. 18 mass-% chromium and 10 mass-% nickel. This steel is the first commercial, non-rusting steel, which is also known as V2A and corresponds to the material number 1.4301.

An exception are the *high-speed steels*. Here a special designation system applies. In first place is the designation HS, followed by the mass fractions of the alloying elements in the prescribed order tungsten—molybdenum—vanadium—cobalt. The mass fractions of the individual alloying elements are given here in whole, rounded numbers.
Example:
HS 6-5-2 C – a standard high-speed steel with 6 mass-% tungsten, 5 mass-% molybdenum and 2 mass-% vanadium (corresponding to the material number 1.3343).

Material numbers

They are issued by the European Steel Registry and consist of the material main group number (first number with point), the steel group numbers (second and third number) and the sequence numbers (fourth and fifth number). In addition, the steelmaking process and the treatment condition can be characterized by two appendix numbers XX. Figure 2.7 shows this numbering system using the example of the 1.5920 – 18CrNi8 tool steel.

The appendix numbers XX are structured as follows:

Position 6: Steelmaking process

0 – indeterminate or without meaning
1 – unkilled Thomas steel
2 – killed Thomas steel
3 – other melting type, unkilled
4 – other melting type, killed
5 – unkilled Siemens-Martin steel
6 – killed Siemens-Martin steel
7 – unkilled oxygen-blown steel
8 – killed Oxigen blast steel
9 – electric steel

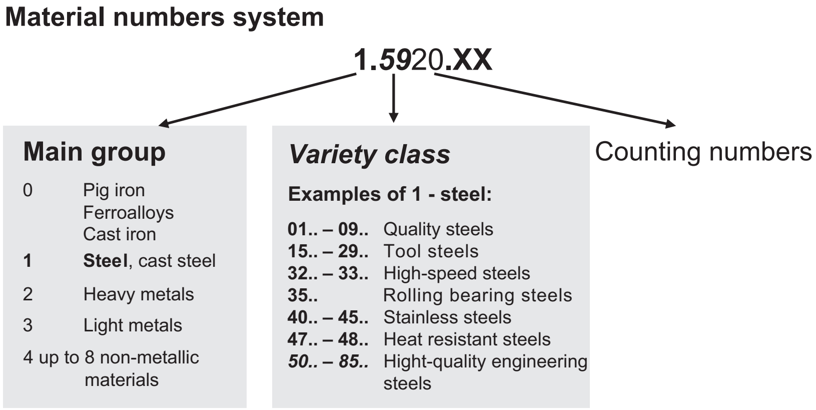


Fig. 2.7 Material numbering system using the example of the 1.5920—18CrNi8 tool steel

Position 7: Type of treatment

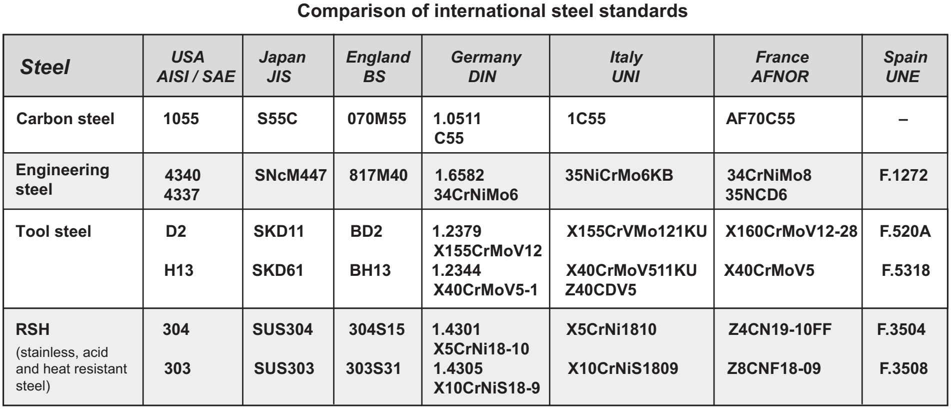
0 – no or any treatment
1 – normalized annealed
2 – soft annealed
3 – annealed for best machining
4 – tough hardened and tempered
5 – hardened and tempered
6 – hard annealed
7 – coldhardened
8 – cold hardened for springs
9 – treated according to special instructions

Brand Names

Some steels are still traded under the brand names legally protected by the steel manufacturers. Here are some current examples:

- Invar (iron-nickel alloy with 36 mass-% nickel, 1.3912, brand name of Aperam Alloys Imphy, France)
- Nirosta (stainless steel, brand name of Thyssen Krupp Nirosta)
- Cromargan (high-quality Cr-Ni steel, trade name of WMF)
- Inconel, Incoloy, Monel, Nimonic, Inco-Weld, Nilo, Brightray, Coronel, Udimet (protected brand names of Special Metals, USA)

In addition, there are historically grown special terms which are still in use in the steel world such as V2A (trial melt 2 austenite, Krupp patent), today the 1.4301 – X5CrNi18-10.



Comparison of international steel standards

Steel	USA AISI / SAE	Japan JIS	England BS	Germany DIN	Italy UNI	France AFNOR	Spain UNE
Carbon steel	1055	S55C	070M55	1.0511 C55	1C55	AF70C55	–
Engineering steel	4340 4337	SNcM447	817M40	1.6582 34CrNiMo6	35NiCrMo6KB	34CrNiMo8 35NCD6	F.1272
Tool steel	D2	SKD11	BD2	1.2379 X155CrMoV12	X155CrVMo121KU	X160CrMoV12-28	F.520A
	H13	SKD61	BH13	1.2344 X40CrMoV5-1	X40CrMoV511KU Z40CDV5	X40CrMoV5	F.5318
RSH (stainless, acid and heat resistant steel)	304	SUS304	304S15	1.4301 X5CrNi18-10	X5CrNi1810	Z4CN19-10FF	F.3504
	303	SUS303	303S31	1.4305 X10CrNiS18-9	X10CrNiS1809	Z8CNF18-09	F.3508

Fig. 2.8 Comparison of the most important international steel standards using some selected examples for carbon steel, structural steel, tool steel and for **r**ust-, **a**cid- and **h**eatresistent steels

> ▶ **Note** Reference has to be made to international steel standardization: e.g. DIN EN (Europe), ASTM/AISI (USA), JIS (Japan). These are the operating fundamentals for the steel producing and processing industries and a consensus between industry, trade, research and consumers. For this purpose, Fig. 2.8 shows an overview comparing the most important international standards for selected steels (Marks & Tirler, 2016).

In practice, the ***classification of steels*** is usually carried out according to the following criteria:

- *Main quality classes*
- *Chemical composition*
- *Structure*
- *Application/properties*

Main quality classes of steels

Basic steels

These include all unalloyed steels for requirements for which no special measures are required in steel production.
Examples: Iron products, iron grills and railings, fences. Figure 2.9 shows, for example, a typical garden fence made of forged iron.

Quality steels

These consist of unalloyed and alloyed steel grades, which, for example, must meet certain requirements in terms of formability, weldability, deep drawability and grain size.

Fig. 2.9 Garden fence made of forgediron, painted to protect against corrosion. (Photo: Schlegel, J.)

These steels usually have a carbon content in the range of 0.2 to 0.65 mass-%. With a maximum of 0.045 mass-% phosphorus and sulfur content, the required purity of the quality steels is ensured during production.

Examples:

Steels for welding constructions in mechanical engineering and for car bodies in vehicle construction. Figure 2.10 shows a car body made of quality deep-drawn sheet metal for an old Jaguar car.

Stainless steels

High quality steels are unalloyed and alloyed steels that can only be produced with a very high purity by means of special conditions and with high expenditure using metallurgical methods. According to DIN EN 10020:2000-07 (terminology for the classification of steels), the sulfur and phosphorus content must not exceed 0.025 mass-%.

Examples:

Steels and other materials for power plant, machinery and equipment construction, for the automotive industry, for tools, for hydraulics and pneumatics, for chemical plants and in medical technology for instruments and implants, as they can be seen, for example, in Fig. 2.11 for the operation (fixation) of a bone fracture.

Fig. 2.10 Raw car body for a Jaguar oldtimer. (Photo from the Internet: Pixabay 24.03.2018, Transport/Traffic)

Fig. 2.11 Medical instruments and implants (plate and bone screw) made of corrosion-resistant, biocompatible stainless steels. (Photo: Bogenschütz, C., Zollernalb Klinikum gGmbH, Balingen)

Classification of steels according to chemical composition

Steels are iron-carbon compounds with additions of chemical elements, i.e. so-called alloys with different chemical composition. The most important additions to alloy steels are the chemical elements chromium, nickel, vanadium, molybdenum, titanium, tungsten, as well as silicon and manganese. With regard to this chemical composition, steels can be divided into *unalloyed, alloyed* and *high-alloyed steels* according to DIN EN 10020.

Unalloyed steels

The unalloyed steels (steels without addition of certain alloying elements) have a manganese content of less than 1 mass-% at different carbon contents.

Alloyed steels and high-alloyed steels

These steels can be distinguished in the following order of increasing alloy content:

- *Microalloyed steels:* Steels with only 0.01 to 0.1 mass-% of aluminum, niobium, vanadium and/or titanium, for example, to achieve high strength by means of carbide and nitride formation as well as grain refinement.
- *Low-alloy steels:* These are steels in which the alloying elements in total may not exceed a mean content of 5 mass-%.
- *Alloyed steels and high-alloy steels:* These steels have at least one alloying element with a mean content of more than 5 mass-%.

When considering the classification of steels according to chemical composition, the *carbon content* can also be used as a criterion. Figure 2.12 shows a simplified overview of steels, classified according to carbon content.

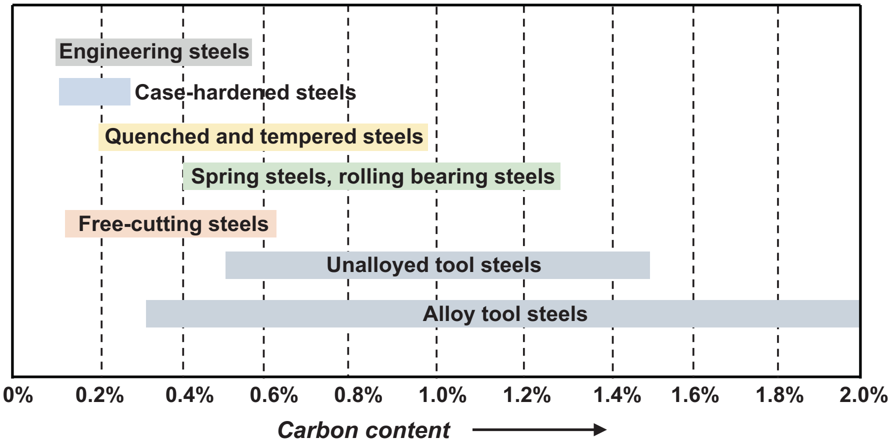


Fig. 2.12 Classification of steels according to carbon content

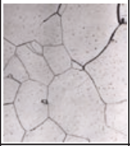
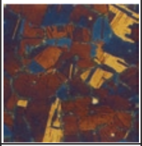
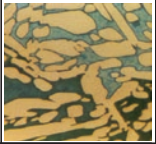
Steel Group	Steel	C-content in %	Microstructure after final heat treatment			
			ferritic	austenitic	martensitic	ferritic-austenitic
						
Case hardening and quenched and tempered steels	Case hardening steels Tempering steels Nitriding steels	0.10 – 0.25 0.20 – 0.65 0.13 – 0.45			x x x	
Tool steels	Cold work steels Hot work steels High speed steels	0.45 – 2.00 0.20 – 0.65 ≤ 1.5			x x x	
Stainless steels	Austenite Ferrite Martensite Duplex steels	≤ 0.1 ≤ 0.1 0.1 – 1.0 ≤ 0.03	x	x	x	x
Scale and heat resistant steels	Valve steels Heating conductor	0.3 – 2.2 ≤ 0.1	x	x x	x	

Fig. 2.13 Classification of steels according to carbon content and microstructure

Classification of steels according to microstructure

Steels are also distinguished by structure into:

- *Ferritic steels*
- *Austenitic steels*
- *Austenitic-ferritic (duplex) steels*
- *Martensitic steels*

Based on this, Fig. 2.13 shows the classification of steels according to carbon content and at the same time also according to the microstructure (source: Dressel, no date).

Classification and designation of steels according to application and properties

Finally, the designation of steels according to their properties and applications is also very common and well understood in practice, e.g.:

- *Normal-strength, high-strength and highest-strength engineering steels*
- *Cold-tough steels*
- *Wear-resistant steels, e.g. manganese hard steels*
- *Concrete steels*
- *Case hardening and quenched and tempered steels*
- *Spring steels*
- *Heat-resistant and high-heat-resistant steels*
- *Steels for low temperatures*
- *Corrosion- and acid-resistant, heat- and scale resistant steels*

- *Valve steels*
- *Steels with special electrical and magnetic properties*
- *Bearing steels*
- *Tool steels: cold work steels, hot work steels, high-speed steels*
- *Steels for screws and nuts*

2.4 Selected Steels and Special Materials

▶ After the explanations of some basics for understanding the material steel and for the classification or labeling of the steels, the most important steel groups are presented below. With the revision of DIN EN 10020, some terms for steels were abolished. However, some terms are still common in the steel world, such as the basic steels or mass steels (Riehle & Simmchen, 2000). Although these steels are now officially classified as quality steels, they should also be mentioned; as well as concrete steels with their interesting history.

2.4.1 Quality Steels

Basic steels

This group only includes a few very simple steels (Group 00 of the material numbers). With the exception of a low-stress annealing, soft or normal annealing, these are not intended or suitable for heat treatment (e.g. hardening). Basic steels do not contain any other alloying elements in addition to silicon and manganese.

Typical examples of basic steels are: 1.0035 – S. 185, 1.0037 – S. 235, 1.0044 – S275JR, 1.0060 – E335, 1.0070 – E360.

Basic steels do not have to meet any special quality requirements, with only certain cases requiring minimum values for a mechanical load, mainly a minimum tensile strength. Based on this, these steels are only used for subordinate applications, e.g. as rods and flat products, for railings, handrails, door and gate fittings (Fig. 2.14) and for forged ironwork.

Mass steels

This steel designation refers to a large quantity of unalloyed and also alloyed steels which, like basic steels, only have to meet low requirements in terms of their properties during use. They are thus clearly distinguished from the stainless steels, which have much higher purity grades.

Mass steel is an outdated term which also included basic steels and mainly referred to steels with moderate properties which were nevertheless sufficient for the intended use and had favourable prices.

Fig. 2.14 Example of an ornate iron fitting on a door of St. Peter's Church in Wolgast. (Photo: Schlegel, J.)

Engineering steels

The largest proportion of mass steels can also be referred to as engineering steel because these steels, as the name suggests, are used for construction purposes.

Engineering steel, unalloyed or low-alloyed, can also be used for machine parts. This engineering steel is then usually referred to as "general engineering steel".

Engineering steels are mainly used in machine and vehicle construction, in civil engineering, in bridge construction, in water and container construction. The engineering steels are mainly processed by welding and often also annealed. An impressive example of a welded steel bridge is the Peenebrücke in Wolgast, Fig. 2.15. This bascule bridge with its distinctive levers is 19 m wide and 42 m long. A total of 2289 t of engineering steel were used for the 256 m long, multi-part road and railway bridge.

According to the new EN standards, engineerung steels are carbon-poor steels are not used directly as tool steel. For the various applications, the tensile strength or the yield strength of the engineerung steels is a decisive criterion. In the past, according to the old DIN 17100 standard, they were referred to in Germany with **ST x**, where x was one tenth of the guideline value for the tensile strength in N/mm^2, or in kp/mm^2, as was common at the time. Today, EN 10025 applies to engineering steels. They are then given a **S** for "structural steel" as a sign. The following number refers to the yield strength in N/mm^2. This is followed by letters for the quality group and for further mechanical properties or applications.

Fig. 2.15 Peenebrücke in Wolgast. (Photo: Schlegel, J.)

K – cold-formed
A – annealed
N – normalized
V – tempered

In addition, the oxygen content of the steel can be made clear with:

FU – cast unkilled (lots of residual oxygen)
FN – simply cast killed (less residual oxygen)
FF – double cast killed, or fully cast killed (oxygen has been slagged)

Example:
S235JR (equivalent to material number 1.0038), hot-rolled engineering steel, suitable for welding, quality group JR. The quality group is defined by the important characteristic value of the notch impact toughness, which represents the resistance of the steel to sudden stress. JR denotes a steel of lower quality with 27 J notch impact toughness at 20 °C. This steel corresponds to St 37-2, i.e. an unalloyed engineering steel with a tensile strength in the range of 340 to 510 N/mm^2 (depending on the thickness of the steel bar or steel sheet). The short designation St 37-2 is still widespread today, but invalid and should no longer be used. Furthermore, today, due to technical progress a distinction between engineering steels and quality steels is no longer appropriate.

Concrete steel

For concrete construction, whether for railway sleepers, concrete pipes, buildings and halls or bridges, concrete steelis needed. This is used to reinforce (strengthen) the load-bearing concrete parts. An older, still valid name is “reinforcing steel”, or also “Monier iron” named after the inventor of this groundbreaking construction, the Frenchman *Joseph Monier* (1823–1906). As a gardener for the maintenance of stately parklands, he was always annoyed that the concrete plant pots for orange trees broke very often during transport. So he experimented with mixtures of cement, sand, slag, brick rubble and water with additional inlays of wire mesh and invented reinforced concrete. He later transferred the principle of the connection of cement and steel mesh to the construction of elaborate rock gardens, water tanks, pipes, smaller bridges and stairs. With the further development of this idea, the gentlemen *Gustav Adolf Wayss* (1851–1917) and *Conrad Freytag* (1846–1921) finally became pioneers of reinforced concrete construction in Germany.

In concrete steel, today we must distinguish between the “reinforcing steel” in concrete (also called “slack steel”) and the “tension steel” in prestressed concrete. In the latter, an additional external tension force (prestress) is applied by means of tensioned steel inserts (high-strength steel wires or bars).

In Germany, mainly concrete steel with the characteristic yield strength of approximately 500 N/mm^2 is used (properties, for example, specified in DIN 488 or in EN 10080). Figure 2.16 shows classic concrete steel in the form of reinforcement mats and bars.

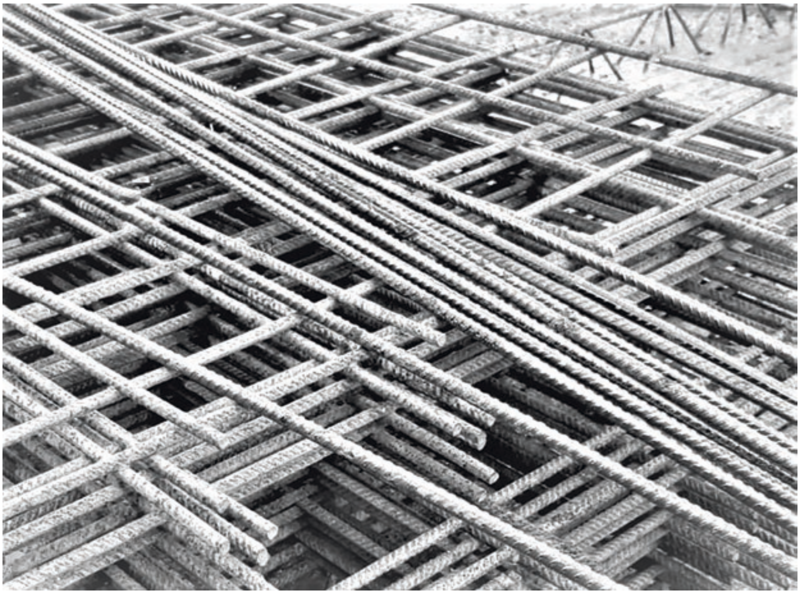


Fig. 2.16 Classic concrete steel, prepared as reinforcement steel for concreting a house ceiling. (Photo: Schlegel, Chr.)

Unalloyed quality steels

According to the latest definition, unalloyed quality steels refer to material numbers 1.00.. to 1.07.. and 1.90.. to 1.97... Unalloyed quality steels are steel grades for which certain requirements such as toughness, grain size and/or formability generally apply, and which are not comparable to unalloyed tool steels. They are also not suitable for targeted heat treatment (e.g. hardening).

Unalloyed quality steels usually have a lower, limited phosphorus and sulfur content (max. 0.045 mass- %) in comparison to the mass steel grades. The carbon content is 0.2 to 0.65 mass- % and is indicated as follows:

Designation: CX with X = carbon content in mass- %, multiplied by 100.

Example:

C60 – an unalloyed quality steel with 60/100 = 0.60 mass- % carbon (corresponding to 1.0601).

Unalloyed quality steels are widely used in apparatus engineering, shipbuilding and in machine and steel construction as construction materials, but also for the mass production of screws, nuts, rivets and all kinds of chains, for the production of sheets and strips, uncoated or coated e.g. for packaging sheets and sheets for household appliances. Figure 2.17 shows an example of the use of unalloyed quality steel, the classical screws and nuts, as you can find them in any hardware store.

In the special application of unalloyed quality steels as unalloyed electrical sheet (with the main symbol M), the requirements regarding magnetic properties such as magnetic losses, magnetic induction, polarization and permeability are also to be observed.

Fig. 2.17 Screws and nuts made of quality steel. (Photo: Schlegel, J.)

Alloyed quality steels

In comparison to unalloyed quality steels, defined higher requirements apply to alloyed quality steels, e.g. with regard to minimum elongation, notch impact toughness, grain size, weldability and formability. These quality steels are also not intended for heat treatment or surface hardening.

The required properties are achieved by adding certain elements, with boundary values not being exceeded in order to distinguish them from stainless steels. The alloyed quality steels include material numbers 1.08.. to 1.09.. as well as 1.98.. to 1.99...

Examples of alloyed quality steels:

Pressure vessel steel, mine support steel, steel for hot and cold rolled flat products, steel for pipes, stud bolts and rails. Figure 2.18 shows typical railway rails at a city railway station.

2.4.2 Stainless Steels

▶ High-quality steels have extraordinary properties and therefore a great potential for applications. In particular, the stainless steels have been in the spotlight for over 100 years. The following section provides an overview of the most important noble steels.

Fig. 2.18 Railway rails made of quality steel. (Photo: Schlegel, J.)

Corrosion occurs through chemical and electrochemical processes caused by reducing or oxidizing agents from the environment, such as seawater, acids, alkalis, salts, usually under the simultaneous action of mechanical influences. Corrosion resistance is the resistance of a material to such “attacks from the environment” during its use (Kaesche 1966).

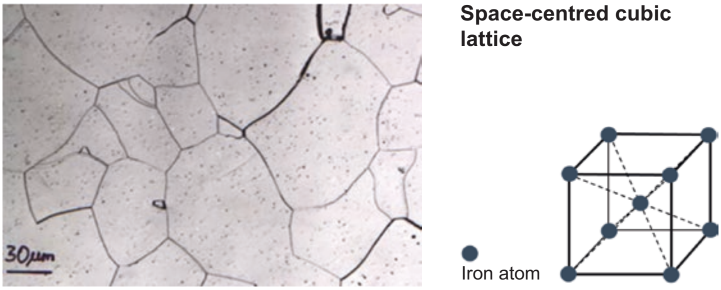
*“*Stainless Steel*”* is today the collective term for about 120 different, non-corrosive steel grades. The term *“*stainless*”* is actually not quite accurate for non-corrosive steels that have the property to be corrosion resistant. Any other steel can also be in the state of stainless under certain circumstances, that is, free of rust, as long as it is not rusted. What is important for the application is not the short-term state of stainless, but the property of not rusting or being corrosion-resistant under the use conditions of the environment.

A large consumer of steel used to be the military. At the end of 1900, an enormous arms race began between industrialized countries. Large defense contractors emerged and built countless cannons, tanks, battleships, airplanes, and other military equipment. The demand for steel grew tremendously. The better the steel, the better the armor or the weapon technology. For the first time, chromium-alloyed and later nickel-alloyed steels were used for ship armor plates. However, all known steels had one disadvantage: at some point they were eaten by rust. And of course, steel rusts particularly quickly in salt-containing sea air and directly in seawater. But even on land, in industrial areas, rust destroyed huge values over time.

It was not until 1912, with the V2A steel by *Eduard Maurer* (1886–1969), that the era of non-corrosive or corrosion-resistant steels began. The chemist and metallurgist *Maurer* and his department head, Professor *Benno Strauß* (1873–1944), examined chromium and nickel-alloyed steels at the Chemical-Physical Testing Institute of the Friedrich Krupp AG. Their *“Experimental Melt 2 Austenite”* (V2A) behaved incredibly after a certain heat treatment: this experimental steel was corrosive- and to a certain extent acid-resistant. With this steel now called V2A, a new era of steel metallurgy began. Such non-corrosive steels are alloyed with at least 10.5% by mass of chromium and form an invisible passive layer in the presence of oxygen without additional surface protection.

When the first stainless steel was developed, probably no one thought of the multitude of possible applications. These are mainly based on the fact that the stainless steels have a wide range of properties and these properties can still be specifically changed and adapted by certain alloying additions and production processes. So it is no wonder that stainless steels very quickly conquered all areas of technology and private life. In addition to high demands on corrosion resistance and mechanical properties, the stainless steels also meet special hygienic and aesthetic criteria. Therefore, their spread is still increasing today.

The stainless steels are all in the material number range 1.40. to 1.45. (Cobb, 2008). The four main groups of stainless steels are presented below, divided into the microstructural states ferritic, austenitic, martensitic and ferritic-austenitic.



Microstructure of a ferritic steel

Space-centred cubic lattice

Fig. 2.19 A typical microstructure of a ferritic steel with a space-centred cubic lattice structure. (Micrograph: BGH Edelstahl Freital GmbH)

Ferritic steels

These steels have a stable ferritic, cubic-centered structure, as shown in Fig. 2.19. This is also maintained at elevated temperatures up to the melting point. Based on this, they do not show any transformation of ferrite into austenite during heating. Also, no martensitic transformation is possible during cooling for hardness enhancement. Thus, the ferritic steels cannot be hardened by heat treatment.

Ferritic steels have only low strengths with high toughness (formability—ductility). This makes them easy to hot- and cold-form. Ferritic steels are ferromagnetic, only conditionally weldable and have a high resistance to chloride-induced stress corrosion. This corrosion phenomenon occurs when chloride ions from the environment act on non-rusting steels under the influence of tensile stresses. Such tensile stresses arise, for example, as internal stresses during generation, e.g. by cold forming or during processing, e.g. by grinding.

Ferritic steels have the following characteristic alloy compositions (in mass-%):

Carbon C: up to 0.10%
Chromium Cr: 11 to 30%
Manganese Mn: 1.0 to 1.5%
Molybdenum Mo: up to 4.5% (Mo-alloyed steels)
Nickle Ni: only in some alloys up to 1.5%

Two groups of ferritic steels are distinguished:

With approx. 11 to 13 mass-% chromium and with approx. 17 mass-% chromium (better corrosion resistance).

Common ferritic stainless steels include, for example:

1.4016 – X6Cr17, 1.4104 – X14CrMoS17, 1.4105 – X6CrMoS17, 1.4509 – X2CrTiNb18, 1.4510 – X3CrTi17, 1.4511 – X3CrNb17, 1.4512 – X2CrTi12, 1.4725 – X8CrAl14-4, 1.4742 – X10CrAlSi18, 1.4765 – X8CrAl25-5.

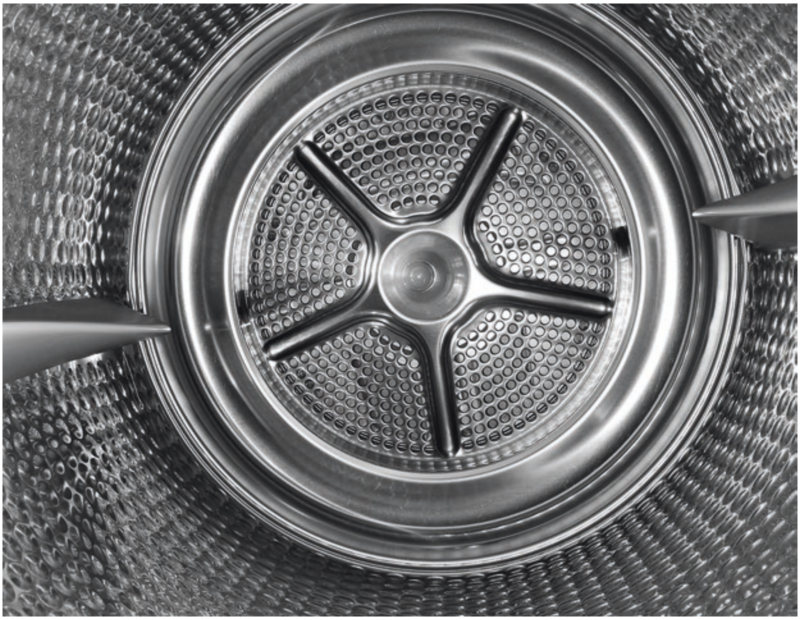


Fig. 2.20 Drum of a household washing machine made of ferritic steel. (Photo: Schlegel, J.)

Application
Ferritic steels are used, inter alia, for household appliances, in the food industry, for exhaust systems, for axles, bolts and fittings. Figure 2.20 shows a drum of a classical household washing machine made of ferritic steel with 16 mass-% chromium, the most commonly used type of ferritic steel (AISI 430, 1.4016 – X6Cr17).

Austenitic steels
Austenitic chromium-nickel steels have an austenitic, cubic-centered lattice structure. This is shown in Fig. 2.21 with a typical micrograph.

Since the austenitic microstructure is only stable above 911 °C in pure iron, chromium, nickel, manganese, molybdenum, cobalt and nitrogen must be added in order to expand the austenite range so that the cubic, close-packed structure remains stable well below room temperature and up to the melting temperature. Pure austenitic steels therefore do not undergo transformation and are not transformation hardenable. However, a hardness increase (cold hardening) is possible by cold working.

Austenitic steels are non-magnetic at room temperature, but can become magnetic depending on the chemical composition by cold working.

In order to achieve the required technological properties, a fine-grained microstructure is necessary. The final heat treatment is a solution annealing at 1000 to 1150 °C with subsequent cooling in water or air (see Sect. 6.2.5: *Solution annealing*).

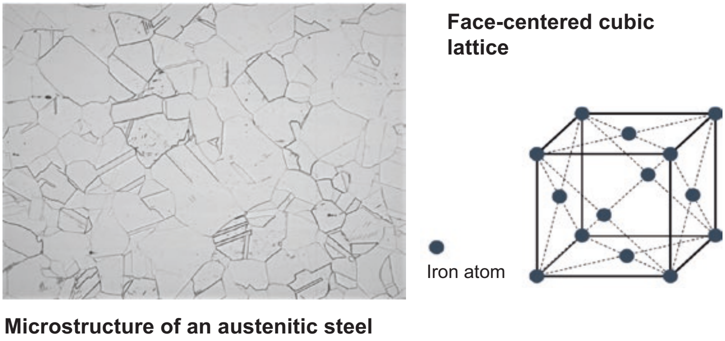


Fig. 2.21 A typical micrograph of an austenitic steel (1.4404 – X2CrNiMo17-12-2) with a face-centered cubic lattice structure. (Micrograph: BGH Edelstahl Freital GmbH)

Austenitic steels have a low yield strength, hardness and strength, but a very high toughness. Therefore, they are also well hot and cold formable. Furthermore, austenitic steels are easy to weld. They have a high thermal expansion coefficient and a low thermal conductivity.

The contents of alloying elements in austenitic steels are in the following ranges (given in mass-%):

Carbon C: up to 0.10%
Chromium Cr: 16 to 28%
Nickle Ni: 6 to 26%
Silicon Si: up to 1.0%
Molybdenum Mo: up to 4.0%
Manganese Mn: up to 2.0% (exception: manganese-alloyed steels up to 18% manganese)

Austenitic steels can be divided into:

Massenaustenite, e.g. 1.4301 – X5CrNi18-10, 1.4305 – X8CrNiS18-9, 1.4306 – X2CrNi19-11, 1.4307 – X2CrNi18-9, 1.4401 – X5CrNiMo17-12–2, 1.4404 – X2CrNiMo17-12–2
Sonderaustenite, e.g. 1.4435 – X2CrNiMo18-14–3, 1.4441 – X2CrNiMo18-15–2, 1.4529 – X1NiCrMoCuN25-20–7, 1.4539 – X1NiCrMoCu25-20–5
Heat-resistant austenite, e.g. 1.4828 – X15CrNiSi20-12, 1.4829 – X12CrNi22-12, 1.4830 – X35CrNiNb25-24, 1.4833 – X12CrNi23-13, 1.4835 – X9CrNiSiNCe21-11–2, 1.4841 – X15CrNiSi25-21, 1.4842 – X12CrNi25-20, 1.4845 – X8CrNi25-21 to 1.4850 – X15NiCrNb32-21, 1.4860 – X16NiCr30-20, 1.4864 – X12NiCrSi35-16, 1.4873 – X45CrNiW18-9, 1.4875 – X55CrMnNiN20-8 to 1.4878 – X8CrNiTi18-10, 1.4892 – X25CrMnNiN23-9–6

High-temperature austenitic steels, e.g. 1.4941 – X8CrNiTi18-10, 1.4948 – X7CrNi18-9 (X6CrNi18-10), 1.4949 – X3CrNiN18-11, 1.4958 – X5NiCrAlTi31-20 to 1.4962 – X12CrNiWTiB16-13, 1.4980 – X6NiCrTiMoVB25-15–2 (X5NiCrTi26-15), 1.4986 – X8CrNiMoBNb16-16 (X7CrNiMoBNb16-16), 1.4988 – X8CrNiMoVNb16-13

Application
Austenitic steels are preferably used as **r**ust-, **s**eawater- and **h**eat-resistant steels (RSH steels) in the chemical industry, in tunnel construction, for highly stressed parts in the automotive industry, in plant engineering, also in medical technology, in the household and sports industry and in many other areas. Figure 2.22 shows, for example, precision turned parts for special applications in the automotive industry. They are very small parts for valves for regulating gaseous fuels, manufactured from the austenitic steels 1.4305 – X8CrNiS18-9 and 1.4435 – X2CrNiMo18-14-3.

Martensitic steels
Martensitic steels are created through a transformation hardening: When heated steel is quenched abruptly, for example by dipping it into a water bath, there is usually not enough time for an orderly exchange of position of the carbon atoms. The cube center is now disputed by both an iron atom and a carbon atom. This can be seen as a "forced state of the lattice": A ferrite with too much carbon in a highly disturbed lattice structure leads to high hardness, but unfortunately also to a brittle state. *Adolf Martens* (1850–1914) was the first to discover such structures in steel, which are now referred to as "martensitic". Figure 2.23 shows, using a micrograph, such a martensitic microstructure of steel 1.4006 – X12Cr13.

Fig. 2.22 Precision turned parts made of austenitic steels. (Photo: Mesa Parts GmbH, Lenzkirch)

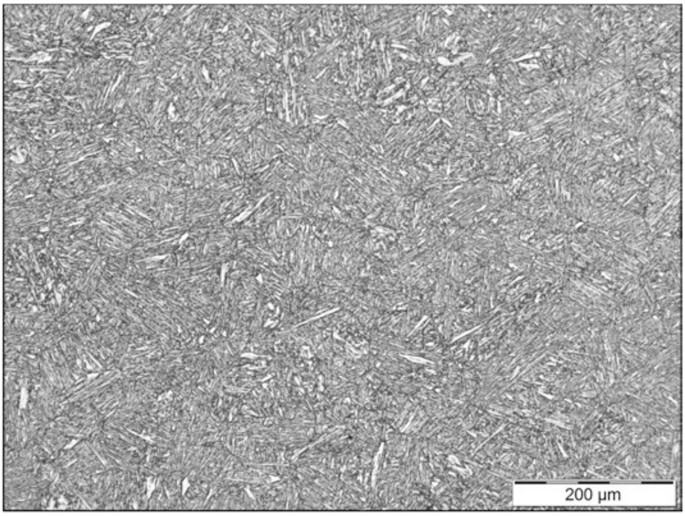


Fig. 2.23 Typical martensitic microstructure, steel 1.4006 – X12Cr13. (Micrograph: BGH Edelstahl Freital GmbH)

Martensitic steels are always used in a heat-treated and tempered state, i.e. hardened and after a second annealing process (650 to 750 °C). This gives them high hardness and wear resistance with a sufficiently good toughness. These properties of martensitic steels are determined by the carbon content and the tempering strength achieved during heat treatment. In general: *The higher the hardness (strength), the lower the toughness.*

The criterion for the assignment of stainless steels to martensites is the given hardenability via the martensite formation. It is therefore also possible to obtain an "annealed without martensitic structure" for martensite. Martensitic steels usually have the following chemical composition (mass-%):

Carbon C: 0.1 to 1.0%
Chromium Cr: 11.0 to 18.0%
Manganese Mn: up to 1.5%
Silicon Si: up to 1.0%
Molybdenum Mo: up to 3.0%
Nickel Ni: up to 2.0%

Typical martensitic stainless steels include:
1.4005 – X12CrS13, 1.4031 – X39Cr13, 1.4037 – X65Cr13, 1.4104 – X14CrMoS17, 1.4112 – X90CrMoV18, 1.4125 – X105CrMo17.

Common martensitic, stainless and heat-resistant steels are:
1.4006 – X12Cr13, 1.4021 – X20Cr13, 1.4024 – X15Cr13, 1.4034 – X46Cr13, 1.4057 – X17CrNi16-2, 1.4116 – X50CrMoV15, 1.4117 – X38CrMoV15, 1.4120 – X20CrMo13, 1.4122 – X39CrMo17-1, 1.4313 – X3CrNiMo13-4, 1.4418 – X4CrNiMo16-5-1, 1.4542 – X5CrNiCuNb16-4, 1.4594 – X5CrNiMoCuNb14-5, 1.4718 – X45CrSi9-3, 1.4731 – X40CrSiMo10-2, 1.4748 – X85CrMoV18-2.

Heat-resistant martensitic steels are, for example:
1.4903 – X10CrMoVNb9-1, 1.4913 – X19CrMoNbVN11-1, 1.4920 – X15CrMo12-1, 1.4921 – X19CrMo12-1, 1.4922 – X20CrMoV12-1 (X20CrMoV11-1), 1.4923 – X21CrMoNiV12-1, 1.4926 – X21CrMoV12-1 to 1.4937 – X23CrMoWV12-1, 1.4939 – X12CrNiMoN12.

Application
Martensitic, stainless and heat-resistant steels are used as shafts, drives, screws, nuts, spindles, knives, surgical instruments, valves in turbines and internal combustion engines, in fittings, in the oil industry, weapons technology, in plant and machinery construction, in vehicle construction, for example for injection systems in internal combustion engines, for sensors, in construction and in many other areas. Figure 2.24 shows, for example, a circulating pump as it is usually installed in the heating and water circuit of a single-family house. Its shaft is made of the martensitic steel 1.4125 – X105CrMo17.

Duplex steels (austenitic-ferritic steels)
Duplex steels have a two-phase microstructure of ferrite and austenite, as can be seen in Fig. 2.25. This allows the properties of non-corrosive chromium steels with ferritic or martensitic microstructure to be combined with those of chromium-nickel steels with austenitic microstructure. The ferrite content in the microstructure gives better resistance to stress corrosion cracking in comparison to purely austenitic steels. Duplex steels are well formable and less weldable than austenites and ferrites.

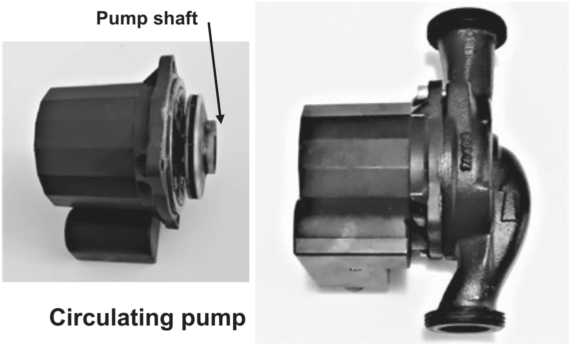


Fig. 2.24 Circulating pump with shaft made of a martensitic steel. (Photo: Schlegel, J.)

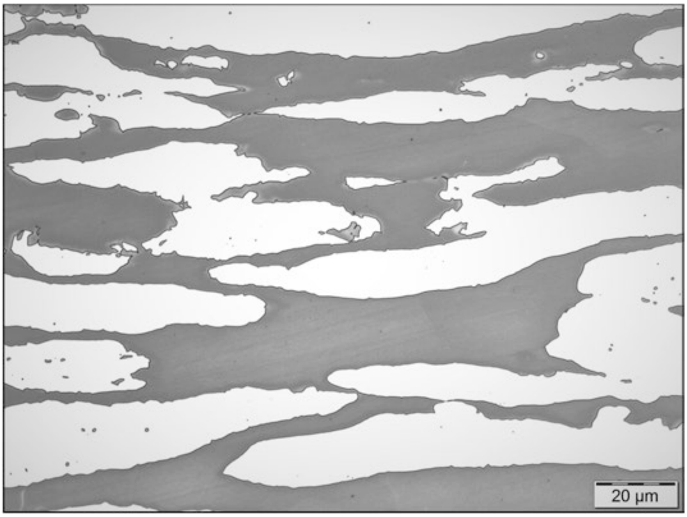


Fig. 2.25 Typical two-phase microstructure, *light:* austenite, *dark:* ferrite, superduplex 1.4501 – X2CrNiMoCuWN25-7–4. (Micrograph: BGH Edelstahl Freital GmbH)

Duplex steels have the following *alloy composition (in mass-%)*:

Carbon C: up to 0.03%
Chromium Cr: 21.0 to 26.0%
Nickel Ni: 3.5 to 8.0%
Manganese Mn: up to 2.0%
Silicon Si: up to 1.0%
Molybdenum Mo: up to 4.0%
Nitrogen N: up to 0.3%

Typical duplex steels are, for example:
1.4410 – X2CrNiMoN25-7–4, 1.4460 – X3CrNiMoN27-5–2, 1.4462 – X2CrNiMoN22-5–3, 1.4501 – X1CrNiMoCuWN25-7–4, 1.4507 – X2CrNiMoCuN25-6–3, 1.4820 – X12CrNi26-5, 1.4821 – X15CrNiSi25-4.

Application
Austenitic-ferritic steels are constantly gaining importance, as shown by the industrial application of steel 1.4462 - X2CrNiMoN22-5-3 in particular. Duplex steels are used above all where very high corrosion loads are present, e.g. in seawater. Examples are components, fasteners, shafts, etc. in the chemical and offshore industries. Fig. 2.26 shows a typical oil platform for this purpose.

Fig. 2.26 Offshore oil platform. (Photo from the Internet)

More recently, so-called *"Superduplex steels"* with further improved corrosion resistance have been developed, which contain approximately 25 mass-% chromium, 7 mass-% nickel, 3.5 mass-% molybdenum, nitrogen, etc. elements.

2.4.3 Tool Steels (Cold Work, Hot Work, High-Speed Steels)

▶ Long before the relationships between the structure of iron alloys and their properties were known, engineers, chemists, and metallurgists painstakingly developed or tested steels with special properties in order to again utilise them as tools for working on steels. Tools are subjected to very different loads during the numerous machining processes. At the point of contact with the workpiece to be machined, extremely high friction forces occur. Therefore, a high wear resistance is expected from each tool. Tool steels are therefore always hardenable steels.

DIN EN 10027-2 divides materials main group 1 according to steel group numbers into:

- unalloyed tool steels: 1.15.. – 1.18..
- alloyed tool steels: 1.20.. – 1.28..
- high-speed steels: 1.32.. – 1.33..

Figure 2.27 shows the classification of tool steels with reference to their possible applications.

Typical areas of application are tools for:

- *Shaping, cutting and shredding* of various materials (knives, scissors, sickles, saws, stamping tools)
- *Metal machining* (turning steels, drills, countersinks, end mills, files)
- *Cold forming* (drawing tools, dies, cold rolling, corrugating rolls, thread rolling tools, coining and stamping tools)
- *Hot forming* (forging dies, press tools, rolls, die casting and centrifugal casting dies, ingots)
- *Woodworking (chisels, drills, end mills, saws, etc.)*
- *Plastic injection molding (dies, moldings)*

The following three types of tool steels are distinguished according to the achievable hardness and the course of hardness as a function of the annealing temperature:

- *Cold work steels*
- *Hot work steels*
- *High-speed steels*

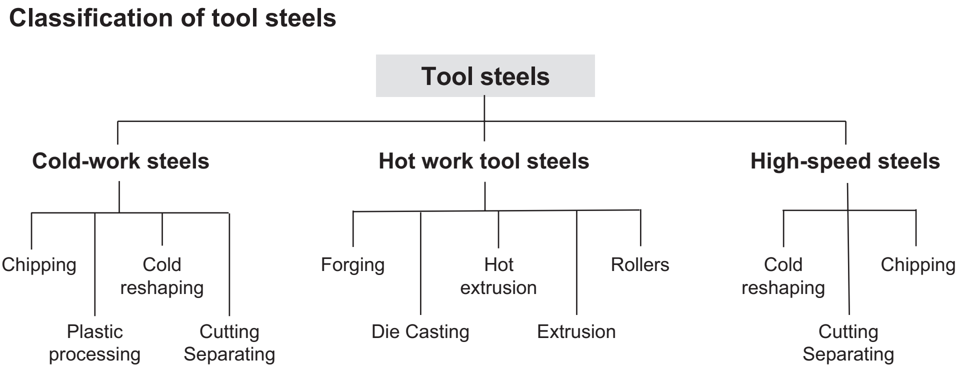


Fig. 2.27 Overview of the classification of tool steels

These three types of tool steels are introduced below.

Cold work steels

Cold work steels are used for machining other materials at room temperature. Here, temperatures do not exceed 200 °C.

The requirements for cold work steels are

- *high wear resistance,*
- *sufficient hardness and toughness,*
- *good compressive strength and sufficient ductility,*
- *easy machinability,*
- *very good dimensional stability during heat treatment.*

The high hardness and the required wear resistance of the cold work steels are based on the martensitic structure generated by a final hardening and tempering at low temperatures, partly also with embedded carbides.

Typical chemical composition

Cold work steels have a high chromium content and usually contain 0.45 to 2.0 mass-% carbon. These steels are delivered in the soft annealed or also in the normal annealed state, machined and then heat treated (hardened and tempered) to achieve the required wear properties. The following subgroups of cold work steels are distinguished:

- *unalloyed cold work steels (0.6 to 1.5 mass-% carbon) and*
- *low and high alloyed cold work steels (1 to 2 mass-% carbon, up to 12 mass-% chromium, tungsten, molybdenum, vanadium).*

Typical cold work steels are, for example:
1.2080 – X21Cr13, 1.2083 – X40Cr14, 1.2208 – 31CrV2, 1.2210 – 115CrV3, 1.2327 – 86CrMoV7, 1.2363 – X100CrMoV5, 1.2379 – X153CrMov12, 1.2419 – 105WCr6, 1.2436 – X210CrW12, 1.2510 – 100MnCrW4, 1.2550 – 60WCrV8, 1.2631 – X50CrMoW9-1-1, 1.2764 – X19NiCrMo4, 1.2767 – 45NiCrMo16, 1.2826 – 60MnSiCr4, 1.2842 – 90MnCrV8.

Application

Unalloyed cold work steels are used, for example, to produce scissors, knife blades, hand hammers, pruning shears, chisels, axes, wood saws, and other tools. Low-alloyed cold work steels are used, for example, for jigs, punches, and woodworking tools, while highly alloyed cold work steels are used for highly stressed machine knives. Figure 2.28 shows, for example, an industrial knife for a power shear for steel sheet up to 4 mm thick.

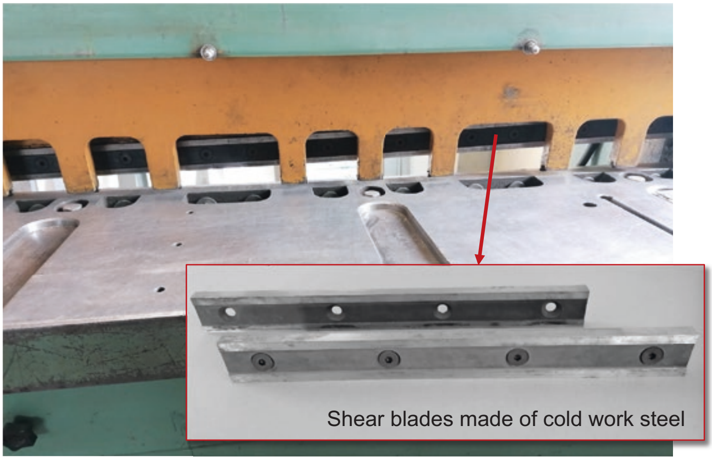


Fig. 2.28 Industrial knife made of cold work steel for a power shear. (Photos: Schlegel, J.)

Hot work steels

Hot work steels are alloyed tool steels that can withstand surface temperatures of up to 600 °C during use. In addition, there are demands on wear and sudden load resistance. Therefore, hot work steels must meet the following requirements:

- *high hot working resistance,*
- *high heat resistance and high heat wear resistance,*
- *high heat toughness and high temperature change resistance with simultaneous good weldability or repair weldability.*

Typical chemical composition

Carbon content of hot-work steels is between 0.2 and 0.65 mass-%. The alloying elements chromium, molybdenum and vanadium (up to 5 mass-%) as well as tungsten, silicon, nickel, manganese and cobalt are adjusted so that a variety of hot-work steels, adapted to the respective application, are available.

Subgroups of hot-work steels

The groups of hot-work steels are based on the element combinations tungsten-chromium-vanadium, chromium-molybdenum-vanadium or nickel-chromium-molybdenum. Some austenitic special steels and nickel-based alloys or nickel-chromium-molybdenum should also be mentioned.

Typical hot-work steels are, for example:
1.2343 – X37CrMoV5-1, 1.2344 – X40CrMoV5-1, 1.2365 – 32CrMoV12-28, 1.2367 – X38CrMoV5-3, 1.2714 – 55NiCrMoV7, 1.2782 – X16CrNiSi25-20, 1.2787 – X23CrNi17.

Fig. 2.29 Ejector pins (standard parts) made of hot work steel, used for plastic injection molds. (Photo: Eberhard – Präzisionsteile, Nordheim)

Application
Hot work steels are mainly used for hot forming (e.g. for forging and pressing dies, extrusion dies, hot shear blades, pilger mandrels), for glass mold making and for ejector pins in injection and die casting molds, as they are depicted in Fig. 2.29. These ejector pins are made of hot work steel 1.2343 – X37CrMoV5-1.

High-speed steels

▶ The experiments of *Frederick Winslow Taylor* (1856–1915) lasted over two decades before he was able to present his new steel to the expert world. In 1900, at the world's fair in Paris, the number of visitors in the machine tool department was particularly large when demonstrations with the new turning steel by Taylor took place. This "miracle turning steel" also worked red-hot. The cutting speeds could be increased fourfold, hence the names "fast turning steel", "fast-cutting steel" and abbreviated "HSS – **h**igh **s**peed **s**teel". The triumph of this high-speed steel was initially accompanied by setbacks. The very high cutting speeds were simply not yet up to the task for the machine tools of that time. A new generation of lathes, much heavier built and with more wear-resistant bearings and holders, was necessary. Mass production and rationalization of work processes, but also accuracy of machine tools, shaped the technical progress from then on. Even the high-speed steel, which so revolutionized toolmaking, was constantly further developed and adapted to the different applications, e.g. for high-performance cutting tools for turning, drilling, milling, sinking, reaming, grinding or sawing.

The high-speed steel is conventionally produced by metallurgically or powder metallurgically (PM steel – see Sect. 5.2.10.1: *Powder metallurgy*). The efficacy of the high-speed steel as a machining tool is based on the carbides embedded in the structure,

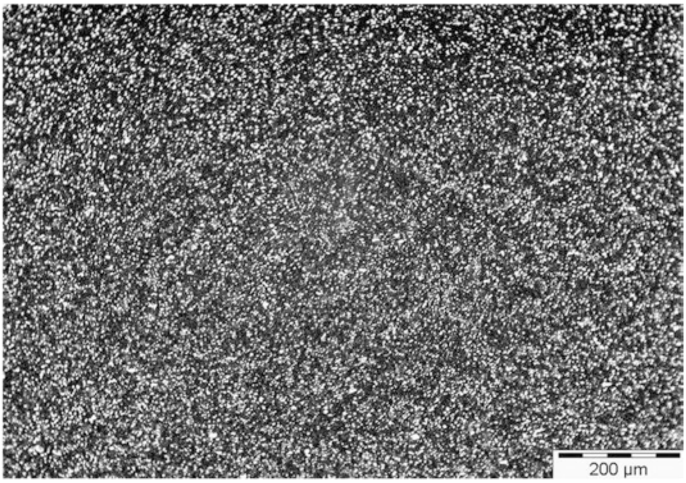


Fig. 2.30 Microstructure of a high-speed steel 1.3343 – HS6-5-2 C, produced by melting metallurgy. (Micrograph: BGH Edelstahl Freital GmbH)

formed by the alloy content of tungsten, molybdenum and vanadium at an adjusted high carbon content. Figure 2.30 The following figure shows a micrograph of a rolled wire made of high-speed steel 1.3343 – HS 6-5-2 C. The many, very small, light-colored carbides are clearly visible.

Properties of high-speed steels

The characteristic or most notable feature of high-speed steel is its exceptionally high resistance to wear. A hardened carbon steel becomes soft at about 250 °C. It loses its hardness and thus its cutting edge. In contrast, high-speed steel retains its full cutting power after an optimal heat treatment up to almost 650 °C. And because of the increased toughness, high-speed steels outperform the competition materials tungsten and oxide ceramics in many applications, despite them having slightly better cutting performance.

Typical chemical composition of high-speed steels

High-speed steels have carbon contents of at least 0.8 to 0.9 mass-%, in order to meet the requirement of a minimum hardness of 65 HRC (Rockwell hardness) via formation of carbides. The chromium content of 4 to 5 mass-% leads to a sufficient hardening. Higher or highest hot hardness is achieved by alloying with cobalt. oday’s common types of high-speed steels can be divided into four groups with different contents of tungsten and molybdenum (given in mass-%):

Group I: 18.0% tungsten and almost no molybdenum (e.g. HS 18-0-1 – 1.3355)
Group II: 12% tungsten and up to 4% molybdenum (e.g. HS 10-4-3-10 – 1.3207)

Group III: 6% tungsten and 5% molybdenum (HS 6-5-2 C – 1.3343)
Group IV: maximum 2% tungsten and 9% molybdenum (HS 2-9-1-8 – 1.3247)

Application
Depending on the wear resistance, different alloys are used today:

1.3207 – HS 10-4-3-10: Turning tools, milling cutters, cold rolls
1.3243 – HS 6-5-2-5: Thread cutters, milling cutters, spiral drills
1.3245 – S. 6-5-2-5 S: Milling cutters, thread and spiral drills
1.3247 – HS 2-9-1-8: Shaft milling cutters
1.3255 – S. 18-1-2-5: Turning tools, milling cutters
1.3341 – S. 6-5-2 S: Tools in general
1.3342 – SC 6-5-2: Tools in general
1.3343 – HS 6-5-2 C: Spiral drill, metal circular saws, saw blades
1.3344 – HS 6-5-3: Countersinks, reamers, taps
1.3355 – HS 18-0-1: Spiral drills
1.3390 – S. 6-3-2: for low loads (DIY tools)
1.3392 – S. 1-5-2: e.g. for drills

Fig. 2.31 shows, for example, some high-performance spiral drills made of 1.3343 – HS 6-5-2 C.

Fig. 2.31 High-performance spiral drills made of high-speed steel, left-hand drill with golden titanium nitride coating for wear protection. (Photo: Schlegel, J.)

2.4.4 High-quality Engineering Steels (Hardening, Case Hardening and Nitriding Steels)

> ▶ Steel fascinates us again and again, being both ancient and modern. With only a small addition of alloying elements to the base element iron, and with sophisticated metallurgical production and processing technology, steels can be specifically produced with properties that meet the highest requirements for a variety of applications. Thus, special high-quality steels are used everywhere where machines and their components have to withstand enormous static and dynamic loads. The names of these high-quality steels already say it: They are treated or treatable in a special way.

Quenched and tempered steels

The quenching and tempering of steels comprises the combination of the heat treatment step of hardening and the subsequent annealing. By means of these heat treatments, the steel is provided with a high strength while maintaining good toughness (see also Chap. 6: *Heat Treatment of Steel*).

Typical chemical composition

The hardening and tempering steels, standardized in DIN EN 10083, differ from the engineering steel by the chemical composition. They are mainly alloyed with manganese, chromium, molybdenum and nickel. The carbon, manganese and silicon contents are more closely toleranced. The carbon content is between 0.2 and 0.7 mass-%. This makes these steels heat treatable , that is, they can be hardened and annealed.

Subgroups

We can fundamentally distinguish between Manganese, chromium, chromium-molybdenum and chromium-nickel-molybdenum steels.

Typical quenching steels are, for example:

1.0503 – C45, 1.5131 – 50MnSi4, 1.6511 – 36CrNiMo4, 1.6580 – 30CrNiMo8, 1.6582 – 34CrNiMo6, 1.7035 – 41Cr4, 1.7218 – 25CrMo4, 1.7220 – 34CrMo4, 1.7225 – 42CrMo4, 1.7227 – 42CrMoS4, 1.7228 – 50CrMo4, 1.7361 – 32CrMo12, 1.7707 – 30CrMoV9, 1.8159 – 51CrV4, 1.8161 – 58CrV4, 1.8519 – 31CrMoV9.

Application

Quenched and tempered steels are used for highly stressed machine engineering and vehicle or engine parts, e.g. for axles, shafts, bolts, tie rods, screws, connecting rods, crankshafts, also as parts for diesel and gasoline engine injection systems and many others. Figure 2.32 shows finished tie rods made of the compensation steel 1.7725 – 42CrMo4. They are installed in automobile presses.

Fig. 2.32 Tie rods for automobile presses. (Photo: Schlegel, J., BGH Edelstahl Siegen GmbH)

Case hardening steels

“Inserting the steels” is a method to enrich steels with a low carbon content of 0.10 to 0.25 mass-% hardly or not at all hardenable, at the surface with carbon to about 1.2 mass-%. The main process is gas carburizing. For example, the already machined components or workpieces are packed together with carburizing agents, the so-called cementing agents such as leather coal, bone coal or barium carbonate, in suitable boxes (inserts) and heated to temperatures between 880 and 980 °C. Carbon is released from the cementing agents. It penetrates into the surface of the components (diffusion), but only where the surfaces are freely accessible. If carbon is not to penetrate into certain areas, these surface areas are covered (e.g. by means of hardening pastes). The higher the temperature and the dwell time, the thicker the carburized edge layer becomes. Typical case hardening depths are 0.1 to max. 2.5 mm. In a micrograph as in Fig. 2.33 the bright carburized edge layer can be clearly seen after hardening.

Basically, today a distinction is made between *powder, salt bath and gas carburizing*. After completion of such a process, the parts consist of the core with tough consistency and of the carburized edge zones with approx. 1 mass-% carbon. After the process (carburizing), the parts are hardened. The core remains tough, and on the carburized surface the so-called “surface hardness” is created. After hardening, the part is allowed to cool down to approx. 200 °C in order to reduce internal stresses and to achieve the required service life. Process hardening can therefore be understood as a process which includes an edge zone carburizing as well as a hardening and annealing of a workpiece.

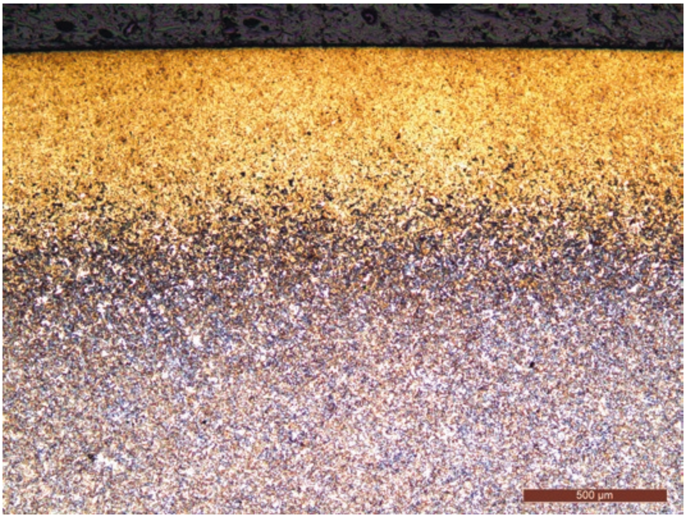


Fig. 2.33 Example of a carbonized edge layer on a cam from a motorcycle camshaft made of the steel 1.7131 – 16MnCr5 in use. (Micrograph: Zilly, A., DHBW Stuttgart)

Properties of case hardeningsteels

Process steels are used to produce parts which require a hard, wear-resistant edge zone. However, the core should remain soft and tough in order to be insensitive to impact and bending stress. The process conditions (carburizing agent, temperature, time) must be adapted to the steel grade and the requirements of the workpiece (size, geometry).

Typical chemical composition

Actioncase hardening steels, standardized in DIN EN 10084, are stainless steels with different alloy content of chromium, manganese, molybdenum and nickel. They have a relatively low carbon content of 0.1 to less than 0.3 mass-%.

Subgroups

Case hardening steels are divided into unalloyed and alloyed steels (chromium and chromium-manganese, chromium-nickel and chromium-nickel-molybdenum case hardening steels).

Typical case hardening steels are, inter alia:

1.0301 – C10, 1.0401 – C15, 1.5752 – 15NiCr13, 1.5919 – 15CrNi6, 1.5920 – 18CrNi8, 1.6523 – 20NiCrMo2-2, 1.6587 – 18CrNiMo7-6, 1.7014 – 17CrS3, 1.7016 – 17Cr3, 1.7131 – 16MnCr5, 1.7139 – 16MnCrS5, 1.7147 – 20MnCr5, 1.7149 – 20MnCrS5.

Fig. 2.34 Typical wind turbines. (Photo: Schlegel, Chr.)

Application
Chromium and chromium-manganese case hardening steels are used for piston rods, barrels, drill spindles, gears, transmission and control parts.

Chrom-nickel steels have a particularly high core toughness and are therefore used for parts of the automotive and aerospace industries and for large gears. Figure 2.34 shows an example of the use of steel 1.6587 – 18CrNiMo7-6 in the form of wind turbines. The gears for their transmission are made of this steel.

Nitriding steels

The nitriding of steels is a special process for surface hardening of steel. That means an enrichment of nitrogen (“sticking”) at the surface of the component, comparable to the case hardening of steels.

In the *nitriding treatment,* for example in nitrogen-containing gases (gas- or plasma nitriding) or in salt baths, nitrogen penetrates into the surface of the component by diffusion. This forms extremely hard and wear-resistant, nitride-containing layers that can be 0.2 to 0.5 mm thick depending on the treatment. In addition, the core area of the component to be treated remains sufficiently tough. The process takes place at temperatures of 500 to 590 °C, with treatment times of 1 to 100 h being possible. The advantage of nitriding is that no metallurgical changes occur during this treatment of the steel. A lower distortion of the component is the result. If carbon is introduced into the surface in addition to nitrogen, the process is called nitrocarburizing.

Properties
If machine components are exposed to the highest sliding wear and also to temperature loads of up to approximately 500 °C, then nitriding steels are in demand. These steels can have surface hardnesses of up to 1200 HV (Vickers hardness). At the same time, a nitriding layer makes the steel corrosion-resistant.

Typical chemical composition
Nitriding steels are alloyed like quenched and tempered steels and additionally deliberately doped with so-called "nitriding promoters" such as aluminium and chromium, partly also with molybdenum, vanadium, titanium and nickel. The carbon content is usually between 0.2 and 0.65 mass-%.

Subgroups
As with quenched and tempered steels, manganese, chromium, chromium-molybdenum and chromium-nickel-molybdenum steels are distinguished.

Typical nitriding steels are, for example:
1.8507 – 34CrAlMo5-10, 1.8509 – 41CrAlMo7-10, 1.8515 – 31CrMo12, 1.8519 – 31CrMoV9, 1.8550 – 34CrAlNi7-10.

Application
Nitriding steels are used, for example, as valve stems, shafts, piston rods, fittings and crankshafts in engine and machine construction, in hydraulics and pneumatics, in particular for construction machinery (mini excavators, wheel loaders, vibratory rollers), mobile cranes, industrial stackers, for harvesting and mowing machines, tractors, sweepers, snow groomers, etc. Here, above all, a high degree of durability is required, which is positively influenced by the nitriding treatment. Figure 2.35 shows a typical snow groomer, which is equipped with a hydraulic drive system. This drive is operated by an axial piston pump, the main drive shaft of which consists of the nitriding steel 1.8519 – 31CrMoV 9.

2.4.5 Nickel Alloys and Special Materials

▶ Nickel and special materials are very special alloys with extraordinary properties. They cannot be assigned to the generally known material groups, since they partly leave the field of steel and iron materials and superalloys and enter the field of non-ferrous metals.

The following groups of nickel and special materials are introduced according to their applications:

- corrosion-resistant materials,
- heat-resistant and high-temperature resistant materials,
- heating conductor materials,

Fig. 2.35 Snow groomer in action

- melting and expansion alloys.

  All of these materials, with the exception of chromium-aluminum alloys, contain the alloying element nickel (nickel-iron and nickel-chromium alloys) and represent so-called nickel-based alloys.

Corrosion-resistant materials

Properties

In addition to very good corrosion and scaling resistance, corrosion-resistant nickel and special materials also have other properties such as weldability, wear resistance, chemical resistance and temperature change resistance.

Typical chemical composition

The chromium content is set to more than 12 mass-% in order to secure the corrosion resistance. The carbon content is usually <0.10 mass-% and the nickel content >32 mass-%. Other possible alloying elements are: tungsten, titanium, copper, niobium, molybdenum.

Typical corrosion-resistant nickel and special materials are, for example:

2.4060 – Ni 99.6, 2.4068 – LC-Ni 99 (Alloy 201), 2.4360 – NiCu30Fe (Alloy 400), 2.4375 – NiCu30Al (Alloy K-500), 2.4602 – NiCr21Mo14W (Alloy 22), 2.4606 – NiCr21Mo16W (Alloy 686), 2.4610 – NiMo16Cr16Ti (Alloy C-4), 2.4660 – NiCr-

20CuMo (Alloy 20), 2.4668 – NiCr19NbMo (Alloy 718), 2.4806 – SG NiCr20Mn3Nb, 2.4816 – NiCr15Fe (Alloy 600), 2.4819 – NiMo16Cr15W (Alloy C-276), 2.4831 – NiCr22Mo9Nb (Alloy 625), 2.4856 – NiCr22Mo9Nb (Alloy 625), 2.4858 – NiCr21Mo (Alloy 825), 2.4887 – X2CrNiMnMoNbN25-18-5-4 (Alloy 24).

Application

Corrosion-resistant nickel and special materials are used in chemical plant construction, marine and offshore plant construction (e.g. 2.4856 as welding wire), nuclear plant construction, the food industry, salt production, for heat exchangers, in oil processing and energy production (e.g. gas turbines). Figure 2.36 shows an example of the special material 2.4668 – NiCr19NbMo, a corrosion-resistant, hardenable nickel-chromium-iron-molybdenum alloy as high-strength connecting elements for nuclear plant construction.

Heat-resistant and high-temperature resistant materials

First, a note on the terms used in practice to characterize the temperature resistance according to temperature ranges:

heat-resistant: 300 to 550 °C,
high-temperature resistant: 550 to 850 °C,
heat-resistant: up to about 1100 °C.

Fig. 2.36 High-strength connecting elements for nuclear plant construction. (Photo: BGH Edelstahlwerke GmbH)

Properties
Heat-resistant and high-temperature resistant nickel and special steels have good mechanical properties even under higher temperatures over a long period of time. At the same time, they are resistant to aggressive media.

Typical chemical composition
Heat-resistant materials have a high alloy content of chromium, nickel and silicon in order to form a dense, adherent chromium oxide layer on the surface of the component under oxidizing conditions. This oxide layer protects the underlying material from further oxidation. By adding nickel, an increase in heat resistance is achieved.

Typical heat-resistant materials include:
Nickel-chromium alloys: 2.4663 – NiCr23Co12Mo (Alloy 617), 2.4816 – NiCr15Fe (Alloy 600), 2.4851 – NiCr23Fe (Alloy 601), 2.4856 – NiCr22Mo9Nb (Alloy 625), 2.4858 – NiCr21Mo (Alloy 825), 1.4876 – NiCr15Fe (Alloy 800).

Typical high-temperature resistant materials include
2.4668 – NiCr19NbMo (Alloy 718), 2.4669 – NiCr15Fe7TiAl (Alloy X-750), 2.4952 – NiCr20TiAl (Alloy 80 A), 1.4980 – X6NiCrMoVB25-15-2 (Alloy A-286).

Application
Heat-resistant and high-temperature resistant nickel and special materials are used where high temperature loads occur: in industrial furnace construction, in ore preparation plants, roasting furnaces, furnace plants of the cement and oil industry as well as in petrochemical plants, in incineration plants, in power plant construction, turbine construction, for outlet valves in combustion engines, as wire mesh and wire fabric for filters and exhaust systems. Figure 2.37 shows an example of this for the use of a heat-resistant special material in the form of wire fabric, used as a filter in environmental technology.

Heating conductor materials
Heating conductors have such a high specific electrical resistance that in the event of a current flow, an energy conversion from electrical energy to heat energy is effectively possible. In addition, heating conductor materials are used at high temperatures and are also resistant to oxidation. The service life depends decisively on the closely toleranced alloy contents, the purity and a very small grain size.

Typical chemical composition
The addition of suitable alloying elements influences the specific electrical resistance of heating conductor materials or deliberately sets it very high. There are two types: ferritic chromium-aluminum alloys with up to 30 mass-% chromium and austenitic nickel-chro-

Fig. 2.37 Wire fabric made of enemy wire for filters. (Photo: DGS Wire Fabrics GmbH, Ellingen)

mium alloys, where the content of the alloying elements can be graduated up to complete iron-free.

The protection of the surface against oxidation is achieved in chromium-aluminum alloys by the aluminum oxide and in nickel-chromium alloys by the chromium oxide.

Typical heating conductors are, for example:
Chromium-aluminium alloys: 1.4725 – CrAl 14 4, 1.4765 – CrAl 25 5, 1.4767 – CrAl 20 5.
Nickel-chromium alloys: 1.4860 – NiCr 30 20, 2.4867 – NiCr 60 15, 2.4869 – NiCr 80 20.

Application
Heating conductor materials are used to generate heat energy, i.e. for heating in industry (e.g. for heating cartridges, heating coils in furnaces), in the leisure/sport sector (e.g. heated seats in cars) and in the household (e.g. for a hair dryer). In ceramic hobs, heating coils made of a chromium-aluminium heating conductor material are also built in, as can be seen clearly in Fig. 2.38.

Melting and expansion alloys
Melting and expansion alloys are materials that have a controlled thermal expansion with linear expansion coefficients of close to zero to approximately 12×10^{-6}/K within a certain temperature range. This ensures a stable and also vacuum-tight glass-metal

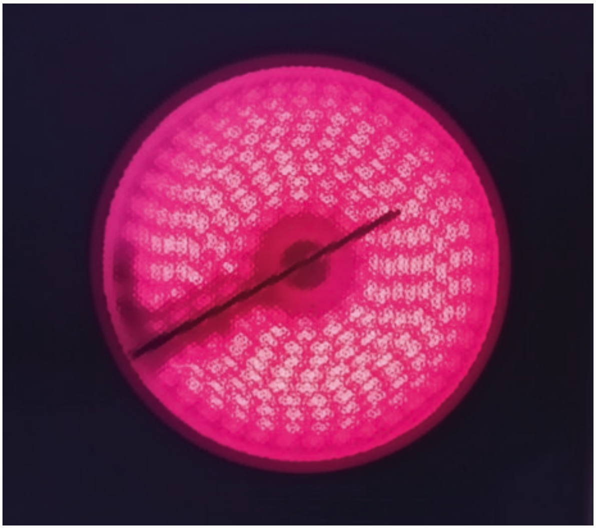


Fig. 2.38 Heating coil in a ceramic hob. (Photo: Schlegel, J.)

or ceramic-metal connection during application. The individual metal-glass or metal-ceramic components have a largely identical thermal expansion characteristic.

Eutectic and expansion alloys are easily cold-formable. Due to their toughness and strength, they behave like austenitic steels during machining.

Typical chemical composition
Alloys based on iron-nickel, iron-nickel-chromium and iron-nickel-cobalt have a nickel content of >29 mass-%.

Typical melting alloys include:
1.3912 – FeNi 36, 1.3917 – FeNi 42, 1.3922 – FeNi 48.

Typical expansion alloys include, for example:
1.3981 – NiCo 29 18, 2.4472 – NiFe 45, 2.4478 – NiFe 47.

Application
The melting and expansion alloys have a wide range of applications as stamping, etching and deep-drawing parts for apparatus and tool construction, as "bimetals" for parts for measuring instruments, thermostats, laser components, in equipment for liquid gas handling, for relay parts, for glass/ceramic metal seals, in X-ray tubes, for transistor sockets, in lighting technology as connecting wires for electrical conductors (e.g. halogen and LED lamps), in optoelectronics, as gas flow sensors, as ignition conductors for automotive airbags, parts for diesel injectors, insulators, expansion regulators, and many others.

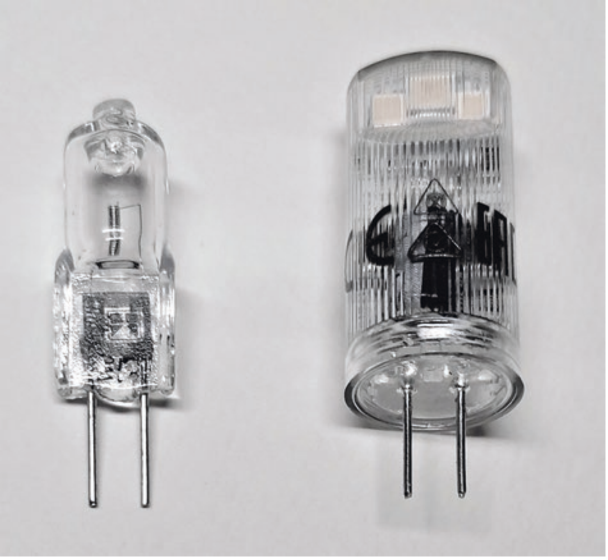


Fig. 2.39 Halogen and LED light sources. (Photo: Schlegel, J.)

In Fig. 2.39, the connecting pins of a glass-melting alloy are clearly visible on the example of a halogen and an LED lamp.

2.4.6 Other Steels

▶ The following should refer to some special steels that play a special role in practice:

- Free-cutting steels
- Spring steels
- Rolling bearing steels
- Valve steels
- Maraging steels
- Solenoid valve steels

Free-cutting steels

These steels with defined phosphorus or sulphur contents are optimised for automated machining with uninterrupted cutting. Sulphur contents of 0.08 to 0.4 mass % form relatively soft inclusions (e.g. manganese sulphides) that lead to chip breakage (short chips). This is desirable because short chips can be removed from the machining zone better and faster than long chips or tangled chips. This results in safe precision machining (see Sect. 8.3: *Machining*). Lead addition also creates inclusions on which the chips break. In addition, lead and sulphides on the surface have a protective and lubricating effect during the machining process.

▶ **Note** Toxic vapours are produced during the steel production of lead-alloyed steels. Therefore, fewer and fewer of such steels are being produced.

Requirements
Free-cutting steels must have very good machining properties (short brittleness of the chips) in order to enable quasi-continuous machining on automatic lathes. Since the surface condition of the bar stock remains partially unmachined on the turned part, it is important to maintain the dimensional accuracy and the required surface characteristics on the stock.

Typical free-cutting steels include:
1.0711 – 9S20, 1.0715 – 11SMn30, 1.0718 – 11SMnPb30, 1.0721 – 10S20, 1.0722 – 10SPb20, 1.0736 – 11SMn37/9SMn36, 1.0737 – 11SMnPb37, 1.0738 – 11SMnPbTe37, 1.0739 – 11SMnPbBiTe37, 1.0758 – 60SPb22, 1.0759 – 70SPb20, 1.1268+Pb – A100Pb.

Application
Free cutting steels are used for the mass production of precision turned parts on lathes and machining centers. Figure 2.40 shows some examples of precision turned parts such as shafts and spindles for small motors. These were manufactured on so-called Escomats, the CNC-controlled lathes for precise and fast production of turned parts. The raw material used is a ring-shaped wire made of free cutting steel.

Fig. 2.40 Examples of precision turned parts made of automation steel. (Photo: Rödel, C., BGH Edelstahl Lugau GmbH)

Spring steels

The outstanding property of a spring steel is its elasticity. Up to the elastic limit, the component can be deformed and then elastically returned to its original state without permanent deformation. Compared to other steels, spring steels have a higher strength and a yield strength ratio (height of the yield strength to the tensile strength) of usually greater than 85%.

Requirements

Important for the targeted adjustment of spring elasticity is the “metallurgical work”, i.e. the alloying technique (chemical analysis) during steel production, in particular the securing of a defined silicon content in the steel and a uniform distribution of carbon in the structure. Also, the compliance with very uniform mechanical properties of the raw material (e.g. the wire for spring production) must be observed.

Typical spring steels are, for example:

1.1231 – C67E 7/C67S, 1.4310 – X10CrNi18-8, 1.5023 – 38Si7, 1.7103 – 67SiCr5, 1.7108 – 61SiCr7, 1.7701 – 52CrMoV4.

Application

Spring steels are used to produce springs of various types for storing potential energy: return springs, clutch springs, springs for clocks, spring scales, suspension springs, springs for torque wrenches, springs for innerspring mattresses, ballpoint pen springs, etc. Examples of classic return springs are shown in Fig. 2.41.

Rolling bearing steels

In rolling bearings, rolling bodies rotate between an inner and outer ring (rolling friction with low friction resistance), locking rotating axes and shafts into position. Thus, these

Fig. 2.41 Return springs made of spring steel. (Photo: Schlegel, J.)

bearings enable rotation with as little friction as possible and at the same time to transmit axial and/or radial forces, depending on the design. There are five basic types of these radial and axial bearings: *ball, cylindrical roller, needle, tapered roller, barrel and toroidal roller bearings.*

Rolling bearings are made of chromium steel. This steel contains chromium carbides formed by the high carbon and chromium content in the structure. This ensures high wear resistance.

Typical rolling bearing steels

The classic of rolling bearing steels is 100Cr6 – 1.3505 with an content of approximately 1 mass percent carbon and 1.5 mass-% chromium. Other rolling bearing steels are, for example, 1.3520 – 100CrMnSi6-4 and 1.3536 – 100CrMo7-3. In these steels, manganese and molybdenum serve the better hardness. For applications in corrosive environments, rolling bearings are made of high-alloy steels, such as 1.4037 – X65Cr13 and 1.4108 – X30CrMoN15-1.

Application

Rolling bearing steels are used to produce outer and inner rings as well as the rolling elements for a variety of types of rolling bearings. Figure 2.42 shows, for example, a radial ball bearing in used condition.

Valve steels

Valves used as inlet or outlet valves in combustion engines are subject to very high and complex loads (temperature, friction, corrosion). Therefore, valve steels must also meet very high requirements in terms of strength, toughness, wear resistance, scaling resist-

Fig. 2.42 Radial ball bearing. (Photo: Schlegel, J.)

ance and formability. Valves are manufactured from the starting material (blank rods or wire) by electro upsettingor flow forming.

Typical valve steels include:
1.4718 – X45CrSi9-3, 1.4731 – X40CrSiMo10-2, 1.4748 – X85CrMoV18-2, 1.4866 – X33CrNiMnN23-8, 1.4871 – X53CrMnNiN21-9, 1.4875 – X55CrMnNiN20-8, 1.4882 – X50CrMnNiNbN21-9, 1.4873 – X45CrNiW18-9, 2.4952 – NiCr20TiAl, 9.4991 – Ni-Cr-Leg. 30/15.

The following groups of valve steels must be distinguished:

- *Ferritic-martensitic valve steels*
  These steels are used as the standard solution for monometallic inlet valves and, in the case of bimetallic valves, exclusively as the material for the stems.
- *Austenitic valve steels*
  The austenitic chromium-manganese steels have proven themselves for outlet valves.
- *High nickel valve materials*
  In the case of very high thermal requirements and highest operational safety (aircraft engines, motors for racing, highly loaded diesel engines), nickel-based alloys are in demand.

Application
Valve steels, as the name implies, are used to produce a variety of valves for a variety of combustion engines (intake and exhaust valves, mono- and bimetal valves) as well as valve seat rings for aircraft, car, truck and ship diesel engines. Figure 2.43 shows, as an example of an application for valve steel, typical exhaust valves for car engines.

Maraging steels
Maraging steels (from English *martensite* + *aging* = martensitic hardenable) are a special group of steels that, at high strengths (yield strengths >1850 to 2400 MPa), simultaneously exhibit good toughness values and also have favorable processing and welding properties. For practical use, high dimensional and surface quality as well as uniform mechanical properties of the raw material are important.

Typical maraging steels are, inter alia:
1.2709 – X3NiCoMoTi18-9-5, 1.6354 – X2NiCoMo18-9-5, 1.6356 – X2NiCoMoTi18-12-4.

Application
Maraging steels are mainly used as hot-working steels, e.g. for die-casting and injection-moulding tools, for gas centrifuges, for the production of knives, also blades for fencing as well as for parts of the watch industry. In Fig. 2.44 such parts made of maraging steel for a mechanical watch movement are recognisable.

Fig. 2.43 Exhaust valves for car engines. (Photo: Schlegel, J., BGH Edelstahl Lugau GmbH)

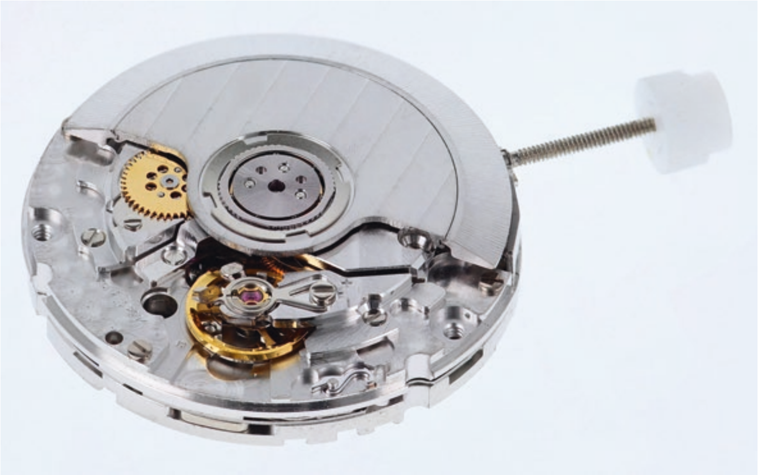


Fig. 2.44 View of a mechanical watch movement of a modern wristwatch. (Photo: Schiess, C.)

Magnet valve steels

A solenoid valve is actuated electromagnetically with very short switching times. For safe operation, defined magnetic properties of the component materials used must be observed. For reasons of manufacturing technology, magnetic properties must be distinguished:

- which can be set with a conventional manufacturing route (steel production and processing technology),
- which can only be achieved by a special annealing at the end of the manufacturing process.

Requirements

- Compliance with the specified chemical analysis (important, inter alia: sum formula of the carbon and nitrogen content)
- High purity
- Resilience (strength, wear resistance), corrosion resistance
- Defined magnetic properties

Typical magnetic valve steels are, inter alia:
1.4003 – X2CrNi12, 1.4005 – X12CrS13, 1.4016 – X6Cr17, 1.4057 – X17CrNi16-2, 1.4104 – X14CrMoS17, 1.4105 – X6CrMoS17, 1.4125 – X105CrMo17, 1.4418 – X4CrNiMo16-5-1, 1.4511 – X3CrNb17.

Application
Magnet valve steels can be found everywhere where liquids flow and need to be measured, controlled and regulated (level, pressure, flow, temperature); for example in electromagnetically operated valves. Figure 2.45 shows, as an example, a modern gasoline direct injection valve for passenger car engines.

Fig. 2.45 Electromagnetically operated high-pressure injection valve for gasoline direct injection for passenger cars. (Photo: Robert Bosch GmbH)

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3

Alloying Elements and Steel Properties

> ▶ Steel can be made very soft and excellently formable, but also very hard and brittle. The properties are very complex and determine the suitability of the steels for certain applications. That is why there are so many steels. In order to understand the effect of the equally numerous alloying elements or their combinations in the steels, or to find one's way around here, an overview of the most important properties should be given first. These generally relate to:
>
> - *the state,*
> - *interactions with other materials,*
> - *the behavior under mechanical stress,*
> - *the behavior during production* (forming, machining, heat treatment, coating, etc.),
> - *the behavior under environmental influences.*
>
> Based on this, the properties are roughly divided into:
>
> - *physical,*
> - *mechanical-technical,*
> - *technological or manufacturing-technical,*
> - *chemical-technical,*
> - *environmental properties.*

J. Schlegel, *The World of Steel*, https://doi.org/10.1007/978-3-658-39733-3_3

3.1 Properties of Steel

3.1.1 Physical Properties

▶ These properties are experimental, i.e. they can be determined by measuring physical quantities on the steel. In addition to density, thermal and tribological properties, as well as conductivity, the mechanical-technical properties can also be measured (Hornbogen et al., 2019).

Density ρ

The density is characterized as the mass of a material per unit volume:

$$\boldsymbol{\rho} = \mathbf{m}/\mathbf{V}\ \left(\mathrm{g/cm^3}\right)$$

- Unalloyed steel: $\rho = 7.85\ \mathrm{g/cm^3}$
- Aluminum: $\rho = 2.70\ \mathrm{g/cm^3}$

Melting temperature

It is the temperature at which a material melts, i.e. changes from the solid to the liquid state. The height of the melting temperature is also a measure of the strength of the chemical bond in materials:

- Pure iron $T = 1536\ °C$
- Aluminium $T = 659\ °C$

Thermal expansion

It describes the behavior of the material or its dimensions at a temperature change. The characteristic value for this is the thermal expansion coefficient or the expansion coefficient α (change in length L_T of a 1 m long rod at 1 °K temperature change):

$$\mathbf{L_T} = \mathbf{L_o}(\mathbf{1} + \alpha\,\Delta\mathbf{T})\ \text{in}\ [10^{-6}\mathrm{K}^{-1}]$$

In colloquial usage, one also uses the term “expansion factor” or short “strain”.

Thermal and electrical conductivity (current)

These parameters characterize a substance’s ability to conduct or transfer heat or electricity within itself.

“Good conductors” are all metals.

“Poor conductors” are most nonmetals, like plastics, glass, ceramics.

Examples:
The soldering iron must have a high thermal conductivity. Therefore it consists of copper. In contrast, insulation (e.g. foam, Styrofoam) is expected to have a very low thermal conductivity.

Specific heat conductivity λ_W [$Wm^{-1}K^{-1}$]
This parameter refers to the amount of heat transported per unit time through the cross section of a material as a function of the temperature gradient.

Specific electrical conductivity λ_{el}
This value indicates how well a substance can conduct an electric current. The specific electrical resistance ρ_{el} [Ωm] is the characteristic value for characterizing the current flow in a material. It is a temperature-dependent material constant and is defined as the ohmic resistance R of a conductor of 1 m length and 1 mm^2 cross section at 20 °C. A small specific electrical resistance means that the material allows a good flow of current. The reciprocal of the specific resistance is the electrical conductivity.

Tribological properties (wear resistance)
It concerns the behavior of a material to wear more or less during a friction process (e.g. sliding friction in bearings, guides and gearboxes made of steel) taking into account the lubrication.

3.1.2 Mechanical-Technical Properties

▶ These properties include the behavior of steel under the influence of mechanical forces (Burgert, 2016). In Sect. 7.2: *Destructive testing* you will find further information on this.

Strength
These describe the resistance of steel to plastic deformation at tough material behavior and against breakage at brittle behavior. Depending on the type of load, for example, the following are distinguished:

- *Tensile strength*
- Compression strength
- *Shear strength*

Hardness
Hardness is the resistance of a material to the penetration of another, harder body. Hardness is also a measure of the wear resistance of steel. The hardness property is required

for those components that are exposed to large forces and high wear, such as gears, rollers, tools, pistons.

Hardness testing methods are usually the static indentation methods according to Brinell, Vickers or Rockwell.

Elasticity
It is the ability of a material to erversibly recover its original shape after an applied force. The characteristic value for this is the elasticity modulus E, that is, the linear range of the stress-strain curve, also known as the proportionality factor in Hooke's law.

Ductility
A material is ductile or plastic if it changes its shape permanently under the action of force, that is, it does not "spring back". The opposite of this is the brittle behavior.

Toughness
This property defines the energy absorption capacity of a material. In other words, it is the resistance against the formation and propagation of cracks or breakage during plastic deformation.

Brittleness
It characterizes the property of a material to break under load without noticeable plastic deformation beforehand. Brittle materials, for example, break into many pieces when struck suddenly (e.g. ceramic, glass, improperly hardened steel).

3.1.3 Technological Properties

▶ These properties describe the suitability of a material for a manufacturing process and for certain conditions of its processing.

Cold Formability
It is the property of a material to be able to be deformed at room temperature (without preheating) by processes such as rolling, bending, stamping, folding, deep drawing, drawing, etc. This cold forming is always associated with an increase in strength (cold hardening).

Warm Formability (Forgeability)
It is one of the most important properties of metals: the ability to be formed in the heated state, that is, to be intentionally deformed at elevated temperatures by force (Winkler & Dahl, 1984). An example of this is the classical forging of steel. Figure 3.1 shows the forging of a semi-finished product on a forging press.

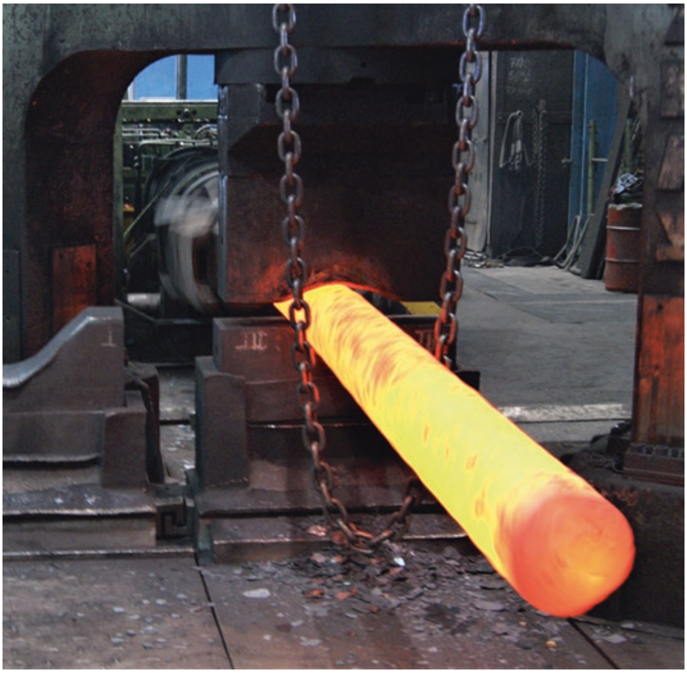


Fig. 3.1 Forging of a semi-finished product on a forging press. (Photo: Schlegel, J., BGH Edelstahl Lippendorf GmbH)

The deformability of steel at room temperature and at elevated temperatures is also referred to as formability (see Sect. 5.1: *Basics of Metal Forming*).

Castability
The castability of the melt of a material or a steel is the prerequisite for the further processing into castings. One distinguishes the semi-finished casting (ingot, billet or strand casting) as well as the die casting. In Fig. 3.2 these casting processes are schematically opposed. The steel melt must always be sufficiently fluid to fill the mold or die casting completely (flowability, filling ability).

Hardenability
It is a property of a material to experience a hardness increase during cooling, usually in the form of quenching a glowing component in water or in another medium (oil, aqueous polymer solutions, salt baths, air). All steels with more than 0.2 mass-% carbon are hardenable (see Chap. 6: *Heat treatment*).

Weldability
This property of steel allows for a metallurgical bonding of individual parts to form a combined component using various welding methods. The resulting welds have, under

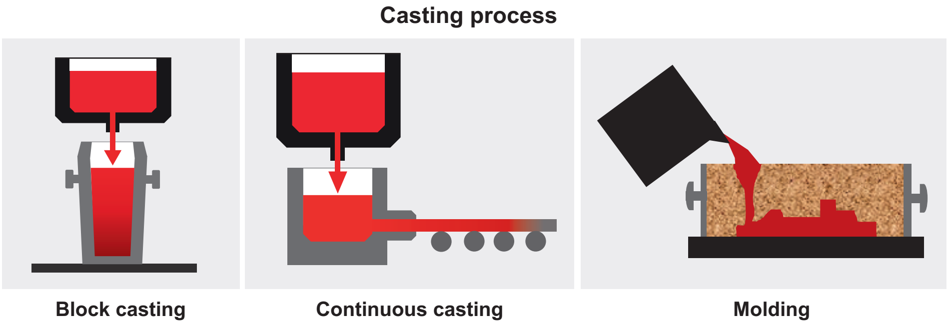


Fig. 3.2 The casting processes ingot, strand and die casting *(from left to right)*

the right selection of welding conditions, in particular the welding filler material, approximately the same strength as the individual joining parts. There are no pores, embrittlements or other material changes.

Machinability
It is an important property because almost all workpieces and many components are machined by a chip-removing process, e.g. drilling, milling, turning, sawing, peeling, grinding, during their manufacture or can only be manufactured by such a machining process. All steel materials as well as most non-ferrous metals and alloys can be machined to a greater or lesser extent. Further information can be found in Sect. 8.3.1: *Basics of Machining.*

3.1.4 Chemical and Technical Properties

▶ They describe the change of the steel by the action of the substances surrounding it as well as by environmental conditions, such as salt water, gasoline, aggressive chemicals, such as acids, alkalis, solvents, etc., at room temperature and at elevated temperatures. These changes are mostly material-destroying processes or negative property changes.

Corrosion resistance
Corrosion (lat. *corrodere*—decompose) is the reaction of a material with its environment, usually resulting in a surface-based destruction by chemical or electrochemical reactions (Kaesche, 1966). This can lead to an impairment of function or even failure of a component. For example, unalloyed steels are not corrosion-resistant, they rust and must be protected against corrosion by paints, galvanizing, chroming, etc. Highly alloyed chromium-nickel steels are, however, corrosion-resistant, i.e. stainless.

Heat resistance
This property is important for components that are exposed to high temperatures, such as engine valves, turbocharger parts, exhaust systems, furnace components, heat conductors, tools for hot forming (forging, rolling). For these applications, particular scaling resistant and high-temperature resistant steels (e.g. valve steels) and special alloys (heat conductor materials) have been developed.

Flammability
Except for magnesium, flammability is not an issue with metals, especially steel, because they are not flammable under normal operating conditions.

3.1.5 Environmental Properties

▶ When selecting materials, health and environmental protection must also be considered. Toxic, health-threatening or environmentally harmful materials are to be avoided or no longer used, e.g. lead, cadmium, mercury, asbestos, formaldehyde. Sustainability, resource efficiency, recycling and environmental balance are today indispensable challenges in the production of materials.

Metallic materials and, in particular, steels are all very recyclable, while plastics are only partially recyclable. And most steels are not harmful to health during their use.

3.2 Basics of Alloy Technology

▶ **Note** When the significant history of iron and steel production began more than three thousand years ago during the Iron Age, people did not yet know the possibilities of alloying. Also, many alloying elements had not yet been discovered. At first empirically, and later with a large number of elaborate test series, new alloys were developed from iron and (hardenable) steel. Only after 1800 could iron and steel metallurgy meet the growing demands for special steel properties using scientific methods.

The properties of the various steel grades are based on their chemical compositions. Each alloying element gives the steel specific properties that can be further increased by additional, added elements. To understand this, some important terms from alloying technology should be introduced first.

Alloys
These are generated by “melting together” two or more metals or metals with non-metallic substances (alloy from Latin ligare—“to bind, to unite”). In the liquid metal melt, all

"alloying partners" must be completely miscible with each other or completely soluble in each other, i.e. the melt must be homogeneous.

Homogeneous:
Uniform state over the entire extent of the material (steel melt, solid steel), thus also the same properties everywhere.

Heterogeneous:
No uniform, homogeneous state. The material (steel part) consists of two or more different components with different properties.

The components of an alloy (except impurities) are referred to as alloying elements. The mixing ratio of these alloying elements is the concentration in mass%, i.e. the chemical analysis. Depending on the type of alloying components, one or more phases may be present after solidification, i.e. in the crystalline state, e.g. austenite, ferrite, cementite.

Phase

A phase in the microstructure of a material comprises all physically homogeneous components that are homogeneous in themselves. They have the same chemical composition and also the same physical properties. Phases are separated from other phases by phase boundaries (Bleck, 2010).

Mixed crystals

They are crystals that contain atoms of different alloying elements in their lattice structure.

Substitution or excange mixed crystals

In such a crystal, atoms of one alloy element are replaced by atoms of another alloy element (foreign atoms). The atoms of these two alloy elements are almost the same size and are usually distributed randomly on regular lattice sites. Figure 3.3 shows schematically the structure of an exchange-mixed crystal for this purpose.

However, if a lattice atom is substituted by a very large atom, then there is a lattice distortion (enlargement, as shown in Fig. 3.4). With smaller atoms, the lattice contracts around this foreign atom.

Inclusion mixed crystals

In this crystal, atoms of an alloy element are incorporated in the lattice gaps, the so-called interstitial sites, between the other alloy elements. Figure 3.5 shows a schematic representation of such an inclusion mixed crystal. This inclusion is usually the case when the incorporated foreign atoms are significantly smaller than the host lattice atoms. The solubility of these foreign atoms incorporated in the lattice gaps is limited.

Fig. 3.3 Exchange mixed crystal consisting of atoms A and B

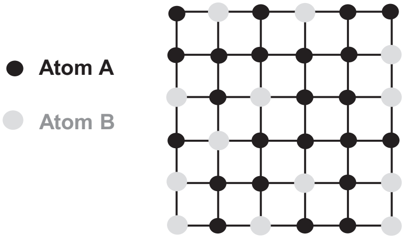


Fig. 3.4 Substitution mixed crystal, schematically shown with a lattice distortion due to a large substitution atom

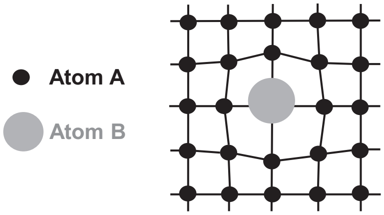
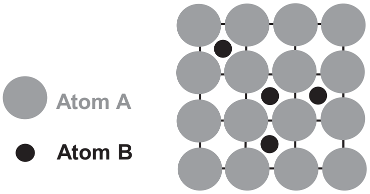


Fig. 3.5 Schematic representation of an inclusion mixed crystal



Crystal defects

▶ At this point, reference must be made to reality in practice: In real materials, including steel alloys, there are disturbances of the geometrical ideal state (lattice or crystal defects). These lead to lattice stresses and increase the internal energy of the material. On the one hand, these disturbances are present in reality, on the other hand they can be deliberately introduced by a treatment (forming, heat treatment) and thus used for property improvement. The occurring crystal defects are classified into zero-, one-, two- and three-dimensional defects. Without going into the thermodynamic processes, conditions and order principles of these structural defects, the following disorder or lattice defects should be mentioned briefly.

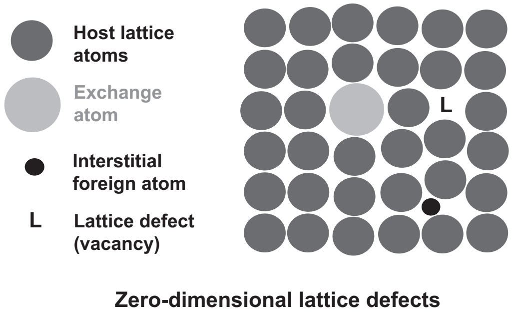


Fig. 3.6 Zero-dimensional defects (point defects): foreign atoms and vacancies

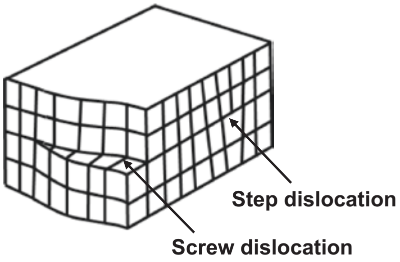


Fig. 3.7 Schematic representation of the lattice defects step and screw dislocations

Zero-dimensional defects

Zero-dimensional defects involve so-called point defects. They include vacancies and foreign atoms (substitutional and interstitial atoms), as schematically shown in Fig. 3.6.

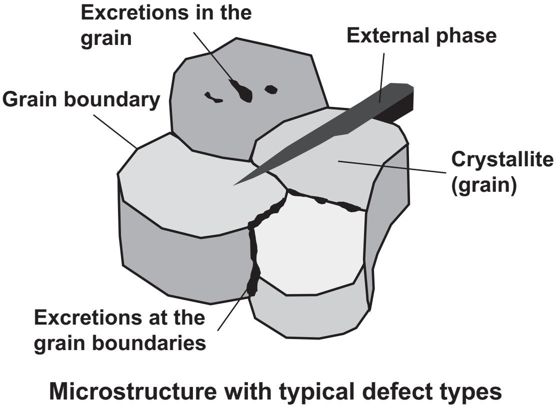
One-dimensional defects

These defects are line defects which can occur during crystal growth and cold forming and increase under the influence of external forces or stresses. This type of defect is characterized by the *displacements*. For example, Fig. 3.7 shows the types of step and screw dislocations. The presence and formation of such dislocations are the prerequisite for the plastic deformation and solidification of the steel. During plastic deformation, the dislocations migrate through the crystal lattice (see Sect. 5.1: *Basics of Metal Forming*).

Two- and three-dimensional construction defects

These defects represent the surface and volume errors. These include the stacking faults, grain boundaries, twin boundaries and phase boundaries. Figure 3.8 shows examples of these construction errors, as they are found in a real steel structure: pores, microcracks, precipitates within the grains or at the grain boundaries as well as foreign phases.

Fig. 3.8 Schematic representation of the microstructural composition with typical defect types



3.3 Chemical Elements in Steel and Their Effect on Steel Properties

▶ The chemical elements in steel can be gaseous elements (nitrogen, oxygen, hydrogen) or solid elements (non-metals, semi-metals, metals). These elements in turn represent either alloying elements (steel modifiers), accompanying elements or "steel-damaging" elements. The most important elements and their effect on steel properties are presented below. The decisive source for these explanations is the steel key pocket book (2019). In general, it must be noted that, in addition to the chemical composition (contents of alloying and accompanying or trace elements and their individual effects), the desired properties of the product are only completed by the processing and finally by the heat treatment of the steel.

3.3.1 Gaseous Elements

▶ The steel properties are mainly influenced by the gaseous elements oxygen, nitrogen and hydrogen.

Nitrogen (N)

Latin "Nitrogenium", German "Stickstoff", atomic number 7 in the periodic system (Fig. 3.9).

1771 nitrogen was discovered by the German-Swedish pharmacist *Carl Wilhelm Scheele* (1742–1786) as a component of air. This was confirmed in 1772 by *Daniel Rutherford* (1749–1819). Nitrogen only occurs elementarily as a diatomic molecule N_2 and is industrially produced by distilling liquefied air.

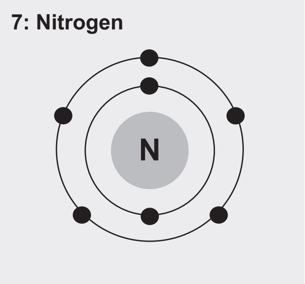


Fig. 3.9 The nitrogen atom model (N)

Nitrogen is usually harmful in steel because it favors precipitation processes that reduce toughness. It also causes sensitivity to aging.

> **Note** Aging is a change or deterioration of physical and chemical properties of steel that occurs over a period of time and during use. As a result, the steel becomes less malleable and tough, but harder and more brittle.

Nitrogen favors blue brittleness (Blue brittleness describes the behavior of unalloyed, lowcarbon hardened steels at annealing temperatures in the range between 150 and 350 °C. Here they lose toughness and become brittle. At these temperatures, the surface gets a blue annealing color—hence the name blue brittleness). In addition, nitrogen can make unalloyed and low-alloy steels susceptible to stress corrosion cracking.

In addition to these rather harmful effects on steel, nitrogen is also deliberately added to the steel as an alloying element in order to expand the cubic-facet-centered austenite range or to stabilize the state with an austenitic structure. In austenitic steels, nitrogen also increases the strength and, above all, the yield strength as well as the mechanical properties at elevated temperatures. With nitrogen, a high surface hardness is achievable through formation of nitrides via nitriding of steels. (Nitrides are chemical compounds of nitrogen, e.g. metallic, very hard nitrides such as titanium nitride TiN and chromium nitride CrN).

Oxygen (O)

Latin “Oxygenium”, German “Sauerstoff”, atomic number 8 in the periodic system (Fig. 3.10).

Oxygen was also discovered in 1771 by *Carl Wilhelm Scheele* (1742–1786). It occurs elementarily only as a diatomic molecule O_2. Liquid oxygen is industrially produced by thermal separation of liquid air according to the Linde process. By the way, there is also a triatomic form, the ozone in the stratosphere.

Oxygen is also a steel contaminant. Depending on the type and composition of the oxygen compounds as well as their form and distribution in the steel, the technological properties, in particular the impact toughness, are deteriorated. In addition, the tendency of the steel to brittle age, to red break (tearing of the steel at 800 to 1000 °C during

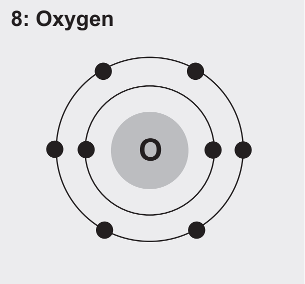


Fig. 3.10 The atomic model of oxygen (O)

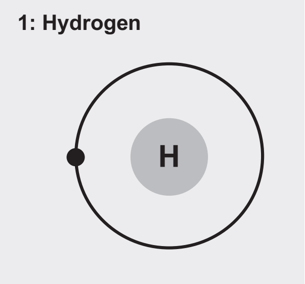


Fig. 3.11 The atomic model of hydrogen (H)

forming), wood fiber break and slate break (fiber-like and slate-like fracture surfaces) is increased.

Hydrogen (H)
Latin "Hydrogenium", German "Wasserstoff", atomic number 1 in the periodic system (Fig. 3.11).

Hydrogen was discovered in 1766 by the English chemist and physicist *Henry Cavendish* (1731–1810). Throughout the universe, the colorless, odorless and tasteless gas is the most common element. It occurs in the form of the diatomic molecule H_2 and is the main component of water and all organic materials.

In steel, hydrogen is a steel contaminant because it causes embrittlement by reducing ductility and by causing strain without increasing strength. In addition, hydrogen causes the feared flaking, an unwanted material separation through hydrogen outgassing.

3.3.2 Solid Elements – Nonmetals

Carbon (C)
Latin "Carboneum" or "Carbonium", German "Kohlenstoff", atomic number 6 in the periodic system (Fig. 3.12).

Carbon is the longest-known element in human history. Of course, the Stone Age people did not know that the black substance resulting from the carbonization of wood was

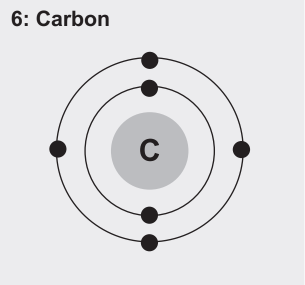


Fig. 3.12 The atomic model of carbon (C)

the chemical element carbon. It was not until 1775 that *Antoine Laurent de Lavoisier* (1743–1794) discovered the elemental character of carbon in the form of soot. Around 1779, *Carl Wilhelm Scheele* (1742–1786) recognized that graphite is also chemically equivalent to the carbon discovered by *Lavoisier*. And finally, in 1796, *James Smithson Tennant (1761–1815)* found that diamond is also a carbon modification. In addition to oxygen and water, carbon is the most important element in our biosphere for life. And because of its atomic structure, carbon is the element that can form the most compounds with other elements after hydrogen. In nature, carbon occurs elementarily as graphite (coal) or diamond.

The element carbon is the most important alloying element in steel. Depending on the carbon content, different phases are formed in steel. With higher carbon content, the strength and hardness of the steel increase, the elongation, forgeability, weldability and machinability decrease. The steel becomes brittle.

Sulfur (S)

Latin "Sulpur", German "Schwefel", atomic number 16 in the periodic system (Fig. 3.13).

Sulfur is a yellow, non-metallic solid that forms many modifications. In nature, it occurs in the pure (native) form and in the form of inorganic compounds (sulfides, sulfates). In industry, the majority of the elemental sulfur obtained is used to produce sulfuric acid (H_2SO_4). It is today technically the most important basic chemical.

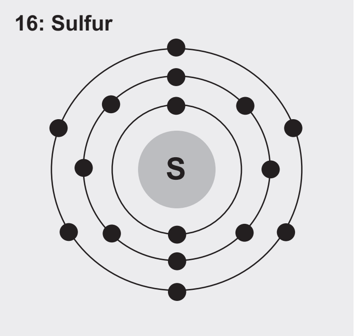


Fig. 3.13 The atomic model of sulfur (S)

Sulfur has been used by humans for a long time, e.g. in China and Egypt around 5000 BC for bleaching textiles, also as a medicine and for disinfection. That sulfur is an element was first suspected by *Antoine Laurent de Lavoisier* (1743–1794). The French chemists *Joseph Louis Gay-Lussac* (1778–1850) and *Louis Jacques Thénard* (1777–1857) then proved sulfur chemically in 1810. The effects of sulfur in steel are diverse. Sulfur tends to strong segregation (formation of sulfides) during the solidification of the steel melt. This segregation can under certain circumstances lead to the undesired red or hot break. Since sulfur has a particularly large affinity for manganese, manganese sulfides are formed at corresponding manganese levels in the steel, which, however, reduce the purity of the steel. Sulfur is deliberately added to the steel, for example, which is intended for machine processing (up to approx. 0.4 mass-%). The manganese sulfides present in the steel structure due to the high sulfur content improve machinability (lubricating effect at the tool cutting edge – longer tool life, short chips). The following stainless chromium and chromium-nickel steels with a sulfur content of 0.15 to 0.35 mass-% can be mentioned as examples: 1.4035 (X45Cr13+S), 1.4104 (X14CrMoS17), 1.4105 (X6CrMoS17) and 1.4305 (X8CrNiS18-9).

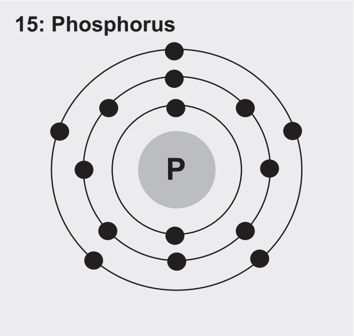
Phosphorus (P)
Latin “phosphorus”, German “Phosphor”, atomic number 15 in the periodic table (Fig. 3.14).

Phosphorus was discovered in 1669 by German pharmacist *Hennig Brand* (1630–1692). It does not occur in nature in pure form, but only in very different modifications, e.g. in phosphates such as white phosphorus P_4. By the way, this was the prerequisite for the beginning of the development of matches. Today, red phosphorus is used for their friction surfaces.

Phosphorus is usually considered a steel contaminant that leads to strong primary and secondary segregation. A homogeneous distribution of phosphorus in steel is hardly possible. Therefore, the phosphorus content in high-quality steels is limited to max. 0.03 to 0.05 mass-%.

In austenitic steels, phosphorus additions increase the yield strength and also precipitation effects. Phosphorus increases the sensitivity to a tempering embrittlement already in

Fig. 3.14 The atomic model of phosphorus (P)



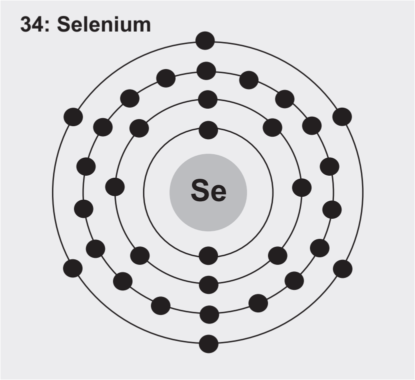


Fig. 3.15 The atomic model of selenium (Se)

trace amounts in steel. This embrittlement usually occurs in the form of a cold brittleness and sensitivity to impact (brittle fracture propensity). In contrast, phosphorus increases the strength and corrosion resistance to atmospheric influences (corrosion-resistant steels) in low-alloy engineering steels with carbon contents of approx. 0.1 mass-%.

Selenium (Se)

Latin "selenium", German "Selen", atomic number 34 in the periodic table (Fig. 3.15).

Selenium was discovered in 1817 by Swedish chemist and physician *Jöns Jakob Berzelius* (1779–1848) in the lead sulfate sludge of a sulfuric acid factory. Selenium is found in inorganic and organic compounds, only in small amounts in solid form. Selenium is a so-called trace element of sulfur-containing ores of the metals copper, lead, zinc, gold and iron.

Similar to sulfur, selenium is added to machine steels to improve machinability. However, in corrosion-resistant steels, selenium reduces their corrosion resistance.

3.3.3 Solid Elements – Semimetals

Silicon (Si)

Latin "Silicia", standard German "Silizium", also written with "c" in chemical jargon, atomic number 14 in the periodic table (Fig. 3.16).

After experiments by *Antoine Laurent de Lavoisier* (1743–1794) and *Joseph Louis Gay-Lussac* (1778–1850), in 1824 *Jöns Jakob Berzelius* (1779–1848) first recognized the elemental character of silicon and named it silicon, derived from silex – "flintstone". Silicon is a classic metalloid that exhibits both metallic and non-metallic properties. The entire earth consists of 15% by mass of silicon. It occurs as a mineral, primarily in the form of quartz and sand (silicon dioxide).

Silicon is added to the steel melt in the form of ferro-silicon for deoxidation (removal of oxygen which is released when the melt cools). Figure 3.17 shows such ferro-silicon as it is used as an inoculant in an electric steelworks.

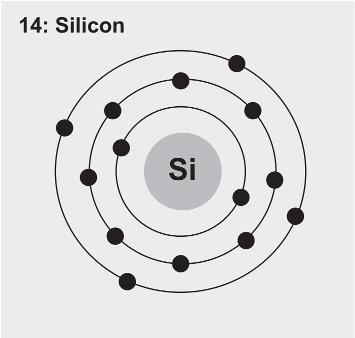


Fig. 3.16 The atomic model of silicon (Si)

Fig. 3.17 Ferro-silicon. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

Silicon is present in stainless steels, similar to manganese, as a trace element and acts as a ferrite former. It increases the strength and wear resistance, for example, in silicon-manganese-alloyed steels. Silicon also increases the yield strength in spring steels and improves the scaling resistance of heat-resistant steels, for example, in 1.4841—X15CrNiSi25-21. Under certain conditions, silicon increases the corrosion resistance to water-based media, for example, in the austenitic steel 1.4361—X1CrNiSi18-15-4. Since silicon leads to a significant reduction in electrical properties such as electrical conductivity, coercive force and watt losses, silicon is specifically used in steels for electrical sheets.

Boron (B)

Latin “boron”, German “Bor”, atomic number 5 in the periodic system (Fig. 3.18).

Boron compounds have been known for millennia. For example, the ancient Egyptians, Persians, Sumerians and Babylonians used Borax (oxygen compound with boron)

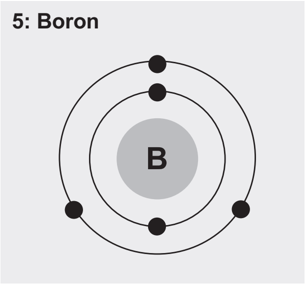


Fig. 3.18 The atomic model of boron (B)

to clean textiles and also for mummification. The representation of the element boron was first achieved by the French chemists *Joseph Louis Gay-Lussac* (1778–1850) and *Louis Jacques Thénard* (1777–1857) as well as the Englishman *Sir Humphry Davy* (1778–1829). However, they did not yet recognize its elemental character. This was first described by the Swedish chemist *Jöns Jakob Berzelius* (1779–1848) in 1824. Boron is a trivalent, rare metalloid that occurs naturally only in oxygen-containing compounds (e.g. borax).

The effect of boron as an alloying element in steels can be described as follows: Austenitic chromium-nickel steels can be hardened to a higher strength by boron precipitation hardening. However, this reduces corrosion resistance. For example, the boron-induced precipitates improve the high-temperature strength properties of austenitic steels. In construction steels, boron increases hardness, for example yield strength in structural steels. Another example are manganese-boron-alloyed steels, e.g. steel 1.5528 – 22MnB5, used for the press hardening of sheet metal parts such as the B-pillar for cars.

Arsenic (As)

Latin “Arsenicum”, German “Arsen”, atomic number 33 in the periodic system (Fig. 3.19).

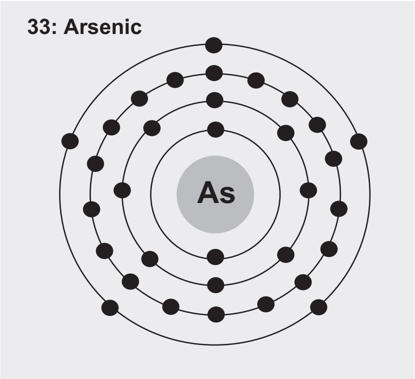


Fig. 3.19 The atomic model of arsenic (As)

When arsenic is mentioned, one usually thinks of the poisonings in the Middle Ages. But at that time they used arsenic trisulfide, an inorganic arsenic-sulfur compound (As_2S_3). It is said that around 1250 the scholar *Albertus Magnus* (around 1200–1280) possibly produced elemental arsenic for the first time. Arsenic occurs in small concentrations almost everywhere in the Earth's crust, both as a mineral in its own right, but mostly in the form of sulfides.

Arsenic is a steel contaminant, since it, like phosphorus, tends to strong segregation in the steel melt. Elimination of the segregation or impurities that have occurred in the steel by diffusion annealing is only possible to a limited extent via diffusion annealing. Furthermore, arsenic reduces the toughness of the steel and impairs its weldability.

3.3.4 Solid Elements – Metals

Aluminum (Al)

Latin "Alumen", German "Aluminium", ordinal number 13 in the periodic system (Fig. 3.20).

Since ancient times, humans have known the alum stone, the aluminum compound of potassium-aluminum sulfate. The aluminum oxide (clay) was first prepared in 1754 by *Andreas Sigismund Marggraf (1709–1782)*. Also *Sir Humphry Davy* (1778–1829) experimented with clay, but could not yet produce the elemental metal. However, he already gave it the name aluminum. Only in 1825 did the Danish chemist *Hans Christian Ørsted* (1777–1851) succeed in the pure state isolation of the light metal aluminum.

Aluminum is the third most abundant element and the most abundant metal in the Earth's crust. Since it has a very ignoble character and oxidizes very quickly in air, it practically only occurs chemically bound in the form of silicates (clay, gneiss, granite). Industrial mass production and use of aluminum began in the early twentieth century. The light metal is produced electrolytically from an aluminum oxide melt. For this purpose, bauxite (aluminum ore) is used as raw material.

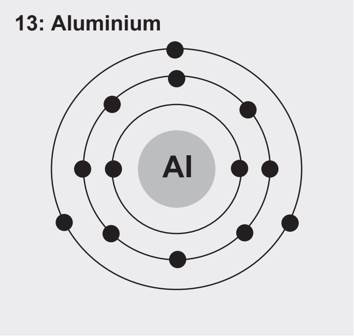


Fig. 3.20 The atomic model of aluminum (Al)

Fig. 3.21 Ferro-aluminium. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

In colloquial terms, today in materials science, “aluminum” refers to all materials such as pure aluminum (min. 99.0 mass-%), purest aluminium (min. 99.7 mass-%) and also aluminum alloys with only about one third of the density of steel. For use in steelmaking, ferro-aluminum is used as a pre-alloy, an alloy of iron and aluminum with about 30 to 75 mass-% aluminum content (usually with 35 mass-% aluminum) and a melting point of about 1250 °C. Figure 3.21 shows such ferro-aluminum, as it is used as a pre-alloy in an electric steel mill for melting.

Aluminum is due to its very strong chemical attraction to oxygen the strongest and very commonly used desoxidation agent in steel production. In addition, aluminum acts as a denitration agent and thus favors the aging resistance of steel. In very small amounts aluminum can support the fine grain formation in the steel (microalloy). Since aluminum forms high hardness nitrides with nitrogen, it is used as an alloying element in nitriding steels. Furthermore, aluminum increases scaling resistance in steel and is therefore alloyed in selected ferritic, heat-resistant steels. In unalloyed carbon steels the introduction of aluminum into the surface (aluminization) leads to an increase in the scaling resistance.

In general, it should be noted that larger amounts of aluminum in steel lead to a deterioration of weldability. Aluminum greatly increases the coercive force and is therefore an important alloying element in iron-nickel-cobalt-aluminum permanent magnet alloys.

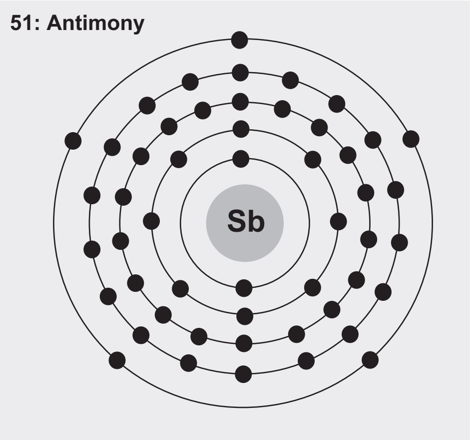


Fig. 3.22 The atomic model antimony (Sb)

Antimony (Sb)

Sb comes from the Latin "**sti**b**i**um", which in the seventeenth century was the name for the Antimony sulfide makeup powder. Latin today "antimonium", German "Antimon", atomic number 51 in the periodic table (Fig. 3.22).

Antimony is a very rare, silver-lustrous, brittle semi-metal. For this element, there is only little information from steel metallurgy. Antimony is a steel contaminant because it reduces the toughness of the steel. In addition, it constricts the gamma area.

Beryllium (Be)

Latin "Beryllus", German "Beryllium", ordinal number 4 in the periodic system (Fig. 3.23).

The French chemist *Louis-Nicolas Vauquelin* (1763–1829) isolated beryllium in oxide form from the gemstone beryl. Elementary beryllium was prepared by Friedrich Wöhler (1800–1882) and also Antoine Bussy (1794–1882) around 1828. Many other chemists were interested in this interesting element. By 1898, *Paul Marie Alfred Lebeau* (1868–1959) was able to produce very pure beryllium by melting electrolysis of sodium beryllium fluoride. Beryllium is a steel-gray, very hard and brittle light metal. It only occurs in minerals. The most beautiful and valuable beryllium-containing minerals include the jewelry and gemstones aquamarine, emerald as well as red beryl.

Beryllium is used as an alloying element in steel because it has a strong deoxidizing effect. Abrasion hardening can be achieved with beryllium. Nickel-beryllium alloys are very hard and corrosion-resistant. They are therefore used, inter alia, for the production of surgical instruments.

Lead (Pb)

Latin "Plumbum", German "Blei", atomic number 82 in the periodic system (Fig. 3.24).

Fig. 3.23 The atomic model of beryllium (Be)

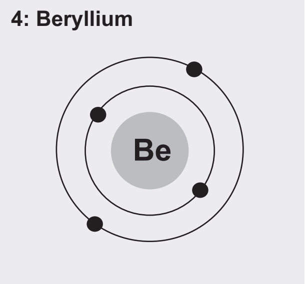
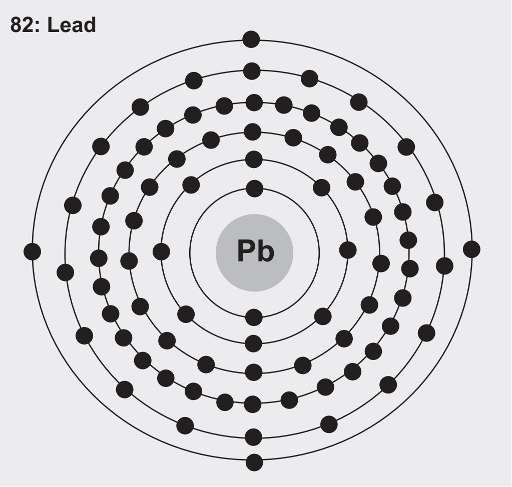


Fig. 3.24 The atomic model of lead (Pb)



Lead is a very toxic heavy metal, which rarely occurs in a pure form, usually in ores as a sulfide (galena). Lead was already known in the early Bronze Age (2200–1550 BC); for example, it was used by the Babylonians for vases, by the Romans for vessels and sling projectiles, for lead seals (hence the name “plumbum”) and water pipes.

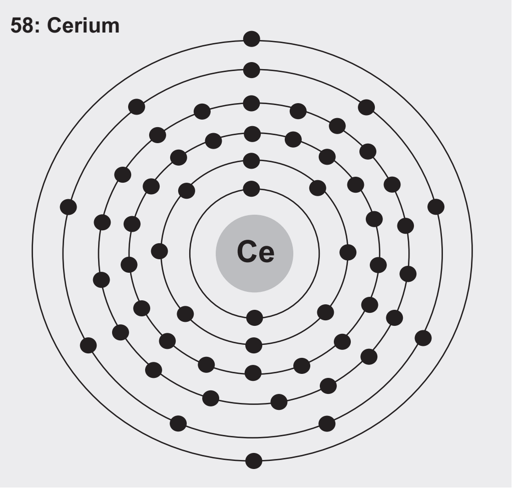
Lead is alloyed only in machining steels, and this increasingly rarely, with about 0.2 to 0.5 mass-%. This extremely fine lead distribution in the steel microstructure leads during machining to the formation of short chips and clean cut surfaces. The machinability of the steels is thereby improved without affecting the mechanical properties. In addition, lead is used in bearing metal because of the excellent sliding properties.

Cerium (Ce)

Latin “Cerium”, German “Cer”, atomic number 58 in the periodic system (Fig. 3.25).

The metal Cerium is assigned to the so-called “rare earths”. This dates back to the time of the discovery of a group of metals, such as Ytrium, Neodym and Cerium, in very rare minerals. Although, for example, Cerium occurs more frequently in the Earth’s crust

Fig. 3.25 The atomic model of cerium (Ce)



than lead, molybdenum or arsenic, the designation "metal of the rare earths" is nevertheless justified because larger deposits are extremely rare. Independently of each other, in 1803 *Martin Heinrich Klaproth* (1743–1817), *Jöns Jakob Berzelius* (1779–1848) and *Wilhelm von Hisinger* (1766–1852) isolated an oxide (oxides were previously referred to as "earths"), called "Cerit", from a black ore, whose metal was called Cerium. After that, an intensive research of the metals of the rare earths began. Cerium is hardly used as a pure metal, mostly as an alloy metal e.g. with Lanthanum and Neodynium.

Cerium acts desoxidizing in steel, thus cleansing. And it also promotes the de-sulphurization. In highly alloyed steels the hot formability is favored and in heat-resistant steels the resistance to scaling. So Cerium has a certain importance as an alloying element.

Fig. 3.26 The atomic model of chromium (Cr)

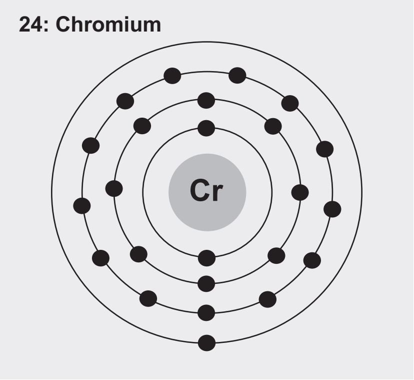


Fig. 3.27 Ferro-chromium. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

Chromium (Cr)

From the Greek “chroma” – color, Latin “Chromium”, German “Chrom”, atomic number 24 in the periodic system (Fig. 3.26).

Chromium is a silver-white, corrosion- and abrasion-resistant, hard metal, tough in its raw state, malleable and forgeable. In 1798, *Louis-Nicolas Vauquelin* (1763–1829) isolated chromium from the mineral crocoite. Around 1854, *Robert Wilhelm Bunsen* (1811–1899) was the first to successfully prepare pure chromium, which is now predominantly mined as ore (chromite) in open-cast mining or at shallow depths. Ferro-chromium is obtained by reduction in an electric furnace. Metallic chromium is obtained by reduction of processed chromium oxide.

The following four modifications of ferro-chromium are available for use as an alloying element in steel production (data in mass-%):

- *Fe-Cr suraffiné: ca. 68% Chromium*
- *Fe-Cr affiné: 57 bis 70% Chromium*
- *Fe-Cr carburé: 65 bis 70% Chromium*
- *Fe-Cr carburé P-arm: 65 bis 70% Chromium*

Figure 3.27 shows ferro-chromium in a form as it is used as a prealloy in an electric steelworks for melting.

Chrom is a carbide former, thereby increasing the cutting edge holding power and wear resistance of the steel. Via chromium addition steel becomes oil and air hardenable, the mechanical properties, the heat resistance and the corrosion resistance are improved. It should be noted that steels with more than 12 to 13 mass-% chromium do not rust. With increasing chromium content, the weldability of pure chromium steels decreases (Gümpel, 2001), (Stainless steels – A success story).

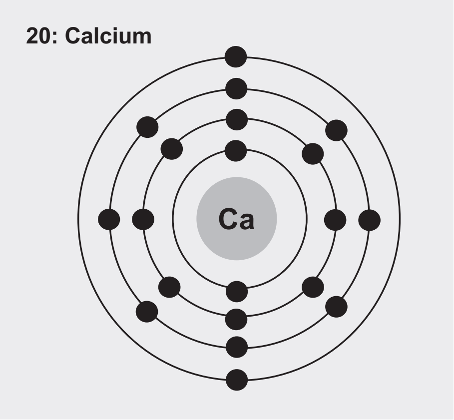


Fig. 3.28 The atomic model of calcium (Ca)

Calcium (Ca)
Latin "calx" (this is how limestone, chalk and mortar made from it were called by the Romans), German "Kalzium", atomic number 20 in the periodic system (Fig. 3.28).

Sir Humphry Davy (1778–1829), Professor of Chemistry in London, first obtained calcium in 1808 by distilling mercury from electrolytically obtained calcium amalgam, an alloy of mercury. Calcium is an alkaline earth metal. It is softer than lead and only occurs on Earth chemically bound as a component of minerals, e.g. in limestone (calcite, marble), chalk and gypsum.

Together with silicon, calcium is used in the form of silico-calcium for deoxidation in steel production. Calcium as an alloying element increases the scaling resistance of heating conductor materials.

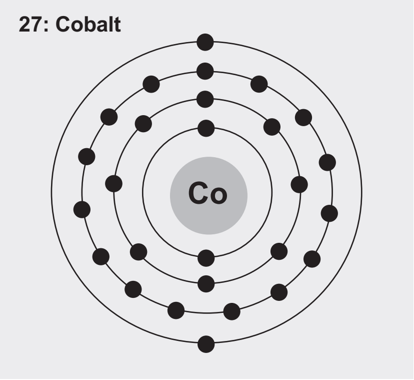


Fig. 3.29 The atomic model of cobalt (Co)

Fig. 3.30 Cobalt metal, lumpy. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

Cobalt (Co)

Latin “Cobaltum”, German “Kobalt”, ordinal number 27 in the periodic system (Fig. 3.29).

Cobalt ores and cobalt compounds have been known for a very long time and were initially used mainly for coloring glass and ceramics. In the Middle Ages, people even thought they were quite valuable silver or copper ores. However, when heated, cobalt ores gave off bad odors because of the arsenic content. There was simply no silver or copper that could be extracted from it. So it was assumed that goblins had enchanted these ores.

Kobalt is a very tough, ferromagnetic transition metal, which is only found in elemental form very rarely in meteorites and in the Earth’s core. Today, Cobalt is mainly extracted from copper and nickel ores. In lump form, as shown in Fig. 3.30, Cobalt is used in steel mills for melting and alloying.

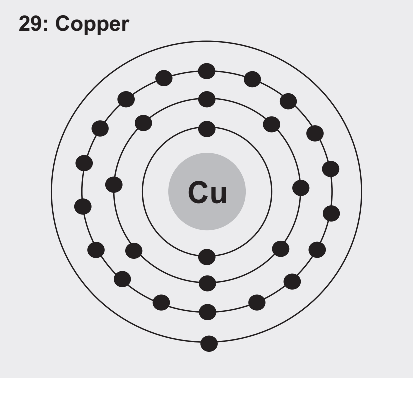


Fig. 3.31 The atomic model of copper (Cu)

In steel, cobalt does not form carbides, but rather inhibits grain growth, improves tempering resistance, wear resistance and heat resistance in highly alloyed, extremely temperature-resistant steels and superalloys. Cobalt is also used in the production of permanent magnet steels.

Copper (Cu)

Latin “Cuprum”, German “Kupfer”, atomic number 29 in the periodic table (Fig. 3.31).

Copper, gold, silver and tin were the first metals that people knew and used. Thus copper was already used by the oldest known cultures about 10,000 years ago. In the period from the 5th millennium BC to about the 3rd millennium BC there was a widespread use of copper, therefore also the name “copper age”. The Roman Empire (an area occupied by the Romans from the eighth century BC to the seventh century AD) was then the largest copper producer. Later, copper was alloyed with tin and lead to the harder bronze alloy (bronze age). Copper was also alloyed with zinc. The golden yellow brass was created, which was already known in ancient Greece.

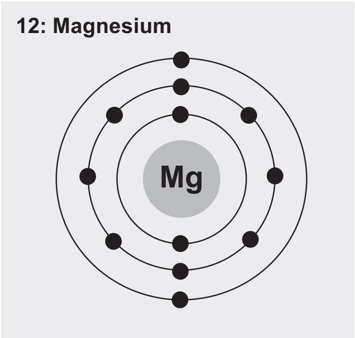
Copper rarely occurs in elemental form, but often as a mineral. Copper as a semi-precious metal is relatively soft, tough and very malleable. Therefore, copper has been and is still used as the best-known coin metal. Copper is also used as an excellent heat and electricity conductor.

Copper is only added to a few steel grades. Copper increases the yield strength and the yield strength-tensile strength ratio and improves toughness. Weldability is not affected. In acid-resistant, high-alloy steels, a copper content of over 1% improves resistance to hydrochloric and sulfuric acids. Copper is often considered a steel contaminant. It can accumulate under the scale of the steel, penetrate into the grain boundaries, and possibly increase the risk of cracking during hot forming.

Magnesium (Mg)

Latin “Magnesium”, German “Magnesium”, atomic number 12 in the periodic table (Fig. 3.32).

Fig. 3.32 The atomic model of magnesium (Mg)



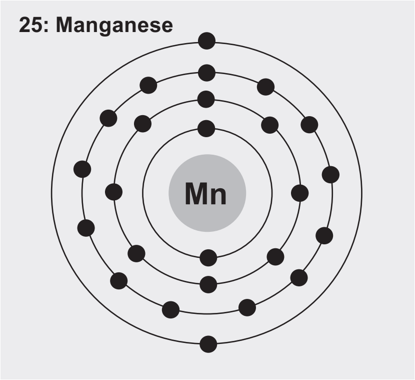


Fig. 3.33 The atomic model of manganese (Mn)

Magnesium is a light metal that is about 1/3 lighter than aluminum. In nature, magnesium does not occur elemental, but as a mineral in the form of carbonates, silicates, chlorides and sulfates, for example, dolomite, magnesite, serpentine.

Before it was possible to generate elemental magnesium, magnesium compounds had been known for a long time, e.g. Magnesia alba (magnesium carbonate) and Magnesia (magnesium oxide). The Scot *Joseph Black* (1728–1799) was the first to investigate these magnesium compounds. In 1828, *Antoine Bussy* (1794–1882) produced small amounts of pure magnesium. *Michael Faraday* (1791–1867) first obtained magnesium by electrolysis. Building on this, *Robert Wilhelm Bunsen* (1811–1899) developed a process for the large-scale production of magnesium by electrolysis of salt melts, which is still preferred today.

Magnesium is added to steel as a deoxidizing and desulfurizing agent. In cast iron, Magnesium creates spheroidal graphite.

Manganese (Mn)

From the French “manganèse” – “black Magnesia”, Latin “Manganum”, German “Mangan”, atomic number 25 in the periodic system (Fig. 3.33).

Manganese is a gray-white, hard and very brittle, relatively unrefined heavy metal with some properties similar to iron. For millennia, humans have used colors with manganese pigments. In 1774, *Johann Gottlieb Gahn* (1745–1818) first reduced elemental manganese. It only gained technical importance from 1860, when successful production of iron-manganese alloys was achieved. In nature, manganese occurs mainly as “brownstone” (collective term for manganese ore) and is produced technically as ferro-manganese, silico-manganese or as manganese metal by reduction (data in mass-%):

- *Ferro-manganese carburé: approx. 78% manganese*
- *Silico-manganese: approx. 65% manganese*
- *Manganese metal: 98 to 99% manganese*

Fig. 3.34 Ferro-manganese. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

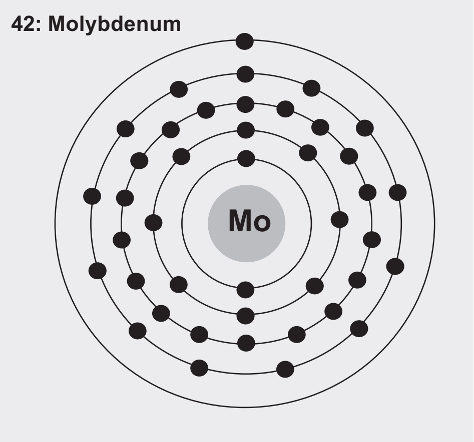


Fig. 3.35 The atomic model of molybdenum (Mo)

In steel mills, manganese is used as an alloying element in the form of the iron-containing prealloy ferro-manganese, as shown in Fig. 3.34.

Manganese acts as a deoxidizer, i.e. it removes oxygen from steel and simultaneously binds sulfur. This improves the hardenability of the steel. Manganese favors forgeability and weldability and increases the depth of hardening. Steels with more than 12 mass-% manganese are austenitic at high carbon content and resistant to impact wear (manganese steels).

Molybdenum (Mo)

Latin “Molybdaenum”, German “Molybdän”, ordinal number 42 in the periodic system (Fig. 3.35).

Fig. 3.36 Ferro-molybdenum. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

Molybdenum is a relatively hard, brittle, and easily worked heavy metal. It usually occurs as molybdenite (molybdenum disulfide). In 1778, *Carl Wilhelm Scheele* (1742–1786) produced molybdenum trioxide, MoO_3, from molybdenite, which is also known as “water lead oxide”. In 1781, *Peter Jacob Hjelm* (1746–1813) reduced elemental molybdenum from this oxide, which was long ignored. Only at the end of the nineteenth century were the useful properties of the alloying element molybdenum in steel observed.

Molybdenum is a strong carbide former, which improves the cutting properties of high-speed steels. In chromium-nickel and manganese steels, molybdenum increases hardness and reduces brittleness. It promotes fine-grain formation and favors weldability, increases strength and yield strength. Forgeability is impaired. In highly alloyed chromium and austenitic chromium-nickel steels, molybdenum increases corrosion resistance and heat resistance. Scaling resistance is reduced. The following molybdenum modifications are interesting for steel production (data in mass-%):

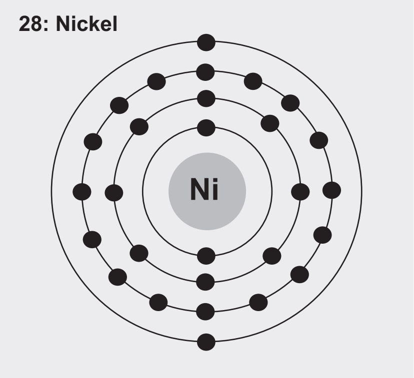


Fig. 3.37 The atomic model of nickel (Ni)

Ferro-Molybdenum: 60 to 72% molybdenum
Molybdenum oxide briquettes: approx. 62% Mo
Molybdenum metal: min. 99% molybdenum

Most of the time, molybdenum is added to steel or the steel melt in the form of the iron-containing pre-alloy ferro-molybdenum, as shown in Fig. 3.36.

Nickel (Ni)

Latin "Niccolom", German "Nickel", atomic number 28 in the periodic system (Fig. 3.37).

Nickel is a silver-white, magnetic, easily malleable and polishable metal. It has been used in copper-nickel alloys for several thousand years, but was first described as an element by *Axel Frederic Cronstedt* (1722–1765) in pure form. He called this metal nickel, derived from the mountain spirit nickel, which was said to have bewitched copper ore. As a metal, nickel only occurs in iron meteorites and in the earth's core. Under natural conditions, it occurs in nickel ores, e.g. in Pentlandite. Mining is economically viable at concentrations greater than 5% nickel. Nickel is an important alloying element for steel finishing. The following modifications are used for this purpose (data in mass-%):

- *Nickel metall: 99.7 or 99.9% Nickel*
- *Nickel cathodes: 99% Nickel*
- *Nickel discs: min. 99% Nickel*

Nickel is often alloyed in the form of nickel metal. Figure 3.38 shows such nickel metal as it is used as a pre-alloy in an electric steelworks for melting.

Nickel increases the notch toughness even in the low temperature range of engineering steels, e.g. in tool, case-hardening and cold-work steels. All transformation points of the steel are lowered by nickel. Nickel in contents of more than 7 mass-% leads to

Fig. 3.38 Nickel metal. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

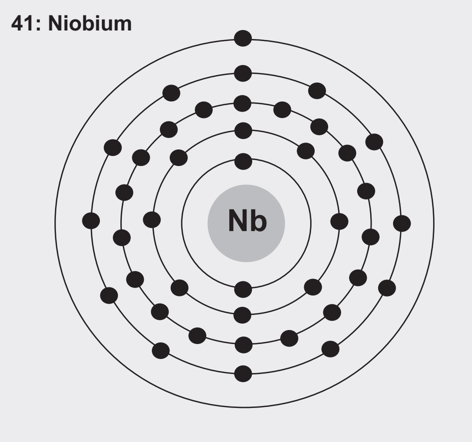


Fig. 3.39 The atomic model of niobium (Nb)

a strong expansion of the γ-area (austenite), thus to an austenite structure in high chromium-containing, corrosion-resistant steels. Nickel alone makes steel only rust-resistant, in austenitic steels in combination with chromium resistance is also achieved against oxidizing substances (high alloyed chromium-nickel steels). High, defined nickel contents lead to certain physical properties in steels, e.g. to very low thermal expansion (e.g. FeNi36). A large proportion of the generated nickel is used for the production of nickel and special alloys, e.g. for the resistance alloy "Constantan" (55 mass-% copper, 45 mass-% nickel). This alloy has a constant specific electrical resistance over a wide temperature range. Also interesting are the nickel-based superalloys (see Sect. 2.4.5: *Nickel Alloys and Special Materials*). These have been specifically developed for use at high temperatures and high corrosive stress (e.g. for gas turbine construction). Also nickel silver, a copper-nickel-zinc alloy with 10 to 26 mass-% nickel, is particularly corrosion-resistant and is used for cutlery and electronic devices. Mention should also be made of the copper-nickel alloy Monel with approx. 65 mass-% nickel, 33 mass-% copper and 2 mass-% iron. Monel is particularly resistant to the highly corrosive fluorine.

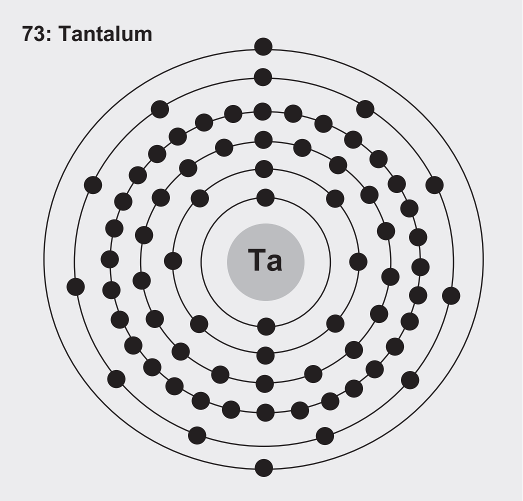
Niobium (Nb)

Latin "Niobium" (obsolete name: "Columbium" with short code Cb), German "Niob", atomic number 41 in the periodic table (Fig. 3.39).

Niobium is a ductile heavy metal. It occurs very rarely in nature and only in ores bound together with tantalum. The element niobium was discovered in 1801 by the English chemist *Charles Hatchett* (1756–1847). At that time he gave this element the name "Columbium" in honor of *Christopher Columbus* (1451–1506), the discoverer of America. Later, the German chemist *Heinrich Rose* (1795–1864) was also able to prove this element, which he called niobium. After more than 100 years, the official name niobium was finally established in 1950.

Niobium increases the heat resistance and creep resistance of steel. Therefore, niobium is used in particular in high-temperature, austenitic boiler steels.

Fig. 3.40 The atomic model of tantalum (Ta)



Tantalum (Ta)

Latin “Tantalum”, German “Tantal”, atomic number 73 in the periodic table (Fig. 3.40).

Tantalum is a very rare transition metal. It does not occur naturally, but is found in ores together with niobium. Therefore, until the middle of the nineteenth century it was thought that it was thought that the tantalum discovered in 1802 by *Anders Gustaf Ekeberg* (1767–1813) was the same element as niobium. It was *Heinrich Rose* (1795–1864) who, around 1844, was able to prove that there are two elements. Since these two elements are very similar and always occur together in the ores (one speaks of “association”), a separation into chemically pure metals is technically difficult and time-consuming.

Tantalum is mainly used for capacitors and because of its high corrosion resistance and compatibility with organic liquids for implants. The effects of the two most commonly used metals niobium and tantalum in steel can be described as follows:

- They are very strong carbide formers and are added as stabilizers in chemically resistant steels.
- Both elements are ferrite formers and reduce the austenite range of steels.

Tellurium (Te)

Latin “Tellus” (Earth), German “Tellur”, atomic number 52 in the periodic table (Fig. 3.41).

Tellur ium a technically unimportant, silver-white, metallic-looking semi-metal that can be easily powdered. It was discovered in 1782 by Austrian chemist *Franz Joseph Müller von Reichenstein* (1740–1825) during investigations of gold ores. Tellurium is very rare in nature and occurs in minerals, is expensive to produce and is obtained as a by-product from the production of copper and nickel.

Fig. 3.41 The atomic model of tellurium (Te)

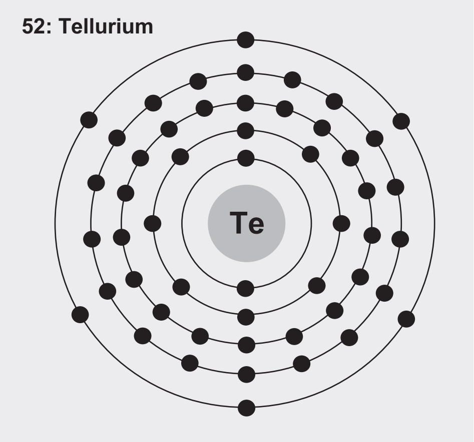
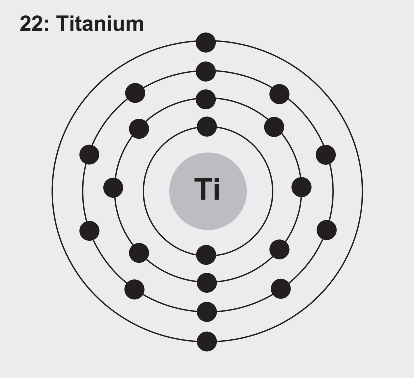


Fig. 3.42 The atomic model of titanium (Ti)



Trace amounts of tellurium are used as an additive in steel (<1 mass-%), cast iron, copper and lead alloys, and corrosion-resistant steels. It increases corrosion resistance, mechanical properties, and workability.

Titanium (Ti)

Latin "Titanium", German "Titan", atomic number 22 in the periodic table (Fig. 3.42).

Titanium is a light, solid, ductile, and corrosion-resistant transition metal. It is one of the ten most common elements in the Earth's crust and almost exclusively occurs in bound form in rocks and minerals. *William Gregor* (1761–1817) discovered titanium in a mineral from Cornwall (county in southwest England) in 1791. Four years later, *Martin Heinrich Klaproth* (1743–1817) also discovered this element, which he named titanium. However, it was not until 1831 that *Justus von Liebig* (1803–1873) was able to produce metallic titanium from ore. Titan has a remarkable high strength-to-density ratio. It is highly resistant to many media and forms a stable oxide protective layer in air.

The following properties justify its use in steel production:

- Titanium is a strong carbide former, strongly binds sulfur, desoxidizes, and denitrifies (removes oxygen and nitrogen from the steel melt).
- Titanium, even as a microalloying element with 0.01 to 0.1 mass-%, imparts high toughness and strength to steel.
- In corrosion-resistant steels, titanium prevents intergranular corrosion.
- Titanium also has grain-refining properties.
- The formation of titanium nitrides increases the creep strength.
- Titanium strongly constricts the γ-area (austenite).
- Titanium's tendency to segregation and banding in steel must be considered.
- At higher titanium levels in steel, titanium causes precipitation processes and is alloyed in permanent magnet alloys (securing high coercive force).

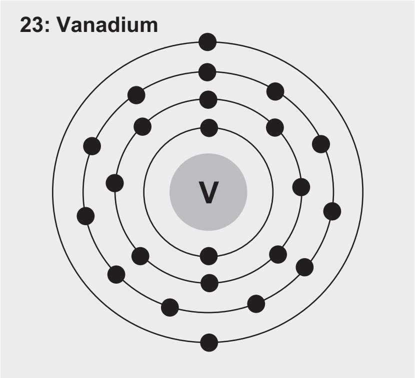
Vanadium (V)

Latin "Vanadium", German "Vanadium", atomic number 23 on the periodic table (Fig. 3.43).

Vanadium is a rare, nonmagnetic, in pure state soft and tough, forgeable heavy metal. It occurs only bound in ores. Vanadium was first discovered in 1801 by the Spanish mineralogist *Andrés Manuel del Río* (1764–1849) and initially called "Panchromium". But he was undecided and revoked his discovery. The Swedish chemist *Nils Gabriel Sefström* (1787–1845) succeeded in the rediscovery in 1830 and now called this element vanadium. In 1903, the first vanadium-containing steel was produced in England. From 1905, the use as a steel alloying element increased sharply when *Henry Ford* (1863–1947) used vanadium steels for the construction of his automobiles.

Today, the majority of the vanadium produced worldwide (over 85%) is used in steel metallurgy, mostly as a ferro vanadium alloy with 78 to 83 mass-% vanadium. Figure 3.44 shows such a ferro vanadium alloy.

Fig. 3.43 The atomic model of vanadium (V)



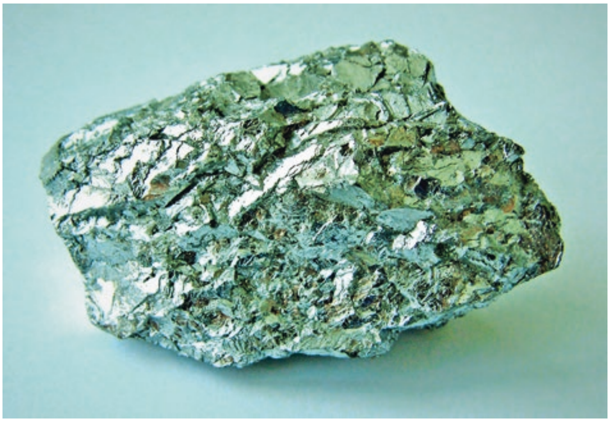


Fig. 3.44 Ferro vanadium alloy. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

Vanadium is a strong carbide former. This increases wear resistance, cutting edge retention and hot hardness in high-speed and hot-working steels as well as in heat-resistant steels. The carbide formation also increases the resistance to pressurized hydrogen. Depending on the intended use, different amounts of vanadium are added to the steels: in construction steels and tool steels up to approx. 0.2 to 0.5 mass-%, in high-speed steels up to approx. 5 mass-%. Vanadium refines the primary grain and thus the casting structure. Vanadium increases the hot resistance and annealing stability and reduces the overheat sensitivity of steels. In addition, the weldability of quenched and tempered steels is favored by the addition of vanadium.

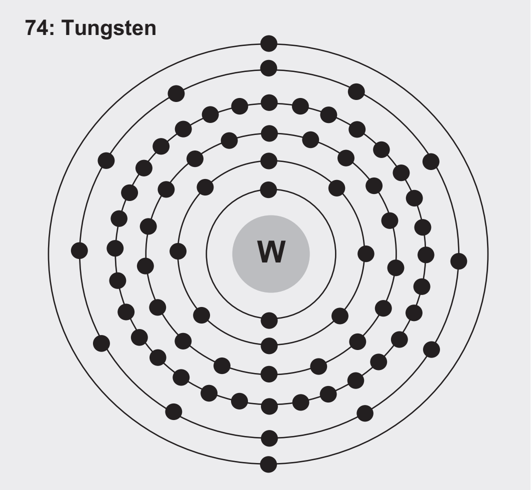


Fig. 3.45 The atomic model of tungsten (W)

Fig. 3.46 Ferro tungsten prealloy. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

Tungsten (W)

Latin “Wolframum”, German “Wolfram”, atomic number 74 in the periodic table (Fig. 3.45).

Tungstenis a very stable, white-glossy heavy metal, which has the highest melting point of all metals at 3410 °C. The glow-discharge in traditional incandescent lamps is therefore also a well-known application of tungsten. As early as the sixteenth century, the mineralogist *Georgius Agricola* (1494–1555) from Freiberg referred to a mineral that occurs in Saxon sphalerites. It made the zinc extraction more difficult or, according to contemporary statements, was like a “wolf that devoured the zinc”. Later this mineral was called tungsten. Metallic tungsten was first produced in 1783 by the Spanish brothers *Fausto de Elhúyar* (1755–1833) and *Juan José de Elhúyar* (1754–1796). Tungsten does not occur naturally. The most important tungsten ores are wolframite and scheelite.

More than 90% of world production is carried out as ferro-tungsten with 76 to 84 mass-% tungsten. In this form, as can be seen in Fig. 3.46, tungsten is used as a prealloy in steel mills.

Ferro-tungsten is used as an an ingredient for hard metalsand as an alloying element for tool steels (cold- and hot-work steels, and high-speed steels). The reason for this is that tungsten forms very hard carbides and thus makes the steel more resistant (increase in hardness and strength). At the same time, tungsten improves the heat resistance, the tempering resistance and the wear resistance at high temperatures. Another area of application are tungsten electrodes for resistance welding. Also in TIG- (tungsten-inert-gas) welding, electrodes made of tungsten or tungsten alloys are used. Because of the high melting point, tungsten-molybdenum alloys are used for turbine blades.

Zinc (Zn)

Latin “Zincum”, German “Zink”, ordinal number 30 in the periodic system (Fig. 3.47).

Fig. 3.47 The atomic model of zinc (Zn)

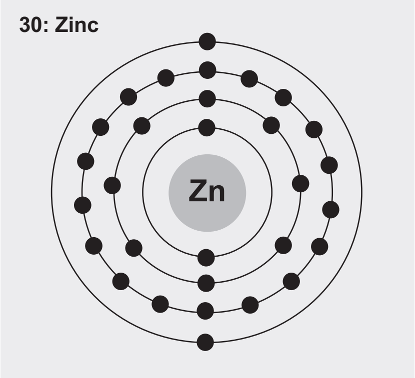
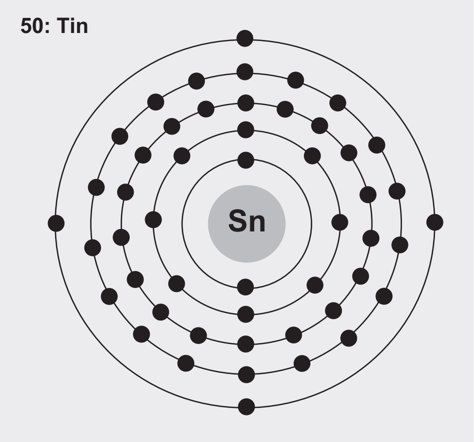


Fig. 3.48 The atomic model of tin (Sn)



Zinc is a bluish-white non-ferrous metal that quickly forms a corrosion-resistant layer in moist air. Based on this, today almost half of the zinc production is used for the corrosion protection (galvanizing) of iron and steel products. Zinc is rarely found in a pure state, mostly in zinc sulfide ores. Already in ancient times, zinc was used as an alloying element for the production of brass.

However, for steel production, zinc is not a usable element.

Tin (Sn)

Latin “stannum”, German “Zinn”, atomic number 50 in the periodic table (Fig. 3.48).

Tin is a silver-white, shiny, very soft heavy metal with a very low melting point of 231.9 °C. The metallurgical production of tin from ores began somewhat later than that of copper. First, tin was used as an admixture to copper for the production of bronze. More generally known applications of tin were later utensils and decorative objects (tin

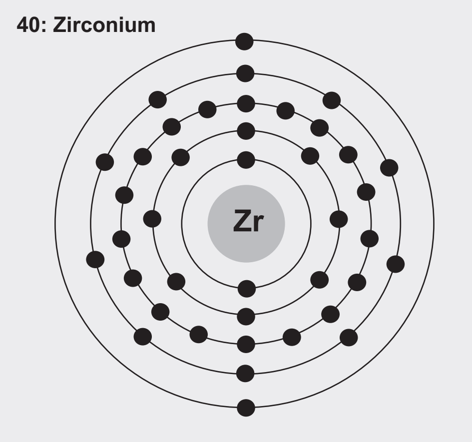


Fig. 3.49 The atomic model of zirconium (Zr)

casting), tinning of canned goods, the production of organ pipes, finally solder, white sheet (tinned iron sheet for canned goods), costume jewelry and tinsel.

Tin is a steel contaminant. It behaves similarly to copper. Tin enriches itself under the scale layer, penetrates along the grain boundaries and causes cracks and brittleness during soldering. In addition, tin is prone to severe segragation and constricts the austenite area.

Zirconium (Zr)

Latin “Circonium”, German “Zirkonium”, atomic number 40 on the periodic table (Fig. 3.49).

Zirconium is a ignoble, very corrosion-resistant, almost insoluble heavy metal. It only occurs in minerals, with the mineral zircon ($Zr[SiO_4]$) already known as a gemstone since ancient times. In 1789, *Martin Heinrich Klaproth* (1743–1817) discovered zircon in a mineral from Ceylon. And *Jöns Jakob Berzelius* (1779–1848) was the first to discover the metal zirconium in 1824. Zirconium forms several different compounds, with zirconium dioxide (ZrO_2) being the most important oxide. Such zirconium compounds are used primarily in technical ceramics, for example for ball bearings and in dentistry as well as for implants.

Zirconium is used metallurgically in steel production as an additive for deoxidation, denitrification and desulfurization. Zirconium is a carbide former and causes a narrowing of the austenite area. As an additive to sulfur-containing machining steels it promotes the formation of sulfides and leads to the avoidance of red fracture. Zirconium increases the service life of heating conductor materials.

▶ A final overview of the explained alloying elements and their influence on selected steel properties is shown in Fig. 3.50. This was created based on (Wegst & Wegst, 2019).

Effect of alloying elements on steel properties

Alloying element	Mechanical properties								Cooling speed	Carbide formation	Wear resistance	Forgeability	Machinability	Scaling	Nitriding capability	Rust resistance
	Hardness	Strength	Yield point	Stretch	Lacing	Notched impact	Elasticity	Heat resistance								
Silicon Si	▲	▲	▲▲	▼	~	▼	▲▲▲	▲	▼	▼	▼▼▼	▼	▼	▼	▼	—
Manganese Mn (for pearlitic steels)	▲	▲	▲	~	~	~	▲	~	▼	~	▼▼	▲	▼	~	~	~
Manganese Mn (for austenitic steels)	▼▼▼	▲	▼	▲▲▲	~	—	—	—	▼▼	—	—	▼▼▼	▼▼▼	▼▼	—	—
Chromium Cr	▲▲	▲▲	▲▲	▼	▼	▼	▲	▲	▼▼▼	▲▲	▲	▼	—	▼▼▼	▲▲	▲▲
Nickel Ni (for pearlitic steels)	▲	▲	▲	~	~	~	—	▲	▼▼	—	▼▼	▼	▼	▼	—	—
Nickel Ni (for austenitic steels)	▼▼	▲	▼	▲▲▲	▲▲	▲▲▲	—	▲▲▲	▼▼	—	—	▼▼▼	▼▼▼	▼▼	—	▲▲
Aluminium Al	—	—	—	—	▼	▼	—	—	—	—	—	▼▼	—	▼▼	▲▲▲	—
Tungsten W	▲	▲	▲	▼	▼	~	—	▲▲▲	▼▼	▲▲	▲▲▲	▼▼	▼▼	▼▼	▲	—
Vanadium V	▲	▲	▲	~	~	▲	▲	▲▲	▼▼	▲▲▲▲	▲▲	▲	—	▼	▲	▲
Cobalt Co	▲	▲	▲	▼	▼	▼	—	▲▲	▲▲	—	▲▲▲	▼	~	▼	—	—
Molybdenum Mo	▲	▲	▲	▼	▼	▲	—	▲▲	▼▼	▲▲▲	▲▲	▼	▼	▲▲	▲▲	—
Copper Cu	▲	▲	▲▲	~	~	~	—	▲	—	—	—	▼▼▼	~	~	—	▲
Sulphur S	—	—	—	▼	▼	▼	—	—	—	—	—	▼▼▼	▲▲▲	—	—	▼
Phosphorus P	▲	▲	▲	▼	▼	▼▼▼	—	—	—	—	—	▼	▲▲	—	—	—

▲ Increase ▼ Decrease ~ approx. constant — not characteristic or unknown

Fig. 3.50 Simplified representation of the effect of the alloying elements on the steel properties

3.3.5 Accompanying or Trace Elements

▶ In steel production, especially in the arc furnace steel production from scrap, unwanted trace or accompanying elements can be introduced into the steel. In order to eliminate the possibility of small quantities of these elements representing a disadvantage to the steel properties, i.e. being harmful, the steel manufacturer must keep their proportion as low as possible. This often means a high metallurgical effort in the steelworks.

In the relevant material standards, no fixed limit values are specified for the content of trace elements. This also applies to such trace elements which, according to previous experience, might have an undesired effect at a certain content. However, the limits for this are fluid and very different for the different steel grades. Since the requirements of the material standard have to be met for a specific property profile of the steels, the steel manufacturer must also take into account the absolute content of various trace elements which are potentially harmful and limit this content by internal measures. However, an arbitrary or precautionary limitation of trace elements can lead to unjustified high production costs and should always be agreed upon between the steel producer and the consumer in a factual manner (Wilke, 2007). The remark in DIN EN 10088-3, Table 3, could serve as a basis for this:

> *"Elements not listed in this table"* (Note: These are the trace elements that are not always listed in the steelworks documents in the chemical analysis.) *may not be intentionally added to the steel without the buyer's consent. Appropriate measures must be taken to prevent the supply of such elements from scrap and other materials used in production that would impair the mechanical properties and usability of the steel."*

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Steelmaking

4

Steel - what a material: So many different steels, so many different alloys with so many alloying elements, so many possibilities for influencing the properties, so many production technologies and above all so versatile. No other material is as impressively complex, as universal and fascinating and still excites with new things. Steel has gained a significant importance in the past and present of mankind (Schwarz, 2013). And if you consider the beginnings of iron and steel production up to today's production, processing and applications, the importance of steel becomes even clearer.

4.1 From the History of Steel

Iron as "metal of heaven", that is, meteoritic iron, was already known before 3000 BC. But the exact point when people first deliberately produced and used iron and other metals is still shrouded in the mist of human history. There is only little concrete evidence. Most of the early objects made of iron have irrevocably rusted over the millennia.

Much has already been researched, new discoveries are being made. Random findings and targeted excavations, as well as new scientific methods for determining the age of found objects, are constantly bringing new insights. In this way, the chronicle of iron becomes clearer and clearer; but it is also so diverse that a comprehensive historical overview is hardly possible. In different regions of the then high cultures and peoples, the use of metals and especially iron began at different times. Knowledge and experience were passed on orally, but often in wars and social upheavals much was lost again. Thus even today steel is surrounded by a hint of the unknown and the mysterious.

J. Schlegel, *The World of Steel*, https://doi.org/10.1007/978-3-658-39733-3_4

Countless textbooks and scientific publications, including popular science works, deal extensively with the historical development of iron and steel production, processing, the technical progress of plant technology, and scientific findings on the material steel, e.g. Lietzmann et al. (1984), Lietzmann and Schlegel (1992), Köthe (2011), Beckert (1981), Kljatschko (1982), Burghardt and Neuhof (1982), Piersig (2012), Schlegel (2015) and others. Therefore, only essential points of iron production and processing from the beginnings to the present day will be pointed out below. The timeline in Chap. 13 also assigns important social and technical events to this.

Metalworking in Early Times

It is interesting to note that people began working with pure metals like gold, silver, and copper very early on, probably after 10,000 BC. This means that they hammered these metals with stone tools in order to make household items, weapons (spearheads), or even jewelery. This took place during a time when people had not yet learned to produce metals from ores on purpose. In these early times they were not familiar with high melting temperatures and had no experience with metallurgy whatsoever.

The use of meteoritic iron is well documented: The Inuit of Greenland made knives from it, the Maya of Yukatan and the Indios of Peru worked with meteoritic iron using hammers made of flint. A piece of a dagger dating back to 3100 BC was found in Ur in Mesopotamia (present-day Iraq). It is one of the oldest pieces of meteoritic iron found to date (Lietzmann, 1984).

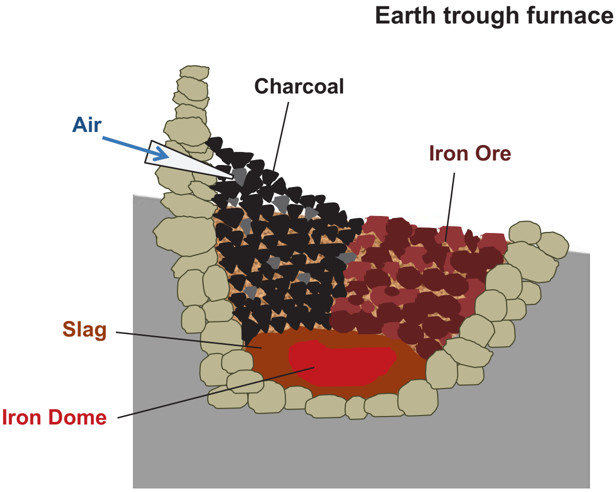
The Beginning of Metallurgical Production of Iron from Ores

After a long period of random discoveries, people also mastered the metallurgical processing of found ores. For this they had to gain the technical ability to generate very high temperatures and know the basic process of smelting metals from ores with charcoal at high temperatures. This smelting means chemically reducing, i.e. removing oxygen from the metal oxides in the ore to obtain metals. When and where exactly this happened is not conclusively documented. Probably the early centers of metallurgical extraction of iron from collected, later mined ores, where the earliest copper objects were found, emerged there: in the mountain ranges of Anatolia and the Armenian Highlands to southern Iran. In furnaces in which copper metal was melted, iron ore could also be reduced to iron. But since the temperatures were relatively low, a only doughy, heavily contaminated iron was created, “sponge iron” (Ledebur, 1892).

Only much later did people realize that by forging these lumps a useful iron material could be produced. This processing of the still red-hot, doughy lumps already required a lot of experience. The lumps were literally hammered through, whereby the lighter charcoal and slag residues could be separated from the iron or pressed out. At the same time, the porous iron was compressed.

The first furnaces used for the process of iron ore reduction were the earth trough furnaces. These melting furnaces were very simple in structure and usually located on a

Fig. 4.1 Schematic illustration of an earth trough furnace for iron smelting around 500 BC



slope in the open countryside. Figure 4.1 shows the structure of such an earth troughfurnace.

It is hard to imagine from today's perspective that the miner, metallurgist and blacksmith of that time, time was actually able to master the quite complicated reactions during the ore reduction process. Only through the experience handed down from generation to generation, and with the help of nature, with fire, wood, ores, clay and water, was he able to produce iron in the form of a spongy-porous lump at an initial temperature of approximately 700 to 900°C. To remove this lump from the furnace, the furnace had to be dismantled again and again. Before each new loading and reduction process, it was then rebuilt with field stones and clay. This metallurgical process later developed into the "bloomery process" in low shaft furnaces made of clay. Figure 4.2 shows the construction of such a blast furnace.

Blast furnaces were already able to achive temperatures above 1000°C via the chimney effect. Wood charcoal and iron ore were placed in layers above a pile of wood. Air was blown in through lateral nozzle openings by means of a bellows. The reduction of the ore to iron took place in the doughy state of the bloom and the slag "ran" out of the furnace after opening it up, hence the reason for the designation of such a furnace as a blast furnace or blast stove. These furnaces produced iron blooms, which also had to be freed from coal residues and slag during subsequent forging. Depending on the size of the furnace and the process, iron with an uneven carbon content and a maximum weight of 50 kg could be produced. For one kilogram of iron bloom, about 30 kg of wood charcoal had to be used at that time.

Lump Furnaces - The Predecessors of the Blast Furnace

Bloomery process was used in Central Europe for more than 3000 years up to early modern times. It took a while until the furnaces for iron smelting were no longer built in the

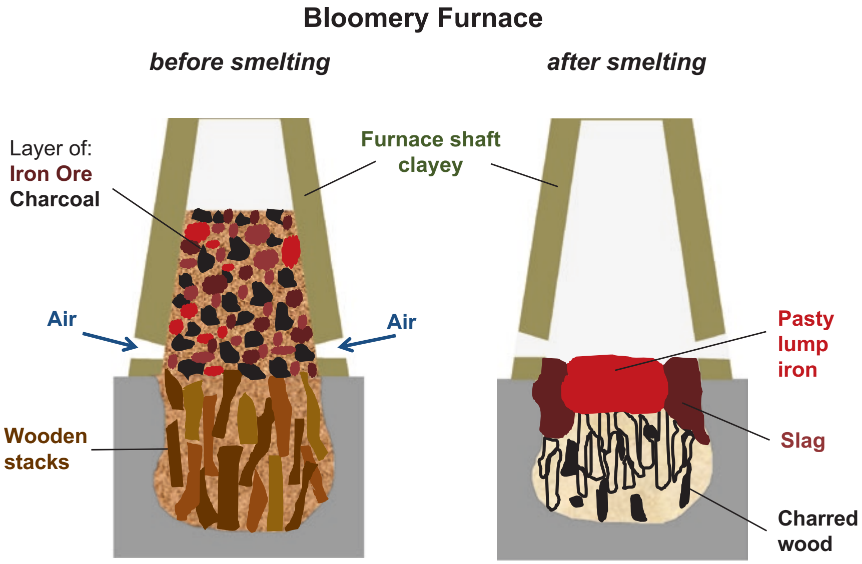


Fig. 4.2 Simplified representation of a blast furnace ("bloomery furnace")

ground or on a slope, but above ground in height. From the 12th century onwards, the predecessors of the of the blast furnaces known today, the so-called "lump furnaces" or "wolf furnaces" arose. These were about 3 to 5 m high. The injection of air ("wind") was already carried out with bellows, driven by water wheels. And the iron produced was further processed in water-powered hammer mills.

Georgius Agricola (1494–1555) became known for his work for mining and metallurgy in the sixteenth century. He wrote the work "De re metallica", which appeared in 1556. The first German version under the title "Vom Bergkwerck XII Bücher" (Technology of Mining and Metallurgy) was published in 1567. In the 9th book of this work, *Agricola* also describes lump furnaces. Figure 4.3 shows a graphic from this work with the loading of such a lump furnace with ore.

It was the epoch of the high Middle Ages in Europe, the center of the Holy Roman Empire; the time of chivalry and the Crusades. The demand for weapons was enormous. So it is not surprising that it was precisely during this time that the technology of hardening iron was developed; primarily for the production of weapons.

The First Blast Furnaces

In the middle of the fourteenth century, the first blast furnaces were built, similar to the bloomery furnaces or lump furnaces, only much taller and with stronger blowers. Nevertheless, these furnaces already delivered up to one ton of liquid iron per day. It was still a very brittle raw iron with a lot of carbon. This carbon content had to be reduced to produce malleable iron, i.e. steel. This technology, called "refining", was invented in the

Fig. 4.3 Masonry lump furnace, depiction by *Agricola* from the 9th book of his work “Vom Bergkwerck XII Bücher”. (Photo: Schlegel, J. from the facsimile printing “Vom Bergkwerck XII Bücher”, Deutscher Verlag für Grundstoffindustrie, Leipzig 1985)

middle of the fourteenth century: The raw iron produced in the blast furnace was subsequently treated in a wood charcoal fire with constant fresh air supply. In this way, the excess carbon burned of, i.e. chemically the oxygen from the air combined with the carbon from the liquid raw iron and escaped as a gas. Unwanted accompanying constituents in the iron were also oxidized during the refining process and settled on the melt surface as lighter slag. A quite clean forge iron was the result. These “refining hearths” could initially take up 150 to 200 kg of raw iron. The metallurgical transition to steel production was set up.

The early blast furnaces had only a limited capacity and were far from comparable to our modern blast furnaces. Over the course of the fourteenth to sixteenth centuries, these blast furnaces were further developed, with wood charcoal still being used for smelting into the eighteenth century. Production increased steadily, and the demand for steel products grew. This soon led to a shortage of wood charcoal. It was *Abraham Darby* (1676–1717), an English iron manufacturer, who replaced wood charcoal with coke in the blast furnace from 1709 onwards. This made it possible to significantly increase the production of pig iron. The first coke blast furnace in Germany went into operation in the Royal Ironworks in Gleiwitz in 1796.

Puddling Furnaces

The increasing use of coke and also hard coal in the blast furnace had also paved the way for the treatment of pig iron in the so-called "puddling furnace", derived from *"to puddle"* – stir. This process was invented by the Englishman *Henry Cort* (1740–1800). It served to convert the pig iron produced in the blast furnace into wrought iron. For this purpose, a "flame refining hearth" was used, as shown in Fig. 4.4.

In the furnace, the hot, viscous raw iron was moved by puddlers with iron rods. This way, the surface of the raw iron constantly came into contact with the flowing gases that were created when coal was burned. As a result, the raw iron finally became the low-carbon "puddle iron". However, the lumps of this puddle iron were still interspersed with slag (non-metallic oxides), which was in turn expelled by forging, now with a steam hammer. Such a puddling furnace could process a maximum of 3 t of raw iron per day.

In the nineteenth century, the puddling process, which used cheap coal, was widespread. For example, *Alexandre Gustave Eiffel* (1832–1923) used pre-fabricated iron parts made by the puddling process to build his famous Eiffel Tower.

It was the time of the beginning Industrial Revolution in England when *James Watt* (1736–1819) invented the steam engine. Steel production could no longer satisfy the increasing steel hunger of industry. Refining raw iron was very laborious and not productive enough. Then, in 1855 the English engineer *Henry Bessemer* (1813–1898) invented the process named after him, the Bessemer process. It was the first really cheap process

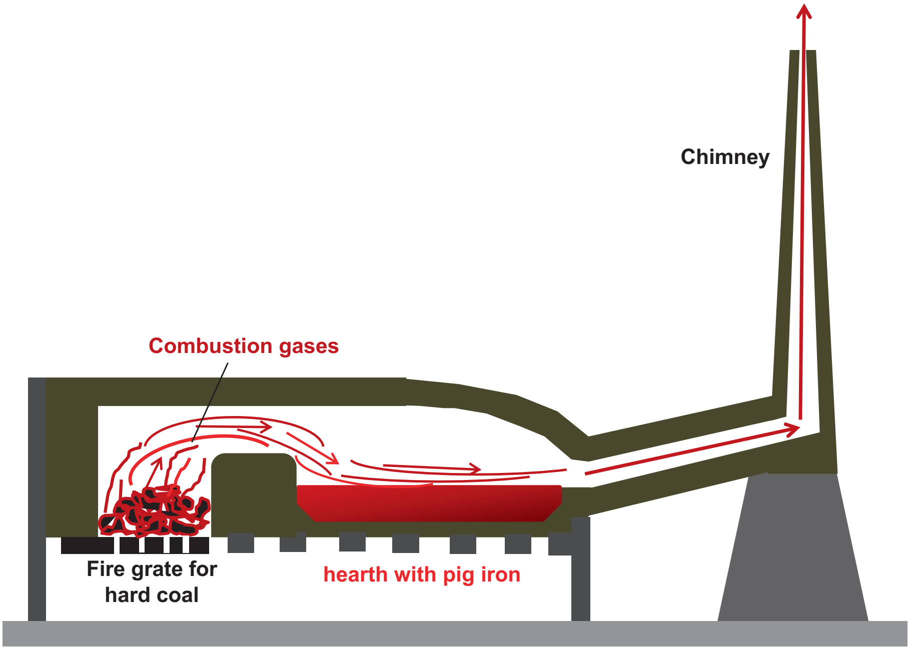


Fig. 4.4 Principle representation of a puddling furnace ("flame refining hearth")

for mass production of steel, which shaped steel production decisively until the end of the nineteenth century.

The Bessemer Process for Refining Pig Iron

In a pear-shaped, tilt-mounted furnace (“Bessemer-pear”), compressed air was injected into the liquid pig iron from below. This caused the iron impurities carbon, silicon, manganese and others to burn. The furnace lining of this converter consisted of a silica-containing quartz sand, so basically an “acid lining”. Figure 4.5 shows a historical drawing of a Bessemer-pear with a simplified sectional view of this “bottom-blowing” converter. Up to 3 t of almost carbon-free steel could be produced in a treatment session of 20 min. However, the disadvantage was that phosphorus could not be removed as a steel contaminant, so only phosphorus-poor pig iron could be “refined” into steel.

The Thomas-Gilchrist Process

Since there were no suitable phosphorus-poor iron ore deposits in Germany at that time, phosphorus-poor iron ore and raw iron had to be imported. The way out for the German steel industry was the introduction of the Thomas-Gilchrist process invented by the metallurgists *Sidney Thomas* (1850–1885) and *Percy Carlyle Gilchrist* (1851–1935). This process only represented a small change to the Bessemer process. Figure 4.6 shows, for example, the Thomas converter of the former Hörder Kesselschmiede (height 7 m, weight 64 t). It was in operation at the Thomas steelworks Phoenix-Ost until 1964 and is now a historic monument to steel metallurgy.

The lining of the equally pear-shaped Thomas converters was switched to a basic-acting mixture. This made it possible to refine phosphorous-containing pig iron in particular. The phosphorous that got into the pig iron was slagged with a lime addition. This slag

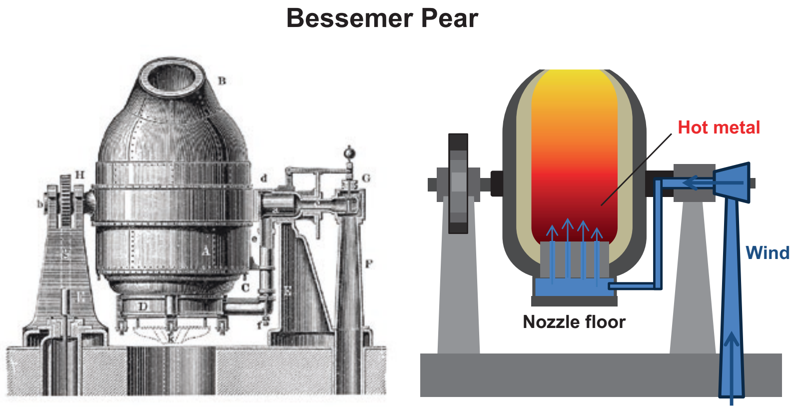


Fig. 4.5 Historical drawing of a Bessemer converter with a simplified sectional view for comparison. (Historical drawing from the Internet: https://de.academic.ru/pictures/dewiki/66/Bessemer-birne.jpg)

Fig. 4.6 Thomas converter of the former Hörder Kesselschmiede

was used in agriculture, finely ground as phosphate fertilizer under the name "Thomas meal". By the way, after the Bessemer or Thomas process an external heat supply was not necessary during refining. The oxidation process of the carbon provided sufficient heat to keep the steel liquid during the refining process. By refining with air, nitrogen and hydrogen were inevitably dissolved in the steel. Nitrogen forms brittle nitrides with iron and the other alloying elements. The steel is less tough as a result, and during steel application, nitrogen embrittlement (material fatigue) was added. In addition, Thomas steels were poorly weldable due to the high hydrogen content.

Thomas steel was used mainly for the production of rails, sectional iron and sheets until the 1970s. In the early 1980s, production of Thomas steel was discontinued in most countries. The oxygen-blowing process (LD process) now replaced the wind-refining process.

Parallel to the development of the processes for pig iron refining, the blast furnace in the form of the typical conical shaft furnace for pig iron production also experienced a giant technical development.. From 1828, hot air was blown in instead of cold air, as proposed by *James Beaumont Neilson* (1792–1865). To do this, a so-called "blower heater" was used. This led to a significant saving in coke. The blast furnaces were now getting taller (up to 36 m) and today have capacities of over 10,000 t per day. Figure 4.7 shows, for example, one of the most modern blast furnaces in Europe, blast furnace 8 of Thyssenkrupp Steel Europe AG in Duisburg. This blast furnace can produce up to 6000 t of pig iron per day.

Fig. 4.7 View of blast furnace 8 of Thyssenkrupp Steel Europe AG in Duisburg. (Photo: Thyssenkrupp Steel Europe AG)

The Crucible Melting Process

In the middle of the eighteenth century, *Benjamin Huntsman* (1704–1776) invented the crucible melting process for special applications (e.g. for watch spring and tool steel). He treated the already forgeable iron produced by puddling or refining in an externally heated crucible. This further decarbonized the pig iron via the additions of iron oxide, and for the first time a steel with less than 2.1 mass-% carbon was created. At the beginning of the nineteenth century, the process was improved by Krupp in Essen and introduced for larger quantities. However, this time-consuming and very special method never gained greater importance for steel production.

The Siemens-Martin Furnace

With the further development of the blast furnace, the process for the purification of pig iron, known as the "Siemens-Martin process", became widely used in the first half of the twentieth century. This process was invented by the engineers *Friedrich Siemens* (1826–1904), *Wilhelm Siemens* (1823–1883), *Pierre-Émile Martin* (1824–1915) and his father *Émile Martin* (1794–1871). The difference to the blast furnace of *Huntsman* consists in the fact that the temperature in the Siemens-Martin furnace can be increased to 1800°C

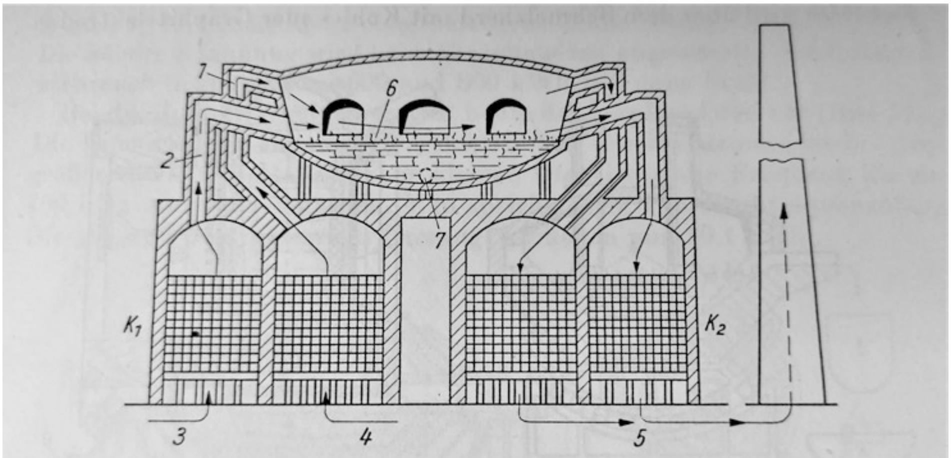


Bild 9. Schematischer Schnitt durch einen Siemens-Martin-Ofen

1 Heißluft, 2 Heißgas, 3 Kaltgas, 4 Kaltluft, 5 Abgas zum Kamin, 6 Verbrennung, 7 Abstich, K_1 und K_2 Kammern für die Regenerativfeuerung

Fig. 4.8 Sectional drawing of the Siemens-Martin furnace. (Source: Eisenkolb [1961], Volume III, page 33)

by a special regenerative firing in chambers under the furnace. Figure 4.8 shows a sectional view of this type of Siemens-Martin furnace with such a lower furnace and an upper furnace (melting space for the pig iron).

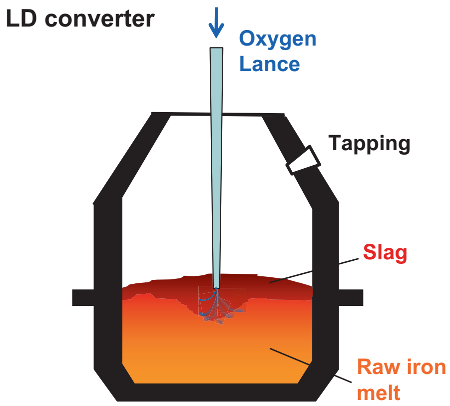
Generator gas or oil was used as fuel. The hot flame gases were conducted over the raw iron melt and could, like the additions of scrap, raw iron ore and lime, act "oxidatively". This produced liquid steel, first in smaller quantities of less than 10 t, later with the use of liquid gas up to 600 t per tapping (Burghardt & Neuhof, 1982).

With the further development of the oxygen-blowing process, the Siemens-Martin process was displaced. The last German Siemens-Martin furnace, by the way, came to a standstill in Brandenburg/Havel in 1993. Also the "bottom-blowing processes" according to Bessemer and Thomas-Gilchrist are no longer of importance today. In the Neue Maxhütte in Sulzbach-Rosenberg, the last German bottom-blowing OBM converter was shut down in 2003. For this converter, oxygen in combination with fuel gas (butane, propane) was blown into the raw iron through the bottom for refining. Hence the name "Oxygen-Bottom-Maxhütte" or "Oxygen-Bottom-Blowing-Metallurgy-Process".

The Linz-Donawitz Process (Oxygen-Blowing Process LD)

Since the 1950s, the oxygen-blowing process has been used in Linz-Donawitz (named after the locations of the Austrian steel mills in Linz and Donawitz). This LD process is an improvement of the Thomas process. Instead of air, oxygen is blown into the raw iron melt in the converter using a lance. The blowing time can be up to 20 min. Figure 4.9 shows a simplified oxygen-enriched converter.

Fig. 4.9 Schematic diagram of an LD converter



- Today, the primary way of steel production from ore via the use of a blast furnace for pig iron production in combination with a blast furnace converter for refining is referred to as the "blast furnace converter route". The second way of steel production is "electrical furnace steelmaking", the basics of which were already known over 100 years ago: With the energy of the arc, scrap steel is melted. This process was developed in 1904 by *Paul-Louis Heroult* (1863–1914). Only with the further development of power generation and the thus possible provision of sufficient power capacities did the melting of metals with electrical energy come into production use at the beginning of the twentieth century (Burghardt & Neuhof, 1982).

4.2 Steel Production

- Iron is the fourth most common element in the earth's crust. The reserves of iron ore are therefore large and globally distributed, and a secure future can be predicted the steel metallurgy. Iron must be won from the mined iron ores by separating the oxygen. This chemical reaction is called "reduction", industrially also "smelting".

  A look at the history of iron and steel metallurgy shows how long and laborious the path was and how long it took until people understood the processes taking place during smelting and could also describe them chemically. These, however, were the prerequisites for the further development of the technology as well as the plants for industrial steel production.

As mentioned, oxygen must first be separated from iron to produce pig iron (crude iron). Subsequently, further treatment in a converter ensures a defined, lower carbon content and thus the production of the desired raw steel (crude steel). This is the classical way of primary steel production from ore, the so-called blast furnace-converter route. More than

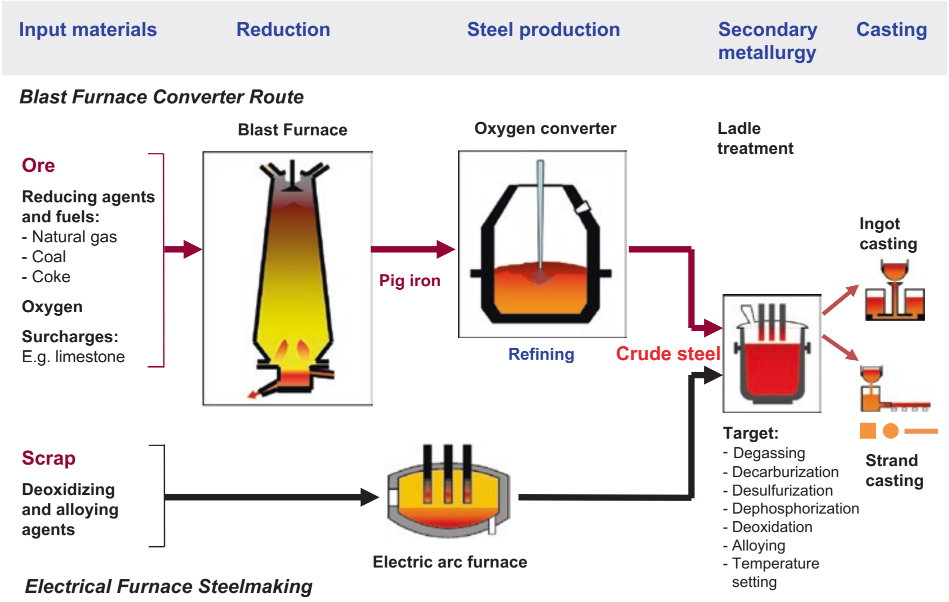


Fig. 4.10 The process routes of blast furnace converter route and electrical furnace steelmaking

40% of the world's steel production is done via the second way by means of electrical furnace steelmaking. This process, also known as secondary steel production from scrap, represents a typical recycling process. Both process routes produce raw steel, which must undergo a subsequent fining in order to achieve the exact alloying and purity settings. In practice, this is referred to as "secondary metallurgy" or "ladle treatment". After completion of this fining process and release of the melt, "shaping" takes place, i.e. pouring the liquid steel into ladles to form ingots or continuously into strands. Figure 4.10 shows a simplified scheme for the process routes of steel production.

4.2.1 Blast Furnace Converter Route

The Blast Furnace Process

Without going into process-typical details and all chemical processes of the blast furnace process, the production of pig iron in the blast furnace is simplified as follows (see Fig. 4.11):

Added through the opening at the upper shaft end (furnace top):

- *the iron ore in lumpy form, as pellets* (sieved and ground iron ore, formed into porous balls with binders and additives and fired in furnaces) or as *sinter* (compound of mixed ores, fluxes and coke fired or "sintered" in a continuous furnace),

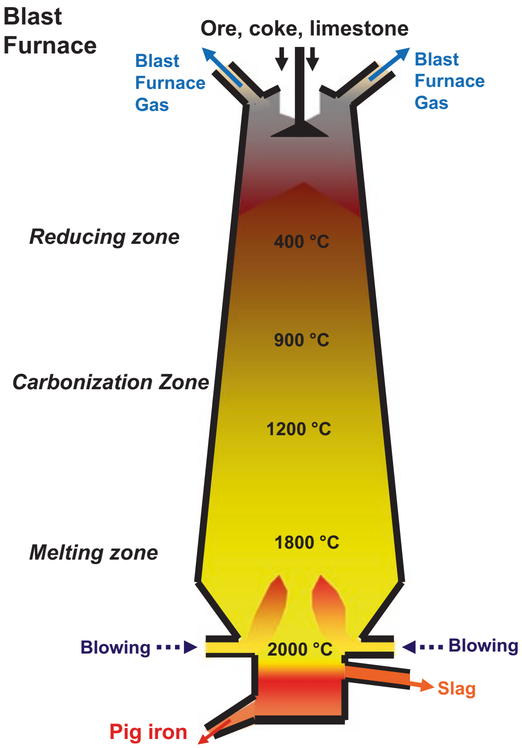


Fig. 4.11 Cross section (simplified) through a modern blast furnace with the three main zones: reduction, coking and melting zone

- *coke,*
- *additives* (e.g. limestone).

This charge (also called “loading”) now moves down through the conical shaft of the blast furnace through various thermal reaction zones. The necessary hot air (wind) is constantly blown in through nozzles. The coke acts as a reducing agent, forming carbon monoxide with the air, which reduces the iron oxide present in the ore. The resulting iron collects at the bottom as liquid pig iron. The accompanying constituents in the ore are converted into a thin liquid slag by the additives (e.g. limestone). This slag collects at the bottom of the frame on the surface of the liquid pig iron, because it has a lower density than the pig iron. At exactly specified intervals, the slag and the pig iron are discharged separately (“tapping”). In this way, the blast furnace process is continuous and the blast furnace is only shut down and put out of service on the rare occasion when the inner wall is worn out and has to be renewed.

Today’s blast furnaces have a total volume of over 4000 m^3. They can be in operation for up to 20 years. Then the entire lining has to be replaced. The slag produced daily is processed and used as a building material in the cement industry or in road construction. The blast furnace gases are also used chemically and energetically, see Chap. 10: *By-products and Waste.*

in the Converter

The raw iron produced in the blast furnace still contains a lot of carbon, which must be reduced to less than 2% by mass in a further process step. This is done today in a converter, also called a blast converter. Oxygen is blown onto and into the liquid raw iron via a lance. This “oxidizes” the carbon. This process is also called “refining” of the raw iron. The addition of an amount of approximately 20% scrap steel prevents the melt from overheating. The unwanted accompanying constituents in the iron oxidize to a gas or are slagged with the addition of lime. After the refining process, the converter is tipped and the finished raw steel flows through the tapping hole into a ladle. Various elements must then be added to the liquid raw steel.

The largest steel mill in Germany that operates this primary steel production from ore via the described blast furnace-converter route is the Thyssenkrupp steel mill in Duisburg. Figure 4.12 provides a view of the Thyssenkrupp Steel Europe AG oxygen steel mill in Duisburg with two LD converters (enclosed), secondary metallurgical treatment facilities, a continuous casting plant, and a rolling mill.

Fig. 4.12 View of the Thyssenkrupp Steel Europe AG oxygen steel mill in Duisburg. (Photo: Thyssenkrupp Steel Europe AG)

4.2.2 Other Iron Ore Reduction Methods

▶ In addition to the described process of the blast furnace-converter route, other special processes have been developed. The aim of these processes is to reduce the iron ore directly, i.e. without the use of coke and without a blast furnace. This results in the terms "direct reduction" and "smelting reduction".

In the **direct reduction**, the oxygen is removed from the ore at low temperatures (iron oxide is reduced). The reducing gas is usually natural gas, converted into hydrogen and carbon monoxide. Neither coal nor coke is needed and no slag is produced. The product is a porous iron sponge, which must subsequently be melted in an electric arc furnace. This reduction process (the best known today is the **Midrex process**) is particularly suitable for small production quantities, i.e. for smaller steelworks, as are in operation, for example, in India, Iran and Saudi Arabia.

In the **smelting reduction** the ores are reduced to sponge iron which is then converted into pig iron using coal and oxygen. This two-stage process (**Corex process**) combines the above-mentioned process of direct reduction (pre-reduction of the iron ore to sponge iron) with a subsequent melting process (final reduction) to obtain pig iron which is comparable to that from the blast furnace process.

▶ The vision for the future is direct production of steel from iron oxides without intermediate steps and with as little CO_2 as possible, e.g. by means of **hydrogen plasma smelting reduction** (Hydrogeit 2020).

4.2.3 Electrical Furnace Steelmaking

▶ In addition to being produced from ore, steel is also produced in electric steel mills. The melting of steel scrap takes place using the energy of the arc, plasma, electron beam, or inductive heating. A variety of furnace types are used: arc furnaces, induction furnaces, resistance furnaces, electron beam furnaces, or plasma furnaces (Burghardt & Neuhof, 1982).

Today, more than 90% of modern electric steel mills operate with arc furnaces for batch sizes up to 200 t. Depending on the steel grade and quality (mass steels or high-quality stainless steels), electric furnaces are used in different technical designs.

Arc Furnace (AF)

In the **a**rc **f**urnace, the current (DC or AC) forms an arc (comparable to electric welding) between the current-carrying graphite electrodes and the scrap. This arc melts the scrap by thermal radiation.

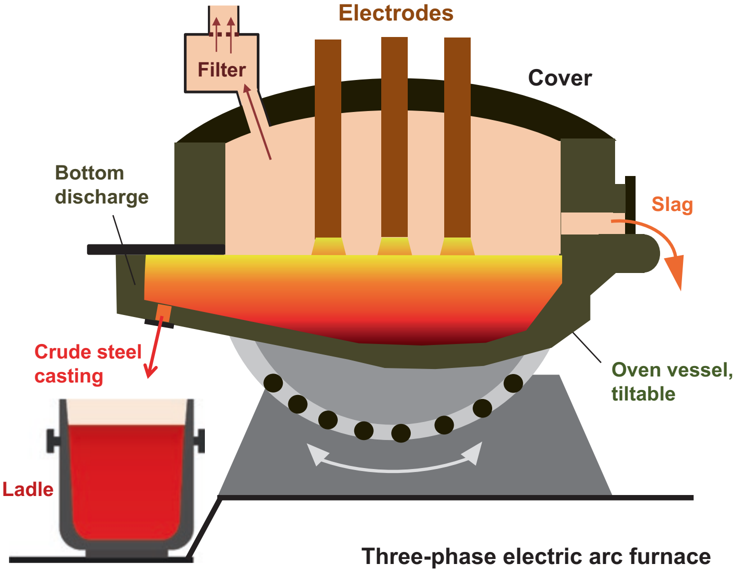


Fig. 4.13 Three-phase electric arc furnace (sectional drawing)

The construction of a light arc furnace is shown in the sectional view in Fig. 4.13. The essential components are:

- *the furnace vessel with fire-resistant wall, outlet and working opening,*
- *the pivotable cover with the three graphite electrodes,*
- *the tilting device,*
- *the transformer.*

The scrap is transported and loaded into the furnace via baskets. This method of loading an electric arc furnace with scrap is shown in Fig. 4.14.

After charging, the cover is closed. The electrodes move down and ignite an arc. This melts the scrap at temperatures up to 1800°C. Then the melt (molten steel) is poured into a preheated ladle at about 1700°C. The pure melting time per charge is about 30 to 70 min. Almost any type of steel can be melted with an arc furnace. Originally used only for stainless steel production, arc furnaces are increasingly being used for melting mass construction steels. Today, in combination with secondary metallurgical processes, they are mostly used only for melting scrap.

Vacuum Induction Multi-Chamber Furnace (VIM)

For the production of special steels and special alloys, so-called **V**acuum-**I**nduction-**M**ultichamber furnaces are used. In these furnaces, eddy currents are induced directly in

Fig. 4.14 A three-phase arc furnace is filled with scrap, charge weight approx. 42 t. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

the metal by an alternating electromagnetic field, which heats and liquefies the metal due to its electrical resistance. It is the oldest vacuum melting process used industrially since 1928.

Both the charging of the scrap, the melting and the melt treatment (degassing, desoxidation, alloying) as well as the casting into blocks take place in chambers under vacuum. Figure 4.15 shows a sectional view of a vacuum induction multi-chamber furnace. The most important components are:

- *the charging, melting and casting chambers,*
- *the tilting melting vessel with refractory lining and water-cooled copper coil,*
- *the ladle car (casting chamber for "rising casting"),*
- *the vacuum pump set,*
- *the transformer.*

In order to achieve a high purity and homogeneity in the produced steel, very clean scrap (no chips, grinding dust or slag) must be charged. Vacuum induction furnaces are used in particular for the production of high-purity materials (high-alloy steels, special alloys, nickel-based alloys), e.g. for medical technology (implant materials), for special applications in the automotive industry and in nuclear power plants.

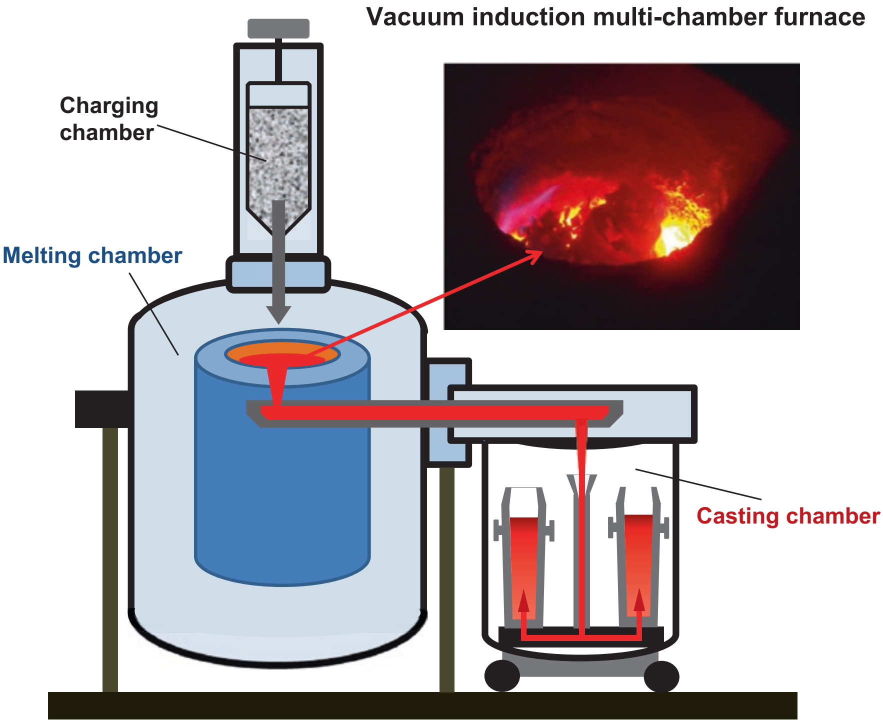


Fig. 4.15 Section (simplified) through a vacuum induction multi-chamber furnace

4.3 Post-Treatment of Steel

▶ The liquid raw steel coming from the converter or from the electric arc furnace is post-treated in the ladle. Inside specialised units, the desired alloying elements are introduced, the melt is homogenized, remaining traces of carbon, sulfur or other elements are removed or reduced, and the desired casting temperature is set. This treatment of the raw steel to produce the desired steel alloy is also called "ladle metallurgy", "fine treatment" or "secondary metallurgy" (Burghardt & Neuhof, 1982). Depending on the steel quality, different methods and plants are used for the treatment of the raw steel. These are presented below. In addition, in Sect. 4.3.2: *Remelting Processes* for further quality improvement (purity, homogeneity) are mentioned.

4.3.1 Ladle Metallurgy

Ladle furnace (**LF** – **L**adle **F**urnace)

After the raw steel is poured into a ladle in the converter steel mill or the electric steel mill, it is subjected to a post-treatment on a so-called ladle stand. The following tasks are performed:

- *Maintaining the melt at temperature* (with an arc via three electrodes in the lid)
- *Alloying, e.g. setting the carbon and phosphorus content*

A ladle furnace also serves as a buffer unit before casting. It is the main unit for secondary metallurgical treatment of bulk steels and selected stainless steels. Figure 4.16 shows, for example, a ladle furnace in an electric steel mill for the production of stainless steel.

RH process (**R**uhrstahl-**H**eraeus process)

Figure 4.17 shows the working principle of the process developed by Ruhrstahl and Heraeus at the end of the 1950s schematically.

Liquid raw steel is vacuum-treated in a ladle for degassing and decarbonization. For this purpose, a part of the steel is sucked into a vessel that dips into the melt surface from above under vacuum. This vessel has two dipping tubes at the bottom that protrude into the liquid steel melt. A part of the melt rises upwards into the vessel via these tubes. Argon (or nitrogen) is blown into the outer tube, causing the melt to rise into the vessel, where it is decarbonized and degassed under vacuum and oxygen supply. As a result of the resulting circulation of a part of the steel melt, this is also referred to as a vacuum circulation process. This process can produce steel with greater purity. In particular, the hydrogen embrittlement of the steel can be reduced due to the possible removal of hydrogen. This Ruhrstahl-Heraeus process is mainly used in converter steelworks.

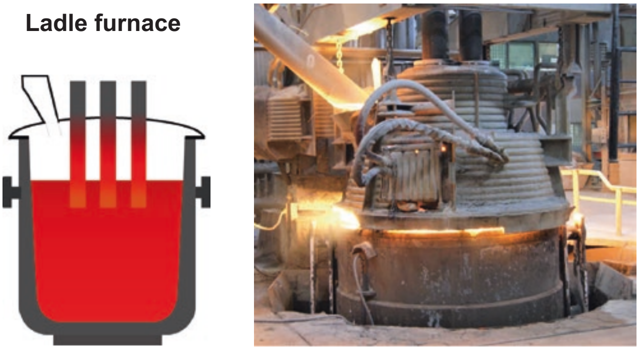
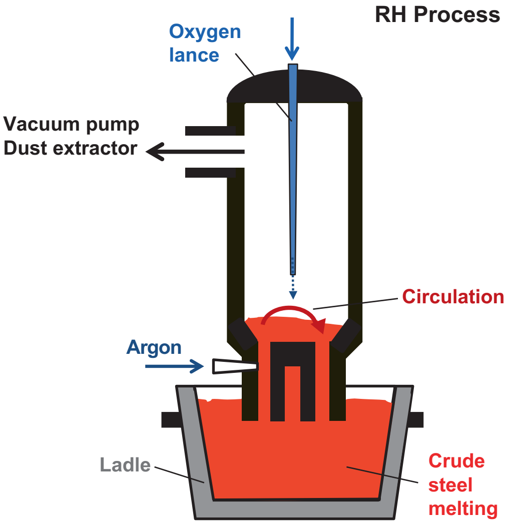


Fig. 4.16 Ladle furnace in an electric steel mill with cutaway view. (Photo: Schlegel, J., BGH Edelstahl Siegen GmbH)

Fig. 4.17 Schematic of the Ruhrstahl-Heraeus process for the vacuum treatment of steel



DH process (**D**ortmund-**H**örde process)
The DH process is also used for the treatment of raw steel melts under vacuum for decarbonization and degassing. The plant for this is, similar to the RH process, a partial degassing plant and is only used to a limited extent. Technically, it is a modification of the RH process, since a similar vessel dips into the steel melt, which is cyclically lifted and lowered. The designation as vacuum lifting process is derived from this. During the treatment and the movements of the vessel, the melt is intensively flushed with argon in the ladle and kept in constant motion.

VD plant (**V**acuum-**D**egasing)
Figure 4.18 shows the insertion of a ladle into the vacuum vessel of the VD plant in a stainless steel works and a sectional view of the ladle in the vacuum vessel.

The following treatment of the steel melt takes place in the vacuum vessel of the VD plant:

- *De-gassing (removal of nitrogen, hydrogen and oxygen),*
- *Alloying,*
- *Reduction of sulfur content,*
- *Improvement of purity by intensive argon flushing under vacuum.*

Such VD plants are used for high-quality steels and special stainless steels.

VOD (**V**acuum-**O**xygen-**D**ecarburization, decarburization under vacuum with oxygen)

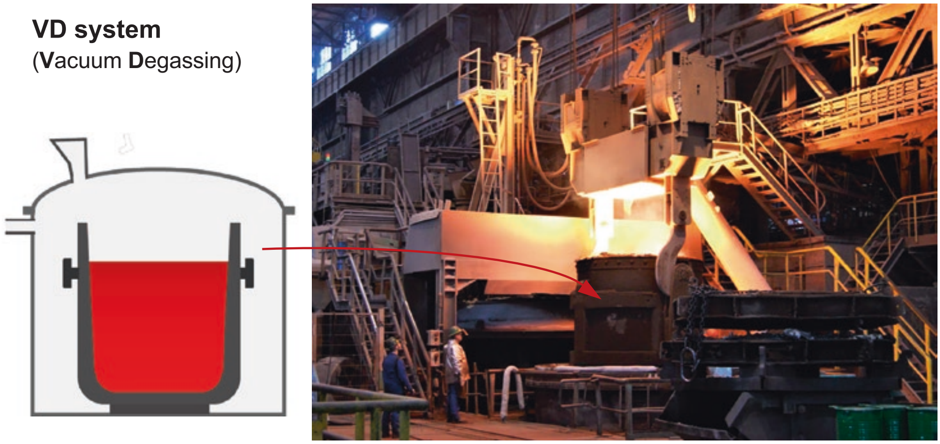


Fig. 4.18 Vacuum degassing plant (VD). (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

Oxygen-refining under vacuum was developed particularly for high-chromium-containing stainless steels with very low carbon contents. Here too, the ladle is placed in a liquid steel vacuum vessel. In comparison to the VD plant, oxygen can be blown in for the "fining process". Figure 4.19 shows the schematic structure of such a VOD plant. The steel melt is treated in a VOD plant as follows:

- *De-gassing,*
- *Oxidation of carbon (thus reducing the C content in the steel),*
- *De-sulfurization,*
- *Chemical reduction of alloying elements.*

AOD-Konverter (**A**rgon-**O**xygen-**D**ecarburization, decarburization with an argon oxygen mixture)

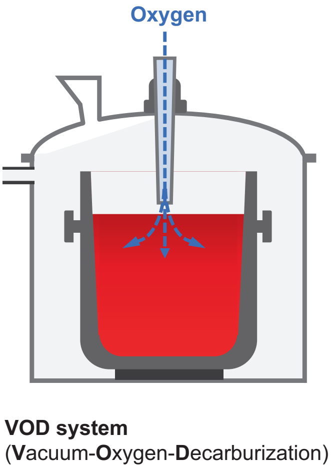
This method of oxygen enrichment with an argon (or nitrogen) oxygen mixture in a converter was developed in 1954. The injection takes place via nozzles in the bottom of the converter, as shown in Fig. 4.20.

AOD plants are used:

- *for degassing,*
- *for the oxidation of carbon,*
- *for alloying,*
- *for desulfurization and the nitridation of steel.*

AOD converters are mainly used for selected, high-quality stainless steels, i.e. for high-alloyed ferritic, austenitic, acid-resistant and heat-resistant steels with low carbon content.

Fig. 4.19 Scheme of a VOD plant (**V**acuum-**O**xygen-**D**ecarburization)



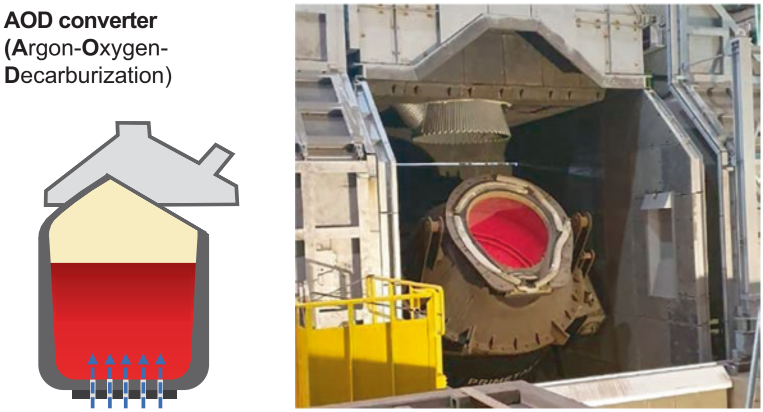


Fig. 4.20 Schematic of an AOD converter and view into an open AOD converter plant. (Photo: BGH Edelstahl Freital GmbH)

4.3.2 Remelting Processes

▶ Particularly in the automotive and aerospace industries, in medical technology, in turbine construction and in highly automated production technology, the requirements for the service properties of steels are constantly increasing. Even with further improvement of the conventional steel production processes and the mentioned secondary metallurgical processes, the desired steel qualities, in particular with regard to purity and microstructure homogeneity, can often not be achieved. Therefore, it is increasingly necessary to subject the already melted, secondary metallurgically treated and cast steel to a further purification process. Unfortunately, microstructures found inside of a cast and possibly already formed steel block which may be considered impurities can not be easily removed. The impurities include, for example, non-metallic inclusions (oxides, sulfides). Only in the liquid state of the steel a purification, thus a removal and thus reduction of impurities can be made. This purification process therefore includes a liquefying (remelting) of the steel under vacuum, protective gases or slags (Burghardt & Neuhof, 1982).

In the past 60 years, various remelting processes have been developed:

- **E**lectro-**S**lag-**R**emelting (ESR)
- **V**acuum-**A**rc-**R**emelting (VAR)
- cElectron-Beam-Remelting
- Plasma-Remelting

In practice, large-scale electro-slag-remelting and melting in a vacuum furnace have been established. These processes are explained below.

ESR (Electro-Slag-Remelting)

The electro-slag-remelting can be carried out under atmospheric conditions (ESR), under inert gas atmosphere or under increased pressure in a pressure chamber(PESR) are carried out. The steel ingot to be remelted is used as an electrode in the ESR plant. The process heat for liquefying this steel ingot is generated via direct current flow when voltage is applied. An electrically conductive, liquid slag generates the electrical resistance. The temperature is increased to the point where, eventually, the electrode, i.e. the ingot being remolten, melts at the front surface, which reaches into the heated liquid slag, and drips off. The slag now absorbs impurities from the many liquid steel drops sinking through it (e.g., non-metallic, oxide inclusions, also sulfur). It thus acts like a chemical filter. The slag consists of a mixture of fluorspar, limestone and clay, each adapted to the chemical composition of the steel being remolten. In a water-cooled crystallizer the individual purified steel drops crystallize and form a new ingot with improved purity and also with improved casting structure (Burghardt & Neuhof, 1982; DEW, 2011). These crystallizers can be designed as fixed or sliding crucibles. In practice, these are also called fixed or sliding moulds. Figure 4.21 shows the structure of an ESR plant for this purpose with fixed mould, as it is used in a stainless steel plant to produce 2,3-t-ESR ingots.

For comparison, Fig. 4.22 shows the schematic structure of an ESR plant with a sliding crucible.

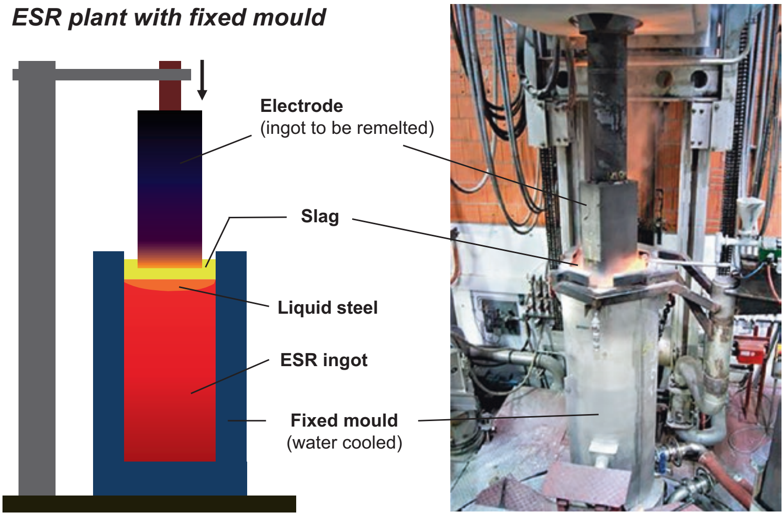


Fig. 4.21 ESR process: scheme and view of a plant with fixed mould. (Photo: BGH Edelstahl Freital GmbH)

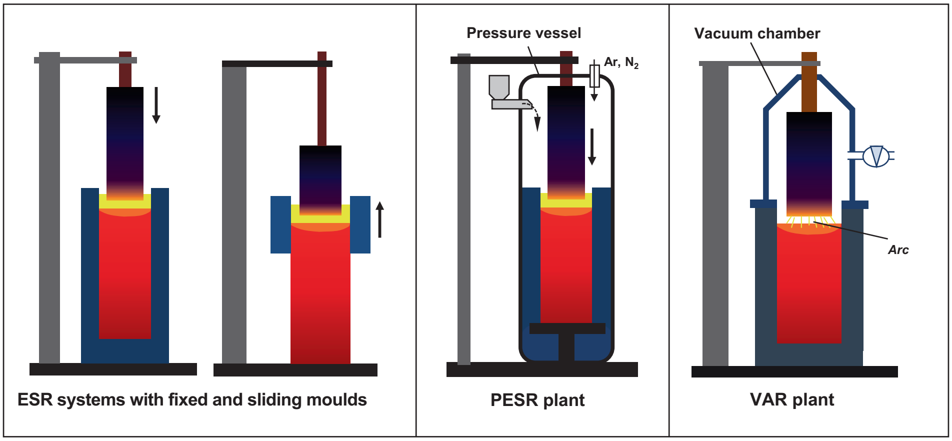


Fig. 4.22 Comparison of remelting plants: ESR with fixed and sliding moulds, PESR and remelting in a **v**acuum **a**rc **f**urnace (VAF)

PESR (Pressure/inert Electro Slag Remelting)

From an engineering perspective, a PESR plant is an ESR plant that operates in a closed pressure vessel. The remelting process is carried out under a protective gas, e.g. argon. This allows for higher purity grades to be achieved in comparison to the standard ESR process. It is also possible to add alloying elements, e.g. an increase in the hydrogen content (DEW, 2011). Figure 4.22 shows a PESR plant with a pressure chamber in comparison to the classic ESR plants.

▶ In summary, the ESR and PESR processes result in a quality improvement:

- *by reducing the oxygen and sulfur content,*
- *by lowering the content of non-metallic inclusions,*
- *by improving the primary structure (the ingot is free of segregation and shrinkage cavities).*

Based on this, these remelting processes are particularly used for high-nitrogen steels, nickel-based alloys, tool steels with homogeneous carbide distribution and for austenitic steels without nickel for use as:

- *medical implants,*
- *braces wire,*
- *surgical knives,*
- *cap rings for generators,*
- *turbine blades,*
- *parts for the automotive industry (e.g. diesel injectors),*
- *high-stress gear parts,*
- *high-gloss polishing tools,*
- *cold rolling for foil production,*
- *components in high-pressure technology,*
- *special rolling bearings as well as*
- *parts for the watch industry.*

VAR (Vacuum Arc Remelting)

In metallurgical practice, one usually speaks of the VAR process. Under vacuum, a high-voltage direct current arc is ignited between the melting electrode (cathode) and the melting pool (anode) in the crucible. This leads to such strong heating of the electrode tip that small metal droplets are released and caught again in the water-cooled standing crucible. There they crystallize into a new block. In Fig. 4.22 the schematic structure of such a VLBO plant is shown.

The metallurgical improvements are due to the vacuum and the solidification conditions. In comparison to the ESR and PESR methods, even better results can be achieved:

- *highest possible degree of purity,*
- *hardly any trace elements and dissolved gases,*
- *better ingot cast structure as well as*
- *isotropic properties.*

Therefore, the VAR process is used for selected highly pure steels and nickel-based alloys (DEW, 2011).

▶ **Conclusion**

The main task of steel cleaning can be solved better the more effort (costs) is used for remelting. In the following order of remelting methods and combination with one or more remelting processes, the purity can be increased up to values close to the best metallurgically possible value:

- **AF** (openly melted in an **a**rc **f**urnace)
- **VIM**
- **AF** and **ESR**
- **AF** and **PESR**
- **AF** and **VAR**
- **VIM** and **PESR**
- **AF** and **PESR** and **VAR**
- *Other variants are conceivable (DEW, 2011)*

The use of melted, highly pure steels will continue to increase due to the associated possibility of material and component optimization for massive forgings with requirements for highest static and dynamic strength, for special steels as well as for pressure and heat-resistant, dimensionally accurate precision turned parts.

4.4 Primary Forming/Casting

▶ The starting point for processing steel is always its first solid state: a form crystallized from the liquid phase, which is produced today in the casting process of a steel mill. Therefore, casting is also considered as "primary shaping", whereby almost all metals receive a shape which is determined by the intended use of the casting. There is a distinction between mould casting and semifinished casting. Mould castings, i.e. "end-dimensioned and contour-cast" parts, can weigh a few grams (e.g. precision casting for medical technology and the automotive industry), but also many tons (e.g. a ship's propeller). Various die casting processes are used, e.g. sand casting, centrifugal casting, pressure casting and precision casting. However, these casting processes will not be considered in the following chapter. The focus is rather on casting processes for the production of semi-finished products made of steel, which can then be further processed by forming. This semifinished casting of steel is carried out in portions in permanent moulds (dies) into ingots, or continuously, almost endlessly, to a strand or band.

4.4.1 Basics of Casting Steel

▶ Since the beginnings of foundry technology, the purpose of use, the properties of use, the shape of the casting and the foundry plant have constantly evolved. However, the basic principle of casting has remained the same: the molten metal is poured into a mold. There it solidifies through the cooling effect of the mold and takes on the shape of this mold.

The transition from the liquid to the solid state with the release of heat is called solidification. The processes taking place during solidification have a decisive influence on steel quality. The solidification of the steel melt begins on crystallization nuclei (groups of atoms in the arrangement of the crystal lattice). This results in small crystallites with different lattice directions. The solidification process is schematically shown in Fig. 4.23.

The boundaries between the crystallites (grains) form the grain boundaries. The size of the resulting grains depends on the number of seeds and the crystallization rate. A large number of seeds and fast cooling thus lead to a very fine-grained structure.

The structure of a cast steel block or strand can be divided into three fundamentally different structures:

- *fine-crystalline, globular edge zone,*
- *stem crystal zone* (dendritic zone with crystals that have a conical structure),
- *coarse-crystalline, globular core zone.*

Figure 4.24 shows the microstructure zones of a steel casting ingot in a cross section, schematically simplified with a real etched slice, ground and chemically treated with an acid to make the structure visible.

As soon as the molten steel is poured into a cold form, the solidification begins at the coldest points, i.e. at the walls of the mould. Since the undercooling is very strong in this area, numerous crystalline nuclei form quickly, which grow into many small

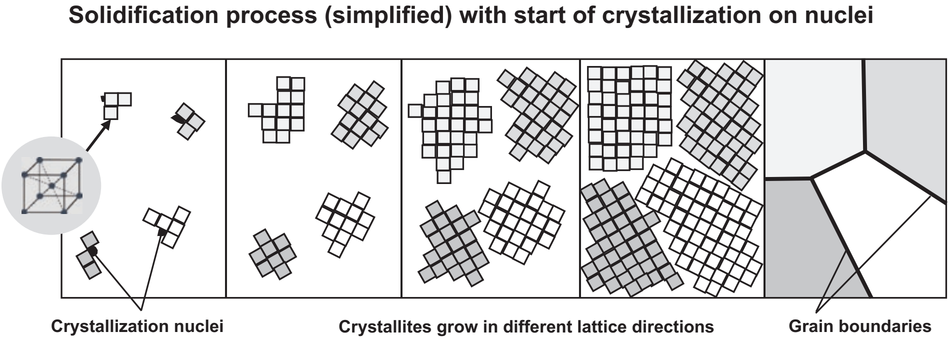
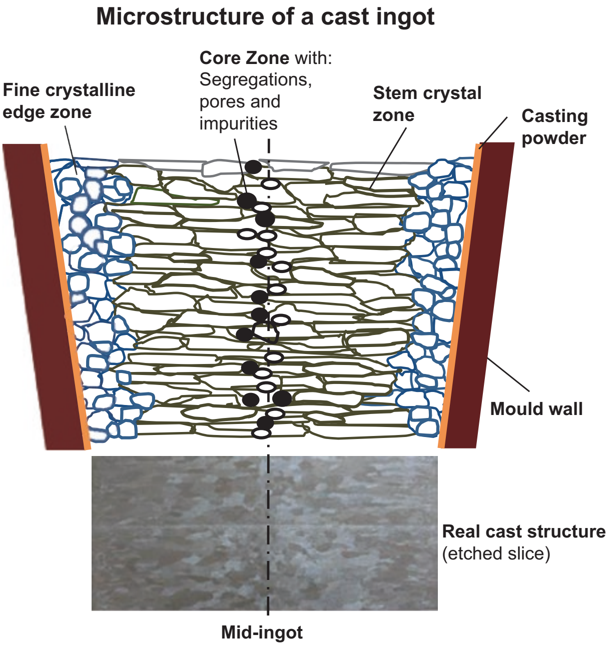


Fig. 4.23 Course of solidification

Fig. 4.24 Structure of a casting ingot. (Micrograph; etched slice: BGH Edelstahl Freital GmbH)



crystals. The second zone is created by the growth of these crystals towards the center of the block with the well-known elongated, stem-like form, dendrites. Impurities, which are contained in every technical metal, are pushed ahead by the stem crystals and then accumulate in the coarse-crystalline core. This third zone forms last (Schatt & Worch, 1996).

The solidification behavior and thus the formation of the microstructure are influenced by the chemical composition, the purity and above all by the casting, pouring and cooling conditions (Bleck, 2010). Of particular importance are the pouring temperature and the nature of the mold, for example size, wall thickness, cross section and temperature of the mold. If, for example, a steel melt is overheated far above its solidification temperature, the number of nuclei decreases. However, these nuclei are the prerequisite for the beginning of solidification. Therefore, the solidification of this melt will only set in later. If warm molds are used for the ingot casting, the crystallization is slowed down. The temperature gradient between melt and mould is smaller. The undercooling of the melt decreases and the crystals begin to grow.

These two examples should show how the solidification of the liquid steel can already influence the future material properties. The smallest technological changes, whether they are a default on the pouring temperature or molds that are too warm, can produce very different casting structures.

In foundry operations, the use of so-called casting powders often plays a special role for process safety and steel quality. However, a distinction must be made between ingot casting, continuous casting and mould casting. In general casting powders have to meet the following requirements:

- *Lubrication to prevent adhesion of steel to the mould wall,*
- *Setting of an even heat transfer between steel and mould,*
- *Protection of the steel from oxidation,*
- *Absorption of non-metallic inclusions from the steel,*
- *Thermal insulation of the molten steel surface.*

Casting powders consist of mineral raw materials such as, for example, calcite, feldspar, fluorspar as well as soda and technical silicates. The composition is always determined by the steel to be poured and the pouring parameters.

Another aspect is the type of casting: “killed” or “unkilled”. These two types are influenced by additives in the steel melt. An unkilled cast steel is present when when no additives are added to the melt. Most of the steel still contains a small amount of oxygen. When the steel melt cools, carbon is released, which now reacts with this oxygen. Carbon monoxide is formed, which rises and is found again as gas bubbles in the steel block when it solidifies. This type of steel is hardly produced today.

In the killed cast steel oxygen-reacting partners are added to the steel, e.g. aluminium or silicon. These bind the oxygen and slag is formed. Instead of carbon monoxide, liquid slag is formed, which rises to the top of the ingot head. As a result, the killed cast steel has less or no air inclusions, less segregation in the solidification zone and thus better mechanical properties and also improved weldability.

4.4.2 Ingot Casting

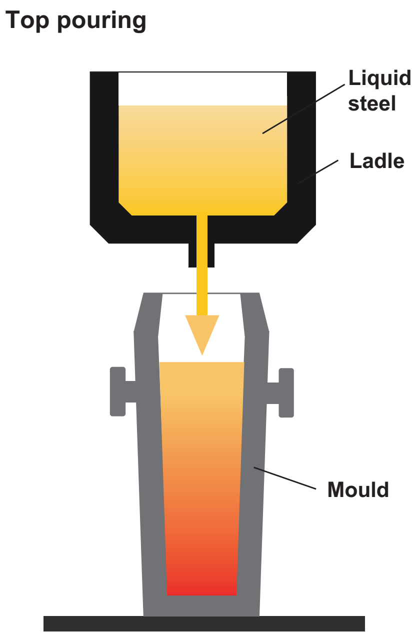
Pouring the liquid steel into blocks is today mainly done for large forgings, difficult to cast alloys (stainless steel) as well as for high requirements regarding homogeneity and purity. The steel melt is poured into fixed permanent moulds (dies) and solidifies into geometrically simple ingots with a square, rectangular, round, oval or polygonal cross-section. After cooling, the “stripping” of the moulds occurs, i.e. the slightly conical moulds are removed from the solidified steel ingots.

The block casting can be carried out in the variants “falling” or “rising” casting.

Top Pouring

The molten steel is poured from the top directly into the individual moulds. Figure 4.25 shows this casting method.

Fig. 4.25 Schematic representation of the "top pouring" type of casting



Bottom Pouring

Liquid steel melt is poured from the pouring ladle into a funnel which stands on a floor plate and is connected to several small moulds via a duct system made of fireclay.. Based on this, one also finds the term "uphill casting" in practice. Figure 4.26 shows this casting process schematically.

In Fig. 4.27 you can see a bottom plate that has been prepared for the bottom casting with four moulds.

In the middle of the bottom plate you can see the inlet onto which the funnel is placed. The four moulds are placed on the four inlet channels located in the corners. If liquid steel is now poured from the ladle above into the funnel, it distributes evenly through the feeding system (principle of communicating tubes) from below into the four moulds. The moulds now fill up with liquid steel, which then begins to solidify in them.

Figure 4.28 shows, as an example from practice, the result of a bottom casting in the form of slightly conically cast ingots of stainless steel, stacked in a ingot storage.

The solidification during rising block casting takes place transversely to the block. A high mold filling speed and a cooling capacity limited by the mold result in a deep pit with a large volume. In practice, technical measures (heat insulation) are used on top of the mold to keep the block head liquid for as long as possible. This allows, for example, impurities and pores to "rise" to the top of the mold, that is, to accumulate in the area of the block head.

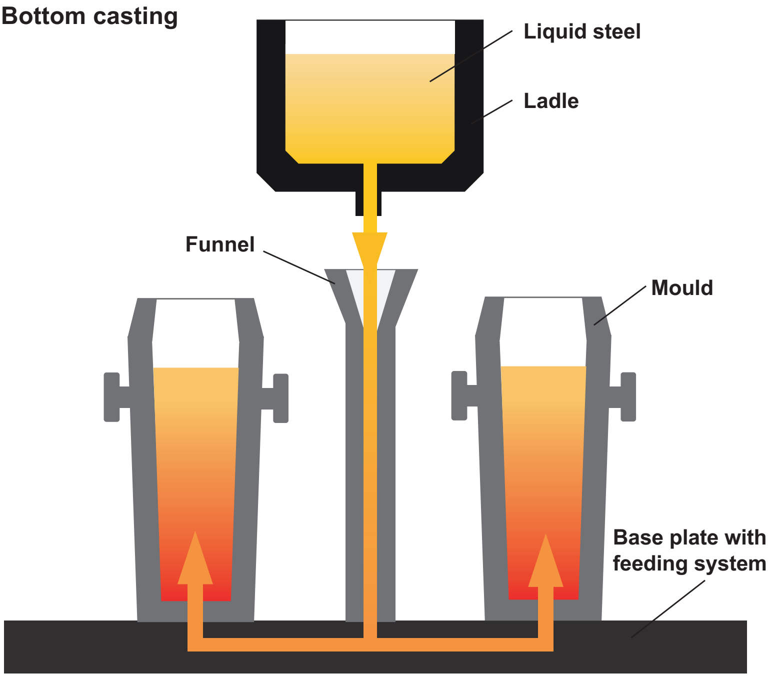


Fig. 4.26 Principle illustration of the “bottom pouring” process

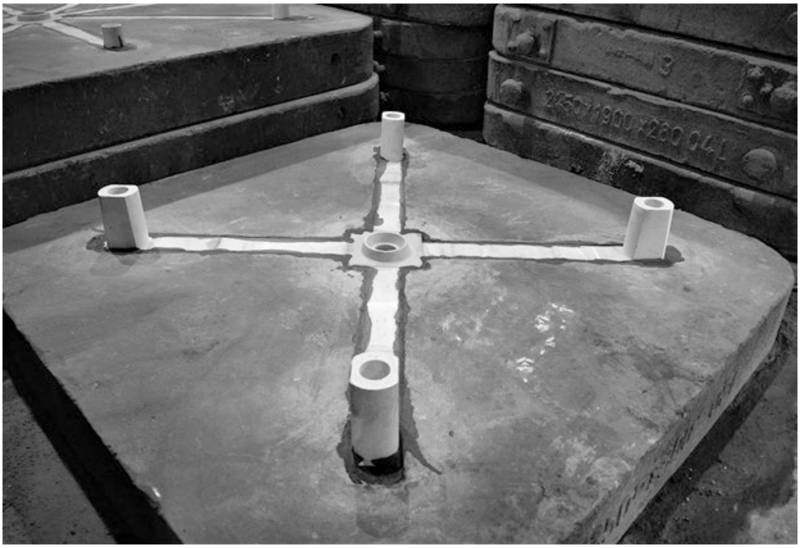


Fig. 4.27 Bottom plate for four moulds. (Photo: Schlegel, J., BGH Edelstahl Siegen GmbH)

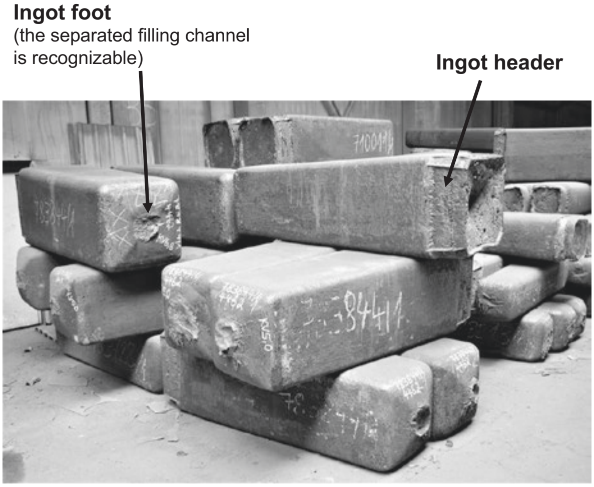


Fig. 4.28 Casting ingots in the storage after removal of the moulds. (Photo: Schlegel, J., BGH Edelstahl Siegen GmbH)

By adapating casting parameters to the steel alloy and block size, the formation of pores, voids, microvoids and segregation as well as the formation of other casting defects are to be minimized. Voids are shrinkage cavities that can form during solidification of the melt. Pores or microvoids form on the surface or on the inside due to trapped gas bubbles. And segregations are demixing of the melt; thus local differences in chemical composition. Figure 4.29 shows a schematic cross section through a block with a simplified representation of the cooling effect of the mold and the possible resulting casting defects after solidification.

Casting ingots are formed by hot rolling or forging (see Chap. 5: *Forming*). It should be noted that the areas of the ingot head and the ingot foot must be separated ("chopped") from the rolled or forged semi-finished product.

4.4.3 Continuous Casting

▶ The continuous casting process did not become widespread until Europe's industrial production increased greatly in the middle of the twentieth century. With the technical perfection of plant technology beginning in 1970, continuous casting increasingly began to replace ingot casting for a wide range of steel grades and dimensions. Today, over 90% of steel is produced using continuous casting. Die casting products are already referred to as semifinished products. They can be further processed into strip, profiles, round bars or wire by rolling or pressing.

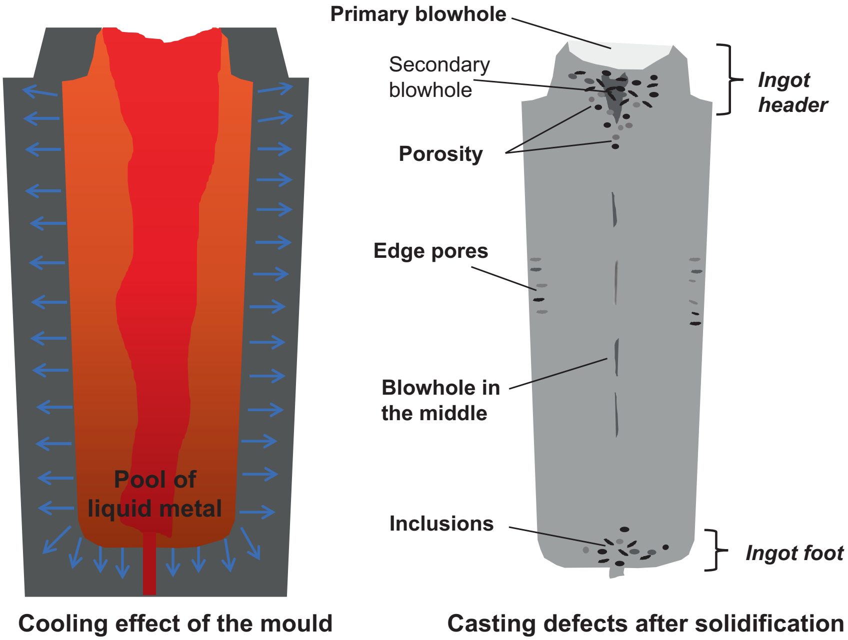


Fig. 4.29 Simplified representation of the cooling effect of the mould during rising casting and the possible resulting casting defects after solidification of the casting (longitudinal section)

Depending on the casting cross-section and thus the product, three different semi-continuous or continuous types of continuouscasting plants are in operation today in practice:

- *Vertical continuous casting*
- *Bend continuous casting*
- *Horizontal continuous casting*

These three types are introduced below.

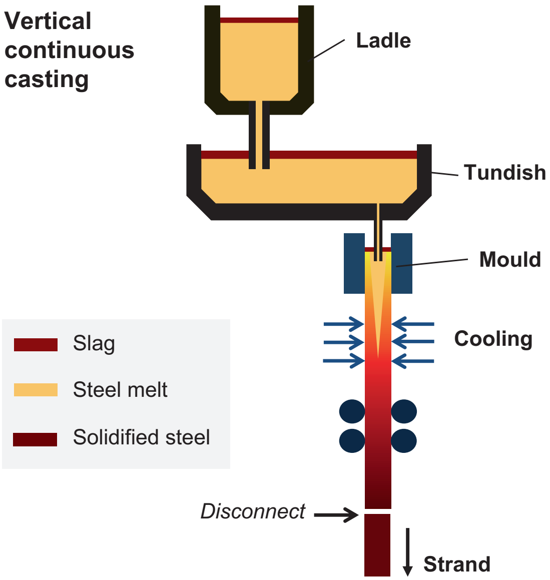
Vertical Continuous Casting

In vertical continuous casting the length of the castable strand is determined by the height of the plant. Round, square and rectangular cross-sections can be cast. Figure 4.30 shows the principle of a vertical continuous casting plant.

Circular curved continuous casting

The strand section is redirected into a circular curved strand after sufficient cooling. In horizontal position, the strand can be discharged and divided in length. The working principle of such a circular curved strand casting is shown in Fig. 4.31.

Fig. 4.30 Schematic illustration of a vertical continuous casting plant



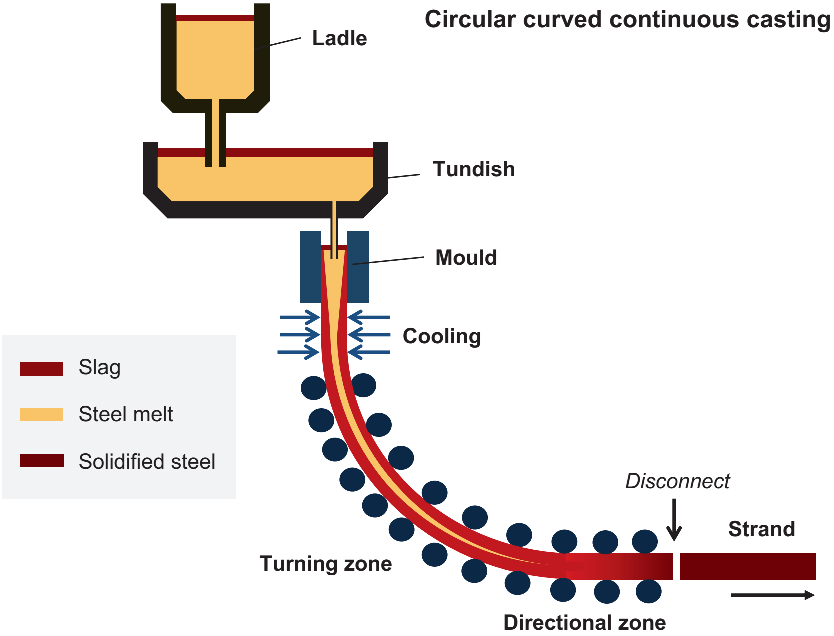


Fig. 4.31 Schematic illustration of a continuous circular curved strand casting plant

There is a distinction between billet and preblock continuous casting for round and approximately square cross-sections as well as slab continuous casting for rectangular cross-sections. Today, rectangular slabs with widths of over 2.6 m and thicknesses of 40 to 600 mm can be produced. These thin slabs are used for steel sheet or steel strip production, whereby their use can subsequently reduce the effort required for strip processing (fewer forming steps and heat treatments).

A further reduction of the following deformation processes is possible through the continuous casting, since a pre-strip with only a few millimeters in thickness can be produced. The aim in this variant of the process is to produce steel products directly from the melt flexibly and economically without interruption (Quitter, 2014). Technically, two different methods of continuous casting can be distinguished:

- the two-roll continuous strip casting plant and
- the strip casting by means of a casting machine (pouring of the liquid steel onto a rotating, cooled casting strip).

The **two-roll continuous strip casting** was already patented in the nineteenth century by *Henry Bessemer* (1813–1898), but did not reach production maturity. Only after 1990 was it used industrially, especially for special corrosion-resistant steels and for electrical steels. Figure 4.32 schematically shows the principle of a modern two-roll continuous strip casting plant.

The liquid steel is filled into the distributor from the pan by means of a dipping tube. From there it passes via a feed system from above between two cooled casting rollers rotating in opposite directions. The solidification to a strip with a maximum thickness of 6 mm begins in the rolling gap. This strip is then led downwards and fed horizontally to a rolling mill. With only one rolling pass, a strip thickness of approximately one millimeter can already be achieved. After intensive water cooling, the winding to the bundle (coil) takes place.

In the second method, **strip casting using a band casting machine,** the liquid steel is poured over a feed system onto a rotating, water-cooled casting band from below. The steel solidifies into a strip about 10 mm thick. This strip passes through a cooling zone and is then immediately fed into an in-line hot rolling mill and rolled to a thickness of about one millimeter. After further cooling, the steel strip is wound into a coil on a winding machine (spool). In Fig. 4.33, this casting process with a casting band machine is shown schematically.

The described strip casting processes enable a very short and fast solidification of the steel melt to a thin strip. This results in a very fine-grained microstructure with advantages for further processing and application. This is used, for example, for the production of new lightweight steels, the so-called HSD steels (“**h**igh **s**trength and **d**uctility”), or currently being further developed. Interesting developments are also being made in the area of profile casting in order to produce components in the cross-sectional shape adapted to the load (Müller, 2020).

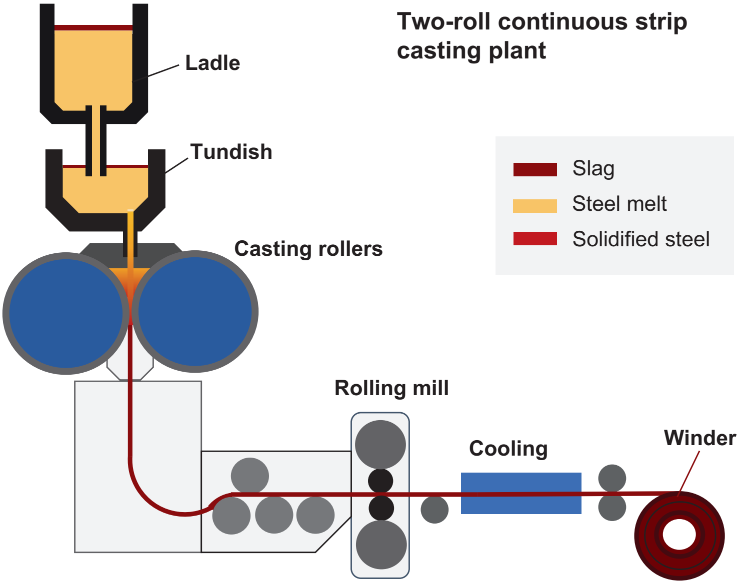


Fig. 4.32 Schematic illustration of a two-roll continuous strip casting plant

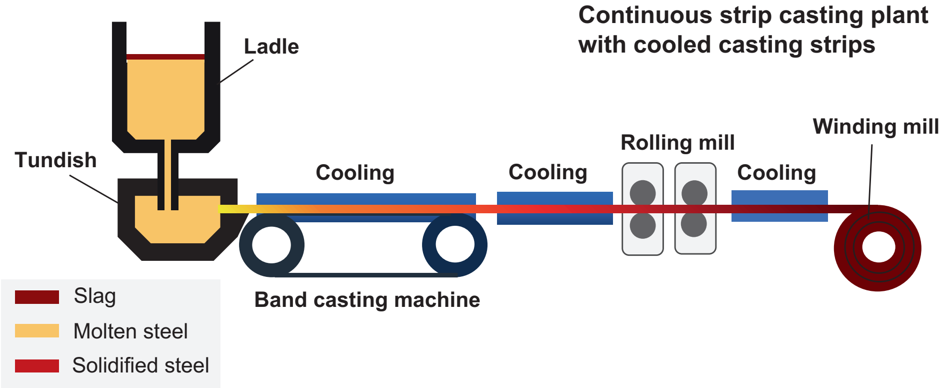


Fig. 4.33 Schematic illustration of continuous strip casting using a cooled band casting machine

Horizontal Continuous Casting

A special type of continuous casting is horizontal continuous strand casting, shown in Fig. 4.34.

The liquid steel flows from the pouring ladle into a cooled die. The shape of this die determines the shape of the strand (round, rectangular or square). At the horizontal die outlet, the strand already has a thick, solidified edge shell. The strand is drawn from the mold in short steps with pauses in between by means of a so-called excerpt apparatus. This is necessary for process reasons in order to avoid the solidifying strand sur-

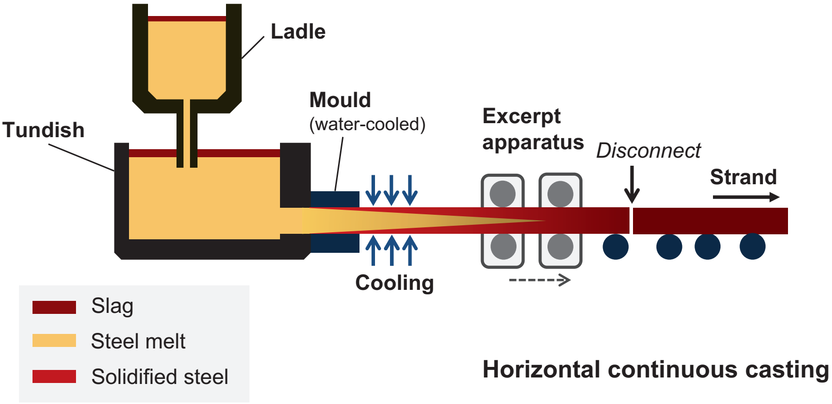


Fig. 4.34 Schematic illustration of a horizontal continuous casting plant

face sticking to the inner wall of the mold. When the strand leaves the mold, it is cooled intensively with water spray. This cooling is decisive for the formation of a uniform solidification structure with good technological properties. The specified strand lengths are separated in continuous casting operation by traveling cutting torches or saws. The separated strands then cool on a cooling bed to room temperature. Figure 4.35 shows, as an example from practice, the horizontal continuous casting plant of BGH Edelstahl Freital GmbH with four possible individual strands.

In horizontal continuous casting, the fast cooling at the strand surface (high cooling capacity) and the relatively small strand cross-sections lead to a pool with a small volume. Compared to ingot casting, solidification takes place in a relatively short time. This high solidification rate and the small pool volume have a favorable effect on reducing macro segregations, particlar around the edge area. Similar to ingot casting the solidification takes place in the transverse direction of the strand, i.e. directed towards the center of the strand. Figure 4.36 shows this crystallization on the basis of a cross section through a continuous round casted strand with a diameter of 120 mm.

▶ **Note**

The described continuous casting processes allow the economic casting of large quantities of steel in a short time into strands with different cross-sections and with almost unlimited lengths. For example, for the production of rolled wire, continuous casting billets are used as raw material. After preheating, they can immediately be processed further via continuous hot rolling to the final rolled dimensions. This technology saves the forming steps of the block and semi-finished rolling (see sect. 5.2.4.2: *rolling process*). Other advantages of the continuous casting process are the achievable finer, more homogeneous casting structure, a minimal void formation and lower investment and operating costs compared to ingot casting.

Fig. 4.35 View of a horizontal continuous casting plant, strand exit to the front. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

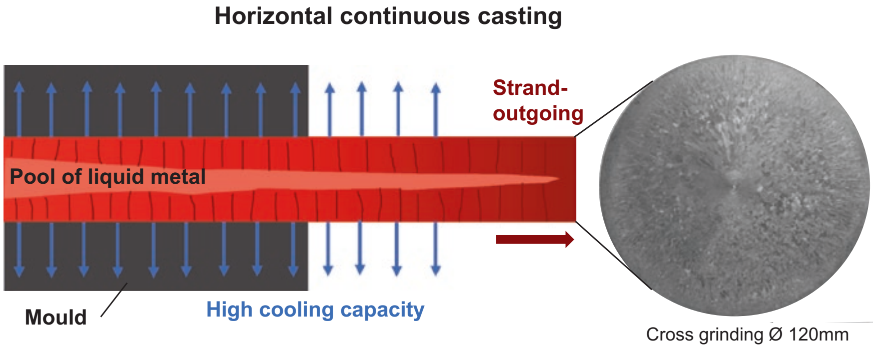


Fig. 4.36 Schematic illustration of the cooling effect in horizontal strand casting of round strand and cross section through a round. (Cross section: BGH Edelstahl Freital GmbH)

In Sect. 4.3.2 remelting processes to improve the purity of the steels are described. These processes do not generate new blocks by pouring a liquid steel melt, but "drop by drop" in crucibles. Therefore, completely different solidification conditions are given here than, for example, in the rising block casting. This should be pointed out at this point.

The **solidification process in the melting processes** ESR, PESR and VAR shows the following features:

- The solidification takes place almost in the longitudinal direction of the ingot.
- The very slow block growth with constant energy supply to the melt pool by the arc creates a flat pool with a relatively small volume.
- This flat melt pool prevents the formation of voids and macro segregations.
- The solidification time in the blocks is relatively large.

This results in blocks with an optimal microstructure and a high density throughout the block volume (free of porosity and micro voids). Figure 4.37 shows such a solidification process during electro-slag remelting (ESR) using an actual microstructure.

▶ The steel in so many alloy variants is now directly (primarily) produced from ore or secondarily from scrap, purposefully purified by remelting and brought into a form (block or strand) by casting. A semi-finished geometry (sheet,

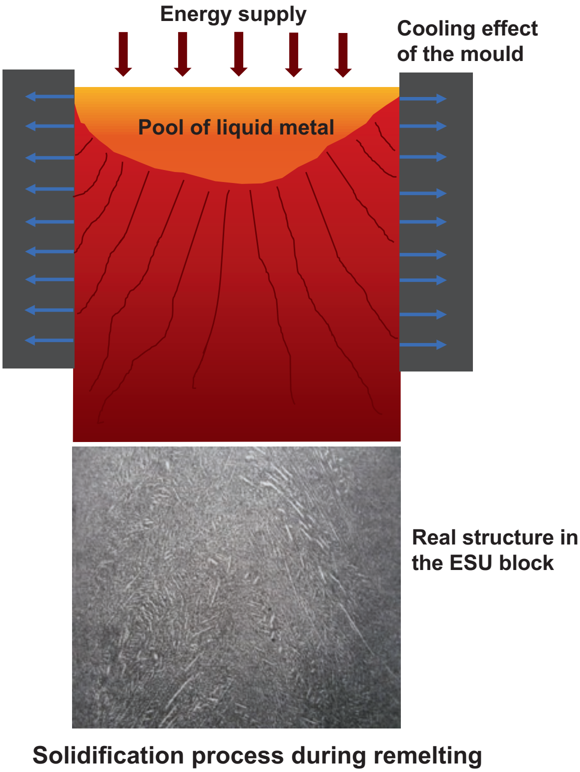


Fig. 4.37 Solidification process during remelting (ESR) with an actual microstructure of an ESR strand. (Micrograph: Weyl, A., BGH Edelstahl Freital GmbH)

strip, profile, round bar, wire) which is close to the one of the final product (mechanically processed components and parts) is subsequently achieved via a forming process (forging, rolling, drawing, etc.). The technical-technological possibilities for this are presented in Chap. 5: *Forming*.

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5 Forming

▶ A look at the desk and we see paper clips, ballpoint pens with small springs, a stapler with two sharpened stamps for paper punching—steel in wire form or as a round rod. With a small, very thin special steel in the form of a blade, a gentle wet shave is possible. Our car usually has steel rims in winter. The engine transfers the torque via transmission, joint shafts and flanges to the wheels. And the car body is made of shaped deep-drawn sheet metal. Stainless steel, corrosion-resistant and beautifully shaped, meets us as a handrail in the stairwell, in the kitchen as cutlery for eating or as a percussion instrument for mixing. Trams and trains roll quietly on steel rails. Steel in various shapes and sizes everywhere, which can only be produced by a forming process with subsequent further processing. Consequently, steel, like almost all metals and their alloys, is also always formed during its production process. Forming means the deliberately chosen geometric change of an already existing raw or workpiece form into a new form. Depending on the process, this causes different forces to cause permanent shape changes without severing material cohesion. The volume before and after forming always remains the same (law of volume constancy).

In practice, “forming”, or “plastic shaping”, is often equated with “deforming”. However, deforming means an uncontrolled, i.e. unwanted plastic shape change, as can be caused, for example, by an accident to the body of a vehicle.

5.1 Basics of Metal Forming

Basically, all metals and alloys have the ability to temporarily elastically deform under the action of external forces. After the external load is removed, the original shape is assumed again. To understand this, Fig. 5.1 shows a look inside to the atomic lattice

J. Schlegel, *The World of Steel*, https://doi.org/10.1007/978-3-658-39733-3_5

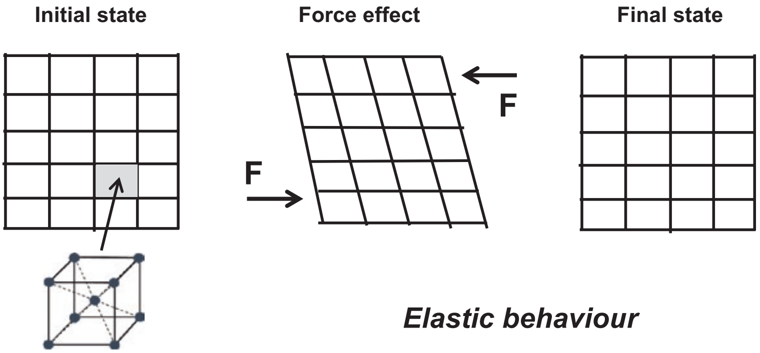


Fig. 5.1 Elastic behaviour, simplified as grid distortion and its rectification

structure. The externally applied force pushes the atoms to give up their position. The lattice is distorted. However, the atoms just barely retain their positions to each other. The acting force is too weak to achieve a sliding of the atoms. If this force is now removed again, the lattice distortion is also removed. The original lattice state is restored. This is the typical behavior, for example, of springs. Here the load remains in the elastic range and this process (load and lattice distortion - unloading and lattice rectification) can take place an infinite number of times.

However, if a certain deformation remains, the effect is referred to as "plasticity". The externally applied forces were so high that an irreversible displacement (sliding) of crystal planes was initiated. This sliding is shown in Fig. 5.2 simplified.

Since the actual material steel also has defects in the structure, e.g. displacements (see Sect. 3.2: *Fundamentals of Alloy Technology*), these too begin to migrate; plastic deformation sets in. With increasing deformation, this process is hindered, i.e. becomes more and more difficult. This is especially the case with deformation at room temperature. The steel resists further plastic deformation. This material behavior finds expression in the

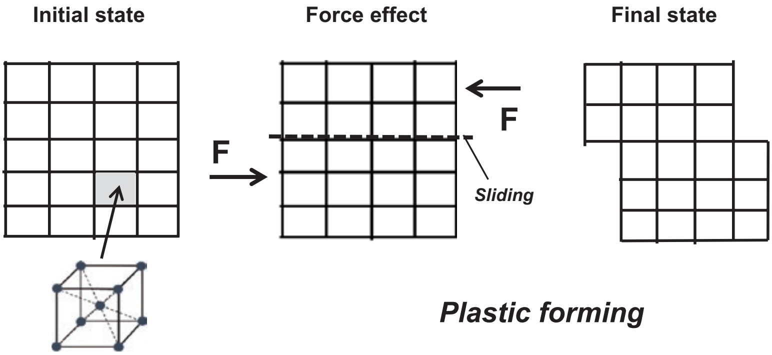


Fig. 5.2 Plastic behavior, simplified shown as sliding of crystal planes

material characteristic “deformation resistance k_w” . The deformation resistance k_w is the ratio of the force F required for forming and the area A required on the deformed object. So if the deformation resistance is known for a certain steel, the force necessary to achieve plastic deformation by the forming machine can be determined.

The changes in physical and technological properties of steel that occur during forming are referred to as “strengthening”. Formed steel tries to return to an ordered state of crystals. However, this is not possible without an energy supply. Only during subsequent heating (annealing) are crystals able to form and arrange themselves completely undistorted; one speaks of “recrystallization”. The steel has become soft and moldable again. This procedure—cold hardening during forming and annealing—can be repeated several times. It is interesting that at high forming temperatures, recrystallization of the structure already begins during deformation. Hardening practically does not occur in these circumstances.

The theoretical penetration and experimental capture of these fundamental processes in the plastic forming of metals began in the 1860s. For example, *Henri Tresca* (1814–1885) researched plasticity and determined the criterion for when a material begins to flow. *Erich Siebel* (1891–1961) dealt with molding, especially with theory of plasticity. And *Richard von Mises* (1883–1953) set up a plasticity theory for tough materials. Building upon this, the calculation methods for determining the force and work requirements and the material flow valid today were created by the scientific work of many more materials engineers. This made it possible to develop innovative forming technologies, new forming processes and ever larger and more powerful forming machines.

The following influencing variables can describe and control a forming process:

- *Material (resistance to deformation, deformation strength - forming ability)*
- *Procedure (pressure, tension/pressure, tension, bending or shearing deformation)*
- *Forming temperature*
- *Forming speed*
- *Forming degree (cross-sectional loss)*
- *Friction conditions (surface state, lubricant)*

The parameter *degree of deformation* is an important size, for which in practice often different names and calculations are used, depending on the profile of the workpiece and the forming process, including degree of deformation, decrease, cross-sectional decrease, cross-sectional change, length change, elongation, elongation degree, compression, compression degree, widening, widening degree, rolling degree. Basically, this parameter is calculated as a logarithmic ratio of the achieved dimension x_1 after the forming to the initial dimension x_0 for a dimensional change, for example in the longitudinal direction (x-direction). With a three-dimensional forming, the changes of the length, width and height of the workpiece are considered, with the “law of volume constancy” applying:

$$\mathbf{V} = \mathbf{l}_0 \times \mathbf{b}_0 \times \mathbf{h}_0 = \mathbf{l}_1 \times \mathbf{b}_1 \times \mathbf{h}_1 = \mathbf{constant}$$

In the case of a gradual transformation, the "total deformation degree" is calculated from the sum of the individual deformation degrees of the respective stages. Starting from the highest deformation degree to be achieved, the necessary forming work or forming force can be calculated quickly and easily using known formulas (Hensel & Spittel, 1978). Of particular interest is the maximum force required to deform a workpiece at all. It must be distinguished whether this force is introduced directly or indirectly into the forming zone. Directly, that is, directly in the forming zone, the force is generated during rolling and forging. In contrast, during drawing and deep drawing, the forming force is indirectly introduced into the forming zone by the workpiece itself.

5.2 Forming Processes

Today, forming processes are classified according to the type of force exerted:

Pressure Forming

- *Free Forming* (Open die forging, Hammering, Kneading, Upsetting)
- *Die Forming* (Die Forging, Coining)
- *Flow Pressing, Strand Extruding*
- *Rolling* (Longitudinal, Skew, Cross Rolling)

Drawing-pressure-forming

- *Drawing* (Bar, Wire Drawing)
- *Deep drawing*
- *Pressing*
- *Inner high pressure forming*

Drawing-forming

- *Lengthening* (Stretching)
- *Widthening*
- *Depthening*

Bending-forming

- *Free bending*
- *Sinking bending*
- *Rolling bending*

Shearing-forming

- *Twisting*
- *Shifting*

Another distinction is made according to the forming temperature:

- ***Hot forming****:* Forming above the recrystallization temperature of the steel
- ***Semi-hot forming****:* Forming in the heated state at temperatures that do not cause recrystallization of the steel, but lead to improved formability (also called “warm forming”).
- ***Cold forming****:* Forming at room temperature

The following advantages and disadvantages must be considered.

Hot forming:

- no solidification during the transformation
- low transformation forces at achievable high cross-sectional reductions
- oxidized surface, risk of edge decarburization
- worse dimensional tolerances

Cold forming:

- Cold hardening of steel depending on the deformation degree
- Very precise dimensional tolerances achievable
- Surface quality higher than in hot forming (no scaling)
- Annealing required for softening

Warm forming:

In order to take advantage of the benefits of cold and hot forming, warm *(semi-hot) forming* is used in particular for difficult to form steels. Typical forming temperatures are between 250 and 850°C. For example, the very difficult to form high-speed steel can be processed into wire by drawing at elevated temperatures in the range of 250 to 300°C. The addition of heat energy during the drawing process facilitates the plastic deformation.

The industrial application of semi-hot forming is limited to a narrow range of products (stainless steels, titanium, etc.) mainly for use in the aerospace and automotive industries.

Innovative in application are also the so-called thermomechanical forming processes. Here, the forming and hardening of the steel are combined in a single forming step with a defined process window for the forming temperature, the cross-sectional reduction and the cooling conditions. The "press hardening" for example in the production of car body parts or the thermomechanical treatment from hot rolling are examples thereof (see also Chap. 6: *Heat treatment of steel,* Sect. 6.2.10: *Press hardening*).

▶ The following methods will be introduced: forging, flow pressing, extrusion, rolling, deep drawing, interesting methods like hydroforming, inner high-pressure and high-energy forming, drawing as well as powder metallurgical and additive methods and plants.

5.2.1 Forging

▶ The forging process has a very long history, indeed it is one of the first manual skills of man. The production technique of forging changed hardly over millennia. Hammer and anvil are the most important tools. With them, the most diverse forging techniques are carried out:

- *Joining* (fire welding, shrinking)
- *Separating* (cutting off, splitting, punching)
- *Shaping* (tapers, widths, offsets, stanchions, stretches, planing, bending, twisting) as well as driving, swaging and folding.

5.2.1.1 Basics

Forging is a classical pressure forming in accordance with the the type of force exerted. A direct pressure is exerted on the workpiece between the forging tools (hammer and anvil or die) that is so high that a plastic deformation occurs. Compared to rolling and the pressures generated in the rolling gap, forging can achieve a better or greater depth effect (penetration). Basically, manual (craft) and industrial forging are distinguished.

Manual (craft) forging

The blacksmith must work out the shape of his workpiece with the hand hammer on the anvil or with a pneumatic hammer; hence also the term open die forging. Figure 5.3 shows the classical forging of a horseshoe.

Already at a very early stage, the blacksmith occupied a special position and contributed to many myths and legends. For millennia he embodied strength and reliability, skill and expertise in the material steel. There are reports of blacksmith gods and forging even has found its way into art (Lietzmann & Schlegel, 1992). Today proverbs from the blacksmith trade are still part of the living language, such as *"Forge the iron while it is hot!", "Forge plans" or "Forge marriages".*

Fig. 5.3 Forging a horseshoe with the hand hammer on the anvil. (Photo from the Internet)

Industrial Forging

Industrial forging produces components for the manufacture of machinery and equipment, as well as for the automotive, aerospace and shipbuilding industries. Piece weights of up to 250 t are possible. Figure 5.4 shows, as an example from practice, a 40 MN two-column forging press for forging blocks with piece weights of up to 32 Tons.

The processes used today in industrial forging differ according to the working temperature as follows:

Hot forging

The working temperature (forging temperature, to which the forging part must be preheated) for hot forging is 950 to 1250°C depending on the steel quality. This gives good formability with relatively low forming forces. There is no hardening of the steel. The oxidation on the steel surface (scaling) during preheating must be taken into account.

Warm forging

Warm forging is carried out at temperatures between 750 and 950°C. In this temperature range, the steel has limited formability. Higher forming forces are required than for classical hot forging. During preheating and warm forging, no or only minor scaling (oxidation) of the steel surface occurs. Forged parts can be produced with tighter dimensional tolerances than for hot forging.

Fig. 5.4 Two-column open die forging press, press force up to 4000 t. (Photo: Schlegel, J., BGH Edelstahl Siegen GmbH)

Cold forging

When cold forging, forming takes place at room temperature. This prevents scaling. Very tight dimensional tolerances are achievable and there is a hardening of the steel.

Thixo forging

Thixo forging is a very special process for selected applications. The workpiece is heated to a temperature range above the usual hot forging temperatures. In this temperature range, the steel takes on a state that can be classified as being between solid and molten, or as being doughy. If forged in this state, very good formability is given, similar to that of casting. Only small forming forces are required.

Depending on the type of force applied and the shape of the forging tools, three forging processes are distinguished, see Fig. 5.5 for this.

Open die forging

Open die forging is usually forging or hammering with two flat tools, the so-called "forging saddles".

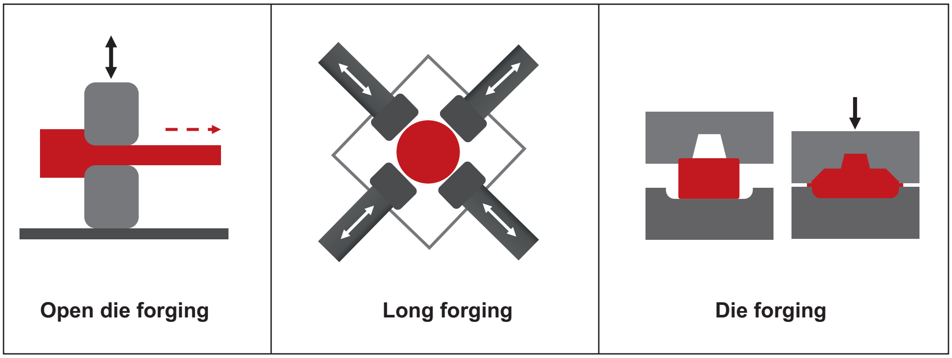


Fig. 5.5 Representation of the forging processes open die forging, long forging and die forging (*from left to right*)

Long Forging

In long forging, semi-finished products are formed with hammers working against each other in a so-called forging machine.

Die forging

The shaping takes place with profiled tools in die forging. This also includes the precision forging of ready-to-install parts, e.g. for the automotive industry.
With regard to the forming speed the following must be distinguished:

Hammer forging

As the name of the hammer forging or hammering indicates: it is hammered, that is, acted upon with a high deformation speed per hammer blow.

Press forging

In forging by pressing the workpiece is deformed at a low deformation speed.

▶ After the explanation of the distinguishing features of the forging process, tips for the forging parameters and forging facilities will follow.

Parameters in forging

Even though free forging gives the blacksmith many liberties, his expertise is still needed to achieve a good result. The most important parameters, always in relation to the steel being forged, are the basis for this:

- *Degree of deformation* (forging degree, compression degree, height loss or dimensional change)
- *Forging temperature*
- *Forming speed*
- *Material* (flow curve, formability—workability)

Degree of deformation during forging:

In forging practice, the following are mainly used:

Forging degree $\boldsymbol{\lambda}$ (deformation relative to the initial and final cross-sectional area):

$$\boldsymbol{\lambda = A_0 \div A_1}$$

A_0—beginning of deformation (area in the undeformed initial state):

$$\boldsymbol{A_0 = \pi \div 4 \times d_0{}^2}$$

A_1—end of deformation (area in the final state, forged):

$$\boldsymbol{A_1 = \pi \div 4 \times d_1{}^2}$$

Examples from practice for usual forging degrees are:

$\lambda > 3.5$ *for austenitic steels*
$\lambda > 3.0$ *for construction steels*

Upsetting factor $\boldsymbol{\lambda_s}$ (deformation relative to the height decrease):

$$\boldsymbol{\lambda_s = h_0 \div h_1}$$

To avoid buckling of the workpiece, the height-to-diameter ratio on the workpiece should be $\mathbf{h_0 < 3d_0}$.

Forming force during forging

Figure 5.6 shows the geometry for upsetting forming before and after the height reduction, ignoring friction processes.

In general, friction occurs in the contact zone between the forging tool and the workpiece during open die forging. This impedes the free spreading (flow) of the material in this area. Therefore, the round steel is actually compressed slightly bulged, as shown in Fig. 5.7. The forming efficiency is consequently slightly lower in practice. However, this can usually be neglected when considering the forming force.

In forging (upsetting), the necessary forming force is introduced directly into the forming zone via the tool surfaces (forging saddles). Therefore, for this direct, immediate force introduction and without taking into account friction, the ideal, necessary forming force $\mathbf{F_{id}}$ is:

$$\mathbf{F_{id} = A \times k_f}$$

The factor k_f is the flow stress that is necessary for the plastic deformation of the respective steel. It is always related to the actually existing cross-sectional area, thus to the true deformation (forming degree φ):

$$\mathbf{k_f = F \div A}$$

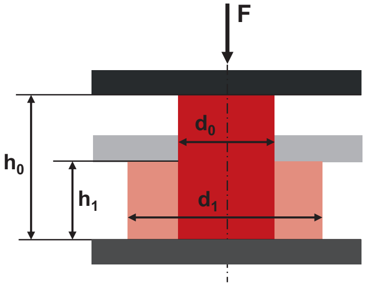


Fig. 5.6 Geometry when upsetting

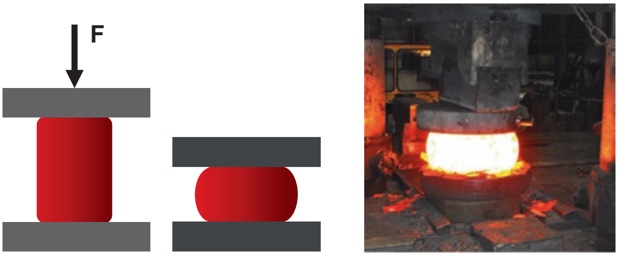


Fig. 5.7 Upsetting process in practice. (Photo: Schlegel, J., BGH Edelstahl Lippendorf GmbH)

This means:

F: the currently measured forming force
A: the current cross-sectional area of the sample

$$\text{Forming degree} \quad \boldsymbol{\varphi = \ln h_0 \div h_1}$$

In this context, the following terms mean:

h_0: the height of the sample before deformation
h_1: the height of the sample after deformation

In the practice of metal forming, flow curves have proven to be useful, which represent a relationship between the forming degree and the flow stress (yield stress), as well as temperature and forming speed (Hensel & Spittel, 1978). Figure 5.8 shows a simplified course of the flow stress as a function of the forming degree and comparatively for hot and cold forming.

Such flow curves can be experimentally determined by means of a compression or tensile test or, in the case of sheets, by means of the bulge test.

Today, numerous databases offer flow curves for a variety of steels in different microstructural states as a prerequisite for determining the force and energy requirements, e.g. steel data from Matplus GmbH.

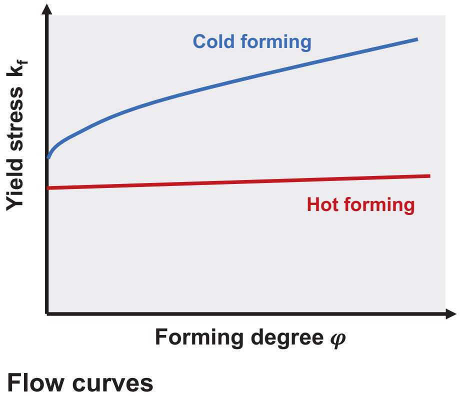


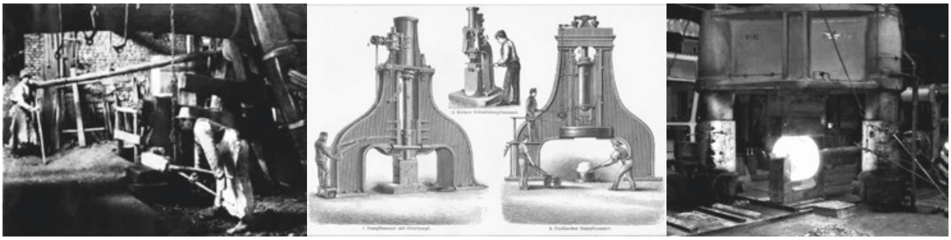
Fig. 5.8 Flow curves for hot and cold forming of steel (simplified)

Plants for Forging

The hammers and forging plants currently in use can be divided according to the type of drive or power transmission (work-related, force-related or path-related) into drop hammers, steam hammers, air hammers, screw presses, crank presses, knee-lever presses, eccentric presses and hydraulic forging presses.

The development of drive technology using water wheels, steam or compressed air up to the modern hydraulically operated forging and pressing plants is interesting. Figure 5.9 shows a comparison of a hammer mill from 1700 and a steam hammer from 1891 with a modern forging press.

The air-powered **hammers** are mostly used for free-form forging. They consist of the working frame with anvil and hammer as well as a compressor and the working cylinder, whose piston acts directly on the hammer head. The piston is moved by means of an electric motor. The air pressure generated in this way is transmitted to the working



Waterwheel hammer **Steam hammer** **Forging press**

Fig. 5.9 Development of forging plants, *from left to right:—Heavy waterwheel hammer* of the hammer mill founded by Gotthard Busch in 1467 in a smelter settlement north of Siegen. (Photo: BGH Edelstahlwerke GmbH).—*Steam hammer,* woodcut from 1891 from: Brockhaus Konversationslexikon, 14th edition 1894 - 1896 (https://www.retrobibliothek.de/retrobib/seite.html?id=5180509&imageview=true)—*Two-column forging press* (2000 t), hydraulically operated (Photo: Schlegel, J., BGH Edelstahl Lippendorf GmbH) cylinder and controlled in such a way that the hammer is lifted and moved with a defined impact force and impact speed to the forging ingot.

This drive technology is also used by the so-called machine hammers, which today can be found in many industrial companies, but also in craft businesses, for example with hammer weights of approx. 50 kg. It is interesting that this drive technology, albeit in a very small design, can also be found in the well-known electric Hilti or Bosch drill hammers.

Drop hammers feature a special technique. Only the free fall of the hammer weight from a defined drop height causes the blow on the workpiece to be formed and thus its deformation. Afterwards, the bear is pulled up again with a strap, a board, a chain or by means of steam, compressed air or hydraulic pressure.

The **counterblow hammers** have in contrast to all other types of hammers a movable anvil, the Schabotte or also called lower bear. This lower hammer moves upwards during the hammer blow, while the upper hammer strikes downwards. As a result, the workpiece is forged from above and from below at the same time.

5.2.1.2 Open Die Forging

▶ In 1795 *Joseph Bramah* (1748–1814) invented a hydraulic press, which was initially used as a packing press for hay, flax and cotton, but later found a wide range of applications. It was *John Haswell* (1812–1897) who first used a hydraulic press for forging steel parts (Lietzmann et al., 1984).

Modern hydraulically operated presses generate pressure using electric motors and high-performance pumps. As already implemented constructively by *Joseph Bramah*, the hydrostatic principle is used to multiply the pressure and thus generate very high pressing forces. This is possible because in hydraulic systems the pressure is always the same regardless of the vessel shape or the vessel cross section. Thus, a small force is required to generate a certain oil pressure in a small pipe. If a cylinder with a large cross section is now connected, the same pressure occurs, but it acts on the much larger cross section of the cylinder—a force multiplication takes place.

Hydraulic presses usually work with oil pressures of up to 300 bar today, with forces of up to 800 MN (80,000 t) achievable depending on the piston diameter. The working pistons in hydraulically operated presses can be arranged above or below the floor level (working level in steel, rolling and forging plants). Figure 5.10 shows, for example, a forging press with an oil hydraulic drive below floor level, i.e. below the working level in the foundation area of the press.

Hydraulic forging presses are primarily producing semi-finished products (long products with round, square or rectangular cross-sections) through forging of shoulders and conical tapers as well as discs, bushes and forged pipes. In addition, v-shaped forging saddles are used as in Fig. 5.10 or even smooth forging saddles as in Fig. 5.4.

Fig. 5.10 2000 t-two-column press with an oil hydraulic drive below floor level. (Photo: Schlegel, J., BGH Edelstahl Lippendorf GmbH)

5.2.1.3 Die Forging

> ▶ Die forging plays a very important role in metal processing; after all, die forged parts (also called "drop forged parts") meet very high requirements in terms of strength and dynamic stress. Typical parts that are produced by die forging are connecting rods, suspension parts, wheel flanges, crankshafts, camshafts, pistons and bolts for the automotive industry. Structural steels are used for bolts, rings, flanges and levers. Wheel hubs, camshafts, crankshafts, axles, hubs and wheels are made of heat-treatable steels. And tool steels are used for levers, gears and other transmission parts.

Gesenke are forming tools which contain the forms to be forged, partially or completely, as negative contours. Die forging can be carried out with a burr to the drop forged part (forging with not completely enclosed drop forge die) or without a burr (forging with completely closed drop forge die). Figure 5.11 shows these die forging variants schematically.

The process of die forging, usually carried out for steel at elevated temperatures, comprises the individual steps:

- *Cutting the blank from the semifinished product*
- *Heating to forging temperature*
- *Preforming* (e.g. mass distribution by means of strech rolling)
- *Preforging*

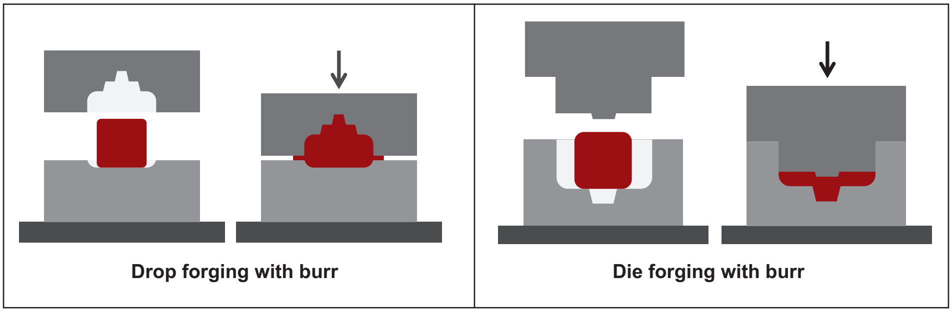


Fig. 5.11 Schematic illustration of die forging with burr and without burr

- *Finish forging*
- *Facing and drilling*
- *Cooling, heat treatment*

Individual process steps are shown in Fig. 5.12 using the example of forging a scissor blade. These pictures were taken in the Hendrichs die forge plant in Solingen, today a museum location of the LVR Industrial Museum Solingen. From 1886 to 1986, Hendrichs forged scissor blanks.

Most die forged parts must be post-treated by machining (milling, drilling, grinding). This can be dispensed with altogether in the case of precision die forged pieces, since an end-contour-like shape with tight dimensional tolerances can already be achieved by die forging without a burr. An example of this are precision die forged gears.

▶ The methods of open die and die forging have not changed over the centuries. With state-of-the-art technology, all basic methods for shaping steel are still used today, such as stretching, forming, upsetting, stamping, setting,

Fig. 5.12 Forging a scissors blade on a hammer, *from left to right:* die forge with the negative engraving of a scissor blade, inserting the preheated flat blank, die forging process and the result: a forged scissor blade with burr. (Photos: Beck, Klaus-Peter, Bergheim)

widthening, punching, drilling, tapping, bending, drop straightening, coining and die pressing. To list all these variants of forging would exceed the scope. Only one method should be mentioned here: embossing. After all, the most interesting coining results accompany us in our wallets every day.

5.2.1.4 Coining

▶ This process is also a manufacturing process belonging to sheet metal forming. Shapes are stamped into a workpiece without chips using contoured stamps. The term coining already refers to a high surface quality, uniformity and exact contours or dimensional accuracy.

The best-known area of application is the minting of coins and medals. The coin blanks are brought into the desired shape or provided with a one-sided or two-sided coining on a press with engraved dies. Up to the end of the fifteenth century this was handicraft (hammer coining). Afterwards, the development of various technical mechanisms began, leading up to the most commonly used toggle presses today. *Dietrich Uhlhorn* (1746–1837) developed the first press suitable for coin minting with a toggle pressing plant. For this purpose, he used the toggle effect for power transmission, as shown schematically in Fig. 5.13.

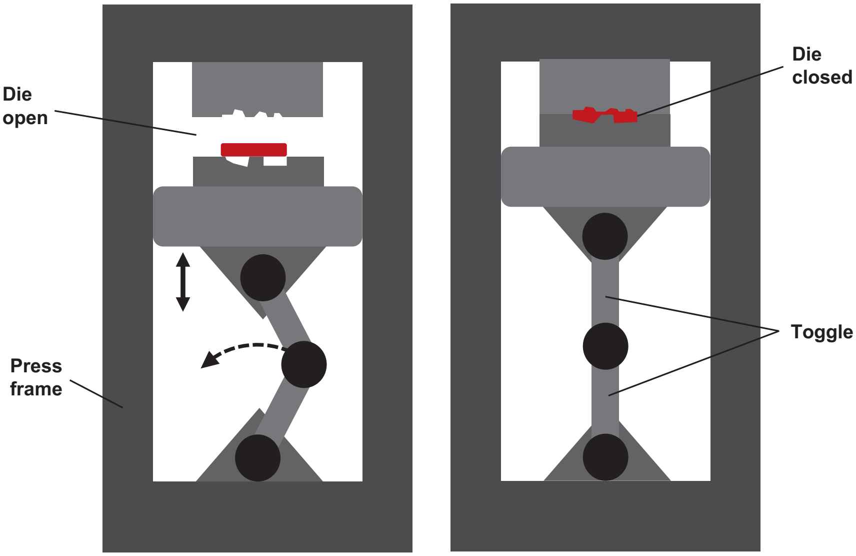


Fig. 5.13 Principle of the function of a toggle press

The introduced force can be increased in the area of the almost extended knee, while beforehand the movement of the die or the coining stamp takes place with less force at higher speed. Modern toggle presses can emboss up to 20,000 coins per minute.

In addition to the toggle presses, friction wheel screw presses and eccentric presses are also used today to stamp a variety of parts from a variety of materials. The function of the friction wheel screw press goes back to the invention of the threaded screw by the Greek scholar *Archimedes* (287-212 BC). But it was not until the late Middle Ages that the first hand-operated presses came into use. These presses convert a rotary motion of the threaded spindle by the thread pitch into a vertically acting displacement. This makes high pressures possible. The modern friction wheel screw presses have two discs at the top, which are attached to an axially displaceable, electrically driven shaft. The screw with the coining tool has a flywheel at the top. If the rotating discs are moved axially, one of the two discs is pressed against the flywheel. The resulting friction causes the screw to rotate and thus the up-and-down movement of the coining tool. Figure 5.14 shows the structure of such a friction wheel screw press.

Modern friction wheel screw presses have a special coupling, an electric direct drive or servo drives.

The **eccentric forging presses** are mostly used today for deburring of forged parts. There are presses with fixed or adjustable stroke lengths. They have a driven eccentric shaft. Its rotation is converted into a vertical movement by means of a connecting rod. Figure 5.15 shows the operation of an eccentric forging press.

Fig. 5.14 Operation of a friction wheel screw press

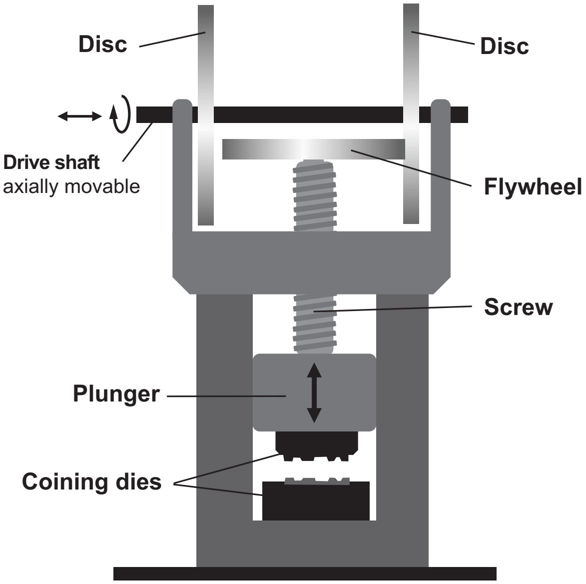
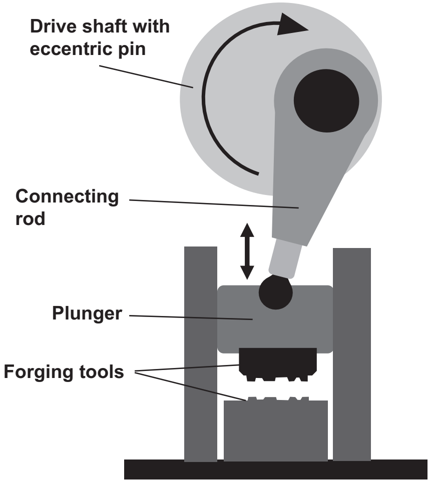


Fig. 5.15 Function of an eccentric forging press



This mode of operation is comparable to the type of combustion engine, only that in these the principle works in reverse: a linear vertical movement of the piston is converted into rotation of the crankshaft by means of the connecting rod. Eccentric presses are used for cutting stamping operations and embossing-bending operations with small press strokes.

Friction wheel screw presses with up to 450 t pressing force and toggle presses with pressing forces up to 1400 t are used today for the production of various steel form parts. These include decorative elements, embossed ornamentation, keys, lock parts, cutlery, scissors, medical instruments, parts for vehicle construction, etc.

▶ So today, coining is not only the established method for the production of coins, but in connection with other methods such as stamping and bending, it is also important for the production of very complex part geometries. In addition to open die forming (forging, hammering, pressing) and die forming (die forging, coining), the following section on pressure forming processes will also introduce flow pressing and strand extruding.

5.2.2 Flow pressing

The therm flow pressing expresses the principle of operation: The material to be formed is put into a well-flowing state and brought into a completely new form. For this, the material must be exposed to such a high pressure in a closed space by a die that the flow limit is exceeded and the material flows through the opening of the die This massive forming process can be used at room temperature (cold forming) or at elevated temperatures (warm or hot forming) for the production of both solid, hollow and for cup-shaped parts. Depending on the direction of flow of the material, a distinction is made between forward, backward and transverse pressing. Figures 5.16, 5.17 and 5.18 show in a simplified representation these processes.

The flow forming of parts can be done in one step or in multiple steps. A combination of individual variants as well as multiple forming processes are possible or necessary; sometimes a post-processing of the flow formed parts has to be carried out. Figure 5.19 shows as an example the 4-step cold flow forming of a connection element (screw blank).

During flow pressing very high compressive stresses occur to which the dies are subjected. For this reason, they are usually provided with a reinforcement which causes a certain pre-stress (compressive stress condition in the dies already before the stress during flow pressing). This, in conjunction with a suitable lubricant, increases the lifetime of the dies. The choice of material (tool steel, carbide or technical ceramics) for all impact extrusion tools such as punches, dies and mandrels must also be adapted to the process and the material to be processed.

Based on the required good formability of the material to be processed, impact extrusion processes are preferably used for non-ferrous materials such as aluminum and copper or their alloys, but also increasingly for the forming of steels. Typical applications for steel extruded parts, mainly hot-formed, include hydraulic components, parts for gearboxes (e.g. hollow shafts), steering, drives, chassis, engines, parts for mechanical engineering, aircraft construction, chemical plant construction and steam turbine construction.

5.2.3 Strand Extruding

▶ The flow pressing presented are used to produce formed parts. The extrusion press process works according to the same principle as flow pressing, whereby - as the name suggests - an extruded strand, that is, a very long, profiled semi-finished product, is produced as a product.

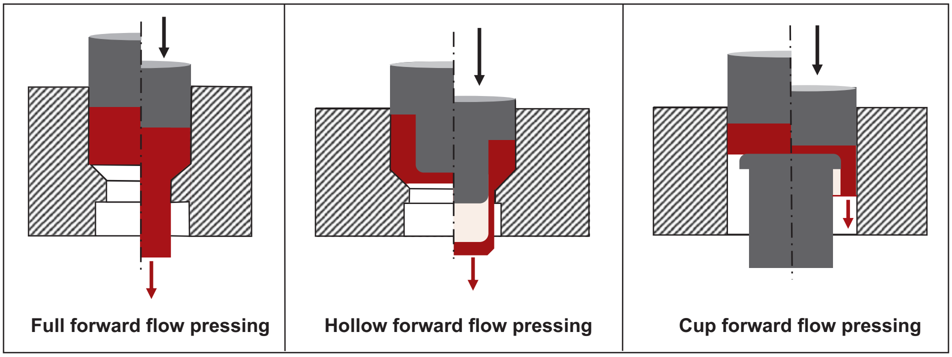


Fig. 5.16 Forward flow pressing process (material flow and stamp movement in the same direction), *from left to right:* full forward flow pressing, hollow forward flow pressing, cup forward flow pressing

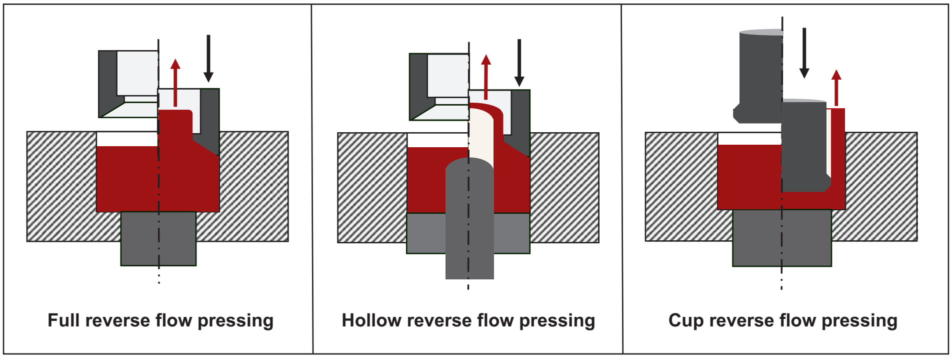


Fig. 5.17 Reverse flow pressing process (material flow and stamp movement opposite), *from left to right:* Full reverse flow pressing, Hollow reverse flow pressing, Cup reverse flow pressing

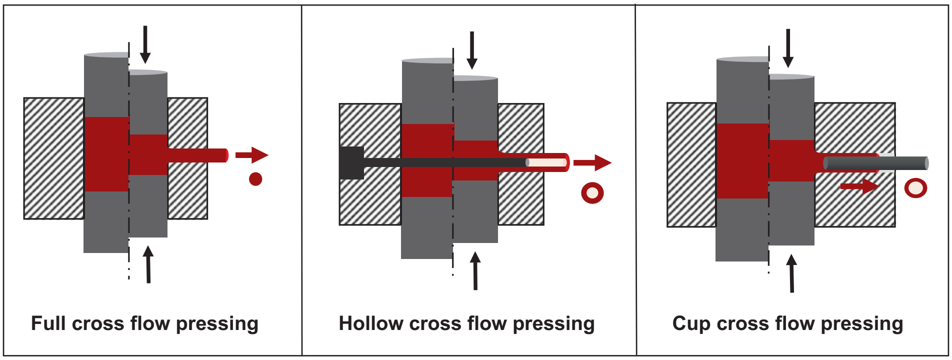


Fig. 5.18 Cross flow pressing process (material flow across the stamping direction), *from left to right:* full cross flow pressing, hollow cross flow pressing, cup cross flow pressing

In strand extruding, often also called "extrusion" (pushing out, ejecting), the billet (round pre-block, heated to forging temperature) is introduced into a pressure chamber (recipient). With a punch, the extruding is carried out by means of a die, whereby the strand assumes the profile cross-section of the die. If a special profiled mandrel is used, internally profiled hollow sections (pipe profiles) can be produced as well.

Depending on the direction of exit of the strand and the direction of movement of the press ram, direct and indirect strand extruding is distinguished, in practice also called forward and reverse strand extruding. Figures 5.20 and 5.21 show in schematic representations these methods for the forming of full and hollow profiles.

The friction forces are very different in these two process variants. In the direct, i.e. forward strand extrudin, the inner friction between the recipient inner wall and the surface of the bloom must be overcome. In contrast, this friction does not occur in the indirect, reverse strand extruding.

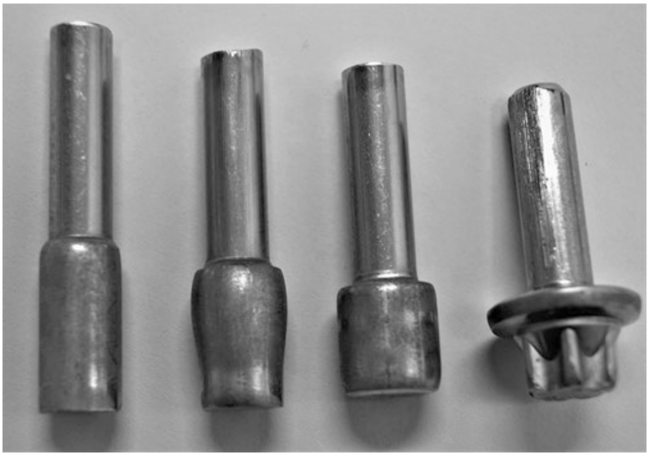


Fig. 5.19 4 stages of cold flow pressing of a screw blank. (Photos: Schlegel, J.)

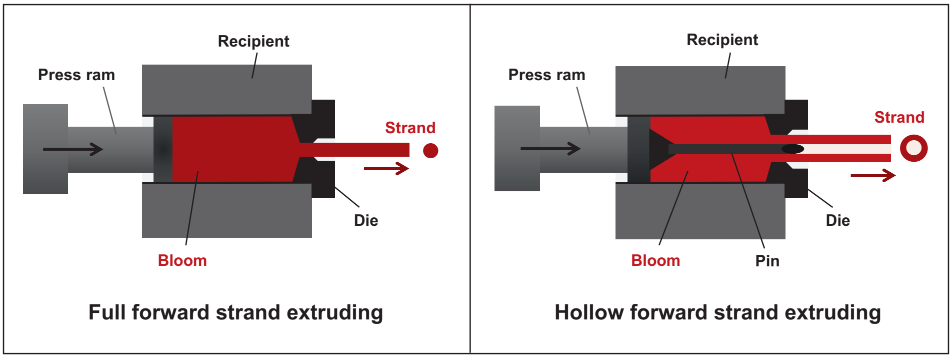


Fig. 5.20 Basic illustration of forward strand extruding of full and hollow profiles (*from left to right*)

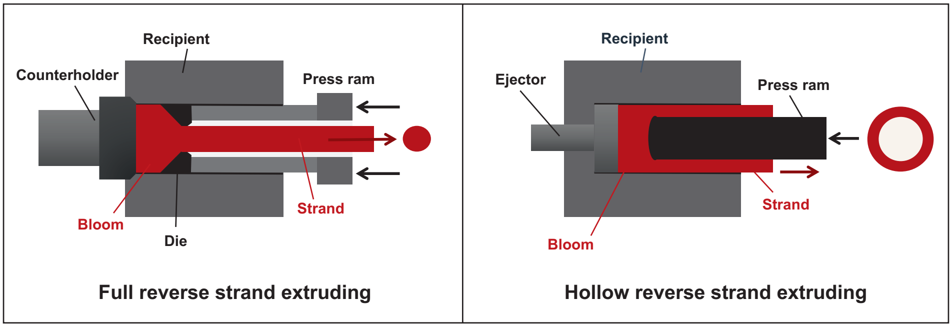


Fig. 5.21 Basic illustration of reverse strand extruding of full and hollow profiles (*from left to right*)

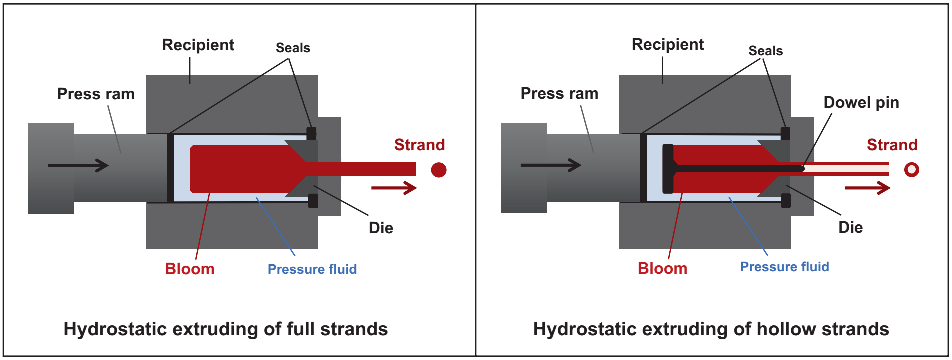


Fig. 5.22 Principle of hydrostatic strand extruding of full and hollow profiles

Even lower is the friction component in hydrostatic extrusion. Here, the pressing force is not applied directly to the bloom, but indirectly via a working medium (water or oil). The hydrostatic pressure surrounding the bloom on all sides in the receptacle, at an appropriate height (up to approx. 20,000 bar), causes the material to be extruded through the die into a strand with no or very little friction in the die. Figure 5.22 shows the principle of this hydrostatic strand extruding. This process can also be used to produce full and hollow profiles.

▶ **Note**

The aforementioned extrusion processes are mainly used for well-formable materials, so-called plastic alloys such as e.g. aluminium, copper and their alloys, for cold forming in order to produce profiles and pipes, sometimes also composite profiles. A high degree of deformation can be achieved in one forming step at relatively low tool costs. Aluminum profiles for the production of windows, doors and facades are particularly well known.

Of course, strand extruding is also suitable for steel under certain circumstances (hot forming). For example, seamless pipes, beams and U-profiles are made of stainless steel. Only if special requirements are placed on such profiles with regard to strength, heat and corrosion resistance and if the quantities are lower, extrusion of steel can make sense.

5.2.4 Rolling

▶ Like a floating city, the large cruise ships sail across the seas; and also tankers, container ships, fishing vessels and other watercraft. They are all built from many, very large steel plates, steel beam profiles, pipes, etc. Rail profiles and wheel rims are needed for the railways and steel strips and sheets for the automotive industry. In construction, for example, seamless pipes are used for water pipes, railings and handrails, as well as reinforcement steels for reinforced concrete construction. And also steel wires, rolled, drawn, galvanized and braided into ropes, find a wide range of applications for elevators, cable cars, bridges and Bowden cables. These mentioned steel products and many more, also raw materials for them, are produced by different rolling processes. This will be addressed below.

5.2.4.1 Basics of Rolling

▶ Rolling is a pressure forming process in which the cross section of the rolling stock is changed between rotating smooth or profiled rolls (Fig. 5.23).

The rolled stock—a casting blank, a pre-rolled billet (rectangular cross-section) or a semi-finished product—is fed to a rolling mill with two or more rolls rotating in opposite directions (Fig. 5.24).

In the roll gap which is narrowing in the direction of rolling, rolling forces are generated by the rotating rolls, which lead to a plastic forming. At the same time, part of the forming work introduced by the rolls is converted into heat energy. Therefore, the rolled stock heats up when passing through the roll gap.

Fig. 5.23 Principle of forming by rolling

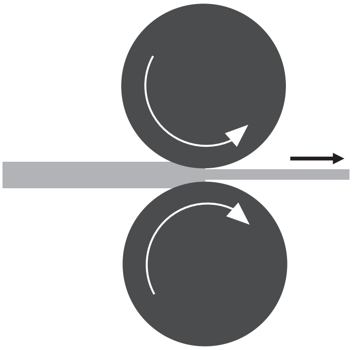
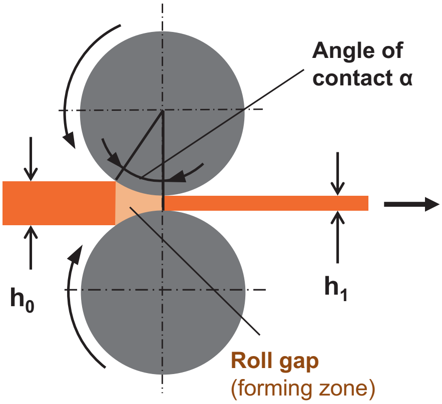


Fig. 5.24 Schematic representation of the roll gap during forming with two rolls



The size of the rolling gap is defined by the angle of contact α. The possible cross-sectional reduction of the rolled material depends on the friction conditions between the rolls and the rolled material, the forming ability of the rolled material as well as the roller diameter and the forming speed (rotating speed of the rolls).. Since the volume of the rolled material generally remains the same during forming, in addition to the height reduction from h_0 to h_1, there is also a broadening (width increase) and above all a stretching (length increase).

The most important rolling parameters are:

- *the material (formability)*
- *the cross-sectional reduction (degree of deformation)*
- *the rolling temperature and the cooling effect of the rollers*
- *the rolling speed (rotation speed of the rollers)*
- *the surface condition of the rollers*
- *the geometry of the rollers (flat or profiled rollers)*
- *the lubrication, thus the friction condition and the gripping condition*
- *the deflection of the rollers during flat rolling*

The processes taking place in the structure of the rolled material during hot rolling are interesting:

The casting structure (fine-crystalline rim zone, stem-crystal zone, core zone) is transformed into a forming structure (new formation of grains). Voids and other cavities are closed (welded). When hot rolling pre-rolled billets, recrystallization (new formation of the structure) already begins during rolling (Palkowski, 2015). This change in structure is shown in Fig. 5.25.

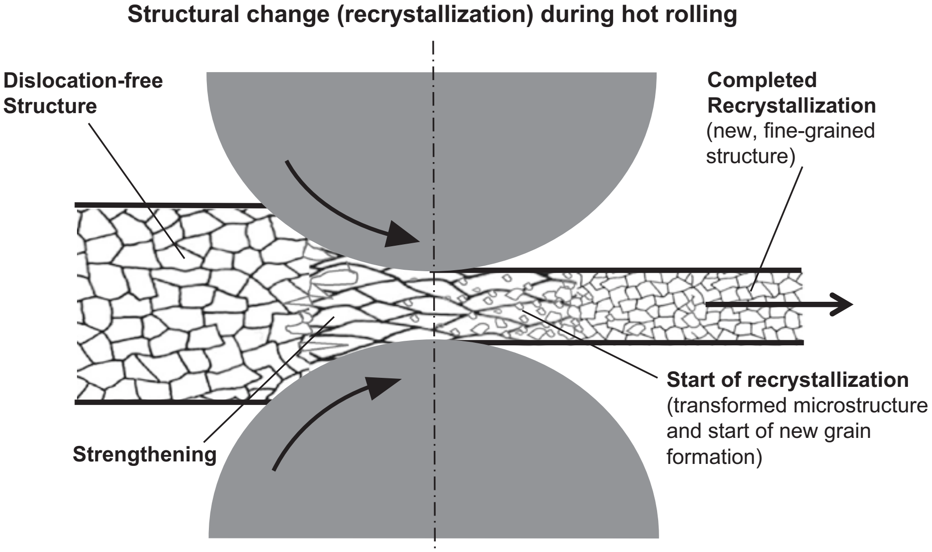


Fig. 5.25 Change in structure during hot rolling

In particular, it depends on the gripping condition whether the workpiece can be drawn in between the rollers and thus rolled at all. This is the case if the pulling friction force component is greater than the normal force component acting in the opposite direction. In this case, large rollers have the advantage that even with large cross-section reductions, this gripping condition is easily met. Smaller rollers are used mainly for smaller cross-section reductions in order to keep the rolling forces low (Hensel & Spittel, 1978).

5.2.4.2 Rolling Processes

▶ In general, rolling processes are distinguished by:

- *Longitudinal rolling*
- *Cross rolling*
- *Skew rolling*
- *Streching rolling*
- *Special rolling processes (e.g. roll forging, thread rolling)*

Figure 5.26 shows a simplified representation of the four main rolling processes for this purpose.
Another distinction relates to the rolling temperature:

- *Rolling at room temperature (cold forming)*
- *Rolling at temperatures above the recrystallization temperature (hot forming)*

In this case, it is again necessary to distinguish when rolling in the longitudinal direction whether a wide-flat product is produced between smooth rolls (e.g. steel strip rolls) or a profile with calibrated rolls. In Fig. 5.27 these different rolling processes are compared.

In addition, depending on the process and product, differently arranged two-roll stands or plants with three and more rolls are used. Up to a maximum of 20 rolls per multi-roll stand are possible, as shown in Fig. 5.28.

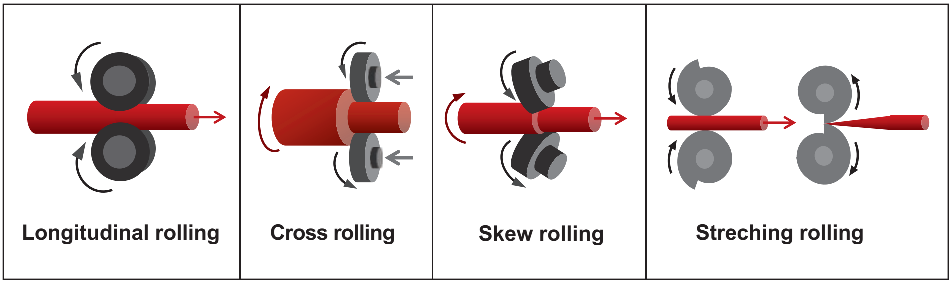


Fig. 5.26 Representation of the processes: longitudinal, cross, skew and streching rolling

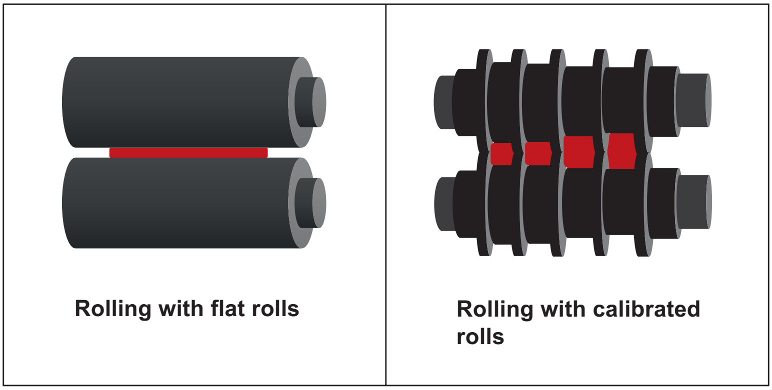


Fig. 5.27 Comparison of the longitudinal rolling of flats and profiles

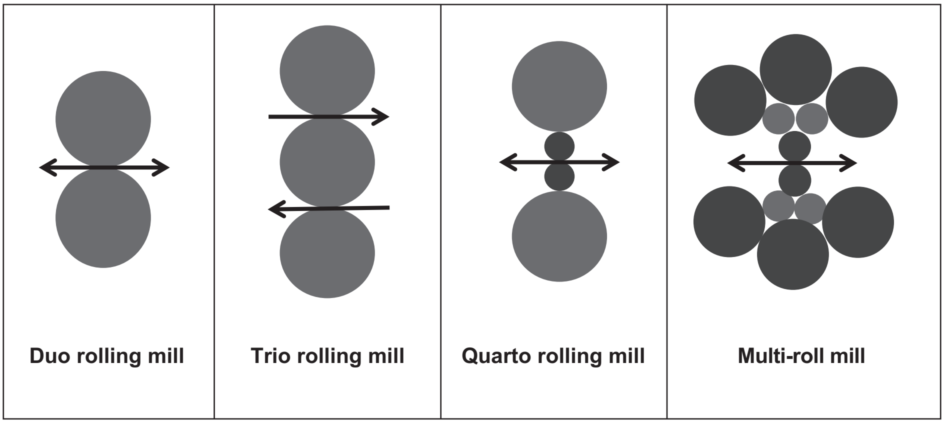
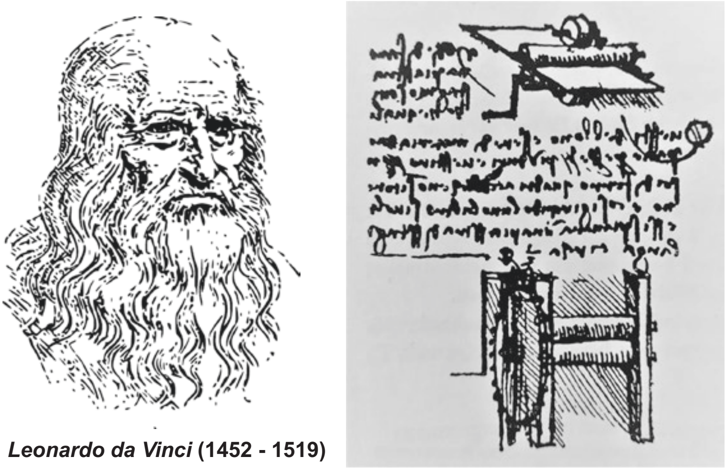


Fig. 5.28 Duo rolling mill and plants with three and more rolls

Note that always only two rolls act as working rolls, and all other rolls support them, i.e. are supporting rolls. These can be operated as single-purpose rolling mills (e.g. Duo-Block rolling mills, Quarto-Band rolling mills, multi-roll foil rolling mills), side by side in so-called "open streets" (e.g. Trio-rolling mills) or in line in continuously operating rolling mills (e.g. continuous wire-rolling mills).

Longitudinal Rolling

▶ In longitudinal rolling, the axes of the rolls are arranged transversely to the rolling direction. Long products are rolled in the longitudinal direction: bar steel, rolled wire, concrete steel and profiles such as rails, spunding piles, I-, H- and U-profiles, as well as wide-flat products such as strip steel and sheets.



***Leonardo da Vinci* (1452 - 1519)**

Fig. 5.29 *Leonardo da Vinci* and his designs for two hand-driven sheet metal rolling mills, drawing from 1495. (From the Internet: Feldhaus, 1913, p. 55)

It is interesting that *Leonardo da Vinci* (1452–1519) already sketched all elements of a rolling mill, for example in 1495 two hand-driven sheet metal rolling mills for tin plates, as shown in Fig. 5.29.

Rolling of iron only began in the seventeenth century. Initially, the most important components of a rolling mill were forged rolls made of iron. Later, a steel plate was welded onto the rolling track (flat rolls) of these forged rolls and hardened (Lietzmann et al., 1984). Today, cast steel rolls are used for hot rolling of steel. For cold rolling, forged and surface-hardened rolls are used.

Blooming Mills

These rolling mills are mainly used for rolling cast ingots and forged blocks. This is also where the name comes from. Two rolls are mounted in a rolling frame, with the upper roll usually being “adjustable”. This roll can be adjusted in height so that a desired rolling gap can be set and thus a cross-sectional reduction of the rolling block can be achieved with each rolling process.

Rolling mills that were already very similar to today’s duo rolling mills were in use in England from 1820. The first shaping of the cast ingots takes place on such blooming mills. Semi-finished products (long products) with a square or rectangular cross-section are rolled reversibly, i.e. forward and back again with decreasing rolling gap. Figure 5.30 shows an example from practice, a duo mill with typical box-type rolls. This blooming mill is reverse rolling.

Fig. 5.30 Duo reversing blooming mill with box pass. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

Profile Rolling Mills

The rolling of profiles, e.g. of railway tracks or T-beam girders, was a special challenge for the rolling mill builders. For this purpose, mostly three-roll (trio) and reversing duo rolling stands with profiled rolls were operated next to each other. This arrangement of the individual rolling stands is referred to as an "open" semi-finished rolling train. Such open roling mills also in use today, e.g. at BGH Edelstahl Freital GmbH as a roughing mill train for rolling round steel up to a diameter of 160 mm. Figure 5.31 shows this rolling mill with two trio stands and one duo stand arranged side by side. The rolls of these stands are connected to each other. Only one drive is necessary for such an "open" stand arrangement.

Around 1900, duo rolling mills were arranged one after the other, alternately as horizontal and vertical rolls (Lietzmann et al., 1984). In the end, the fully continuous rolling mills in use today with different technical designs emerged. These are divided into pre-, main- and finishing roll stands and are used to produce bars and wire with different caliber sequences (shapes and dimensions of the cross-sections to be rolled one after the other). Figure 5.32 shows a section (main stand) of a continuous rolling mill for wire and rod made of stainless steel.

In such continuous rolling mills, so-called rolling blocks are integrated as a final stage for exact adjustment of the profile end cross-sections (round). These consist of several rolling units arranged one behind the other, with two, three or even four disc type rolls. Figure 5.33 shows, for example, the arrangement of two and three disc type rolls.

In one pass, starting from a semi-finished product with a diameter of approximately 120 mm, today's high-performance rolling mills can continuously produce rolled wires

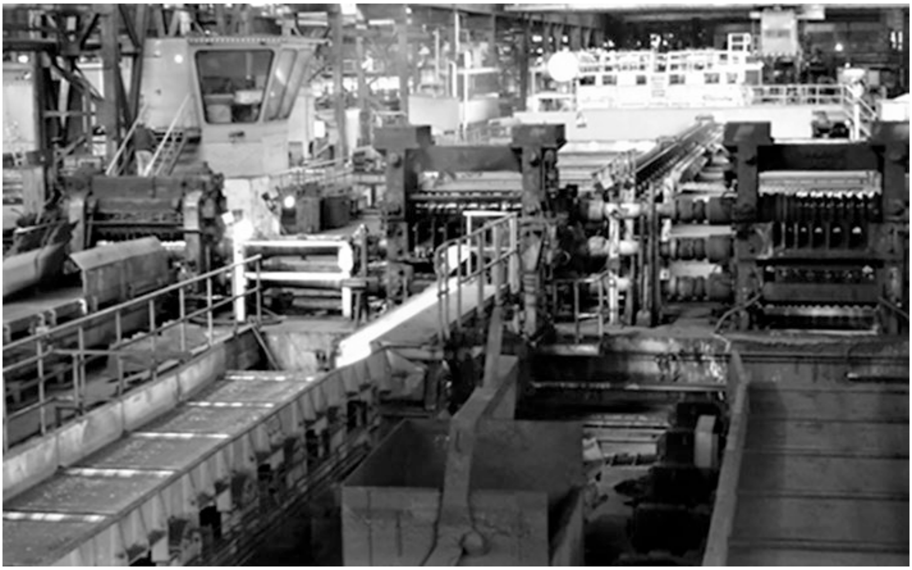


Fig. 5.31 Roughing mill as an "open" rolling mill for rolling semi-finished strands, clearly visible *from right to left*: two Trio roll stands, one Duo finishing stand arranged side by side. (Photo: BGH Edelstahl Freital GmbH)

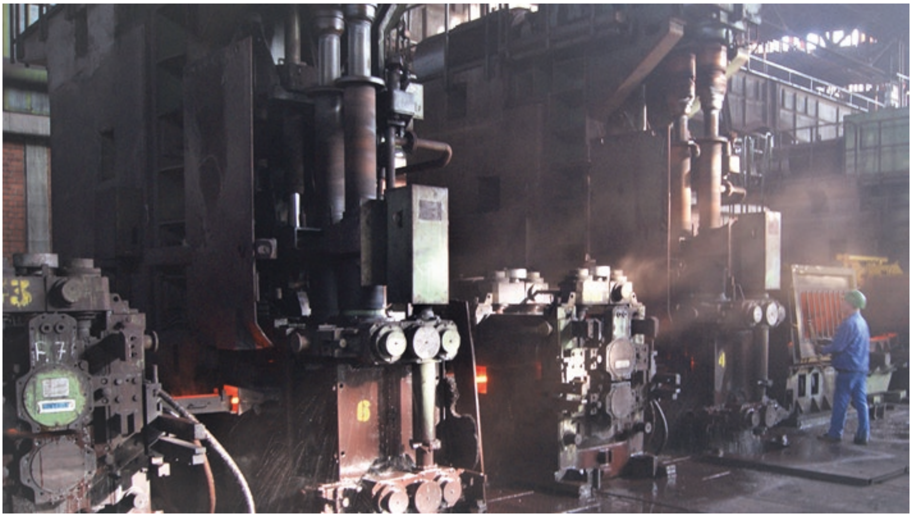


Fig. 5.32 Example of a continuous rolling mill (center section) for bars and wire. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

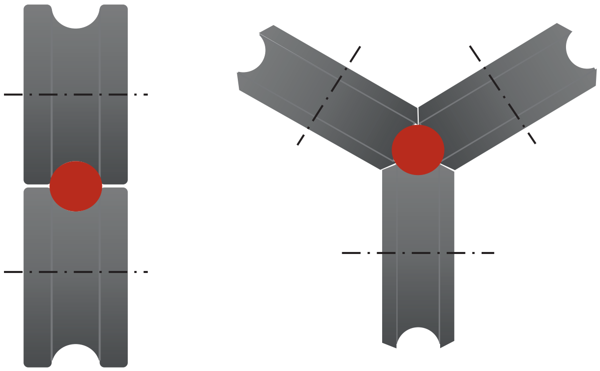


Fig. 5.33 Arrangement of two and three disc type rolls, as used in rolling blocks for wire rolling

with an final diameter of 5 mm. Figure 5.34 shows this for a hot-rolled steel wire with a diameter of 5 mm at the outlet of a continuous wire rolling mill.

Calibration

The blooming mills and profile rolling mills described in the context of longitudinal rolling work with rolls that have profiled (calibrated) roll paths. The shapes cut into the roll bodies (e.g. box pass) result, together with the shape of the counter roll, in the achievable roll profile, taking into account the roll spacing. With each individual rolling pass, the rolled material is gradually brought closer to the final geometry by the individual cross-section changes. This sequence of individual forming steps is called a caliber sequence. The specification of the geometries of the individual rolling steps (individual forming degrees) in dependence on the steel quality (formability) is called calibration. This is carried out using modern calculation methods. Reference should be made here to this calibration (*"A science in itself!"*), without going into details of the calculation basics.

An important basic type of pass shapes are the open and closed box passes

These box-shaped caliber geometries (Fig. 5.35) are mainly used in duo blooming mills. When rolling in the open box caliber the caliber height and the roll stroke (roll position) determine the roll height. A closed box caliber allows all-sided shaping of the rolled material without burr formation.

Further caliber shapes are shown in Fig. 5.36, for example for the continuous rolling mills for the rolling of semi-finished products: diamond-shaped caliber, square caliber, oval caliber and round caliber. In addition, an example of a possible caliber sequence for rolling an angle iron is shown.

Fig. 5.34 Wire with a diameter of 5 mm directly at the outlet of a continuous rolling mill. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

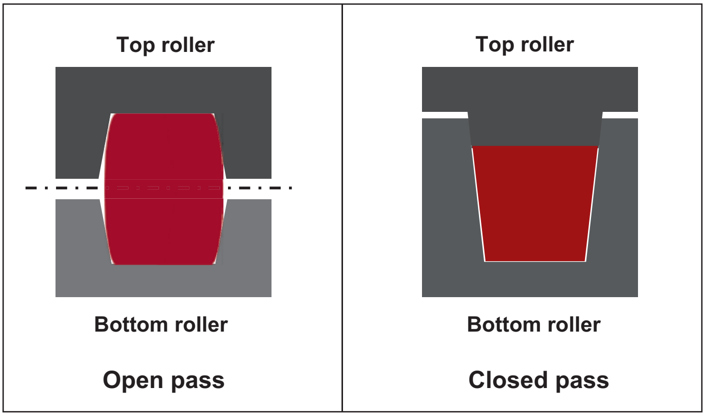


Fig. 5.35 Schematic representation of the open *(left)* and closed *(right)* box caliber shapes for blooming rolling mills

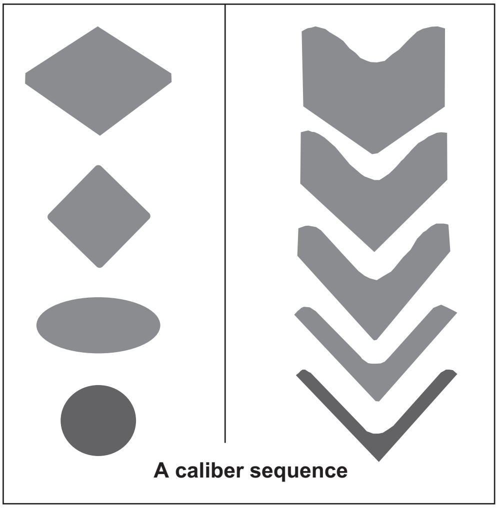


Fig. 5.36 Schematic representation of caliber forms, *left from top to bottom:* diamond caliber, square caliber, oval caliber, round caliber, *right from top to bottom:* a caliber sequence for an angle iron.

Rolling Mills for Flat Rolling

▶ For rolling of wide flat semi-finished products, i.e. slabs, sheets and strips, mainly reversing mills in the form of single units as well as rolling lines with several reversing mills arranged in tandem are used. The deflection of the flat working rolls (rolls in contact with the material being rolled) is reduced or prevented by setting a pre-tension of the working rolls in the rolling stand. The supporting rolls also reduce horizontal and vertical deflection of the working rolls during the rolling process. At the same time, a special roll grinding (cambering) and/or targeted, local roll cooling is used.

Differently designed rolling mills are used for both hot strip and cold strip rolling.

Hot strip rolling

Hot strip is the pre-product for cold rolling of strip and sheets. It is usually rolled with thicknesses of 0.8 to 25 mm. With regard to the widths, the following are distinguished:

- *Narrow strip with < 100 mm width*
- *Medium strip with 100 to 600 mm width*
- *Wide strip with 600 to 2300 mm width*

Hot strip is produced from cast and rolled slabs in several rolling passes on hot strip mills. These hot strip mills usually consist of several four-high (Quarto) rolling stands arranged in series. Figure 5.37 shows, as an example, the hot wide strip mill of Thyssenkrupp Steel Europe AG as a finishing mill with seven Quarto rolling stands arranged in series.

Fig. 5.37 Hot wide strip mill of Thyssenkrupp Steel Europe AG, Duisburg. (Photo: Thyssenkrupp Steel Europe AG)

Billets with a thickness of approximately 240 mm are used, which have been pre-rolled to a thickness of 30 to 40 mm. The hot band can be rolled with final thicknesses between 2 and 3 mm. After passing through a cooling section, the hot band is rolled into a coil. In this form it then enters the cold rolling mill.

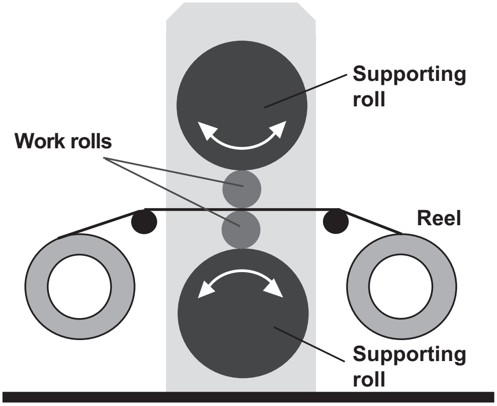
Today, hot bands can be produced with widths up to 2300 mm and thicknesses of approximately 0.8 to approximately 12 mm. Rough sheets are produced on quarto reversing stands with widths up to 5 m and thicknesses of up to approximately 250 mm by hot rolling.

A hot rolling line can also be directly connected to a casting plant. This makes it possible to produce hot band from a continuously cast thin slab with a thickness of approximately 70 mm at low cost (see also Sect. 4.4.3: *Continuous casting*).

Cold strip rolling

▶ From the first cold-rolled sheets at the end of the seventeenth century, the cold-rolled white sheet (thin rolled and galvanized steel sheet with thicknesses of 0.1 to 0.5 mm) known since 1810, to today's steel strip qualities, it was a long way of enhancements of the plant technology.

Fig. 5.38 Quarto reversing stand, operated as single roll stand for cold strip rolling

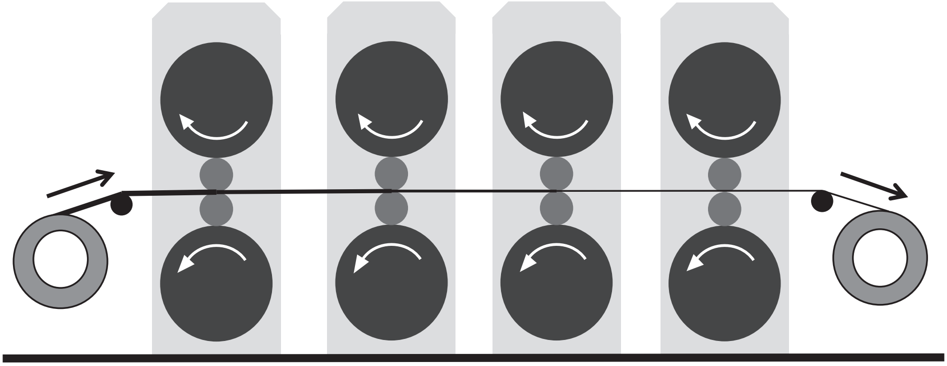


Quarto reversing stand

Cold rolling mills today process warm pre-rolled steel strip into even thinner cold strip with thicknesses below 1 mm, while certain properties are set. Individual reversing stands (Fig. 5.38) or so-called tandem rolling lines with 4 to 6 Quarto rolling stands arranged one behind the other (Fig. 5.39) are used.

A speciality are the already mentioned multi-roll stands, which are predominantly used for stainless steels. The best-known type is the Sendzimir rolling stand with 20 rolls, named after the inventor *Tadeusz Sendzimir* (1894–1989). Figure 5.40 shows the structure of such a multi-roll stand schematically.

After the rolling process, the cold strip is wound into a coil. Figure 5.41 provides a view of this in the cold rolling mill of Thyssenkrupp Steel Europe AG. In the foreground are the cold-rolled strips in coil form.



Tandem rolling mill for cold strip

Fig. 5.39 Tandem-rolling mill, consisting of four quarto-rolling stands for cold-rolling of steel strip

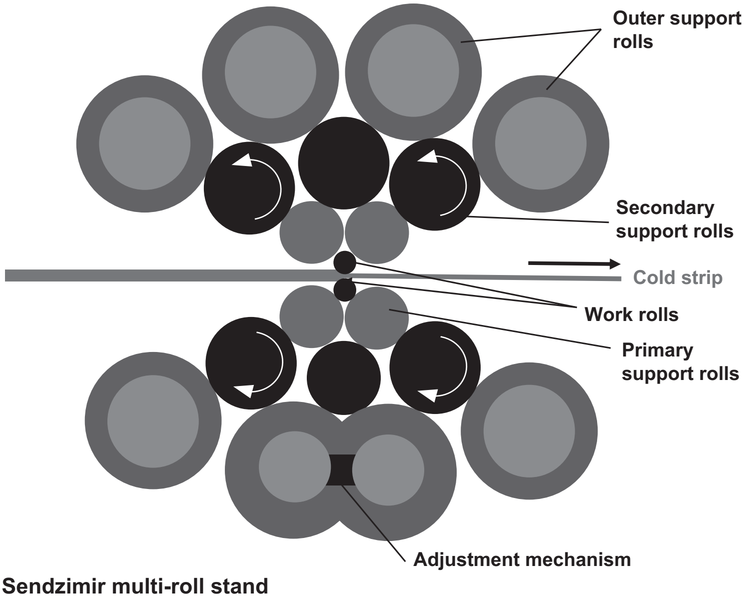
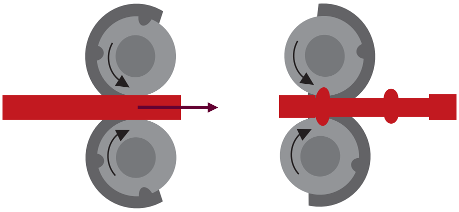


Fig. 5.40 Schematic structure of a Sendzimir multi-roll stand for cold rolling

Fig. 5.41 Cold rolling mill Duisburg. (Photo: Thyssenkrupp Steel Europe AG)

Fig. 5.42 Principle illustration of the strech rolling process



The cold bands are examined for errors, possibly cleaned and subjected to a subsequent surface coating for corrosion protection. Depending on the further processing, a longitudinal division into narrow bands or a transverse division into sheets can take place (see Chap. 9: *Finishing*).

Strech Rolling

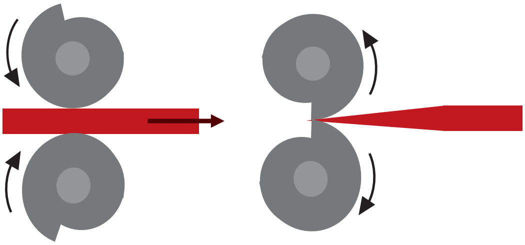
▶ A special variant of longitudinal rolling is the strech rolling process, also called "roll forging". Here, a change in the cross sections of raw parts is achieved by two counter-rotating rolls. These have a special profiling over the circumference, which leads to a corresponding profiling of the rolled material during rolling.

Principle illustration of the strech rolling process is shown in Fig. 5.42.

In rolling, the raw parts are profiled in a single rolling step in each case with one revolution of the roll pair, i.e. it is a discontinuous rolling. Similar to in cross rolling strech rolling is used to generate blanks with favorable mass distribution for subsequent forming steps, e.g. for die forging. This rolling process is also used for tapering of bars and wire in order to be able to draw them into a drawing die for a drawing process. Figure 5.43 shows the principle for tapering of round wire ends.

The two streching rolls have an increasingly larger diameter over half the circumference. The rolled material is quickly introduced when the rolls just have the smallest

Fig. 5.43 Principle illustration of tapering of round wire ends by means of strech rolling



diameter. Then the back-rolling with corresponding minimization of diameter of the rolled material takes place.. This procedure of forward and back-rolling can be repeated several times. In practice, this is also referred to as “pilgrimage” and is mainly used in the further processing of seamless pipes.

Pilger Step Rolling Process

> The reduction of the pipe wall thickness is the goal of this special rolling process, named after the step sequence of a Luxembourgish pilgrimage procession: *“Two steps forward, one step back.”*

This rolling process also involves constantly rolling forward and back. A pipe billet is used as rolled material. This is a pre-rolled and pre-drilled blank that was usually produced by skew rolling. This blank is moved back and forth by two rotating rolls in opposite directions. Inside the blank is a mandrel that determines the inner diameter of the pipe. One distinguishes between hot or cold pilgrimage of pipes.

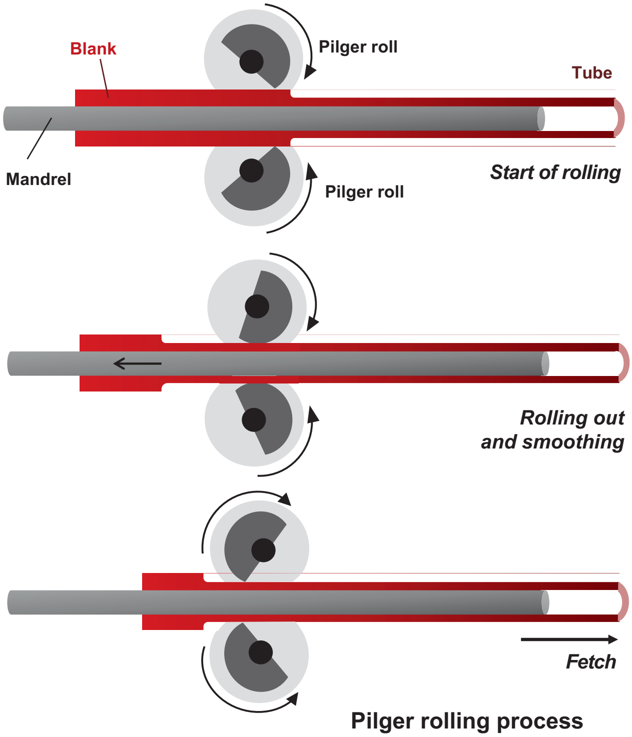


Fig. 5.44 Principle representation of the pilger step rolling process for reducing the wall thickness of seamless pipes

Figure 5.44 shows schematically this rolling principle of the "pilger step rolling" to reduce the wall thickness of seamless pipes.

When the largest free space is formed between the two rotating rolls, the blank with the mandrel can be inserted one working length in the opposite direction to the rolling direction. Then, due to the narrowing space between them, the rolls grip the blank with the mandrel and reduce the wall thickness of the tube during further rolling. After that, the roll pair releases the tube with the mandrel again and both can be advanced further. These processes are repeated until the complete length of the tube is reduced, that is, its wall thickness is reduced. Wall thickness reductions of up to 80% can be achieved.

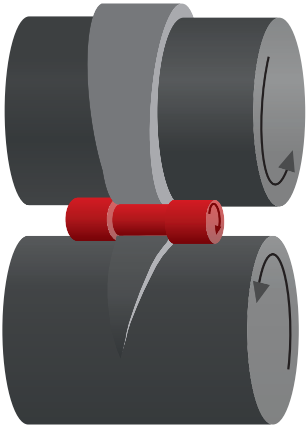
Cross Rolling

▶ Cross rolling is a forming process in which rotationally symmetrical parts are formed between two axially parallel, counter-rotating rolls (cross wedge rolls or round cross rolls) or between two flat jaws (flat jaw cross rolls). The aim is to obtain a mass distribution as a preform in order to achieve almost complete material utilization in subsequent further forming steps, in particular by die forging. This is realized on an industrial scale, for example, for the production of connecting rods. In addition, a near-final component contour can be achieved by cross rolling, which can be machined mechanically without further forming steps. This applies, for example, to the production of gear and drive shafts (Kolbe, 1995).

Round Cross Rolls

Figure 5.45 shows the principle of round cross rolling between two counter-rotating rolls, which have a wedge-shaped profiling. This rolling principle is also called cross-wedge rolling.

Fig. 5.45 Principle of the round cross rolling between two counter-rotating rolls with wedge-shaped profilings



A special variant of the cross wedge rolling is the “axial-feed cross rolling”, which is schematically shown in Fig. 5.46. This forming variant was developed at the end of the 1970s at the Chair of Manufacturing Engineering/Forming Technology of the Technical University of Dresden.

The disc-shaped or wedge-shaped rolling tools are moved towards each other in a radial direction. This forms a rolling gap in which the rotationally symmetrical workpiece is located, which is set in rotation by friction between the rolling tools. The rolling tools are now moved closer to each other. This rolls a groove into the workpiece. If the workpiece is now rotated in the direction of the workpiece axis while moving, the groove widens. By further moving the rolling tools while axially moving the workpiece, the desired geometry, for example, of a detached shaft, can be generated flexibly and automatically. Even hollow parts can be profiled in this way.

Flat Jaw Cross Rolling

Flat jaw cross rolling is an old forming principle that was already presented in 1888 in the British trade journal “Iron Age” and described as follows: *“Rods are moved between two parallel plates moving up and down in opposite directions to give them different diameters at any point.”* (from: Kolbe, 1995). Figure 5.47 shows this principle of flat jaw cross rolling, in which the rolled material is rolled between two plates moving against each other with a wedge-shaped profiling.

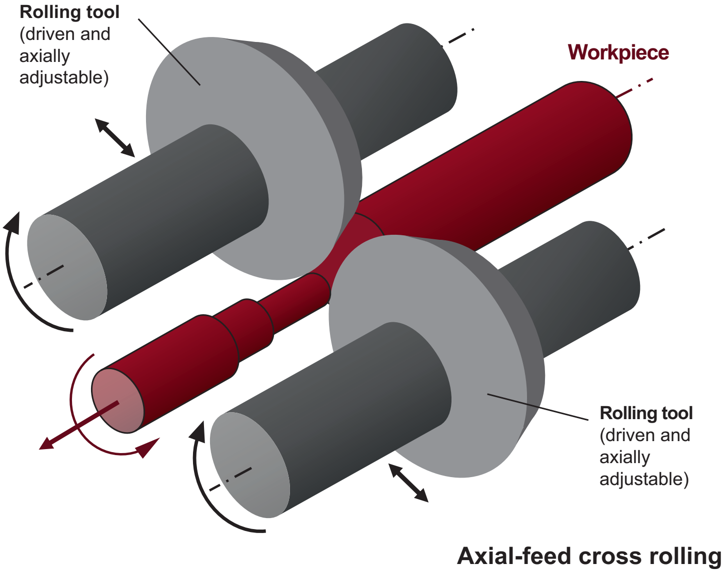


Fig. 5.46 Principle of the axial-feed cross rolling

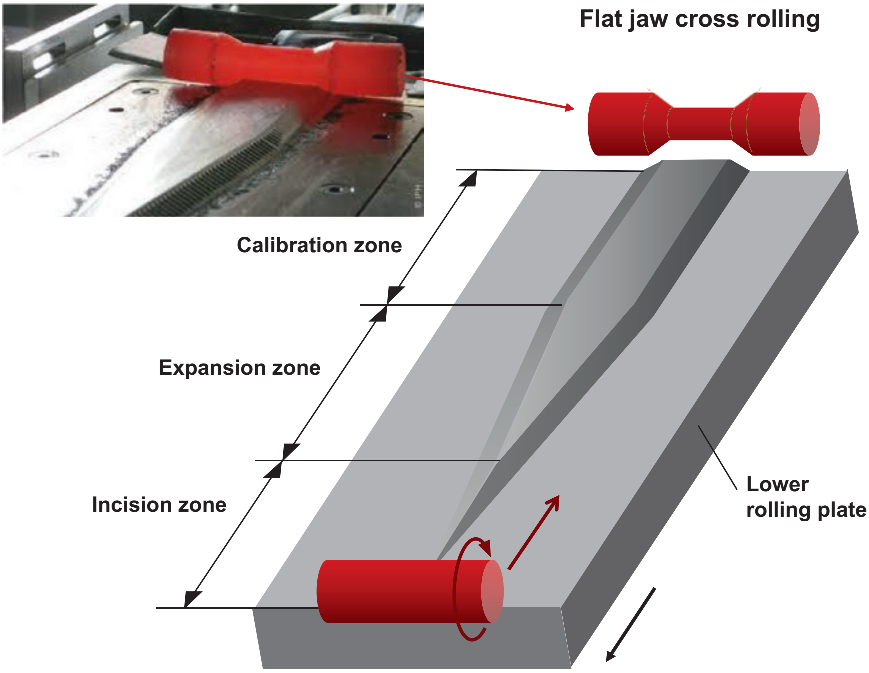


Fig. 5.47 Principle of flat jaw cross rolling according to (Kriwall, 2020a).

Skew Rolling

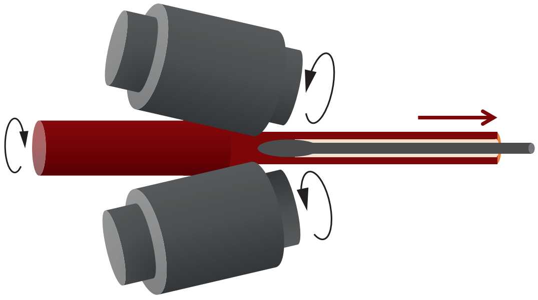
▶ In this rolling process, the rolls are not arranged parallel to the axis of the rotating workpiece, but obliquely to it. This results in a longitudinal feed and, at the same time, a reduction in diameter of the workpiece due to the narrowing roll gap. If a fixed mandrel is used, a tube can be produced from a full round block.

Mannesmann Skew Rolling of Tubes

This process was invented at the end of the nineteenth century by the brothers *Reinhard* (1865–1922) and *Max* (1857–1915) *Mannesmann* and used for the hot rolling of seamless steel pipes. The principle of this Mannesmann skew rolling process for the production of seamless pipes is shown in Fig. 5.48.

Since only a very thick-walled pipe can be rolled with this method, the subsequent step-by-step rolling to a precision pipe with very thin walls, tight diameter tolerances and good surface quality is carried out according to the above-mentioned pilger step rolling process at room temperature. This is the classic way, for example, to produce seamless stainless steel pipes.

Fig. 5.48 Principle illustration of the skew rolling process for pipes according to the Mannesmann brothers



Planetary Skew Rolling of Round

A special type of rolling round material are the planetary rolling mills. Like the planets around the earth, three cone-shaped rolls orbit the rolling material, arranged obliquely to its rolling direction, and thereby reduce its diameter. Figure 5.49 shows the operation of such planetary skew rolling mills.

These rolling mills are used, inter alia, as the first forming unit of a continuous rod or wire rolling train for the hot rolling of round ingot blanks.

Other Rolling Methods

- Without going into all technical details and without making an assessment of industrial use, a selection of other rolling methods currently in use will be presented below.

Ring Rolling

On a ring rolling mill, pre-drilled ring blanks are rolled to their final dimensions, partly also profiled. During the rolling process, the gap between the driven main roll and the mandrel roll is constantly reduced. This reduces the wall thickness of the ring, while the

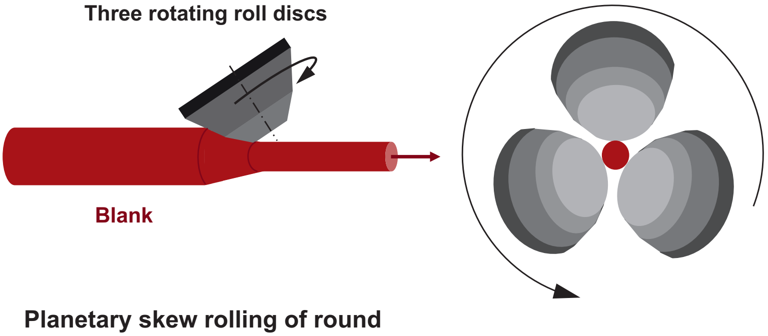
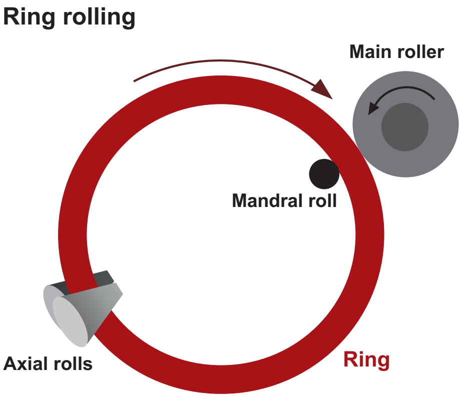


Fig. 5.49 Operation of planetary skew rolling mills for rolling round material

Fig. 5.50 Principle of the ring rolling process (top view)



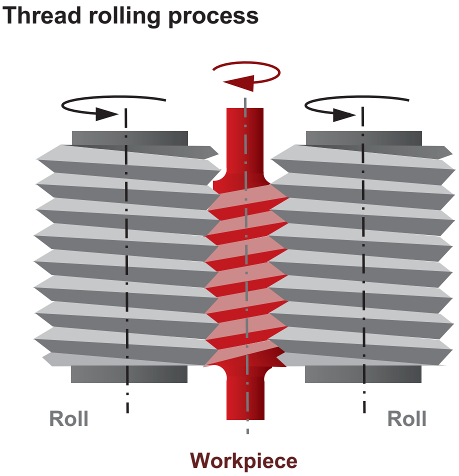
ring diameter increases. The width of the ring is adjusted to the desired size by means of two axial-cone rolls. Figure 5.50 shows the principle of the ring rolling process in top view.

Rings with an outer diameter of a few centimeters to over 8 m can be produced, for example, wheel tires for the railway or also large rolling bearing rings.

Thread Rolling

This process, often also called roll threading, is used to produce threads on round bars, for example for screws. For this purpose, compression stresses are applied to the raw material by two axially parallel, rotating and correspondingly profiled rolls. This results in the impression of the roll profile on the raw material. The thread profile is formed. Figure 5.51 shows this rolling process schematically.

Fig. 5.51 Principle of the thread rolling process



Rolling the thread can take place continuously in the pass of the blank through the rolling pair. In this case, the rollers are usually slightly inclined to the axis of the blank. Or a thread profile is genearated in segments via thread rolling.

In addition to this thread rolling, there is also the flat-plate thread rolling. Here, the rolling principle resembles the already mentioned flat jaw cross rolling.

Roll forming

In order to form steel profiles from sheet metal or strip, so-called roll forming plants are used. These consist of several profiling rolls arranged in pairs one behind the other, which allow a continuous bending of the flat sheet metal or strip running through to a defined profile. One also speaks of a roll bending, roll shaping or cold rolling of profiles. The principle of operation of this roll forming, for example of sheet metal, is shown in Fig. 5.52.

The number and the stepwise changing profile cross-sections of the rollers are specified according to the desired profile. As a multi-stage forming process, it is usually combined with subsequent manufacturing steps such as stamping and embossing.

More recent developments in plant engineering now also allow flexible profiling with roller positions that change during the rolling process. This makes it possible to produce cross-sectional profiles that can be changed over the length of the sheet or strip (Hiestermann et al., 2003). Applications of flexible rolling profiling include, for example, lightweight profiles for the automotive industry.

Roll Flow Forming

The ancient technique of pottery also works with steel or with all “kneadable” metals and metal alloys. By means of rotating pressure rollers, the preform, for example a sheet metal round, is “stretched” over a rotating conical or cylindrical mandrel, i.e. brought to flow. This creates a profiled rotationally symmetrical part. Figure 5.53 shows this principle of the process in comparison to the classical pottery of clay.

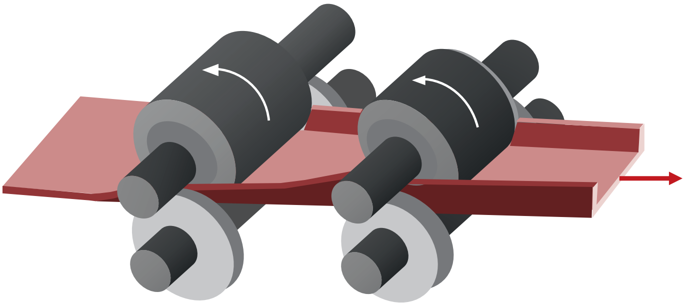


Fig. 5.52 Principle of roll forming sheet metal

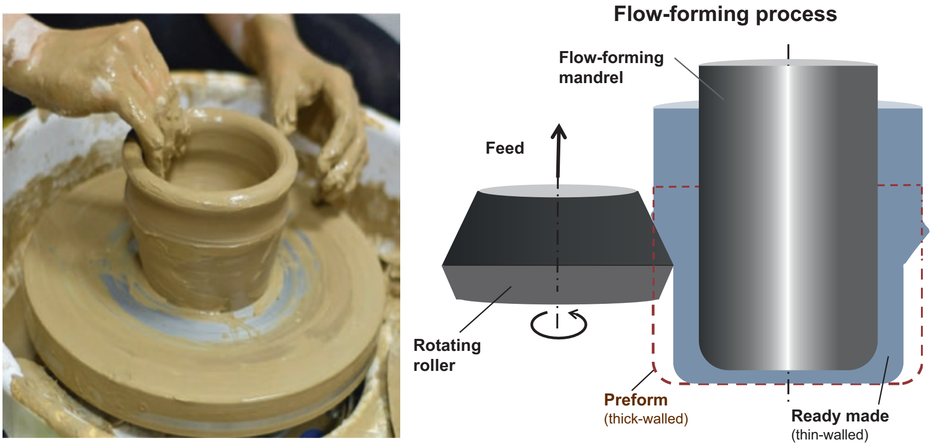


Fig. 5.53 Comparison of the pressure rolling of steel rounds with that of pottery of clay.

The roll flow mandrel used can also be profiled. This profile is then formed into the interior of the formed part.

Usually, this roll flow process, also called “flow forming”, is carried out at high contact pressures and room temperature, that is, with corresponding cold hardening of the material. With this very special process, economically end-contour-close cylindrical and conical precision hollow parts can be produced, such as hydraulic cylinders, complex drive components, cooking utensils, fire extinguishers, centrifuges and also car rims.

Roll Cladding

> ▶ Composite materials are gaining in importance. These materials consist of two or more different materials, thus combining the favorable properties of the materials to be joined and at the same time offering cost advantages. In this way, properties such as strength and density or electrical conductivity can be specifically improved or changed in the composite. It is important to generate an intimate, long-term connection of the materials even under load.

One way to produce composite materials is by using roll cladding. By means of pressure between two rotating rolls and temperature (possibly also including a subsequent annealing), an inseparable connection is produced between a base material and the metal coating to be applied. Figure 5.54 shows this principle of roll cladding.

For example, roll clad composites made of stainless steel-soft steel or stainless steel-soft steel-stainless steel are known; each with strip thicknesses of 0.5 to 1.5 mm (trade name: WINOX). Wherever the highest surface requirements have to be met, such a stainless steel composite can be used with economic and also ecological advantages, e.g. for deep-drawn cookware (suitable for induction) or for facade claddings. Today, composites

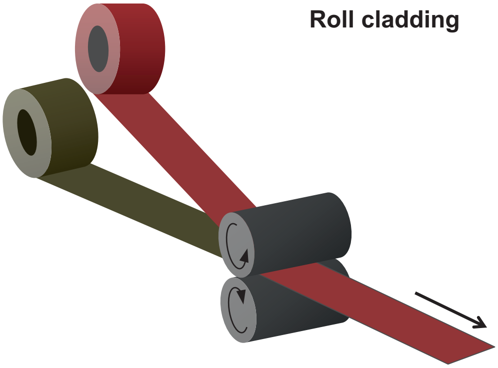


Fig. 5.54 Principle of roll cladding of steel strip

made of copper-stainless steel-copper (*Copper-Plus*) and stainless steel-aluminum are also produced as strips and sheets, mainly for architectural applications.

Conclusion

From the first designs of*da Vincis* around 1495 for sheet metal rolling mills to today's hot strip, cold strip and foil rolling mills, from the small, hand-operated rolling mills for hollowing out window lead from 1500 to the modern profile rolling lines, from the hammer mills in the Middle Ages to the high-performance wire rolling lines and from other advances in rolling, much more could be told. And also about how the driving forces (manual operation, water power, steam power and electric motor) as well as the constantly increasing demand and the call for improved quality influenced the technical development of the plants.

Consequently, rolling for forming of steel is an impressive process with a long tradition. And it still has a lot of potential for innovation, e.g. in terms of increased performance while reducing energy consumption, saving process steps (use of casting heat, combination of rolling with heat treatment), a flexible, fully automatic control of the rolling line with modern testing technology, the use or recycling of exhaust gas heat and reduction of cooling losses.

5.2.5 Deep Drawing

▶ Every day we come into contact with beautifully shaped deep-drawn parts, such as car bodies. Sheet metal parts with such shapes, as well as beverage cans, pots, mufflers and other products are produced using the most important sheet metal forming process, deep drawing. It is a classical tension-compression forming process. Pre-rolled sheets are used.

A sheet metal circular blank is placed in a fixed tool (drawing die) with a certain contour. The drawing punch moves into the forming area of the drawing die, thereby creating tension and compression stresses and causing the sheet metal blank to be formed into a hollow body (deep-drawn part). The hold-down device prevents the edge of the sheet metal from forming wrinkles during this process. This principle of deep drawing a sheet of metal is shown in Fig. 5.55. The achievable deformation is enormous, just think of the well-known deep-drawn part, the beverage can.

Deep drawing using hydraulic presses in forming tools is also a proven method for sheet metal forming of non-rotationally symmetrical parts. The main application is in body construction. Huge deep drawing presses, usually arranged one after the other in a line for several deep drawing stages, form the body parts made of quality deep drawing steel in mass production. Modern lines work fully automatically with very short tool change times. The presses are equipped with servo direct drives by means of torque motors (electric direct drive with high torque at low speeds). The individual and flexible strokes of these presses can be adapted to the different forming processes, to the tool geometries and steel grades. Figure 5.56 shows, for example, a modern, fully automatic servo press line with a press force of 10,000 t for the production of car body parts for automobiles.

▶ In addition to the classical deep-drawing process, the deep-drawing process with working media (gases, liquids) and with working energy (e.g. with the pressure wave of an explosion) is used for the production of special shaped parts. These very special forming processes should also be mentioned.

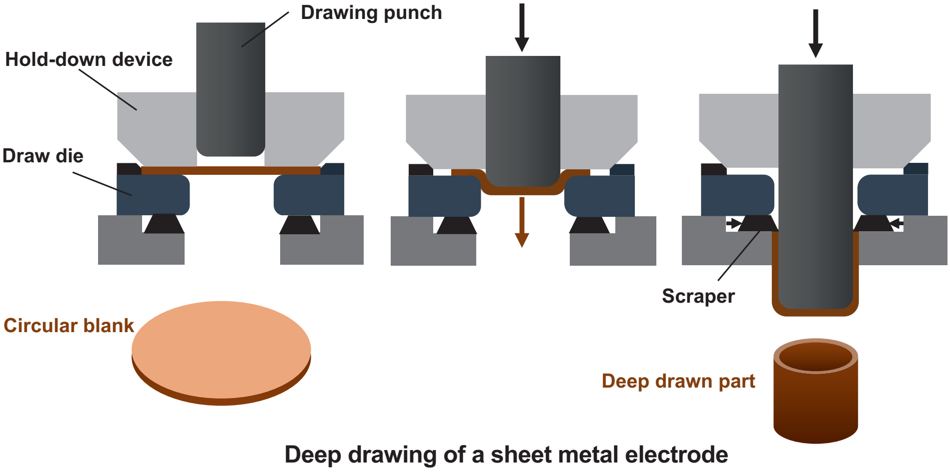


Fig. 5.55 Principle of deep drawing a sheet of metal

Fig. 5.56 Fully automatic servo press line with a press force of 10,000 t for the mass production of car body parts for automobiles. (Photo: Schuler AG, Göppingen)

5.2.6 Hydroforming Process

In classical deep drawing forming can only occur linear, since the drawing die can only be moved in one direction. During this movement, no change of direction is possible from a technical point of view. However, this is possible in the so-called hydroforming process, since no stamp is used, but a liquid, e.g. emulsion or water. The liquid is injected under high pressure, so that the sheet metal can be formed into the inner contour of the tool in all directions. In particular, special sheet metal forms can be produced for body construction. Fig. 5.57 shows the mode of action of the hydroforming process with a liquid working medium.

5.2.7 Internal High Pressure Forming

A similar principle is used for the internal high pressure forming.This process uses a inner pressure liquid to form hollow bodies in a closed tool. The inner pressure is generated, for example, by a water-oil emulsion. This emulsion is injected into the hollow space of the body to be formed (pipe), the latter is then sealed with sealing stamps and the inner pressure is increased to up to 30,000 bar. This initiates the plastic deformation

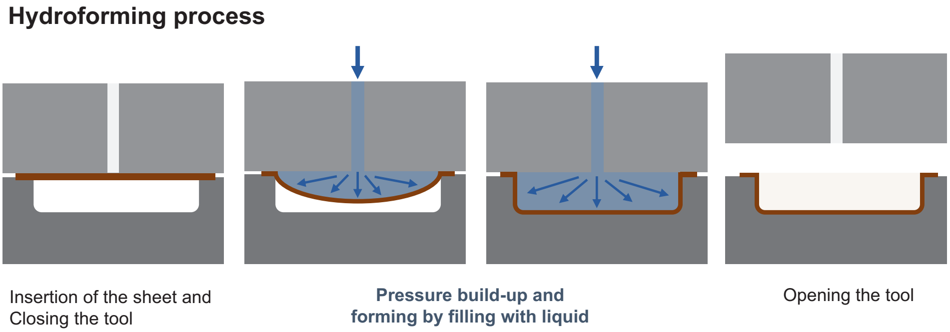


Fig. 5.57 Mode of action of the hydroforming process with a liquid working medium

(enlargement), whereby the contour of the mold is assumed. For example, pipes can be selectively enlarged. Figure 5.58 shows this IHU working principle.

Since the 1990s, deep drawing has been increasingly used as a special process for the production of steel parts for the automotive industry. This process is used, for example, to produce weight-optimized hollow camshafts. Figure 5.59. shows an example of an IHU camshaft for a passenger car.

The first mass-produced vehicle to be fitted with internal high pressure formed was, incidentally, the AUDI A8.

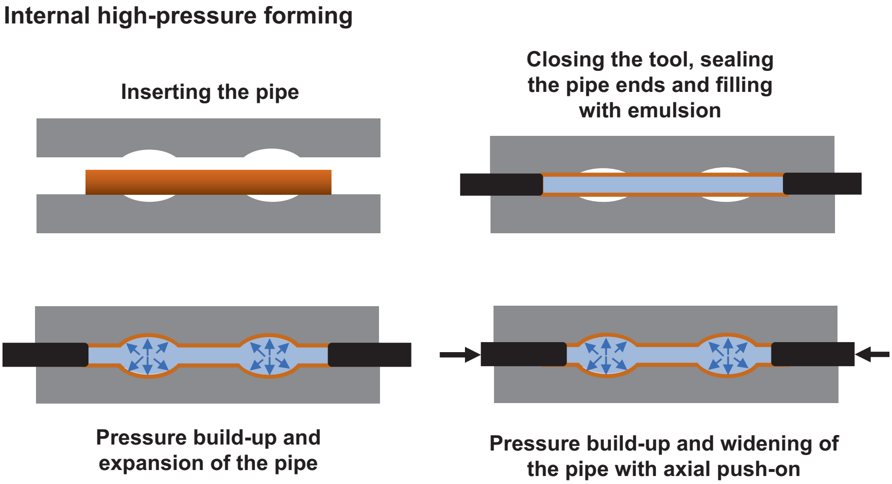


Fig. 5.58 Working principle of the internal high-pressure forming of a pipe

Fig. 5.59 Example of an internal high pressure formed (hydroformed) hollow camshaft for a passenger car. (Photo: Jansen AG, Oberriet CH)

5.2.8 High-Energy Forming

High-energy forming is a drawing-pressing forming of a workpiece, which is exposed to a sudden impulse. This then leads to plastic deformation, i.e. to molding into a contoured tool, and this with a very high forming speed (high-speed forming). Depending on the type of impulse generation, the following are distinguished:

- ***Explosive forming:***

The pressure wave is generated by the explosion of explosives (explosive plates, explosive welding),

- ***Hydroelectric forming:***

The shock wave is caused by an electrical discharge in a liquid (water or oil). This liquid serves as the working medium at the same time.

- ***Hydro-Impulse Forming:***

A shock or a shock wave occurs in a medium when a projectile or a falling weight is used.

- ***Magnetic Forming:***

The pressure impulse is generated directly in the conductive workpiece by a magnetic field.

The areas of application of these high-energy forming processes are already very specific, e.g. for shaping sheets with one-sided tools or for explosive cladding of composite materials. For example, steel plates made of carbon steel are provided with thin layers of corrosion-resistant materials (e.g. stainless steel, nickel alloys, titanium). Steel is also explosion-welded to materials that would otherwise not be weldable together.

5.2.9 Drawing

▶ If parts formed by deep drawing are the result, then drawing generally relates to very long products, such as wire, bars, pipes and profiles. When pulling a metal through a conically or trumpet-shaped narrowing hole (drawing channel) of a drawing tool (drawing die or drawing matrix), the compressive forces in the drawing channel arise from the applied tensile forces. They act on the drawn product, which has already been reduced in cross-section. Of course, the material of the part to be drawn must also be able to transmit the tensile force required for forming. The drawing process thus represents a tension-compression forming. Depending on the product, the drawing of wire, rod or pipe, each as round or as profile, via fixed drawing tools and via drawing rolls can be distinguished. Process variants and drawing plants are presented below.

5.2.9.1 Wire Drawing

▶ Wire is, in terms of cross-section or diameter, an impressively long, formed and flexible product. Whether made of unalloyed or alloyed steel, as coarse, medium or fine wire, with dry drawing soap or wet with oil or fat emulsion, single or multi drawn, bright or coated, untreated or heat-treated, with properties optimally adapted to the intended use: wire has today a wide field of applications and is being utilised in more, new applications constantly. There are round, flat, square and profile wires.

First indications of the use of wire an already be found around 5000 BC. Initially, the wire was used only for jewelry and profane structures. When and where the cut gold and silver threads of the drawn wire emerged is no longer clearly verifiable. In Germany, wire drawing is practiced since about 700 years (Lietzmann et al., 1984). So the drawing of a wire, as well as the forging of formed parts or the coining of coins, has a remarkable long history. The principle of wire drawing is almost unchanged to this day: A wire with the initial diameter d_0 is drawn through a drawing die to the final diameter d_1, as shown in Fig. 5.60.

From the change in diameter d_0 to d_1, and thus the change in cross-sectional area A_0 to A_1, the cross-sectional decrease or the logarithmic forming degree φ can be calculated. The law of volume constancy applies here:

$$\boldsymbol{\varphi = \ln A_0 \div A_1 \times 100\%}$$

The main influencing factors during drawing are the following:

- *the material (formability)*
- *the wire treatment (cleaning, coating)*

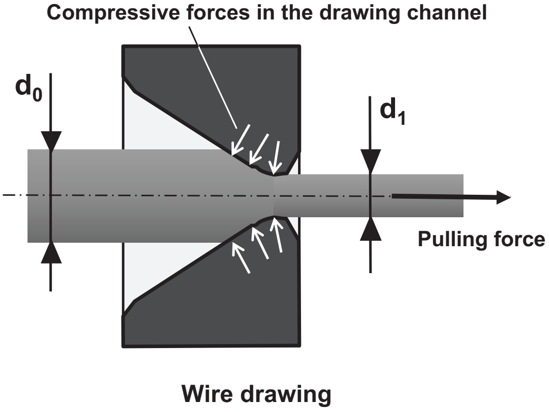


Fig. 5.60 Decrease in diameter when pulling a round wire through a drawing tool

- *the drawing parameters (temperature, lubricant, cross-sectional reduction, drawing speed)*
- *the drawing tool (drawing die geometry, wear—materials of the drawing dies or the drawing matrices and mandrels)*

Usually, the wire is drawn without preheating, that is, at room temperature. The drawing process can be repeated several times (drawing sequences), until the final diameter is reached or the formability of the material is exhausted by the resulting cold work hardening. Figure 5.61 schematically shows the microstructure change (lattice distortion) during drawing of the wire through a conical drawing die (drawing plug.

Because of this cold work hardening, an intermediate annealing must be carried out to soften the wire (soft-annealing) in order to be able to continue the drawing process (see also Sect. 6.3: *Types of heat treatment*). After the last forming step (final drawing), a final heat treatment is usually carried out, as with all other forming processes. This results in favorable mechanical and technological properties for further processing. This final annealing can be omitted if the cold working of the wire that occurs during the drawing process is beneficial for further use. Or a single drawing is carried out deliberately before the wire is delivered to the customer in order to set a defined hardness desired by the customer.

Drawn steel wires are produced today in a large range of dimensions:

- ***Coarse drawing:*** *Wires with diameters of 20 to approximately 5 mm*
- ***Medium drawing:*** *Wires with diameters of 5 to approximately 1.5 mm*
- ***Fine drawing:*** *Wires with diameters of 1.5 to approximately 0.8 mm*
- ***Very fine or micro wires:*** *Wires with diameters smaller than 0.4 mm*

▶ The drawing process in general is technically not rocket science, but technologically very demanding in terms of effort and know-how. An overview will be given below of the drawing tools, wire pre-treatment, drawing process and drawing machines used.

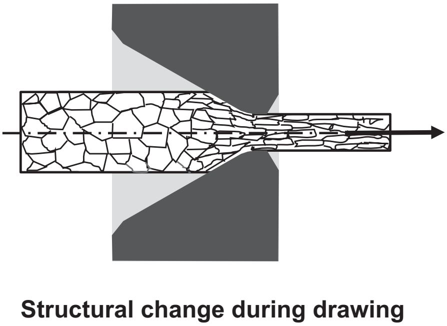


Fig. 5.61 Microstructure change (lattice distortion) during drawing of a wire through a drawing die

Wire Drawing die

For a long time draw iron was used as a drawing tool, until in 1928 tungsten carbide drawing stones came into use. A selection of tungsten carbide drawing dies for steel wire drawing is shown in Fig. 5.62.

For thin and ultra-thin wires (fine wires) as well as for the final drawing stone for the finest wire surfaces, today drawing dies from natural single-crystal diamonds or from synthetic, single- or polycrystalline diamonds are used. The hard metal cores as well as the diamonds are embedded in special steel housings. Figure 5.63 shows the schematic structure of such hard metal draw die in cross section.

Important for a drawing process without wire breakage are the friction conditions in the drawing channel. This is also expressed by the term “slip drawing”, a term often used for drawing. A well-functioning lubrication system reduces wear of the drawing tools

Fig. 5.62 Tungsten carbide drawing dies with different diameters for the dry drawing of steel wire. (Photo: Schlegel, J., BGH Edelstahl Lugau GmbH)

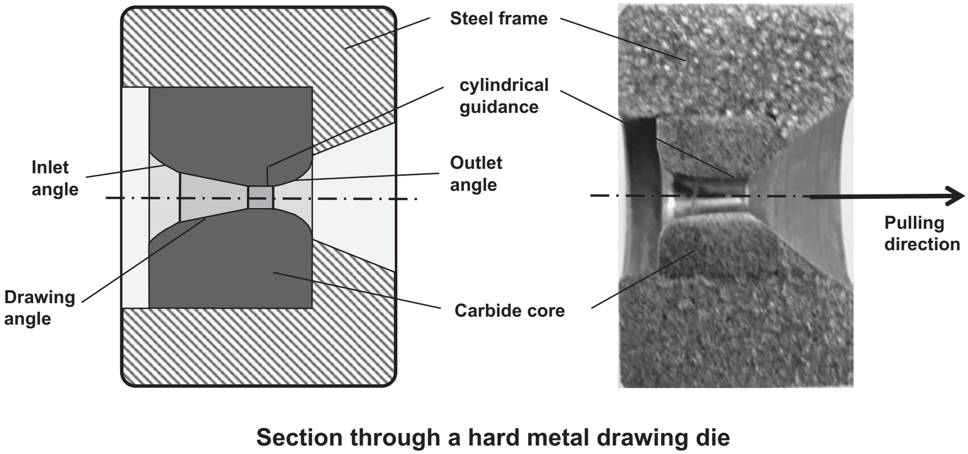


Fig. 5.63 Cross section through a hard metal draw die with representation of the draw channel. (Photo: BGH Edelstahl Lugau GmbH)

and prevents formation of rifts on the wire surface. The lubricating effect is influenced not only by the lubricant used (dry or wet drawing lubricant) but also by the geometry of the drawing channel. This geometry also determines the achievable degree of deformation, based on a certain initial diameter d_0, and is defined by the parameters inlet angle, drawing angle and length of the contact zone in the cylindrical guide part. Therefore, depending on the wire material to be drawn, drawing dies with adapted draw hole geometries are used. Here, the years of experience of the drawers and the results of countless scientific studies are required.

Wire Treatment for Drawing

▶ The wire (rolled wire or already pre-drawn and soft-annealed wire) must have a wire surface suitable for drawing. Therefore, it is subjected to a special wire treatment. Depending on the wire material and the required surface quality, this includes cleaning and conditioning of the wire by means of pickling (derusting), blasting or peeling processes as well as coating with a lubricant carrier. These process steps are explained below.

Pickling

Pickling is a chemical process in which oxide compounds (rust, scale) form the steel wire surface by means of liquid media (lyes, mineral acids, hydrofluoric acid and additives) are removed. The aim is an optimal pickling effect with minimal attack on the base material. This pickling process is simplified as follows: The acid penetrates through cracks and pores in the scale layer to the base metal and dissolves the lower scale layers.

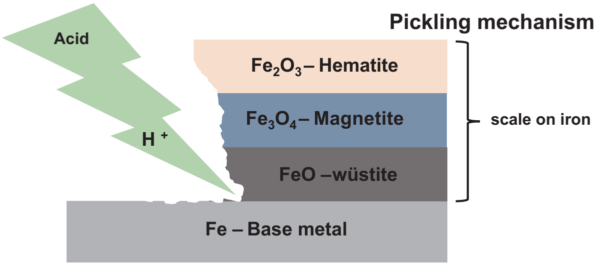


Fig. 5.64 Pickling mechanism during acid attack on steel surface with scale layers. (Figure according to Dumrau, 2014)

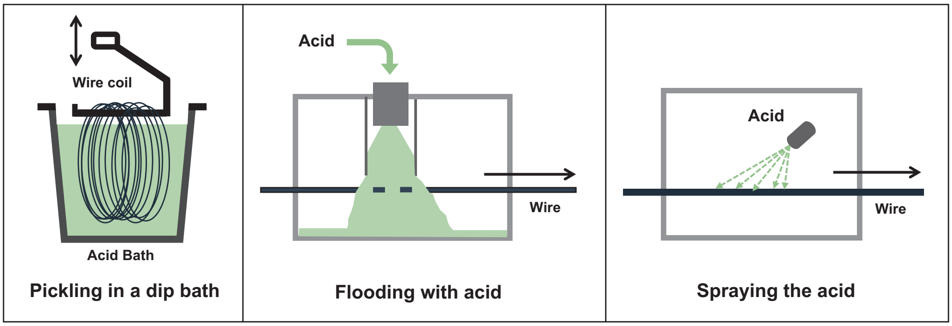


Fig. 5.65 Wire pretreatment by pickling in an acid dipping bath, by flooding the wire with pickling medium or by spraying the pickling medium

In a reaction with the base metal, hydrogen is formed, which favors the detachment of the scale layer. The scale is “blasted” (Dumrau, 2014). Figure 5.64 shows this pickling mechanism in a simplified way.

The wire can be treated by the liquid etching medium (acids or mixed acids) in different ways: in a dipping bath, by flooding the wire or by spraying with pickling medium. Figure 5.65 shows these possibilities for pickling treatment of wire.

The most commonly used pickling technologies in immersion baths differ by the selection and combination of pickling and rinsing baths as well as by the residence times in the individual baths. Figure 5.66 shows the view of an automated pickling line for rolled wire.

▶ Important for a good pickling quality are the control and the “re-sharpening” of the pickling baths. For a clean pickling economy, used pickling baths have to be treated environmentally friendly and their volume has to be minimized for disposal. Also, the exhaust air has to be treated accordingly, taking into account environmental legislation (see also Chap. 10: *By-products and Waste*). If it is technically possible and the steel quality allows it, mechanical surface

Fig. 5.66 Automated pickling line for rolled wire. (Photo: BGH Edelstahl Lugau GmbH)

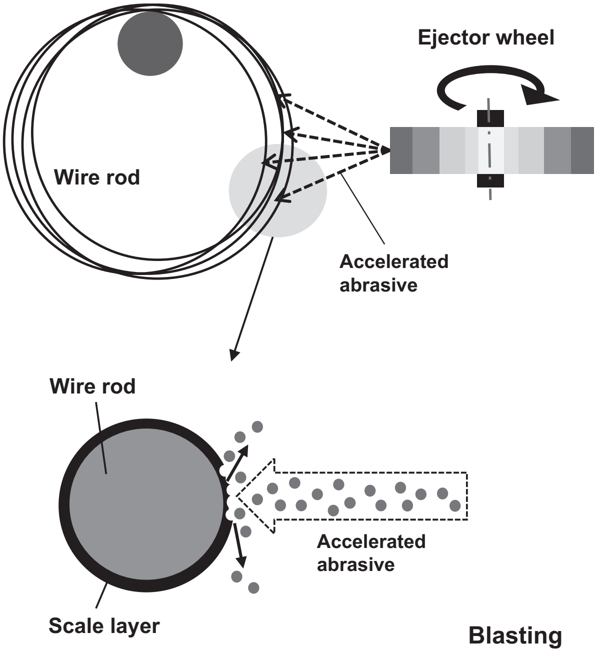
treatment methods have to be preferred over chemical pickling. For this purpose, the processes of blasting and peeling of the wire can be considered.

Blasting

▶ Blasting is a mechanical surface treatment method, colloquially known as "sandblasting". Whether for cleaning machines and plants, semi-finished products (wire, profiles, etc.), for cleaning facades, masonry, for rust and paint removal from steel structures, for roughening surfaces, also for decorative design, for structuring glass and textiles - today there are suitable blasting techniques for every application.

Technically, , e.g. sand, corundum, plastic, glass beads, metallic powder, slag from the smelting process or dry ice. The grain-shaped blasting medium particles, accelerated with high energy, hit the wire surface and cause a mechanical removal of the surface layers of scale and impurities, as well as roughening of the surface. This process is used in particular for breaking the scale of hot-rolled steel wire before pickling, in order to

Fig. 5.67 Principle of blasting wire rings by means of blasting medium accelerated by an ejector wheel.



reduce pickling times and acid consumption. The following blasting processes are distinguished:

- *Blasting media is blasted using a carrier medium (compressed air, water pressure).*
- *Blasting media is slung onto the steel surface to be blasted via centrifugal force (ejector wheel).*

Figure 5.67 shows the principle of blasting a steel wire ring by means of an ejector wheel. For example, steel shot is used as a blasting medium, which causes high cleaning intensity with long service life and low plant wear.

If highest requirements are placed on the surface quality of a drawn wire as a precursor to the production of bright steel (bar) or as a raw material for the production of precision turned parts, the wire may or must be peeled.

Peeling

▶ Peeling is a process for mechanically removing surface layers (see also Sect. 8.3.5: *Peeling*). This primarily removes the oxide surface layers and material defects. And this is done with a greater material removal than is possible with pickling. For such wire treatment, the continuous processes of rotary peeling or draw peeling are used.

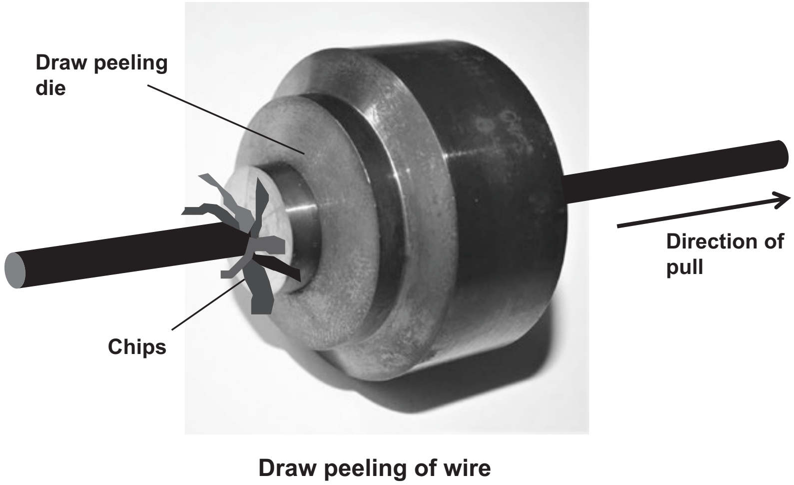


Fig. 5.68 Principle of draw peeling of steel wire. (Photo: Schlegel, J.)

In **rotary peeling**, a rotating tool around the wire continuously removes a certain depth. This process is also used for peeling rod material.

In **draw peeling of wire**, the wire to be drawn is pulled through a fixed, circular tool (draw peeling die). This is done with a drawing plant which is basically similar to a single drawing machine. Figure 5.68 shows the principle of draw peeling of steel wire. This process is used today for wire diameters up to a maximum of 20 mm.

Coating

After the wire surface has been cleaned by pickling, blasting or peeling, a coating of the wire to be drawn is always applied with a lubricant carrier (phosphate, lime, borax). This ensures, in connection with the lubricant used during the drawing process (dry drawing soap or wet drawing lubricant), the desired lubricating effect in the drawing die. At the same time, the freshly treated wire surface is “passivated”. All non-corrosion-resistant steels are very sensitive and oxidize quickly after surface treatment by pickling, blasting or peeling. This is prevented by a suitable lubricant carrier layer.

The coating is carried out as a dip coating, for example, directly as the last step in the pickling plant or in the pull-through annealing furnace after an intermediate heat treatment (soft annealing) of the already drawn wires.

Wire drawing processes

The wire drawing of steel wire is divided into dry and wet drawing depending on the lubricant used.

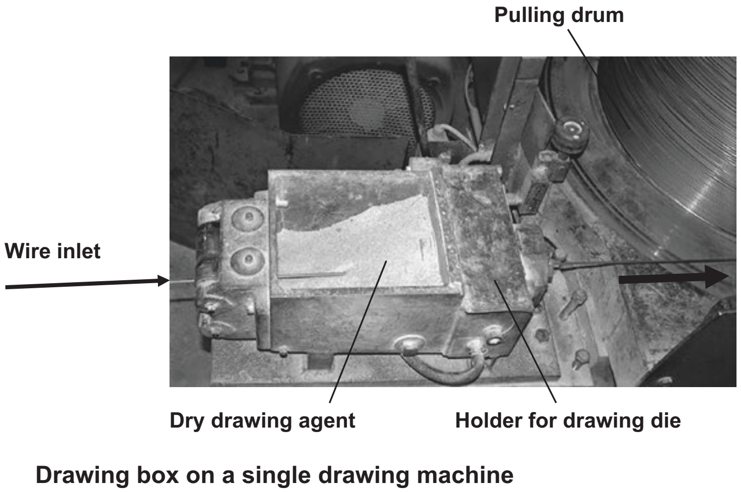


Fig. 5.69 Use of dry drawing agent in the drawing box of a single wire drawing machine. (Photo: Schlegel, J., BGH Edel Lugau GmbH)

Dry Drawing

The wire drawing is carried out using powdered dry drawing soaps directly in front of the drawing die in the so-called “drawing box”. Such a box with dry drawing agent on a single wire drawing machine is shown in Fig. 5.69.

The wire to be drawn is placed as a ring (coil) on a rotating rack. The wire tip is sharpened. For this purpose, a special rolling mill is used (see Sect. 5.2.4.2*: Rolling processes,* Fig. 5.43: Principle illustration of tapering of round wire ends by means of strech rolling). The tip of the wire is now inserted into the inlet cone of the drawing die. The pointed wire end protruding from the drawing die outlet is grasped by a pair of pliers. These are connected to a chain on the drawing drum. The drawing drum (horizontally or vertically arranged) is set in rotation and the wire drawing process begins. After a few turns of wire have been drawn around the drawing drum, the pliers can be released and removed with the chain. The friction between the drawn wire turns and the slightly conical drawing drum is now sufficient to apply the necessary pulling force. The drawing can now be carried out until the end of the inserted wire ring is reached.. There is always a certain number of turns of wire on the drawing drum. The remaining drawn wire turns are constantly released and wound on single wire drawing machines to the finished wire ring, taken off as a ring or fed to the next drawing stage on multi wire drawing machines.

Important for the drawing process is the inlet angle in the drawing die. This determines how much lubricant enters the drawing channel through the wire movement during dry drawing. In addition to optimizing the geometry of the drawing channel, various drawing die systems have been developed to press drawing lubricant onto the wire surface with higher pressures and thereby reduce friction, thus achieving longer service life

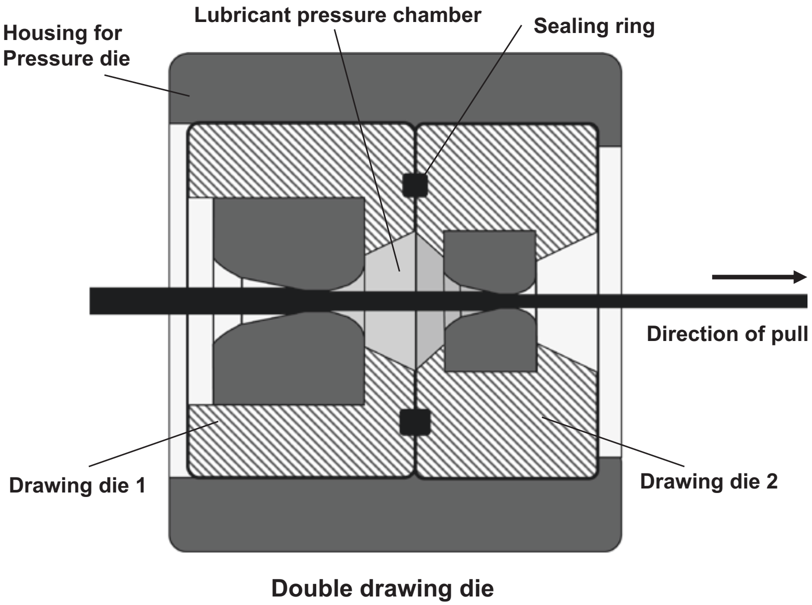


Fig. 5.70 Sectional view of a double drawing die (pressure drawing die) for dry drawing of steel wire

and higher drawing speeds. An example of this are the so-called “pressure drawing dies”. Most of these pressure drawing dies consist of two drawing dies arranged one behind the other in a special socket. Figure 5.70 shows a sectional view of the structure of such pressure or double drawing dies. A sealed pressure chamber is formed between the two drawing dies. Drawing lubricant is constantly introduced by the incoming wire during the drawing process and by external supply, and a high pressure is generated.

▶ The dry drawing process is used for steel wire in the diameter range from approx. 1.0 to 20 mm. For smaller dimensions, mostly below a diameter of 2 mm, the wet drawing process is used.

Wet Drawing

The forming process in wet drawing is carried out with liquid drawing agents, such as soap emulsions for example for galvanized steel wires and mineral oils for stainless steel wires. Special multi wet drawing machines with dipping baths are used. Figure 5.71 provides a view into a multiple wet drawing machine for stainless steel wire. The oil bath has been drained. The two drawing cones, the drawing dies inserted in the holder, and the course of the wire to be drawn are clearly visible.

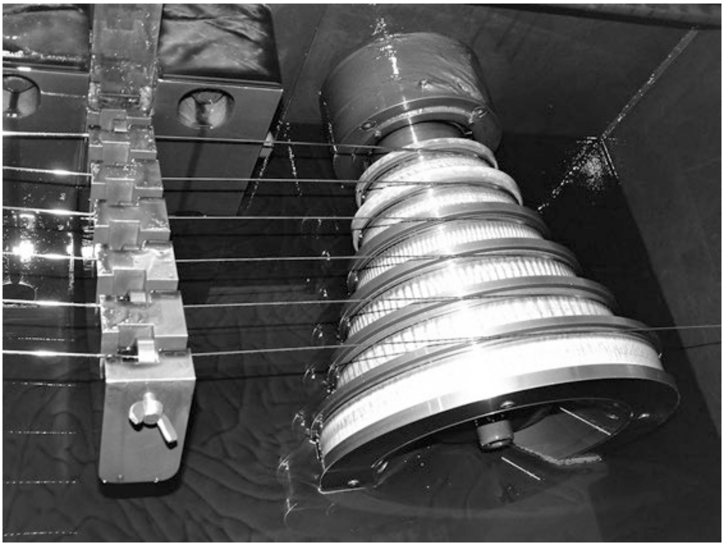


Fig. 5.71 Detail of a multi wet drawing machine for stainless steel wire: drawing bath for oil drained, drawing cones and drawing dies in the holder. (Photo: Schlegel, J., BGH Feindraht GmbH)

The liquid drawing lubricant reduces friction in the drawing die and cools the wire during the drawing process at the same time. This makes it possible to achieve higher drawing speeds and to produce wire with a very high surface quality. Based on this, the wet drawing process is mainly used for the production of fine and very fine wires made of steel with a diameter of up to 0.08 mm. In comparison, a normal human hair has a diameter of 0.06 to 0.08 mm.

Under certain circumstances, the last pass can also be carried out with oil as a drawing lubricant. This results in a particularly smooth, shiny wire surface, which is of interest for optical reasons in special finished turned parts.

Starting from the many technological variants, today's single and multi-wire drawing machines for wire products are used in plant engineering, both for dry and wet drawing, for rough, medium and fine drawing and for the production of round and profiled wires.

Single drawing machines only allow one forming stage. They only have one drawing die and one drawing drum. For small wire diameters, these single drawing machines also work with standing drawing drums.

Multi drawing machines for dry drawing have a varying number of individual, consecutive single drawing machines. In practice, 2 to 14 draws are common. These machines are operated in combination, making them very demanding in terms of control technology. Figure 5.72 shows, as an example from industrial production, a 14-fold dry drawing machine as used by BGH Edelstahl Lugau GmbH for the production of stainless steel wires.

14-fold dry drawing machine

left: Box with dry drawing medium, water-cooled drawing die holder and drawing drum

Fig. 5.72 Multi dry drawing machine with 14 draws and spooler. (Photo: Schlegel, J., BGH Edelstahl Lugau GmbH)

To ensure a defined roundness of the finished wire desired by the customer, the first draw on such multi drawing machines is usually carried out with a rotating drawing die. A well formable steel, for example an austenitic steel quality, can be drawn on such a 14-fold drawing machine from a starting wire diameter of 5.5 mm directly to an end diameter of 1.0 mm. The finished wire is wound onto a steel spool.

Modern wire drawing machines work with up to 36 drawing stages. This is done in liquid-tight, sealed baths (tubs). The drawing forces per drawing stage are applied via drawing cones. These are arranged one after the other according to the drawing sequence. Figure 5.73 shows a wire drawing machine with such drawing cones and the drawing die holder.

Wire products can be found everywhere today as:

- *Wire for bulk forming* (cold upsetting of screws, rivets, etc.)
- *Wire for axles and shafts*
- *Bending, weaving and braiding wire* (mesh, sieves, metal fabric),
- *Brush and rope wire*
- *Wire for medical technology* (dental wires, needles)
- *Spring wire, textile needle wire*
- *Fine wire for lighting technology* (e.g. for light bulbs, fluorescent lamps)
- *Heating conductor wire* (e.g. for heating coils in household appliances) and others.

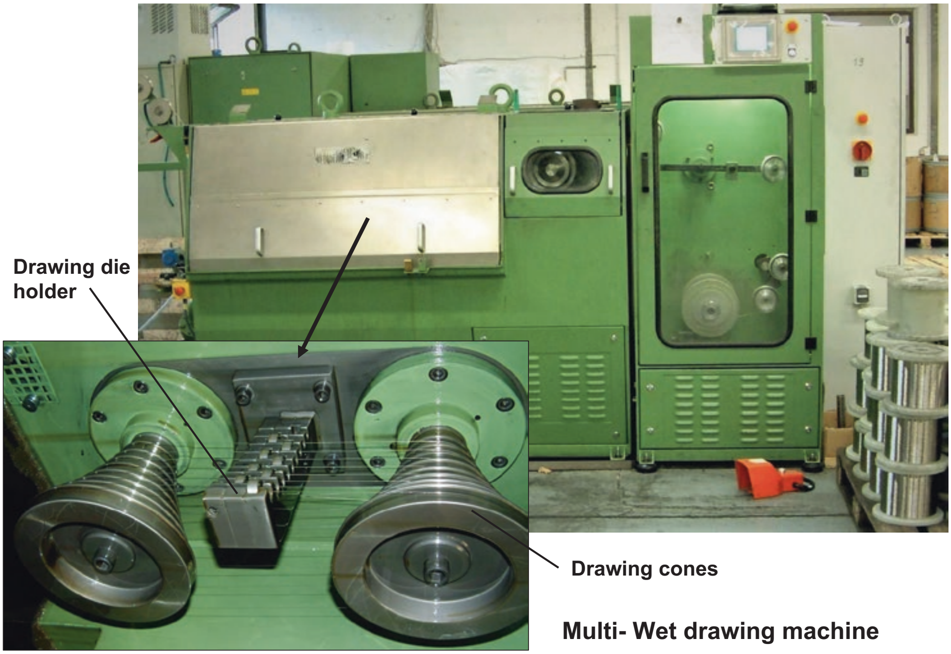


Fig. 5.73 Multi wire drawing machine with a view into the oil bath with drawing cones and drawing die holder. (Photo: Schlegel, J., BGH Feindraht GmbH)

▶ The wire drawing process described here is also used for larger dimensions for round and profile bars. This bar drawing will also be presented.

5.2.9.2 Bar Drawing

Bar drawing is in principle comparable to wire drawing, except that it is not performed continuously by means of a drawing drum or a drawing disc, but rather bar by bar in a straight line along the length of the bar. For this purpose, so-called "draw benches" are used, which operate as single draw benches (bar by bar is drawn one after the other) or also as multi draw benches (several bars are drawn side by side at the same time). Such bar drawing machines can apply tensile forces of more than 100 t. A simplified representation of the design of such a drawing bench is shown in Fig. 5.74.

The drive chain is constantly moving in the direction of the draw. The bar that was previously sharpened with a strech rolling device is placed on the feed and guided with its tip through the drawing tool (drawing die) into the open tong grap on a slider. The lever with a hook attached to the front of the draw slider. (also known as "draw carriage") engages into the chain. This lever is mechanically connected to the tonggrap like a pair of scissors. The hooking into the chain pulls the lever down. This results in pressure on the tong grap, which now clamp the tip of the rod. The chain pulls the engaged draw slider with it. The draw slider runs slightly uphill in the direction of the draw. At

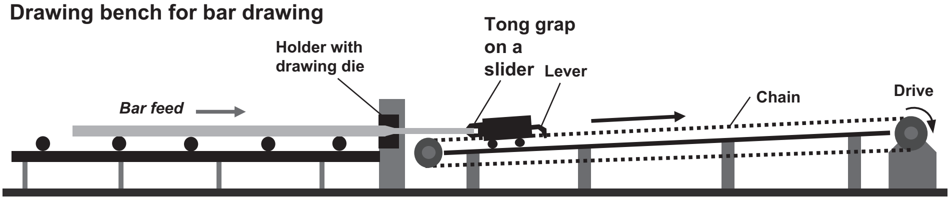


Fig. 5.74 Schematic layout of a drawing bench for bar drawing

the end of the draw, the lever disengages. The tong grap are opened and the drawn bar is ejected. The chain continues to run in the direction of the draw, but the draw slider moves back to the starting position by its own weight. Then another bar is placed and drawn individually over the entire length for cross-sectional reduction and profiling. This process is repeated with each new draw.

Even when drawing rods, a pre-treatment of the material to be drawn, the selection of the drawing agent and the drawing tool (influence of the draw angles) must be carried out according to the steel grade. The result is a bright steel, round or profiled, with high dimensional accuracy and surface quality. For round bright steel, an additional grinding process is usually carried out.

The drawn profiles are in demand for a wide range of applications (standard profiles such as square, flat and special profiles according to customer requirements). Figure 5.75 shows some profiles as examples in the form of the hard metal drawing dies to be used.

Fig. 5.75 Examples of drawing dies profiles for drawing bars from steel. (Photo: EZM Edelstahlzieherei Mark GmbH, Wetter)

The following product groups of drawn profile bars can be specifically mentioned:

- *Linear guide rails for machine tools*
- *Clamping elements* e.g. for industrial vices, tool holders in CNC machines, T-slot blocks for clamping
- in medical technology: *Clamping rails for hospital beds, Rails for fixators* in case of bone fractures, *Guide elements* in medical devices
- *Pressure plates for printing machines*
- *Gear profiles,* e.g. for drive pinions
- *Splined shafts,* e.g. for agricultural machinery

▶ At this point, the application examples can also be extended to tubular drawn profiles, as **pipe drawing** is basically comparable to bar drawing. The process of pipe drawing will be presented separately in the following chapter.

5.2.9.3 Tube Drawing

Tube drawing is also referred to as flow drawing of hollow bodies (Tschätsch, 2001). Today, various variants of tube drawing are used. An internal mandrel (fixed or "flying") is used when, in addition to the outer diameter of the tube, the wall thickness of the tube to be drawn should also be reduced. With a profiled mandrel, the inner wall of the tube can also be profiled. Figure 5.76 shows a schematic comparison of tube drawing without mandrel (tube wall thickness constant) and with mandrel in the variants of stationary mandrel, flying mandrel and moving mandrel bar.

In tube drawing, seamless precision tubes with defined dimensions (outer diameter and wall thickness) and high-quality surface qualities are produced, as required, for example, in medical technology, high-pressure applications and aerospace engineering. Control and measuring tubes, hydraulic and heat exchanger tubes are also important applications of drawn tubes.

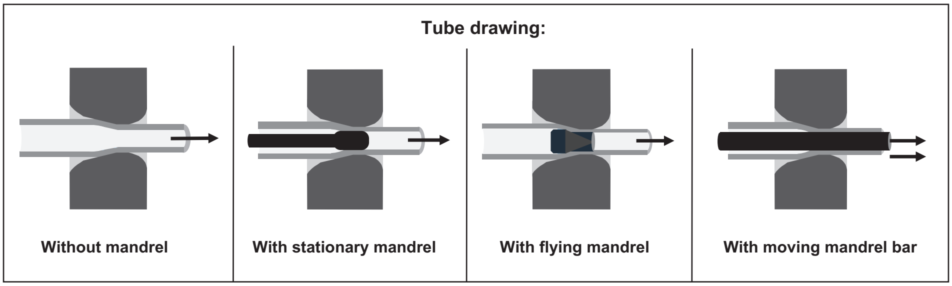


Fig. 5.76 Comparison of tube drawing without mandrel and with mandrel in the variants of stationary mandrel, flying mandrel and moving mandrel bar (*from left to right*)

5.2.9.4 Roll-Drawing Process

The roll-drawing process is basically comparable to that of drawing (drawing pressure forming), only no fixed tool (drawing die) is used, but movable, non-driven forming rolls (drag rolls). Figure 5.77 shows this in a simplified representation of the principle of roll-drawing with two drag rolls. For example, a round wire can be profiled into a square wire.

The drag rolls, set in rotation by the passage of the material to be formed, cause less friction. Therefore, this roll-drawing, also called slide rolling, offers an alternative when stronger hardening or difficult to form steels are to be profiled.

The production of square wire by means of four drag rolls arranged at right angles to each other is also known. These four smooth rolls surround a square opening, which is transferred to the round wire when it is drawn through. Figure 5.78 shows such a four-roll drawing machine. Square wires produced in this way are used, for example, for piston rings in engine construction.

5.2.10 Special Forming Processes

▶ The shaping of metals, in particular of steel, can be carried out in various ways. The forming, i.e. the plastic shaping without material loss, was outlined earlier, such as rolling, forging, stamping and drawing. In order to bring steel into a certain shape, a blank can also be machined mechanically. This results in material removal (chips), such as when turning, milling, grinding. These machining processes are explained in Sect. 8.3: *Machining*. In addition, there are special forming processes for the production of semi-finished products or of finished parts, which are assigned to powder metallurgy. These processes will only be briefly discussed below, especially in connection with the modern additive processes (3D printing of metals).

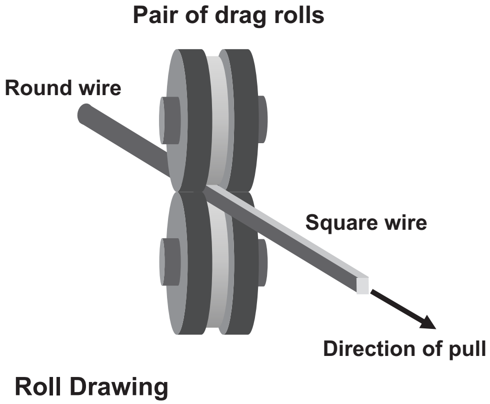
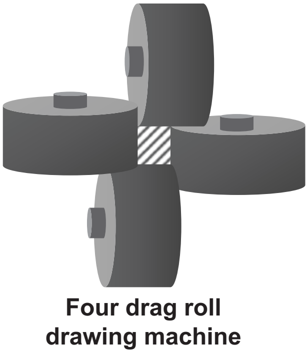


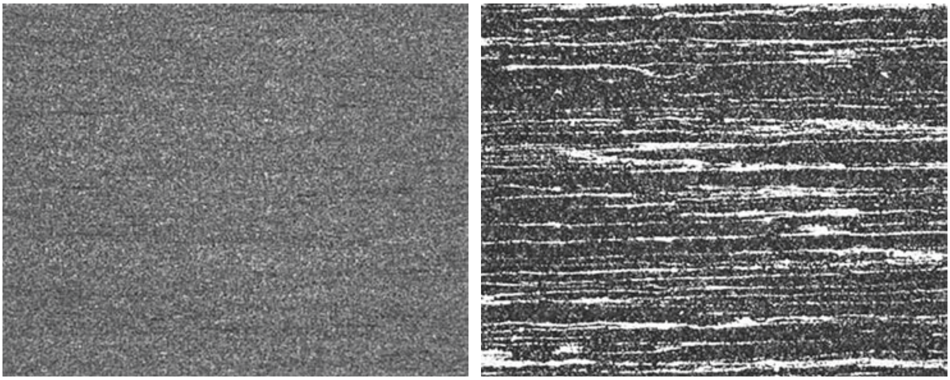
Fig. 5.77 Roll-drawing with two drag rolls

Fig. 5.78 Four drag roll drawing machine for profiling round wire to square wire



5.2.10.1 Powder Metallurgy

> **Note**
> Powder metallurgy is a special branch of metallurgy and provides components and semi-finished products with high dimensional accuracy and in a wide density range from high density to high porosity. Compared to melt metallurgical production, powder metallurgical production offers some advantages. For example, alloys can be produced that are not or only difficult to produce by melt metallurgy (segregation, demixing). Very homogeneous, non-segregated materials with evenly distributed phases are produced, for example carbides in high-speed steels. Figure 5.79 shows this very clearly with



ERASTEEL ASP®2030 (1.3294 – PMHS 6-5-3-8):
produced by powder metallurgy,
Soft annealing structure Rod Ø 118 mm
Longitudinal microsection: V ~ 100:1

ERASTEEL E M35 (1.3234 – HS 6-5-2-5):
produced by melting metallurgy,
Soft annealing structure rod Ø 91 mm
Longitudinal microsection: V ~ 100:1

Fig. 5.79 Microstructures of powder metallurgically and conventionally melt-metallurgical produced high-speed steel (Micrographs: ERASTEEL) a comparison of the microstructures of powder metallurgically and conventionally melt-produced semi-finished products made of a high-speed steel.

Powder metallurgy can also be used to produce raw components with near-final form at low cost. In addition, manufacturing based on metal powders offers the opportunity to produce composite materials. Powder metallurgical manufacturing techniques and applications are correspondingly diverse.

Fundamentally, powder metallurgy includes the three main steps: powder production, powder pressing/compacting and heat treatment/sintering.

Production of metal powder

The powder properties, such as particle shape and size (usually smaller than 0.6 mm), particle size distribution, structure and microstructure, as well as surface quality, are decisive for the processing, final density and properties of the semi-finished product or formed part. Therefore, the methods of powder production play a special role. The following main methods are distinguished:

Mechanical Methods for the Production of Metal Powder

- *Grinding of solid metal*
- *Atomization* (pulverization) of a metal melt by means of compressed air, water pressure or gas. Figure 5.80 shows the principle of this pressure atomization of a metal melt into powder.

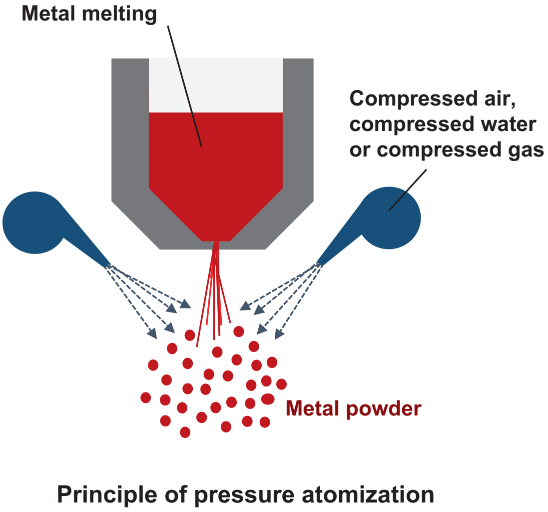


Fig. 5.80 Pressure atomization of a metal melt into powder

Chemical Processes for the Production of Metal Powder

- Reduction process (Reduction of a metal oxide in the solid phase)
- *Carbonyl process* (Carbonyl = carbon atom with a double-bonded oxygen atom, also called CO group. A compound of iron and such a CO group in the form of iron pentacarbonyl Fe $(CO)_5$ is decomposed into chemically pure iron powder at high temperatures).

Other powder production processes, such as the vaporization of the metal and the subsequent condensation, the atomization of the metal in an arc or also electrolytic processes usually do not concern steel alloys and are only used for special applications.

Pressing/compacting of metal powders

The compaction process is based on whether a formed part (sintered part) or a semi-finished product is to be produced. Metal powders are cold-compacted in special molding matrices using mechanical, servo-electric or hydraulic powder presses for the compacting of parts. The individual powder particles are pressed so closely together that they interlook or even cold-weld together. The resulting, still porous blank has such good strength already that further processing steps (e.g. re-pressing, sintering, calibration) can follow. The pressing or compacting can also be carried out under vibration, with additions of lubricants or binders, as well as under isostatic pressure (cold isostatic pressing). A special process of powder compaction is carried out at elevated temperatures: powder forging. A forging can be produced in one step with very high density and good strength properties.

Heat treatment/sintering

The heat treatment of the precompacted porous blank leads to the individual powder particles sintering together at their contact surfaces, i.e. forming a solid bond by diffusion of the atoms. Therefore, this process is also called sintering. This sintering is usually carried out in hood furnaces or continuous furnaces under protective gas. The result are sintered parts, which can have densities of up to 99%. After calibration on a die-press, a finished part with very high dimensional accuracy is obtained. Applications include, for example, oil pump wheels, gear wheels, coupling parts, levers, cams and hinges.

The powder compaction and sintering described above can also be carried out in a single process step using the so-called “**H**ot **I**sostatic **P**ressing” (HIP). Here, the metal powder is filled into a flexible, dense envelope or, as a pre-compacted part, surrounded with such an envelope. Then air is evacuated and the envelope welded shut. This is followed by isostatic pressing in a heatable pressure chamber at temperatures up to 1150°C and pressures up to 100 MPa under protective gas. Figure 5.81 shows this HIP process for powder compaction.

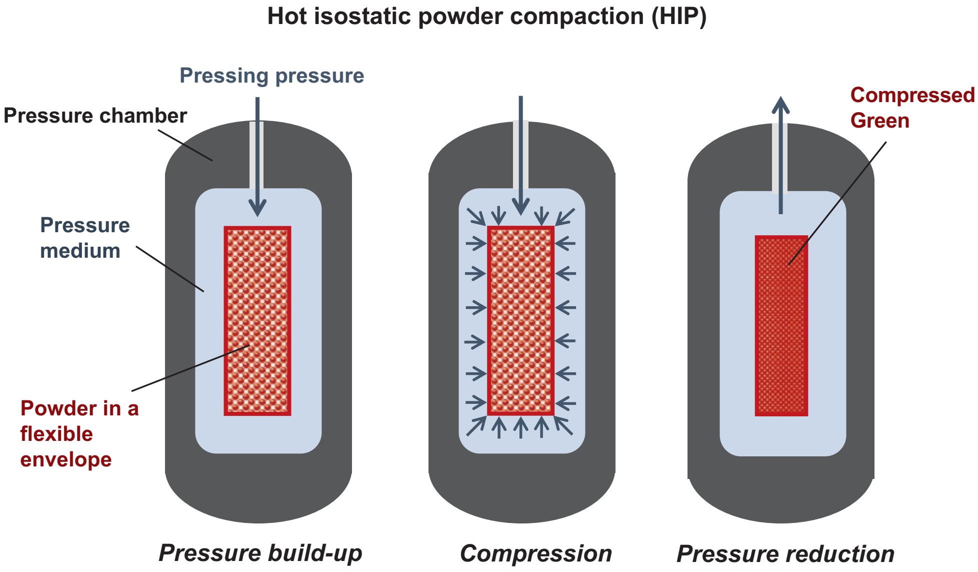


Fig. 5.81 HIP process for powder compaction

The result of the HIP process are blocks in the form of semi-finished products or components with extremely high density and isotropic properties. That is why this process is used for post-compacting of sintered metallic parts for aerospace, automotive, and shipbuilding industries and medical technology (implants). It has the advantage of being able to combine different groups of materials, which is not possible in this form and quality during sintering. Furthermore, using the HIP process, solid and powdery materials can be combined with each other (composite materials), and these can also be made from different alloys at the same time. The powder material, for example, is applied to the location where it is needed for wear reasons.

An interesting application is, for example, the powder metallurgical production of high-speed steel (HSS) for high-performance cutting tools. The required HSS powder is produced by gas or water atomization. The gas-atomized powder receives a spherical shape and can be filled directly into capsules and hot isostatically compacted into a preform. Figure 5.82 shows the result after the HIP process. The structure of the compacted high-speed steel has a high density and very evenly distributed, fine carbide grains (light).

The thusly genereated HIP preform is subsequently processed further by hot forming (rolling or forging) to the required semi-finished product dimensions. The finished product, a special tool, e.g. a spiral drill or a milling cutter, is finally produced by machining with final heat treatment (hardening and possibly also coating).

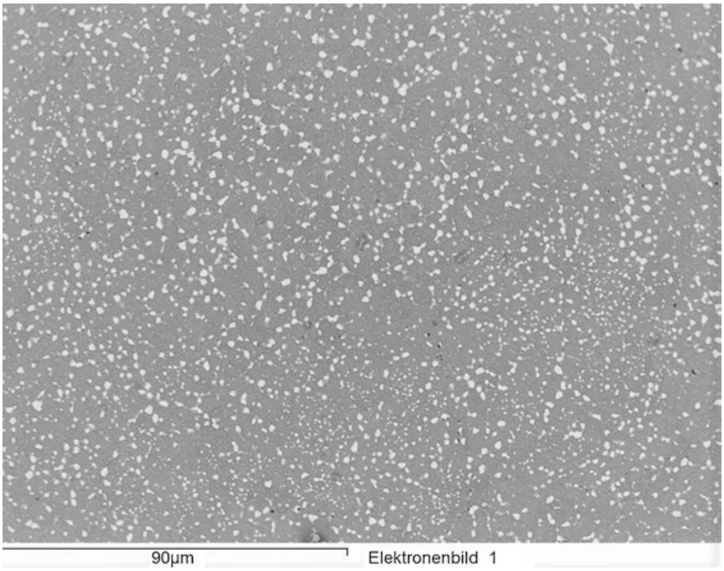


Fig. 5.82 Structure of the powder metallurgically produced high-speed steel PM 1.3343 (HS 6-5-2 C) immediately after the HIP process (Micrograph: DEW Deutsche Edelstahlwerke Specialty Steel GmbH & Co. KG)

The water-atomized powder has a rather irregular, spongy shape. As a result, these powder particles can already interlock well with each other in the cold state. The further processing takes place by cold isostatic pressing, sintering, hot forming and mechanical processing including final heat treatment (hardening) of the finished HSS tools.

In recent years, many new powder metallurgically produced parts have been developed for various applications, such as for the automotive industry, aerospace, mechanical engineering, electrical industry and medical technology. Sintered parts are particularly suitable for smaller, lighter molded parts with complex geometries and for mass production. Typical products are, for example, bearing shells, engine and transmission parts, sieves, filters and various tools.

Also to be mentioned are mold parts that are produced by metal powder injection molding. This process, which has been used industrially since about 1980, has its origins in plastic injection molding technology, hence the English term MIM (Metal Injection Moulding) also comes from this. In this injection molding process, fine metal powder is mixed with an organic binding agent. This easily moldable mixture is given its final form by means of an injection molding machine. The binding agent is removed and the mold part is sintered in a furnace. The advantages are the production of very demanding component geometries, which are not possible or only possible with great effort using conventional methods. The most important areas of application are small precision parts up to approx. 150 g for the automotive and machine construction, for measuring and control technology, for the watch and clock industry, for the lock and hardware industry, for toolmaking and for household appliances, which are produced in large series using the MIM process.

5.2.10.2 Additive Processes (3D Printing)

▶ The "additive" manufacturing processes, also called "generative" manufacturing or usually referred to as "3D printing", are increasingly attractive for the production of prototypes and components with very complex geometries. A special feature of these methods is that components can be produced without tools or forms, only on the basis of a 3D file created on the computer. This creates a high degree of flexibility in the manufacturing process and ensures the cost-effective production of models, patterns, prototypes, tools and end products in single production and small series. In addition, designs and functions that have not been implementable to date can be realized. For example, the cooling of injection molds from the inside or electric motors with a cooling system integrated into the housing wall can be mentioned here.

Finally, we have arrived at the three-dimensional printing of workpieces controlled by a computer, invented by the American *Chuck Hull* (born 1939).

The 3D printing of plastic parts has long been known, and 3D printing of vehicles or concrete for houses (or parts thereof) is now also being tested, lately even the printing of chocolate and other sweets. The rapid technical development now allows hobbyists to produce their own parts, 3D print ceramics and even metals such as aluminum, stainless steel (e.g. 1.4542 - X5CrNiCuNb16-4), tool steel (e.g. 1.2709 - X3NiCoMoTi), titanium, nickel or silver.

For metals, laser melting (SLM) or electron beam melting is also used. Layer by layer, almost without defects such as pores and cracks, the energy-rich laser builds up components made of metal powder, with melting and hardening processes taking place. This principle of selective laser melting is shown in Fig. 5.83.

The more complex the form with filigree lattice or porous structures, with irregularly running, internal channels, which are not conventionally representable by casting and / or machining, the more suitable are the additive manufacturing processes. The metal powders to be used are subject to the highest requirements. Therefore, special powder production plants (atomization of metal melts) have been developed further and put into operation for 3D printing. Figure 5.84 shows, for example, a metal powder produced for 3D printing from the austenitic chromium-nickel-molybdenum steel 1.4404 - X2CrNiMo17-12-2.

In recent years, the range of applications for additive manufacturing processes has expanded. In addition to the use of special metal powders, a new laser processing head can also be used to process metal wire with almost complete material utilization to produce components with high geometric freedom.

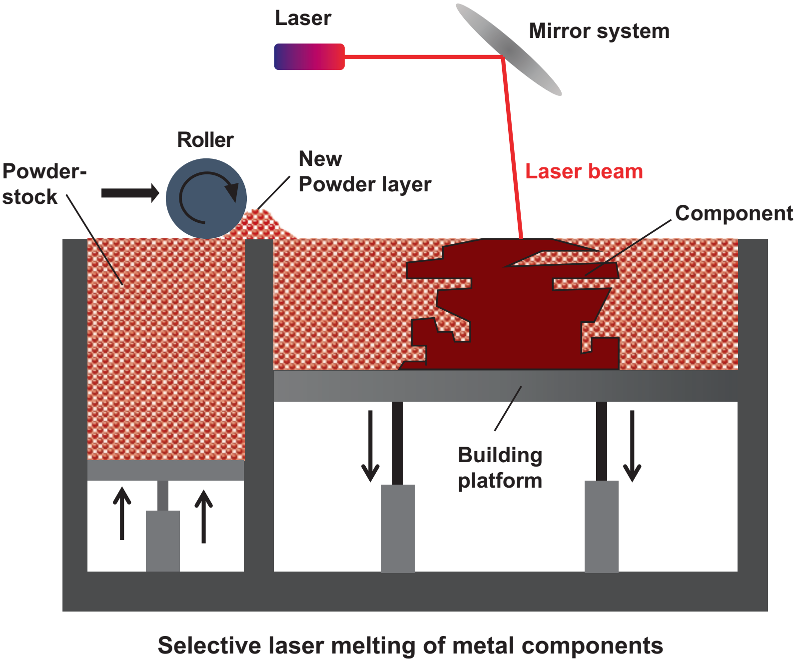


Fig. 5.83 Principle of selective laser melting of metal components

Fig. 5.84 Steel powder for 3D printing with a particle size distribution of 10 to 53 µm. (Photo: DEW Deutsche Edelstahlwerke Specialty Steel GmbH & Co. KG)

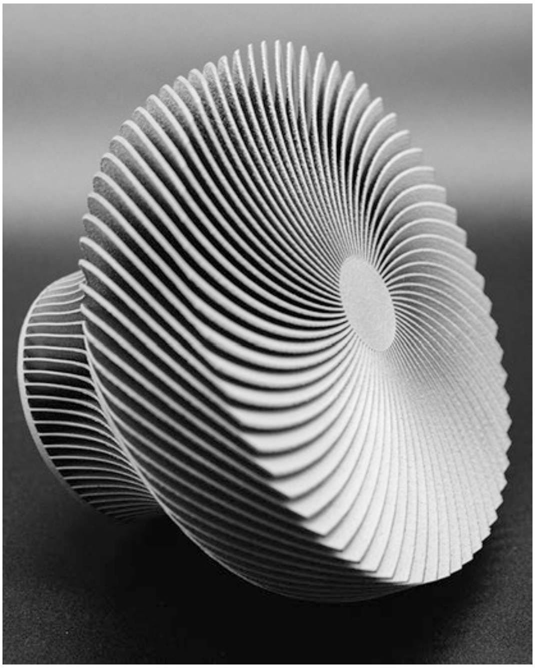


Fig. 5.85 Fan wheel produced by 3D printing (trial part) made of stainless steel 1.4404 - X2CrNiMo17-12-2. (Photo: PARARE GmbH, Frickenhausen).

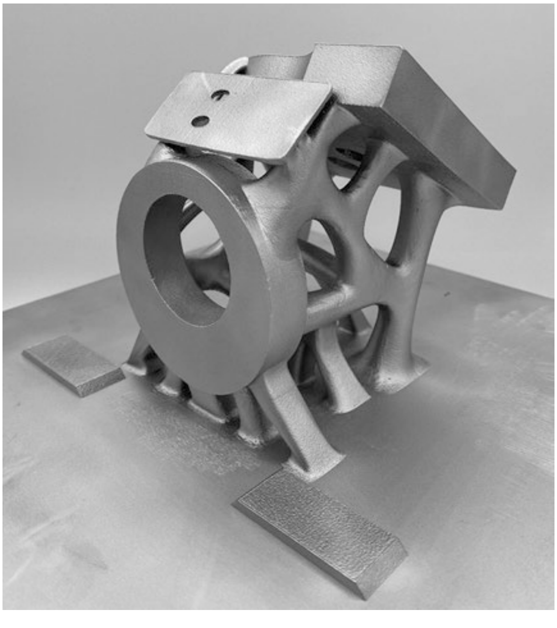


Fig. 5.86 Raw part produced by 3D printing for a bionic robot gripper made of martensitic tool steel 1.2709 -X3NiCoMoTi18-9-5. (Photo: PARARE GmbH, Frickenhausen)

Fig. 5.87 Dental prosthesis, 3D-printed from Printdur CoCrF74 powder (medical engineering material) with a particle size distribution of 10 to 53 μm. (Photo: DEW Deutsche Edelstahlwerke Specialty Steel GmbH & Co. KG)

▶ What an innovation from the color laser printer, which was still incredibly expensive in the 1970s, to today's 3D metal printing: an artificial hip joint, metal dental prosthesis, titanium bone replacement, nickel-based turbine blades, tools, automotive and aerospace components made of corrosion-, acid- and heat-resistant steels as well as of tool and spring steels, even jewelry pieces made of silver, are today "printable" as prototypes and in small series production. Examples of this are shown in Figs. 5.85, 5.86 and 5.87. The impeller wheel made of stainless steel 1.4404 - X2CrNiMo17-12-2 impressively shows the possibilities of the 3D printing process. The gripper made of a tool steel opens up new lightweight construction designs for robotics. And a dental prosthesis made by 3D printing will certainly be used more and more.

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Heat Treatment of Steel

6

▶ Knowing the effect of alloying elements, a steel is primarily produced from ore via the blast furnace-converter route or secondary from scrap in an electric steelworks, poured into a ingot or strand and formed into a semi-finished product or finished part. The principles, processes, facilities and applications for this are covered in the content of the first five chapters. In order to obtain an assembly-ready component, however, further technological steps are necessary, such as heat treatment, testing, machining and finishing work. These shall be introduced below, starting with the heat treatment of steel.

6.1 Remarks

▶ A mystery for almost 3000 years and shrouded in much superstition, it was not until the nineteenth century that the breakthrough in understanding the processes taking place during the heat treatment of steel occurred. In the microstructure, as with all metallic materials, the atoms can leave their lattice sites and migrate to other sites during heat treatment. Phase changes and new microstructural states occur (Kutz, 2013). The knowledge around this is constantly "refined". And yet, even today, the processes with or without phase transformation in iron and steel alloys are not always easy to explain due to the confusing variety of microstructural phenomena.

The heat treatment includes the treatment of semi-finished steel products and of metallic components in the solid state with thermal, chemical-thermal or mechanical-thermal

J. Schlegel, *The World of Steel*, https://doi.org/10.1007/978-3-658-39733-3_6

effects in order to improve or achieve certain properties. The processes used mainly cause a change in structure. Reference is made to this in Sect. 2.1 *(What is steel?)*.

During heating, a transformation takes place from a body-centered cubic lattice to a face-centered cubic lattice. And during cooling, this process can be reversed. This is now specifically exploited in many heat treatment processes of steel (see Sect. 6.2: *Heat Treatment Types*). These processes, which cause a complete microstructure transformation in the heat-affected zone, include the thermal processes **annealing** and **hardening.** Increasingly, heat treatment processes are also gaining importance, which are not carried out separately, but in connection with the forming process as controlled cooling processes **(thermomechanical treatments).**

In addition, there are heat treatment processes that only cause a change on the surface of the semi-finished steel or component. These include, for example, diffusion and coating processes that aim to increase surface hardness.

There are also processes that influence physical and/or mechanical properties without changing the microstructure, for example stress relieving.

> ▶ Only the thermal methods for heat treatment of steel should be considered below. Depending on the product to be treated (wire, rod, profile, pipe, strip, sheet, molded part with a few grams up to several tons in weight), there are so many variants of methods and plants that would exceed the scope of this publication to present them all in detail. Therefore, the focus is on the most important heat treatment methods of semi-finished steel and components.

After the semi-finished product is produced by forging, rolling or drawing, the steel products usually do not yet have the properties desired by the customer. On the one hand, these should warrant further processing, for example by forming or by mechanical processing (processing properties). On the other hand, the properties should already correspond to the requirements in the final application (use properties). Therefore, these properties must be specifically changed or adapted by a **final heat treatment**. This mainly affects the mechanical and technological properties such as strength, hardness, toughness and stress state, partly also physical parameters, e.g. magnetic properties.

An **intermediate heat treatment** is carried out between the forming steps during the production of semi-finished products in order to reduce the hardening that has occurred and to set a favorable microstructure state for the subsequent forming, thus achieving good formability.

All heat treatment types are governed by the influencing factors of heating (heating and holding time), temperature, atmosphere (air, vacuum, protective gas) and cooling (cooling rate). These cause changes in the steel microstructure in different combinations and sequences (change of the microstructure phases, change in their proportion, arrangement, shape and composition), whereby the desired properties are set. The heating is regulated such that the temperature increase in the heat-treated material can take place evenly (temperature compensation between edge and core) and a warp (minor dimensional change due to internal stresses) is avoided as much as possible.

The selection of the annealing temperature depends on the composition of the steel, in particular on the carbon content and the desired heat treatment result. The basis for this is the iron-carbon diagram. For some processes, e.g. normalizing and hardening, the aforementioned ferrite-austenite phase transformation of the steel must be carried out.

The holding time in the specified temperature range must ensure the desired microstructure change.

The use of suitable atmospheres (protective gas, vacuum) can avoid scaling, discoloration of the annealing surfaces and edge carburization.

The cooling rate depends on the desired properties of the steel (e.g. hardness) and on the type of heat treatment. Figure 6.1 shows a schematic time-temperature curve for the heat treatment of a steel part with due regard for the temperature equalization between the edge and the core.

In addition, the overview in Fig. 6.2. presents the most important heat treatment processes as such time-temperature curves.

The temperature ranges of these heat treatment types, based on the simplified iron-carbon diagram, are also shown in Fig. 6.3. Depending on the carbon content of the steel to be treated, an initial estimate of the temperature range of the respective heat treatment process can be made.

In practice, the so-called **time-temperature-transformation diagrams** (TTT diagrams) have proven themselves. These represent the microstructure development at

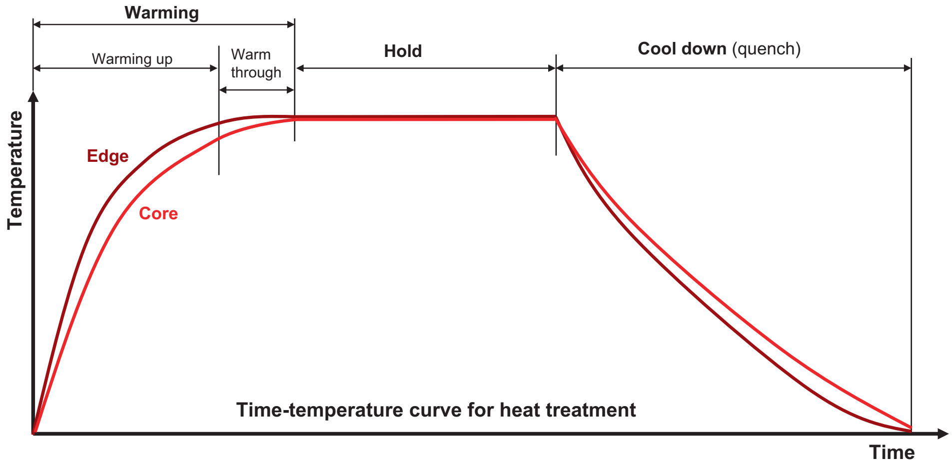


Fig. 6.1 Time-temperature curve for the heat treatment of a steel part with consideration of the temperature equalization between the edge and the core

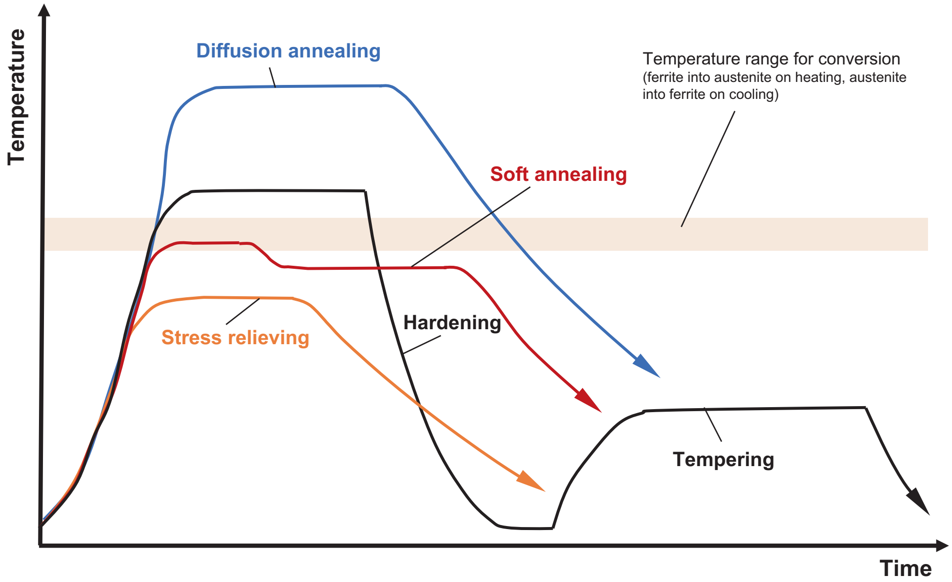


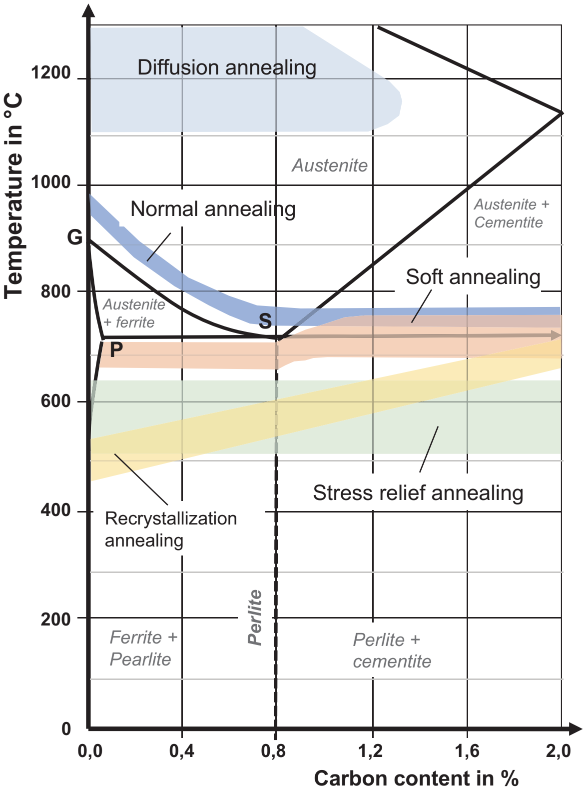
Fig. 6.2 Time-temperature curves for different heat treatment processes

different time-temperature profiles for each steel alloy (Eckstein, 1971). For many steels, such TTT diagrams have been determined and user-friendly stored in steel databases. With the associated information about the respective steel alloy (chemical composition), the starting microstructure and the previous time-temperature treatments, the structure fractions or the hardness, TTT diagrams are today the basis for the determination of the heat treatment parameters. Figure 6.4 schematically shows a typical TTT diagram for a nitriding steel. Areas of different structural states are delimited, such as martensite (hardness structure), austenite, ferrite, pearlite and an intermediate stage structure (bainite).

The transformation course in the steel structure can be traced back via the shown cooling curves with different cooling rates. Thus, with a rapid quenching (first cooling curve on the left in Fig. 6.4) the austenitic structure is immediately transformed into the hardening structure martensite. This also results in a very high hardness (see Sect. 6.2.7: *Hardening*). With much slower cooling, the steel passes through various structural states, and the final hardness is lower.

A practical example should show how technological recommendations for heat treatment can be derived from a TTT diagram, and not only in terms of the hardness to be achieved, but also to obtain a certain microstructure. A customer manufactures extruders for injection molding from the nitriding steel 1.8550 - 34CrAlNi7-10. The raw material for this must have a maximum of 3% ferrite content in the hardened state. Therefore, the

Fig. 6.3 Temperature ranges of the most important heat treatment types, shown in the simplified iron-carbon diagram



cooling rate must be chosen so that the cooling curve for this steel is realized according to the TTT diagram shown in Fig. 6.5. With a lower cooling rate the ferrite area would be traversed, and the ferrite content in the structure after cooling would then be too high for this special customer request.

6.2 Heat Treatment Types

▶ The "classic" heat treatment types for steel, such as normalizing, annealing, recrystallization, diffusion, solution and stress-relief annealing, hardening/tempering (quenching), precipitation hardening, cold working and press hardening, are explained in a condensed version with regard to purpose, process and application.

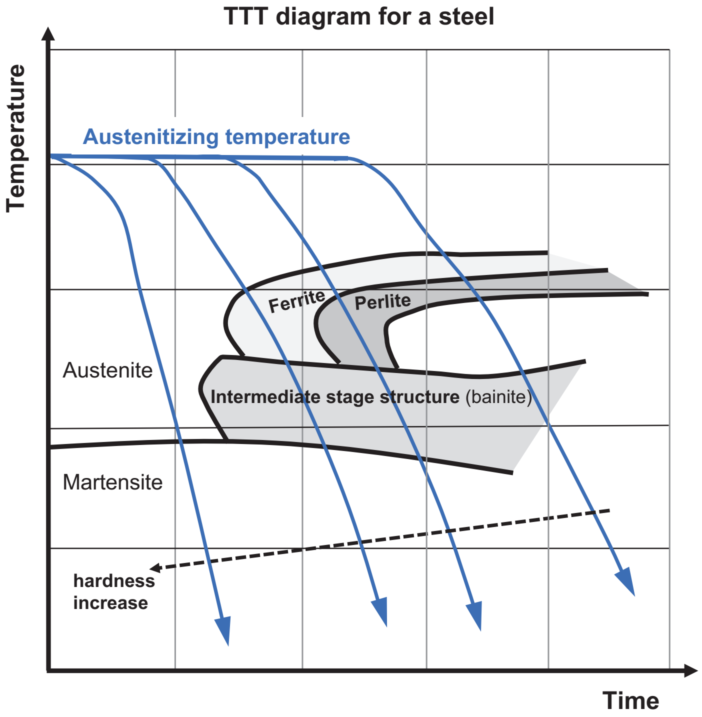


Fig. 6.4 Typical TTT diagram for a steel (simplified representation)

6.2.1 Normalizing

Purpose

Normalizing is used to achieve a uniform, fine-grained microstructure with high toughness and good machinability. All microstructural and property states that the steel had before are reversed (Kutz, 2013).

Procedure

- Heating to approx. 20 to 50°C above the upper transformation point (temperature at which the transformation from ferrite to austenite is completed, also referred to as Ac_3 (Weißbach, 2012),
- usually short holding times for the formation of austenitic structure,
- cooling in air at rest.

The structure becomes finer the faster the cooling takes place. Two passes through the α-γ-α transformations during heating and cooling leads to the elimination of the uneven, coarse-grained structure.

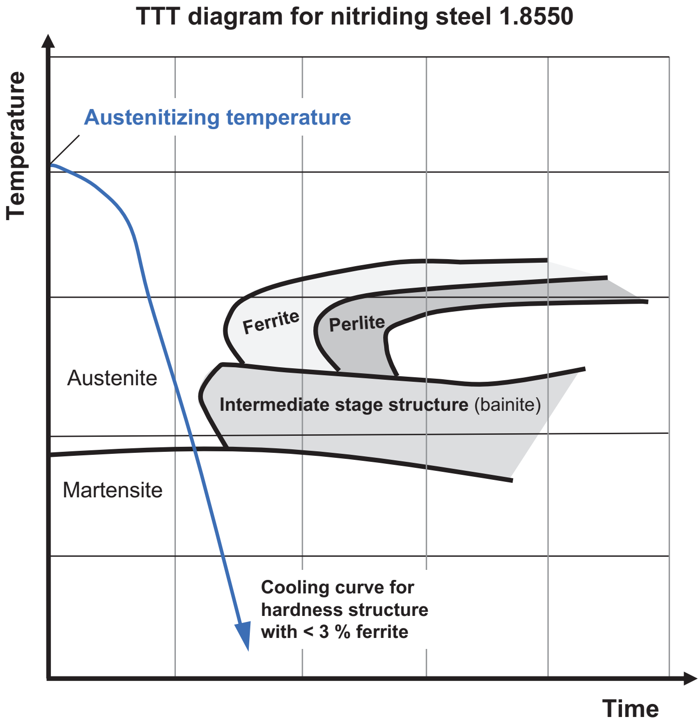


Fig. 6.5 TTT Diagram with cooling curve for nitriding steel 1.8550 - 34CrAlNi7-10 to achieve a hardness structure with less than 3% ferrite content

Steels that do not show such a transformation cannot be normalized. This affects the “transformation-free” ferritic and austenitic steels.

Application

Rolled and forged parts made of low-alloyed construction steels and case-hardening steels, e.g. 1.0460 - P250PH (heat-resistant construction steel for valve construction), 1.0488 - P275NL1 (fine-grain construction steel for boiler and pressure vessel construction), 1.1181 - C35E (unalloyed case-hardening steel for automotive and machinery engineering), 1.1213 - C53G (steel with good induction hardenability for axle parts in automotive engineering), 1.7225 - 42CrMo4 (case-hardening steel for highly stressed parts such as connecting rods, shafts, crankshafts, gears, sprockets, gear shafts), 1.7228 - 50CrMo4 (case-hardening steel for automotive and machinery engineering, e.g. for rings, discs, barrels, shafts).

6.2.2 Soft Annealing

Purpose

As the name soft annealing already suggests, the purpose of this heat treatment is to achieve a soft, malleable structure that can be reformed after quenching; in other words, to temper a hardened or quenched steel. The reduction in hardness is achieved by the healing of defects, such as displacements. Tensions in the steel are also relieved. This results in recrystallization with the formation and growth of new crystals.

Procedure

- Heating to just below the temperature P-S-K (Ac_1), see Fig. 6.3, sometimes briefly above or around this transformation temperature,
- long holding times, sometimes for several hours, especially when annealing on spherical cementite (GKZ annealing),
- slow cooling in the furnace usually to 600°C, then further in air.

Application

Tool steels, high-speed steels, knife steels, cold-drawn and cold-rolled steels, bearing steels, etc. 1.2210 - 115CrV3 (cold work steel for dies, pins, stamps, engraving tools), 1.3343 - HS6-5-2 C (high-speed steel with high toughness and good cutting performance), 1.3505 - 100Cr6 (classic bearing steel), 1.3536 - 100CrMo7-3 (bearing steel), 1.5752 - 15NiCr13 (nickel-chromium alloyed steel for plastic mold construction, machinery and automotive construction), 1.7103 - 67SiCr5 (spring steel).

Figure 6.6 shows the microstructures before and after annealing of the steel 1.4116 - X50CrMoV15, a martensitic, stainless and heat-resistant steel. This steel is used, among other things, for high-quality cutting tools and surgical instruments. Compared to the state after hot rolling, the microstructure, as a result of annealing, shows nicely formed, rounded carbides and is therefore well formable.

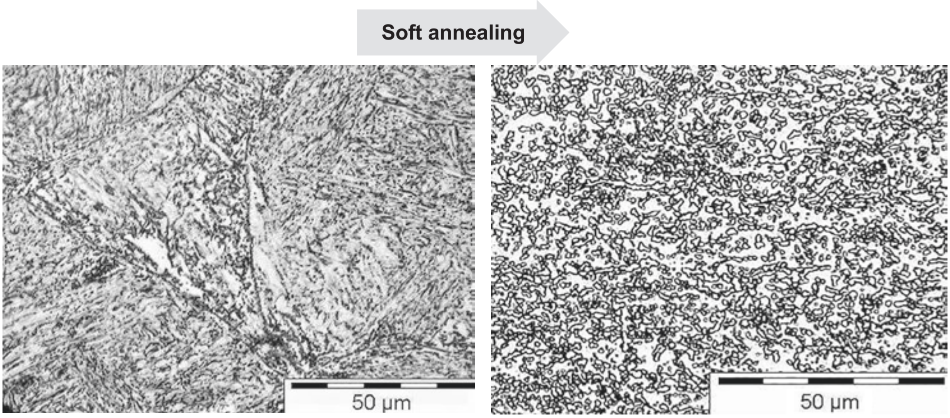
A special variant of annealing is the **annealing on speroidal cementite**.

Purpose

After a deformation, cementite components usually occur in lamellar form. These are to be spheroidized by soft soft annealing. In the tough ferrite, hard carbides are then present in spheroidized form. This makes the steel well formable and tough, but it also loses hardness. So in practice, a compromise between good machinability and hardness must always be found.

Procedure

Annealing with very long holding times (several hours), then very slow cooling.



1.4116 flat, rolled, untreated

1.4116 soft annealed

Fig. 6.6 Microstructures before and after annealing of the steel 1.4116 - X50CrMoV15. (Micrographs: BGH Edelstahl Freital GmbH)

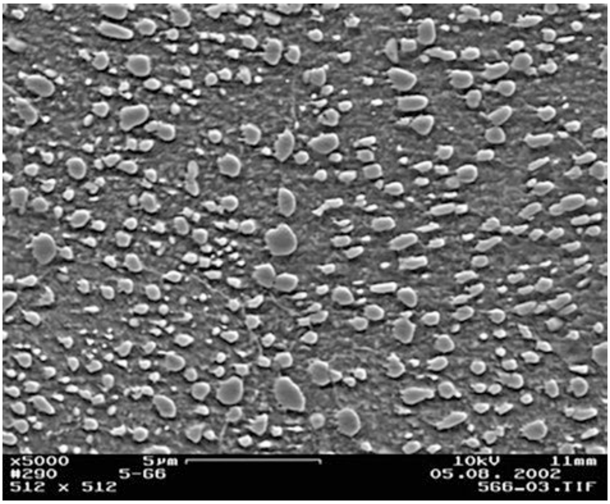


Fig. 6.7 Rolling bearing steel: 1.3505 - 100Cr6 with spherical carbides (scanning electron microscope image)

Application

The annealing on speroidal cementite is used for steels with a carbon content > 0.8 mass%. They contain enough carbon to form the hard component cementite (Fe_3C) in the microstructure. A classical example of this are the rolling bearing steels. Figure 6.7 shows the microstructure of the rolling bearing steel 1.3505 - 100Cr6 after such a heat treatment. The spherical carbides stand out clearly from the ferritic matrix.

▶ Other variants of annealing are also applied to those steels which are generally intended for soft annealing. However, special requirements regarding structure and hardness have to be fulfilled.

Annealing to a best determined strength.

Purpose

Heat treatment of steel products in order to achieve a certain strength (hardness) range. For this annealing the designation + **TH** is used today for steel denominations.

Procedure

- Heat to 850 to 950°C
- Cool
- Temper at about 500 to 550°C

Annealing to a best structure

Purpose

Heat treatment of steel products in order to achieve a certain structure, in particular to improve the machinability of tool steels. Today this process is carried out with a defined cooling curve so that a pure ferrite-pearlite structure is formed. Therefore, the designations "treated on **F**errite-**P**earlite structure" or "Pearlitizing" known.

Procedure

Heat treatment (Austenitizing) at 900 to 1000°C with subsequent rapid, controlled cooling and holding in the temperature range of the perlite transformation, so that the austenite can transform into ferrite-perlite.

6.2.3 Recrystallization Annealing

Purpose

The term recrystallization annealing refers to the purpose: annealing in a temperature range where recrystallization takes place. This usually takes place with steel between 550 and 700°C (see Fig. 6.3). Recrystallization means grain refinement, thus the softening of cold-rolled, drawn or pressed steels. Therefore, recrystallization annealing is carried out between individual cold forming steps and also afterwards. In doing so, the steel loses brittleness and becomes tough and malleable again. The microstructure prior to cold forming is now restored without a microstructure transformation taking place. Figure 6.8 shows this schematically for the course of grain refinement with increasing recrystallization time and the changes in formability, hardness and strength caused by this.

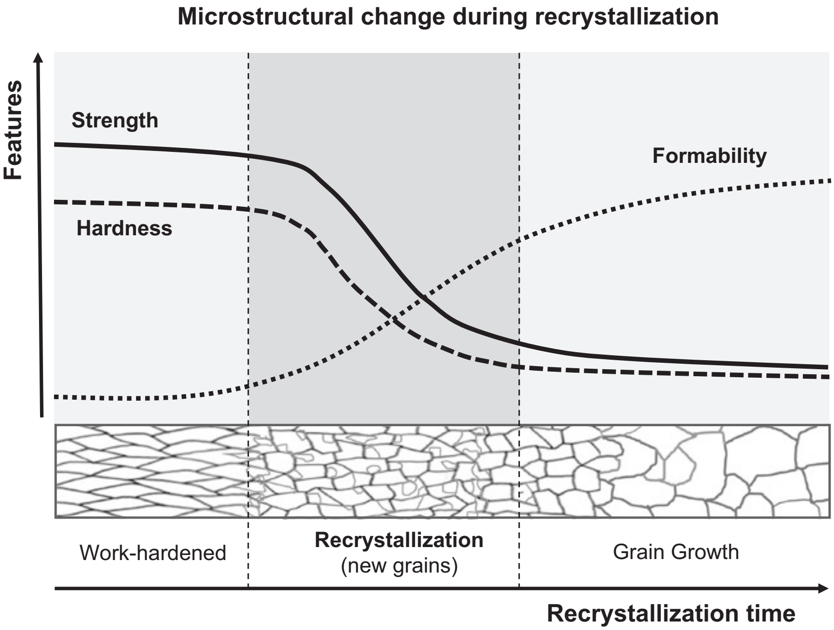


Fig. 6.8 Structure change with progressing recrystallization duration and impact on the formability, hardness and strength

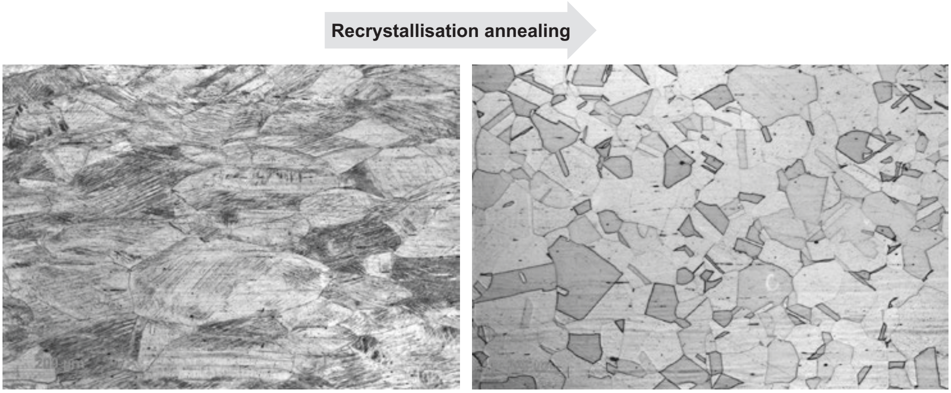
Procedure
Classic:

- Heating to 500 to 700°C for ferritic steels, to over 1000°C for austenitic steels in combination with solution annealing,
- long holding times,
- slow cooling.

Rapid heating:

- high heating rates, higher annealing temperatures,
- short holding times, partly only about 60 s,
- slow cooling.

The new formation of the structure due to nucleus formation and grain growth leads to the reduction of lattice defects, the reduction of hardness and strength and the workpiece is again malleable. Figure 6.9 shows, using the example of austenitic, non-rusting steel 1.4303 - X4CrNi18-12, used for cold drawing and cold rolling, the change in structure during annealing.



1.4303 wire, drawn, strengthened

1.4303 recrystallisation annealed

Fig. 6.9 1.4303 - X4CrNi18-12, wire drawn and after annealing. (Micrographs: BGH Edelstahl Lugau GmbH)

As drawn wire, thus cold-hardened, the starting state shows stretched grains with martensite formation, caused by cold forming. The structure in the recrystallized state now shows the newly formed grains and is therefore again malleable.

Application

Cold-formed, hardened steels, such as 1.4016 - X6Cr17 (ferritic steel with good bending, deep drawing and polishing properties), 1.4034 - X46Cr13 (stainless, martensitic chromium steel with good corrosion properties, for components in machine engineering, medical engineering and pharmaceutical industry), 1.4104 - X14CrMoS17 (chromium steel with improved ductility for the production of nuts, screws, pins, shafts, etc.), 1.4105 - X6CrMoS17 (a chromium steel with similarly improved ductility due to the sulfur content, mainly used for components in the automotive industry), 1.4112 - X90CrMoV18 (corrosion-resistant martensitic chromium steel with high hardness and wear resistance, for plastic moulds, surgical instruments, knife blades, guide bars, pump shafts, components in the automotive industry), 1.4301 - X5CrNi18-10 (known as V2A steel, relatively soft non-magnetic austenitic, corrosion-resistant steel, wide range of applications), 1.4303 - X4CrNi18-12 (austenitic Cr-Ni steel, with good corrosion resistance, weldability and very good machinability, for parts in the automotive industry, machine and plant engineering, chemical industry, architecture, etc.), 1.4310 - X10CrNi18-8 (austenitic, corrosion-resistant stainless steel, good mechanical properties, good polishability, for springs, stamping and bending parts as well as other parts in the automotive industry, food industry, mechanical engineering, drive technology).

6.2.4 Diffusion Annealing

Purpose

Diffusion annealing is used to reduce inhomogeneities in the microstructure (local, segregation-induced differences in the chemical composition of steels). Therefore, the common names homogenization annealing or equalization annealing.

Procedure

Since diffusion processes are strongly temperature- and time-dependent, heating to very high temperatures (for steel between 1100 and 1300°C) is required, see Fig. 6.3. Furthermore, very long holding times are necessary, possibly up to 50 h. The cooling must be done slowly, or an immediate forming step is to be carried out.

Application

Diffusion annealing is very elaborate and expensive because of the high temperatures and the long annealing times. It is predominantly used when microstructure segregations cannot be avoided during the casting process in another way. This may apply to high-alloy steels (e.g. 1.7228 - 50CrMo4, a heat-treatable steel for forged, rolled rings, discs, shafts and other forgings), nickel-based alloys and bearing steels (e.g. 1.3505 - 100Cr6, the classic bearing steel).

6.2.5 Solution Annealing

Purpose

Precipitations present in the microstructure from previous production steps are to be brought into solution. That is why this annealing process is also called homogenization. In addition, a more uniform distribution of the alloying elements leads to an increased corrosion resistance of stainless steels.

Procedure

- Heat to approximately 1000° to 1100°C,
- Hold time 30 min to several hours,
- Quench in water.

Application

Austenitic steels, e.g. 1.4301 - X5CrNi18-10 (known as V2A steel), 1.4307 - X2CrNi18-9 (a steel with slightly improved corrosion resistance due to the lower carbon content compared to 1.4301), 1.4401 - X5CrNiMo17-12-2 (good corrosion resistance to acids and chlorinated media, used in the food and chemical industries), 1.4441 - X2CrNiMo18-15-3 (stainless steel for medical implants and medical instruments), 1.4871 - X53CrMnNiN21-9 (valve steel), 1.4882 - X50CrMnNiNbN21-9 (valve steel).

Duplex steels, e.g. 1.4410 - X2CrNiMoN25-7-4 (a super duplex steel for use in seawater), 1.4462 - X2CrNiMoN22-5-3 (duplex steel for the offshore industry), 1.4501 - X2CrNiMoCuWN25-7-4 (duplex steel with excellent seawater resistance for the offshore industry.

Nickel alloys, e.g. 2.4856 - NiCr22Mo9Nb (nickel-based alloy for marine engineering, shipbuilding, flue gas cleaning systems, chemical, oil and gas industries).

6.2.6 Stress Relieving Annealing

▶ Heat can help relieve muscle tension in humans, or do good for muscle stiffness. Heat helps to break down internal tensions in steel as well.

Purpose

Internal stresses caused by uneven cooling after tempering or during straightening or mechanical processing are to be reduced. Otherwise, the internal stresses would release before, or at the latest during further processing, and lead to geometric deviations (warping) or, under certain circumstances, to cracks.

Procedure

- Heating to temperatures usually between 450 to 650°C, in any case about 30 to 50°C below the annealing temperature of the steel,
- Annealing with adapted holding times,
- Slow cooling.

Application

Stresses in the semi-finished steel or formed part are not visible; but, depending on the history of production, usually present. In order to ensure distortion-free further processing and to avoid the occurrence of possible hardening, a stress-relief annealing is therefore carried out on almost all materials or steels, often after hardening.

6.2.7 Hardening

▶ Hardening of steel has, unlike other heat treatment processes, a uniquely long history shrouded in mystery and a special importance. Hard tools and weapons were already in great demand in pre-christian times. It was a long path of more than 3000 years from the past quenching of the red-hot iron in water to the modern methods practiced today, and from the artisanal experience to

> the modern, scientifically sound hardening process. During this time, “hard as steel” has become a generally accepted saying. Because even today, steel with the highest resistance to deformation and wear is indispensable in many areas of technology. Therefore, new hardening techniques are constantly being developed, for e.g. the local hardening of component surfaces, the inductive hardening, the laser hardening, etc., also using numerical simulations.

Purpose

Hardening serves to increase the mechanical resistance (hardness, strength) of the steel by a targeted change in the microstructure. Basically, three methods are distinguished:

- *Hardening by transformation*
- *Hardening by precipitation*
- *Hardening by cold working*

6.2.7.1 Transformation Hardening

This hardening process works because the steel to be hardened shows a microstructural transformation from ferrite to austenite or from austenite to ferrite during heating and cooling. Steels that are austenitic or ferritic in terms of alloying elements and thus do not show such a microstructural transformation cannot be hardened by transformation.

Procedure

- Heating to temperatures above the upper transformation point,
- Holding for transformation of ferrite to austenite,
- Quick cooling with cooling media water, oil, polymer or air. This causes superficial or penetrating formation of the brittle hardness microstructure martensite. The greater the undercooling or the stronger the cooling effect, the more martensite is formed. Characteristic are the needle-like structures of the martensite microstructure, as they are recognizable in Fig. 2.23 on page 37. They arise when, due to the rapid cooling, there is no time for an orderly reversion of austenite to ferrite.

The task with hardening is to achieve the critical cooling rate for the treated steel after its heating and transformation into austenite. This material constant is to be taken from the relevant TTT diagram and relates to the cooling rate which is at minimum necessary for martensite formation. Based on this, the quenching medium can be selected according to ecological and economic considerations: air, oil, polymer or water (in this order with increasing quenching effect). Also to be considered are the quenching phases (steam skin, boiling and convection phase), which occur simultaneously on a hot piece when dipped into the quenching medium and can also be the cause of distortion, hardening cracks and zones with different microstructures.

Application

Hardening can take place both on the semi-finished product as raw material for machining (hard machining) and on the finished component. The hardness achievable during transformation hardening depends on the carbon content of the steel. This must be at least 0.2 mass-% (Kutz, 2013). In general, the higher the carbon content, the higher the possible hardness. And of course the steel must also be transformation hardenable, i.e. it must show a microstructure transformation during heating from a body-centered cubic lattice to a face-centered cubic lattice and back again during slow cooling.

The classic end quench test is used to test the hardness of steel. A cylindrical sample (100 mm long and 25 mm in diameter) is quenched with water from the bottom of the end face after heating to the hardening temperature. Starting from the edge on the planed cylinder jacket surface, the hardness is determined at intervals of 1.5 - 3 - 5 - 7 - 9 - 11 - 13 mm, etc., according to Rockwell (HRC) or Vickers (HV) (see Sect. 7.2.2: *Hardness testing*). The maximum hardness and the hardness profile in depth characterize the hardness (https://en.wikipedia.org/wiki/Hardenability).

There are quenched and tempered steels, tool steels and martensitic, corrosion-resistant steels, e.g. 1.7225 - 42CrMo4, (a classic quenched and tempered steel for highly stressed components in the automotive industry), 1.8519 - 31CrMoV9 (nitriding steel for wear parts in machinery and vehicle construction), 1.3343 - HS6-5-2 C (high-speed steel for machining and forming tools), 1.2344 - X40CrMoV5-1 (hot working steel for extrusion and forging dies, forging hammers, hot shears, etc.), 1.4313 - X3CrNiMo13-4 (stainless soft martensitic steel with good toughness for the oil industry, pumps, turbines in hydroelectric power plants, tools for die casting), 1.4901 - X10CrWMoVNb9-2 (high-temperature steel for power plant construction).

6.2.7.2 Tempering

Purpose

Immediately after hardening, tempering occurs. The workpieces are reheated and held at the tempering temperature for different lengths of time. In particular, hardening stresses are relieved. The brittle martensite is transformed into a microstructure with slightly lower hardness but slightly higher toughness. The steel becomes softer the higher it is heated during tempering. For each steel there are so-called tempering diagrams which show the course of the hardness decrease with increasing tempering temperature. In Fig. 6.10 such a tempering diagram is shown schematically. The tempering temperature can be selected according to the desired hardness (strength) from these diagrams.

Tempering is usually done under normal atmosphere, whereby the characteristic starting colors form due to oxidation on the surface. But it can also be done in protective gas or vacuum systems, in salt baths or in induction systems. If necessary, Tempering is repeated several times.

Figure 6.11 shows this heat treatment combination of hardening and tempering.

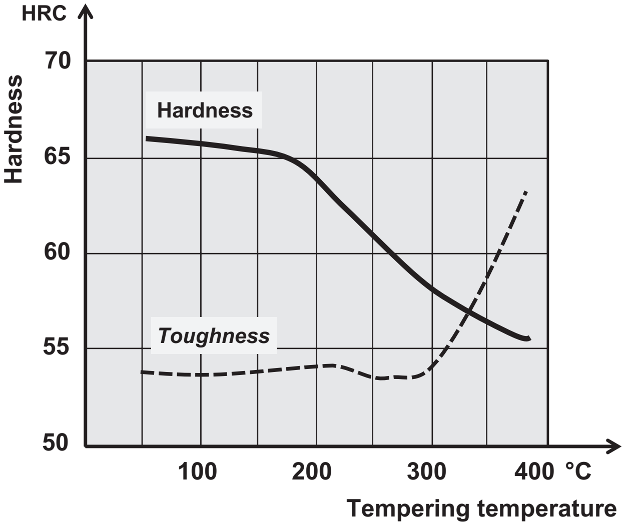
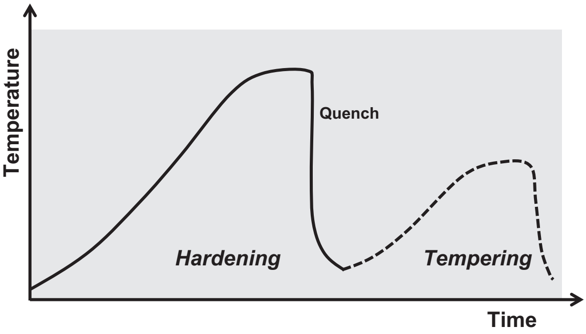


Fig. 6.10 Tempering diagram for a heat-treatable steel (schematic)

Fig. 6.11 Temperature course during hardening and tempering



Procedure

- Reheating of the steel to a temperature level below the transformation point (depending on the type of steel and the intended use at temperatures between 200 and 700°C),
- Holding and cooling in air.

Temperature and holding time determine the degree of hardness drop.

Application

All hardened steels.

6.2.8 Precipitation Hardening

Purpose

In this heat treatment process, an increase in the strength of the steel is achieved by deliberately setting many small precipitations in the microstructure. This precipitation process is based on the fact that the solubility of alloying elements in the iron lattice decreases with decreasing temperature. Therefore, at certain alloy compositions, the precipitation of many homogeneous particles occurs. These then present obstacles to dislocation movements in the microstructure and the sliding on lattice planes is made more difficult. This is somewhat equivalent to the case when one tries to pull a sled on a snow-covered but gravel-strewn path. The sled is braked, one needs a higher pulling force. And for steel this means similarly that it now has a higher strength due to the precipitated particles in the microstructure.

Procedure

The process of precipitation hardening comprises three heat treatment steps:

- *Solution annealing* (Diffusion annealing, Homogenizing):
  The steel is heated and held at solution annealing temperature until all the alloying elements necessary for precipitation are dissolved.
- *Quenching:*
  Diffusion and, as a result, the formation of precipitates are prevented. There is now a supersaturated microstructure.
- *Aging* (Precipitation):
  Only via final aging at temperatures of around 150 to 190°C (450 to 550°C for maraging steels) is diffusion again stimulated, and the desired precipitates are formed in a targeted manner. In order to achieve an optimum size and fine, evenly distributed particles for the strength increase, the aging treatment time and temperature must be exactly coordinated, depending on the steel (Kutz, 2013).

Application

The strength increase through a heat treatment, which specifically produces precipitates in the structure, is common in aluminum alloys. Only steels that meet the requirements for hardening (mixed crystal formation with limited solubility, decreasing solubility at lower temperature, precipitates lead to lattice stresses) can be hardened. This affects special, corrosion-resistant stainless steels (e.g. the maraging steel 1.4542 - X5CrNiCuNb16-4, 17-4PH, used for highly stressed components in the aerospace industry) and some nickel-based alloys (Volk et al., 1970).

6.2.9 Cold Hardening

▶ In the past, you could often hear short, characteristic hammer blows at the edge of the field or on meadows. It was the farmer who sharpened his scythe. In this way he could then mow the grain or grass by hand for longer. He increased the service life of his scythe by cold hardening, it stayed sharp longer.

Purpose
A deliberately created solidification by cold forming (hammering, pressing, rolling, drawing, deep drawing, blasting, etc.) increases the material strength. This creates defects in the lattice, which impede the sliding process. Therefore, this process is also called cold hardening.

Procedure
The steel is acted upon at room temperature by means of a forming process and a defined deformation (degree of deformation) is generated. This degree of deformation determines the extent of the achievable cold hardening up to a limit imposed by the forming process (end of formability). Figure 6.12 shows the typical course of the cold hardening of steel as a function of the degree of deformation.

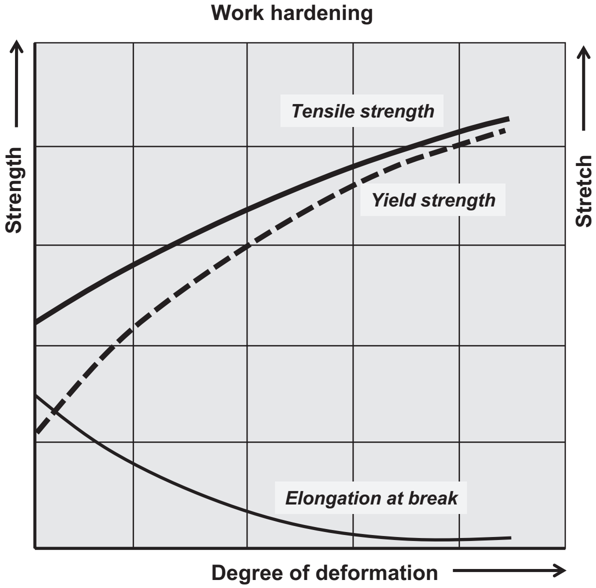


Fig. 6.12 Typical course of the cold hardening of steel as a function of the degree of deformation

Application

Hardening by cold forming can basically be achieved with all steels. This may also result in changes in the electrical and magnetic properties. Cold forming is deliberately used for such steels which, due to their chemical composition, do not show any transformation during heating and cooling, i.e. they are not transformation-hardenable. If now end products are to be manufactured from such steels with high strengths, only the use of a final treatment by cold forming with a defined forming degree remains. This mainly affects the ferritic and austenitic, corrosion-resistant steels (see Sect. 2.4.2: *Stainless steels*).

6.2.10 Press Hardening

▶ In order to produce cost-effectively, resource-efficiently and thus environmentally friendly, new, innovative hardening processes have been developed in recent years and used above all for the production of sheet metal parts for the automotive industry (e.g. for the B-pillars of cars). This relates the process of press hardening, also called "forming hardening".

As the name suggests, a cut and preheated sheet metal is, while being hot formed, simultaneously hardened in a controlled manner directly during pressing (forming) in the cooled press tool. This allows for higher strengths to be achieved that would not be possible with conventional cold forming (deep drawing). Figure 6.13 shows the principle of press hardening of sheet metal parts in a simplified manner.

The hot forming of hollow profiles is also possible. The high requirements for structural components of modern car bodies (weight—lightweight construction, crash behavior, costs) are not only the driving force for the development and use of innovative form hardening processes, but also for special, to these hardening methods adapted steel alloys, e.g. manganese-boron-alloyed quenching steels (IWU, 2012).

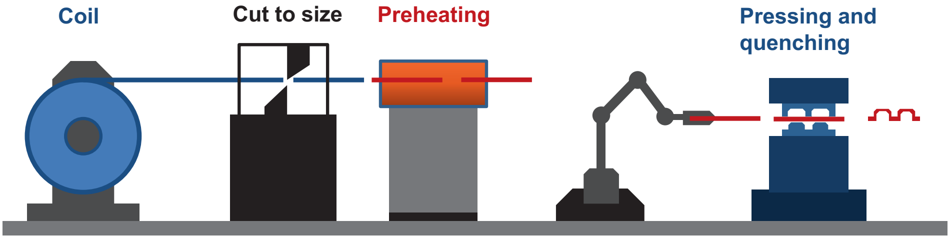


Fig. 6.13 Principle of press hardening of sheet metal parts

6.3 Plants for Heat Treatment

Depending on the format of the heat-treated goods (block, semi-finished product, bar or wire, shaped part), the type of heat treatment, the necessary cooling and control of the process flow and the necessary atmosphere, the following plants are used today (heated with gas or electricity):

- *Chamber furnaces*
- *Hood type annealing furnaces*
- *Pot annealing furnaces*
- *Vacuum furnaces*
- *Protective gas furnaces*
- *Bogie hearth furnaces*
- *Roller conveyor furnaces* furnaces)
- *Pull-through type furnaces* (for wire)
- *Special furnaces* (e.g. induction heat treating and hardening plants)

The following is a small selection of different heat treatment furnaces from practice. Figures 6.14 to 6.18 show examples of heat treatment plants for stainless steel semi-finished products.

Fig. 6.14 Bogie hearth furnace for semi-finished rolled products. (Foto: Kopsch, St., BGH Edelstahl Freital GmbH)

Fig. 6.15 Hood type annealing furnace for forged semi-products. (Photo: Kopsch, St., BGH Edelstahl Freital GmbH)

Figure 6.14: Bogie hearth furnace for hardening and tempering, normalizing, solution annealing, diffusion annealing and aging treatment of rolled semi-finished products

Figure 6.15: Hood type annealing furnace for the solution annealing, stress relieving annealing, soft annealing and normalizing of forged semi-products

Figure 6.16: Pot annealing furnaces annealing of drawn wire in coil form.

Figure 6.17: Wire pull-trough type furnace for the recrystallization and solution annealing of drawn wire.

Figure 6.18: Special annealing plant: induction single-rod annealing plant for rolled rods

Figure 6.19 shows modern vacuum hardening facilities for temperatures up to 1250°C and cooling options with nitrogen or helium gas for the hardening of components made of cold and hot work steels, high-speed steels, powder metallurgical steels, as well as corrosion-, acid- and heat-resistant steels and the associated protective gas annealing furnaces, which can also be used for gas nitriding.

Fig. 6.16 Pot annealing furnaces for annealing of drawn wire. (Photo: Schlegel, J., BGH Edelstahl Lugau GmbH)

Fig. 6.17 Wire pull-trough type furnace for the recrystallization and solution annealing of drawn wire. (Photo: Schlegel, J., BGH Edelstahl Lugau GmbH)

Fig. 6.18 Induction single-rod annealing plant for rolled bars. (Photo: Kopsch, St., BGH Edelstahl Freital GmbH)

Fig. 6.19 Vacuum hardening facilities and protective gas annealing furnaces. (Photo: G & M Vacutherm Härterei- und Oberflächentechnik GmbH, Brand-Erbisdorf)

Conclusion

Three conditions are important for setting the steel properties (Liedtke, 2005):

- *chemical composition*
- *processing*
- *heat treatment*

In the process chain of steel product manufacturing, heat treatment is a decisive factor in setting the desired mechanical-technological properties with a certain ratio of strength to toughness and with a defined microstructure.

Almost all heat treatment methods (except stress relieving) lead to a more or less optically visible microstructure change in steel. In addition to determining the mechanical properties, the success of a heat treatment can therefore also be easily determined by means of a microstructure examination. In the following Chap. 7: (*Material Testing*) the metallographic methods are introduced, as well as of course all other material testing methods.

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Material Testing

7

▶ Steel, malleable, solid, highly durable, but also with errors, internal deficiencies, smallest cracks, must be thoroughly tested before a binding decision can be made about its use for a component with a certain requirement profile. Sometimes it is also almost invisible things in the microstructure of the steel, which can have unforeseeable consequences, for example a microcrack in a turbine blade. So checking is in order to limit or exclude damage. The development of material testing in Germany began in the late nineteenth century. It was given a boost in the 20s of the twentieth century with the discussion about the sparing use of scarce resources and about the importance of product quality on the world market.

7.1 Basics

Today, material testing provides reliable data on the condition and properties of the materials: chemical composition, purity, structure, strength, toughness, hardness, corrosion resistance, surface condition, machinability, etc. These data or values are determined under mechanical, chemical and/or thermal stress on standardized samples, on semi-finished products or on finished components. They are indispensable for material selection and for the constructive design, for example of components, machines, vehicles, buildings, for quality control during ongoing production, for the determination of causes in case of damage and also for a targeted improvement or further development of the materials themselves.

J. Schlegel, *The World of Steel*, https://doi.org/10.1007/978-3-658-39733-3_7

The properties of steel are influenced by the following factors:

- *Alloy composition,*
- *metallurgical conditions* (non-metallic inclusions, purity, freedom from defects),
- *Processing technology* (e.g. forming and heat treatment parameters).

In turn, these factors relate to the respective production stages of melting, casting, forming, heat treatment, machining and finishing. Each stage has specific qualitative requirements to be met. The success of quality assurance is determined by means of material testing, from which its outstanding importance becomes apparent.

Quality

Increasing quality requirements, competition, stricter product liability, especially product innovations require the highest level of process-safe quality. Quality is not a coincidence and not only the goal with the end product, but a very complex, controlled, continuous process. Quality is characterized by the "agreement with the requirements", that is with the customer specifications. Thus, quality is also a measurable term.

Quality in production is specified in so-called performance standards (quality plans, customer standards, specifications). These define the permissible deviations. In a wider sense, the quality term deals with:

- *Material properties and product dimensions*
- *Processes for generating quality* (steel production, forming, heat treatment, machining)
- *Processes for determining quality* (material testing)
- *Standards and codes*
- *Application-related criteria*

In order to be able to deliver a flawless product, in addition to the quality-compliant production, the receiving inspection of the raw material, the process-accompanying inspections and the final inspections must be carried out accordingly. Based on this, quality assurance comprises planning (specification of the process and inspection regulations in accordance with the product requirements), production (technology-compliant production of the semi-finished and finished products), the tests to be carried out and finally shipping (Pfeifer & Schmitt, 2010). From the beginning of production to the delivery of the products, the quality level to be observed and specified by the customer is thus established.

With the test certificate the results of the material testing for the material or product to be delivered by the manufacturer are certified in comparison to the customer's specifications:

- *material, product form, dimensions, heat treatment condition,*
- *number of delivered items, weight,*

- *Confirmation of compliance with the customer's order specification or the material specification,*
- *melt batch number, chemical analysis,*
- *mechanical properties,*
- *if applicable, results of ultrasonic, surface and dimensional inspections,*
- *other information agreed with the customer, such as purity, microstructure, surface condition—roughness.*

Material testing—Procedure

▶ Mechanical testing is considered the oldest discipline in materials testing. As early as the fifteenth and sixteenth centuries, *Leonardo da Vinci* (1452–1519) and *Galileo Galilei* (1564–1642) made considerations for determining the bending stress, the elastic behavior, and the strength of materials (Krankenhagen & Laube, 1983). From the eighteenth century, the first testing machines were developed.

The diversity of steels and the different, increasing demands on their load-bearing capacity have led to the development and application of a variety of testing methods that simulate defined, practical stresses. Since the way in which the test is carried out also influences the results, the testing methods, testing equipment, and evaluation methods are mostly standardized. This is the only way to ensure the comparability of results, e.g. between a steel supplier and the processor. Basically, one distinguishes between non-destructive and destructive testing, with destructive testing also including loads over a longer period of time (time-resistance and durability tests, endurance vibration tests, lifetime tests). Figure 7.1 shows a classification of the common testing methods, which are explained in the following sections.

7.2 Destructive Testing

▶ Mechanical and chemical short- and long-term testing require a sample to be taken and, in most cases, an elaborate, standard-compliant production of the test specimen from this sample by machining. For testing, characteristic loads that occur in practice during use are usually simulated in an idealized manner. This eventually leads to damage or destruction of the test specimen. That is why the term "destructive testing" is used.

Tensile and toughness testing occupy a central position in destructive material testing. The mechanical testing methods, which are also divided into static and dynamic methods (test load is applied slowly or quickly, often even abruptly or with changing size and direction), today include:

Destructive test methods

■ **Mechanical test methods**:	- Testing for strength, hardness - Mechanical-technological tests
■ **Physical test methods:**	- Determination of electrical and magnetic properties - Conductivity testing (heat, electricity)
■ **Metallographic test methods:**	- Microstructure examination (purity, grain size) - Thermal analysis - Electron microscopy - Micro-area analysis
■ **Chemical test methods:**	- Chemical composition - Corrosion behaviour

Non-destructive test methods

Detection of surface and core defects by means of:	- X-rays - γ-rays - Ultrasound - Eddy current - Magnetic leakage flux - Inductively excited thermography - Dye penetrant inspection
Further non-destructive tests:	- Leak test - Leak detection - Confusion check

Fig. 7.1 Classification of material testing methods based on Blumenauer (1994)

- Tensile, compressive, bending, torsion tests (static short-term tests)
- Hardness tests (static according to Brinell, Vickers, Rockwell; dynamic: impact hardness and rebound hardness)
- Charpy impact tests (dynamic short-term tests)
- Endurance tests (static long-term test)

In addition, different tests are used in an application-oriented manner, e.g. folding, bending, torsion, deep drawing, machinability tests, tests on pipes, wires and ropes. These test methods are also referred to as technological tests in practice.

The classic test methods tensile test, hardness test and Charpy impact test are explained below.

7.2.1 Tensile Test

▶ Under strength one understands a tension (force related to a certain cross section), which the material can withstand before it deforms plastically or tears permanently. If the force is acting in the tensile direction, one speaks of tensile forces. These are applied e.g. in the tensile test to determine the tensile strength.

Fig. 7.2 Tensile test with sand—test arrangement by *Leonardo da Vinci*. (Redrawing of the original sketch from: Krankenhagen & Laube, 1983)

Leonardo da Vinci (1452–1519) first described an experiment for determining the tensile strength of wire using sand (Krankenhagen & Laube, 1983). Figure 7.2 shows this oldest drawing of a tensile test, a container with sand and a basket that is attached to a wire. This wire is the tensile specimen. Now sand slowly trickles into the basket until the wire breaks. The sand feed is stopped. The tensile force resulting from the weight of the basket now filled with a certain amount of sand divided by the cross-sectional area of the wire specimen results in its tensile strength.

This is also how modern tension testing facilities work. However, the pulling force is applied electrically or servohydraulically, the testing process is automated, and a stress-strain diagram is recorded.

Methods and Parameters

Tensile tests are carried out using elongated, rotationally symmetrical, or flat specimens with a defined geometry. These specimens are clamped vertically and loaded with increasing tensile force. The specimen is then stretched until it breaks. After the tensile force is removed, the elastic deformation and stretching revert. The plastic deformation remains as both a change in length (strain) and a reduction in cross-section (necking). The elongation of the specimen and the changing tensile force are recorded and output as a stress-strain diagram. Figure 7.3 shows such a stress-strain diagram as an example for a well formable, i.e. ductile, steel.

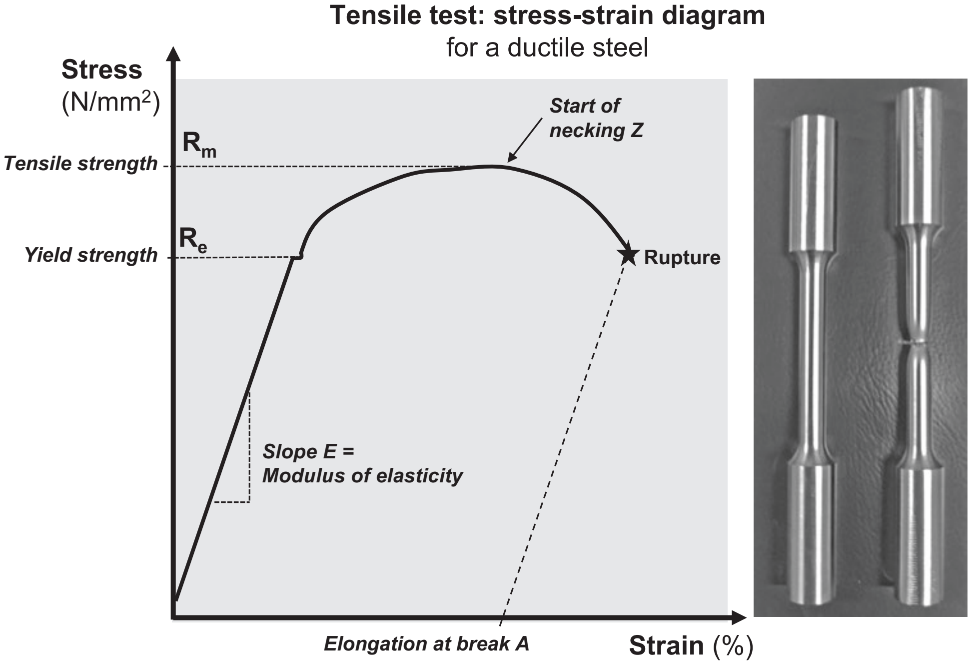


Fig. 7.3 Typical stress-strain diagram for a ductile steel with a pronounced yield point, *right:* corresponding tensile test specimen before and after the tensile test. (Photo: Schlegel, J.)

The following technically relevant parameters for the steel samples examined are derived from the stress-strain diagrams:

- *Yield strength* R_e *(N/mm² = MPa):*
  This is the technical limit of the elastic state. A load beyond that causes a permanent, plastic deformation. Therefore, the yield strength is also the most important parameter for the designer when dimensioning assemblies. In practice, steel alloys do not always have a clearly recognizable yield strength. For these cases, a determination of the tensile strength R_p is carried out, for example, as 0.2-% tensile strength $R_{p0.2}$ for an assumed elongation of 0.2%.
- *Tensile strength* R_m *(N/mm² = MPa):*
  This is the highest tensile force that the sample can just barely hold, based on the cross-sectional area of the sample. Once the tensile strength is exceeded, the sample begins to neck, and it breaks. With the beginning of constriction, the "supportive" cross-sectional area becomes smaller, and thus the "sustainable" tensile stress is lower.
- *Rupture strain A (%):*
  It quantifies the permanent elongation (strain) after rupture.

- *Necking Z (%):*
  This characterizes the cross-sectional reduction at the rupture point and is to be expected above all in ductile steels. Brittle steels do not show plastic behavior, and therefore no necking. They break immediately upon reaching the tensile strength, see Fig. 7.4.
- *Modulus of elasticity E (N/mm^2 = MPa):*
  This proportionality factor (slope) of stress and strain is the measure of resistance against elastic deformation displayed by the steel being tested.

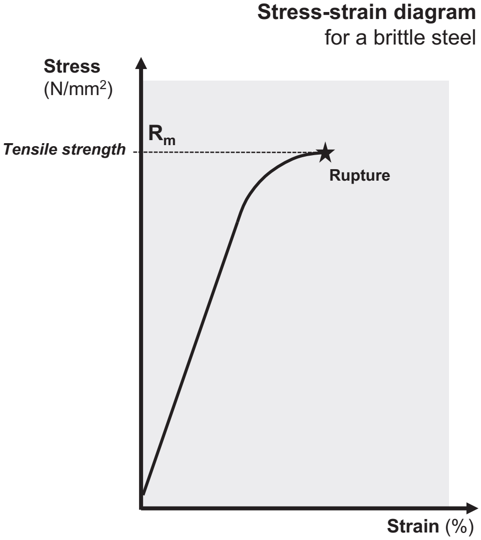
Equipment for Tensile Tests

Modern tensile and universal testing machines, electrically or servohydraulically driven, with computer coupling and X–Y recorder are today's standard. Figure 7.5 shows, for example, the clamping heads on a universal tensile testing machine for flat specimens and Fig. 7.6 a universal tensile testing machine with PC coupling for round wire specimens.

Application

The tensile test is standardized in terms of specimen shape, size and performance and is today the most important, internationally recognized strength test. It can be used anywhere if tensile specimens in wire or rod form or as a flat specimen can be taken from the material to be tested and, if necessary, be produced by additional machining.

Fig. 7.4 Typical stress-strain diagram for a brittle steel



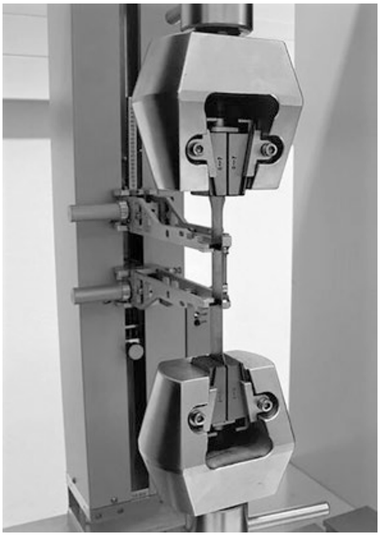


Fig. 7.5 Universal tensile testing machine for flat specimens. (Photo: Kurdewan, T., DHBW Stuttgart)

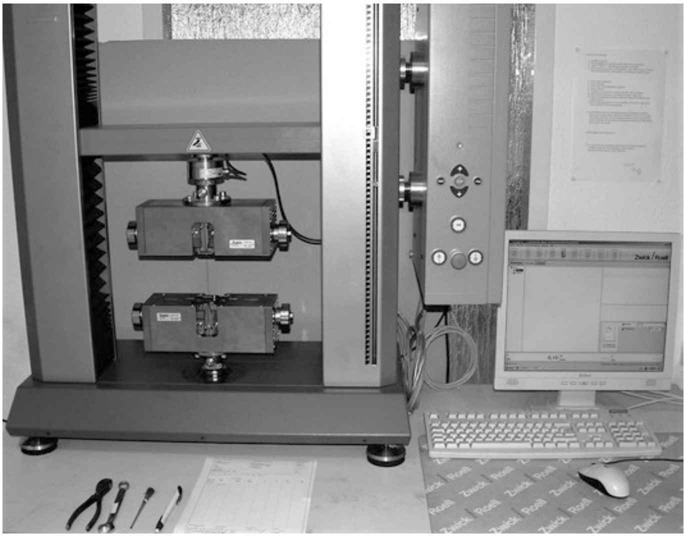


Fig. 7.6 Universal tensile testing machine for fine wire samples. (Photo: Schlegel, J., BGH Edelstahlwerke GmbH)

7.2.2 Hardness Test

▶ Hardness is the mechanical resistance that a body opposes to the penetration of another body. Hardness tests are therefore usually based on statically acting penetration methods. Since there is a fixed relationship between tensile strength, hardness and elongation in metallic materials, conclusions can be drawn about the strength from the hardness values (Eisenkolb, 1958).

Methods and Characteristics

In a hardness test, a standardized, very hard body is pressed into the test specimen under specified conditions with a defined test force:

- *Macro hardness measurement: test force > 50 N*
- *Small load hardness measurement: test force 2 to 50 N*
- *Micro hardness measurement: test force < 2 N*

The smaller the resulting indentation, the higher the hardness of the test specimen.

In practice, different hardness testing methods are used:

Brinell Hardness Test HB

This test method was developed in 1900 by the Swedish engineer *Johan August Brinell* (1849–1925). A hard metal ball with a diameter D is used to generate an indentation in the steel surface. The measured diameter d_1 of the round indentation is the measure for the hardness HB. are today's standard. Figure 7.7 shows this principle of measurement the Brinell hardness test.

Vickers Hardness Test HV

The Vickers hardness test was developed in 1925 and named after the British aircraft company Vickers. For the generation of a permanent indentation, an equilateral diamond cone is used. The hardness HV is determined from the diagonals d_1 and d_2 of the square indentation obtained. Figure 7.8 shows this hardness testing principle according to Vickers.

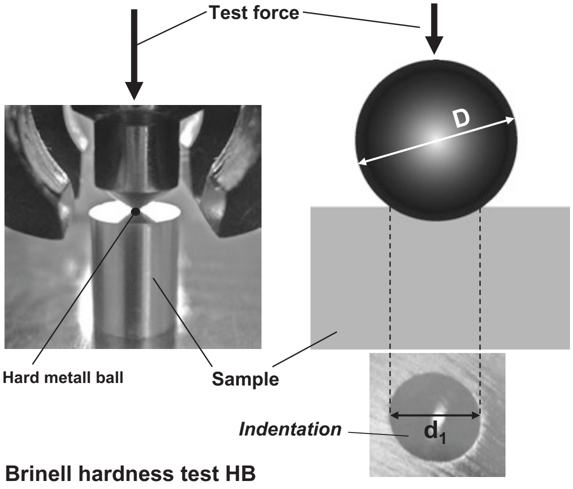


Fig. 7.7 Principle of the hardness test according to Brinell. (Photo: Schlegel, J.)

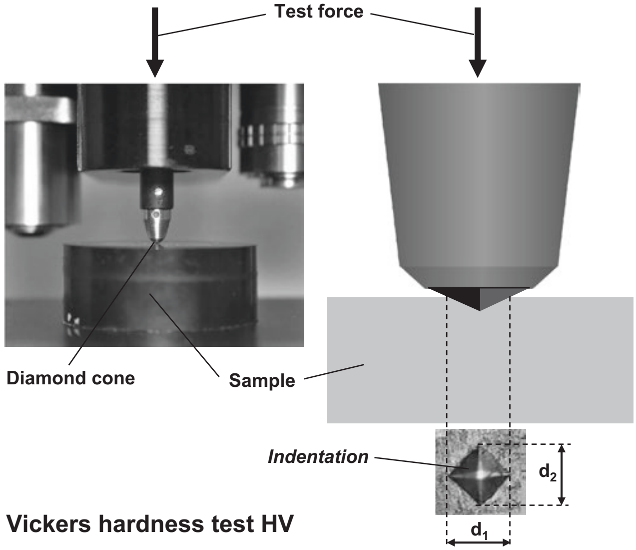


Fig. 7.8 Principle of hardness testing according to Vickers. (Photo: Kurdewan, T., DHBW Stuttgart)

Rockwell Hardness Testing HRB or HRC

As early as 1908, the proposal was made to not measure the size of the permanent indentations, but to use the indentation depth of a diamond cone to assess the hardness of a material. Based on this, Americans *Hugh M. Rockwell* (1890–1957) and *Stanley P. Rockwell* (1886–1940) developed a special hardness testing method which quickly found its way into industry. Depending on the test force and shape of the indenter, the Rockwell hardness test is distinguished by:

- *Rockwell B-method—HRB* (ball)
- *Rockwell C-method—HRC* (cone)

The Rockwell test is simple and quick to perform, but it places high demands on the clamping of the test piece in the testing machine. Figure 7.9 shows the structure of a Rockwell hardness testing machine schematically. First, a low preload is applied in order to exclude any play that may be present in the testing machine due to its plant technology. Then the main load is applied. The depth of penetration can be read from the meter or it is automatically registered. It is important for an exact measurement of the path of the penetrator that the test piece does not yield elastically and that the test force is introduced perpendicular to the surface. With increasing hardness of the material, the depth of indentation decreases (Eisenkolb, 1958).

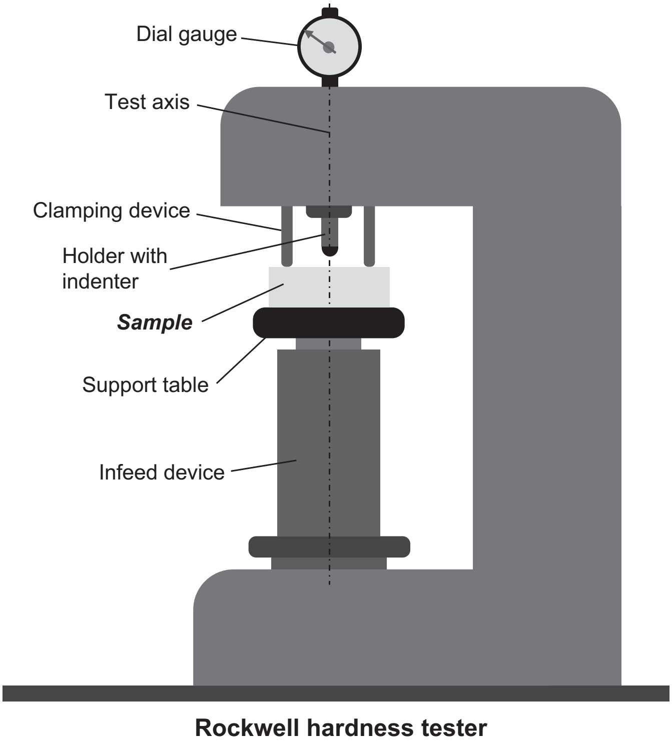


Fig. 7.9 Schematic structure of a Rockwell hardness tester.

Hardness Testing Equipment

For the aforementioned static hardness testing methods, it is characteristic that a permanent indentation is left behind at the test site statically, i.e. without impact. Its generation is standardized and should be easily and quickly achievable in practice. Based on this, stationary hardness testing machines are in use today, which are set up in testing laboratories. Figure 7.10 shows, for example, a classic Brinell hardness testing machine with manual analysis of the indentation displayed on the screen.

In addition to the purely statically acting hardness testing machines according to Brinell, Vickers or Rockwell, devices are also used in practice in which the indentation of the test body takes place abruptly, that is, dynamically plastic. Usually, the hardness test is carried out directly on the test sample (e.g. on a shaft, on a roller or on other shaped parts) on site with a small hammer. Such classical impact hardness testers are the Baumann hammer and the Poldi hammer. In the handy Baumann hammer, a tension is generated by spring force. After the device is placed vertically on the test surface, the tension is released and the spring presses the test ball abruptly into the surface of the

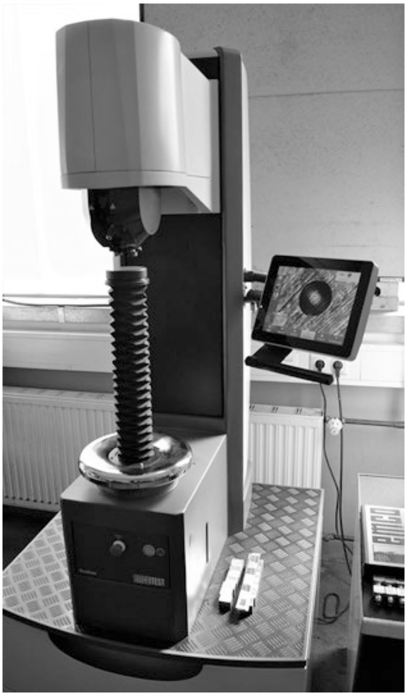


Fig. 7.10 Classic Brinell hardness testing machine in a testing laboratory of a steelworks. (Photo: Schlegel, J., BGH Edelstahlwerke GmbH)

sample. The remaining indentation is measured as in the Brinell hardness test. The Poldi hammer is also particularly handy. For hardness measurement, a rectangular comparison rod is required, which is inserted into an opening of the Poldi hammer between the test ball and the punch. Again, this device is placed vertically on the test surface and struck with a hammer on the punch. The test ball presses into the surface of the comparison rod as well as the test piece. Since the hardness of the test rod is known, the hardness of the material to be tested can be determined from the diameter difference of the indentations by means of a table (Eisenkolb, 1958).

All of these described methods leave a permanent indentation on the test surface, i.e. the plastic deformation of the material is used as a measure of hardness. This may require a sample to be taken from the material to be tested (e.g. a steel semi-finished product), or the hardness test may be carried out mobile directly on the semi-finished product or component to be tested. In contrast, the elastic behaviour of the material to be tested can also be used to assess hardness. For this purpose, a hard steel ball is simply dropped onto the surface. It will now bounce back. The resulting rebound height can be used to infer hardness. The following devices are used for these test methods: the Shore hardness testers with drop hammer principle or the rebound hardness testers according to Leeb, which catapult the impact body onto the sample surface with spring force. Figure 7.11 shows an example of the mobile use of a rebound hardness tester on the surface of a cold roll.

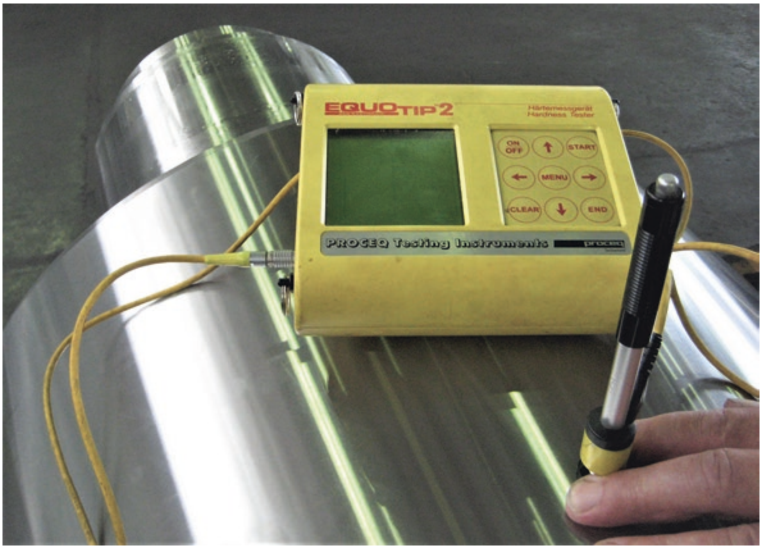


Fig. 7.11 Hardness measurement on the surface of a cold roll using the Leeb rebound method. (Photo: Schlegel, J., BGH Edelstahlwerke GmbH)

Application

Without going into further details of hardness tests, the following orientation can be given for the application of the mentioned hardness test methods in practice:

- ***Brinell hardness test (HB):*** preferably for soft to medium-hard steels,
- ***Vickers hardness test (HV):*** for hard steels, also surface-hardened steels and for microhardness testing to detect individual microstructural components and segregation zones as well as hardness gradients across the cross section (surface to core) of semi-finished products or components,
- ***Rockwell hardness test (HRC):*** simple and fast hardness test, requires careful clamping of the specimen, not suitable for elastically resilient test specimens.

▶ ***Note*** In the practice of the steel world, when dealing with the various hardness testing methods, a comparison of the measured hardness values according to one method with those of other methods is often required, that is, a reevaluation, for example of measured HB values into HRC values. For this purpose, so-called comparison tables were created using a large number of comparative measurements, which, among other things, also allow an estimation of the strength from measured hardness values and vice versa. These tables based on empirical values can be used as a guide.

7.2.3 Charpy Impact Test

▶ In addition to strength and hardness, steels are characterized by very different toughness values or brittleness. However, these properties are not only dependent on the material or the steel grade, but also on the loading conditions during use, such as stress states, deformation rates and temperatures (Hornbogen & Warlimont, 1991). Based on this, the steels must also be tested for their toughness properties under these conditions, which correspond to technical practice (multi-axial and/or impact loading). For this purpose, in 1905 Augustin Georges Albert Charpy (1865–1945) introduced the method named after him, the Charpy test. According to this method, the notch impact toughness can be determined relatively easily and quickly, that is, the ability of the steel to absorb impact energy.

Method (Charpy Test Arrangement)

The name of the test procedure already indicates it: A notched, geometrically defined specimen is placed in a device (pendulum impact device) and fixed by means of abutments at both ends. Figure 7.12 shows this arrangement of specimens with a photo of notched bending specimens before and after the test.

Figure 7.13 illustrates the principle of the Charpy impact test and shows a pendulum impact machine in a material testing laboratory.

If the pendulum hammer falls from a defined height h_1 with a certain kinetic energy E_p (potential work capacity of the pendulum hammer) in a circular shape onto this sample at the lowest point of its fall, this sample is shattered or pulled through the abutment

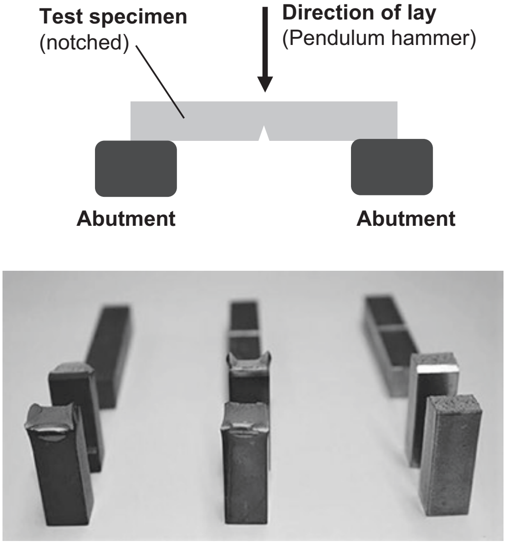


Fig. 7.12 Charpy Impact Test: Test arrangement with notched bending specimens. (Photo: Kurdewan, T., DHBW Stuttgart)

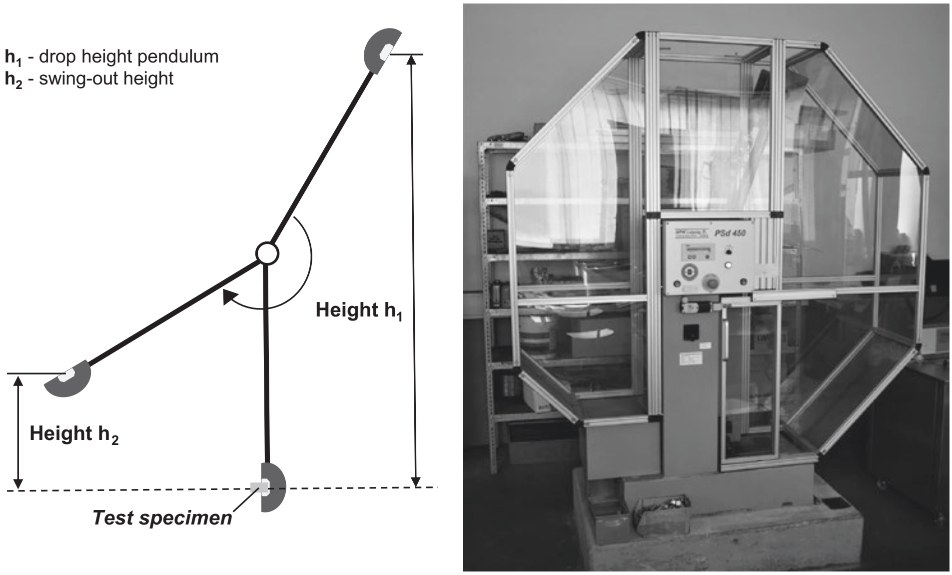


Fig. 7.13 Principle of the Charpy impact test and photo of a pendulum impact machine in a material testing laboratory. (Photo: Schlegel, J., BGH Edelstahlwerke GmbH)

due to deformation processes. At the moment of impact of the hammer on the notched sample, a part of the kinetic energy of the hammer is used up by deformation processes in the sample. With the remaining energy (surplus work E_s), the hammer swings up to a height h_2 (swing-out height), which is of course lower than the original drop height h_1. The amount of fall energy absorbed by the sample is calculated from the comparison of the original drop height with the swing-out height of the hammer:

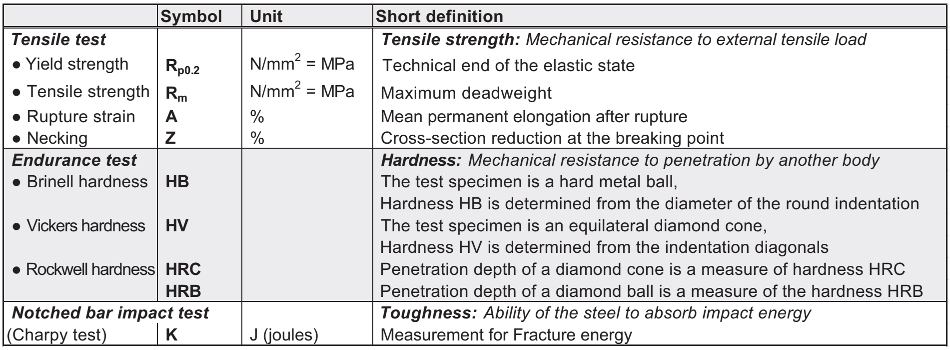
Notch work (fracture energy) $\mathbf{K = E_p - E_s = F\,(h_1 - h_2)}$

E_p = **p**otential work capacity

E_s = **s**urplus work

This value K is the measure for the notch impact work in J (Joule) of the examined steel at a certain temperature. Simply expressed: If the hammer swings out very high, the sample has absorbed only little energy, it is thus very brittle under the given test conditions and has used up little or no energy for the forming work.

It must be noted that the determined values for the notch impact work of a steel are only comparable if these were determined on samples with the same geometry. These geometries with different cross sections as well as round or pointed notches are standardized. The notch impact bending test is a standard procedure in the test laboratories of the steel industry, because the knowledge about the deformation behavior or the toughness properties is important for a comprehensive material assessment and it can also be the selection criterion. For example, a steel component could behave brittle in practice despite best strength values in case of multi-axial loading and low temperatures at the same time and possibly break.



	Symbol	Unit	Short definition
Tensile test			***Tensile strength:*** *Mechanical resistance to external tensile load*
• Yield strength	**$R_{p0.2}$**	N/mm^2 = MPa	Technical end of the elastic state
• Tensile strength	**R_m**	N/mm^2 = MPa	Maximum deadweight
• Rupture strain	**A**	%	Mean permanent elongation after rupture
• Necking	**Z**	%	Cross-section reduction at the breaking point
Endurance test			***Hardness:*** *Mechanical resistance to penetration by another body*
• Brinell hardness	**HB**		The test specimen is a hard metal ball, Hardness HB is determined from the diameter of the round indentation
• Vickers hardness	**HV**		The test specimen is an equilateral diamond cone, Hardness HV is determined from the indentation diagonals
• Rockwell hardness	**HRC**		Penetration depth of a diamond cone is a measure of hardness HRC
	HRB		Penetration depth of a diamond ball is a measure of the hardness HRB
Notched bar impact test			***Toughness:*** *Ability of the steel to absorb impact energy*
(Charpy test)	**K**	J (joules)	Measurement for Fracture energy

Fig. 7.14 Overview of the most important mechanical test methods

Note

In summary, Fig. 7.14 shows an overview of the most important mechanical test methods described, with brief definitions and the characteristic values that can be tested.

In addition to these mechanical testing methods, metallographic, physical and chemical methods are also included in destructive materials testing. In particular, the chemical analysis of steel is the most important method for process control in the steel mill, as well as in conjunction with the metallography for clarifying material behavior and determining the cause of damage cases.

7.2.4 Analysis Methods for Steel

The first historical mention of the determination of the content of a metallic alloy (chemical composition) was the verification of the gold content of the crown of the then ruler, King of Syracuse, *Hieron II.* (around 306-215 BC), by *Archimedes.* A legend tells of *Archimedes of Syracuse* (287-212 BC), the famous Greek mathematician, physicist and engineer of antiquity, that he once got out of the bathtub naked and thus also ran through the streets of his hometown Syracuse (Sicily). He kept shouting: *"Heureka—I found it!"* He had discovered the principle of buoyancy of bodies in water while bathing. Figure 7.15 shows a historical graphic of *Archimedes* in the bathtub. He used this principle of buoyancy to determine the gold content of *Hieron II.'s* crown non-destructively. By the way, he also found that the crown displaced more water than a gold bar of the same weight. The goldsmith had added cheaper silver of lower density to the gold.

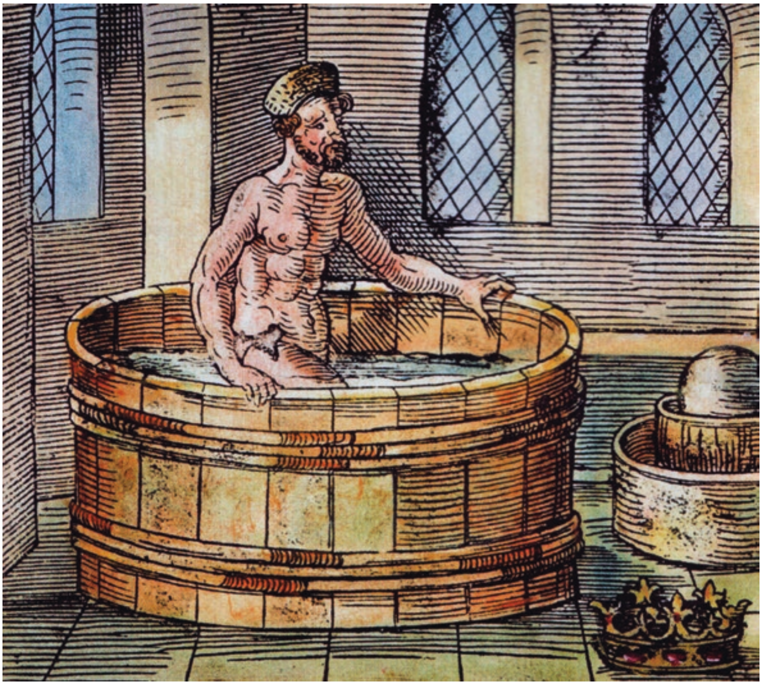


Fig. 7.15 Archimedes discovers buoyancy, sixteenth century illustration. (From the internet: https://de.wiktionary.org/wiki/Archimedes#/media/Datei:Archimedes_bain.jpg)

The composition of a steel alloy can today be examined either chemically or spectrally. Up to 1950, the time- and material-intensive wet chemical analysis dominated. Afterwards, various and today almost unmanageable methods of instrumental chemical analysis based on physical measurement principles (e.g. X-ray fluorescence analysis and optical emission spectroscopy) emerged. When using them, the tasks of a steelworks laboratory (timely, fast and highly accurate determination of all chemical elements of the steel melt for process safety) and those of quality assurance (exclusion of a material mix-up) must be distinguished.

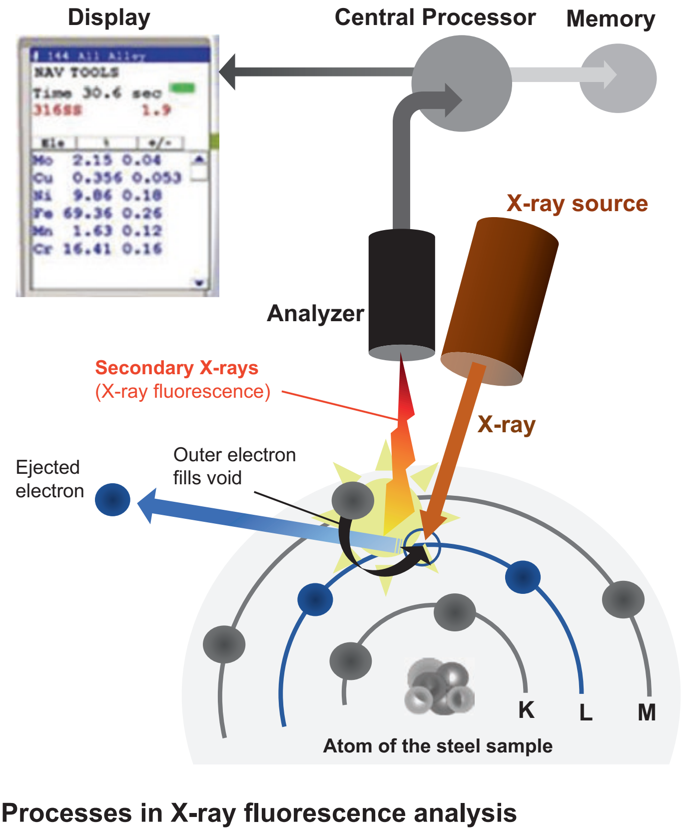
The following analytical methods X-ray fluorescence analysis (XRF), optical emission spectrometry (OES) and combustion analysis are introduced.

7.2.4.1 X-Ray Fluorescence Analysis

Method

In **X**-**r**ay **F**luorescence Analysis (**XRF**) a primary X-ray radiation emitted from an X-ray tube hits the sample to be analyzed. As a result, secondary X-ray radiation is emitted from the sample, which is characteristic in individual components for the chemical composition of the sample. This process is based on the physical law of atomic structure. A chemical element is characterized by an atom with the atomic nucleus, which has a corresponding number of protons and neutrons, and by the surrounding shell with an identical number of electrons. The shell is divided into different shells or energy levels, which are characterized from the inside out by K, L, M, etc. K is the closest shell to the nucleus and has the lowest energy (Demtröder, 2005).

If X-rays now strike an atom of an element, an electron is removed from a shell close to the nucleus (emitted). Another electron from a higher energy shell now goes over to the lower lying shell and fills the resulting gap. The resulting energy difference leads to the emission of a secondary X-ray radiation characteristic to the chemical element, which is referred to as “X-ray fluorescence”. The wavelengths and intensities of this X-ray radiation are detected and evaluated by a computer controlled analyzer. The alloy elements determined in this way and their percentage proportions can then be read off directly on the screen of the XRF device, as shown schematically in Fig. 7.16.



```
# 144 All Alloy
NAV TOOLS
Time 30.6 sec
316SS          1.9

Ele  %     +/-
Mo   2.15  0.04
Cu   0.356 0.053
Ni   9.06  0.18
Fe  69.36  0.26
Mn   1.63  0.12
Cr  16.41  0.16
```

Fig. 7.16 Schematic representation of the processes in X-ray fluorescence analysis. (Graphic from: analyticon instruments gmbh, Rosbach v. d. Höhe)

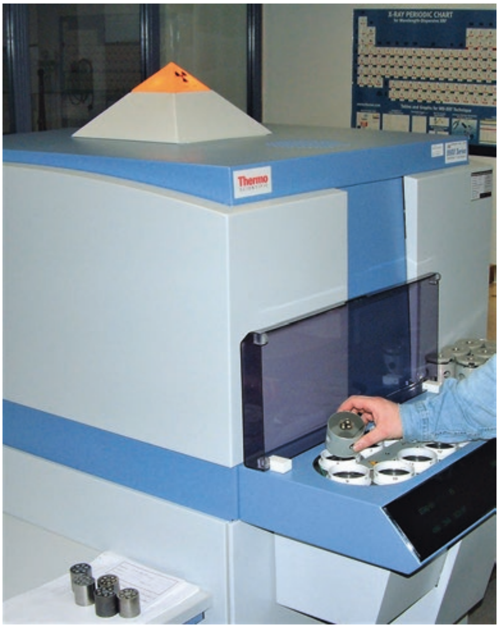


Fig. 7.17 Example of a fully automated XRF device in a steelworks laboratory. (Photo: Schlegel J., BGH Edelstahl Freital GmbH)

Equipment

Fully automated XRF devices are used in steelworks laboratories. Figure 7.17 shows an example of such a device with automated sample feeding.

Mobile, handheld XRF devices are used for quick analysis of steel samples, including scrap. Figure 7.18 shows such a mobile XRF device.

Application

RFA analysis is particularly suitable for the determination of alloying elements with high atomic weights. Lighter elements absorb X-rays too strongly (Hahn-Weinheimer et al., 2000). Based on this, in the steel industry the RFA method is used for high-alloy steels and special alloys such as titanium, cobalt and nickel base alloys in order to ensure high accuracy of the chemical analysis (Erhardt, 1988).

7.2.4.2 Optical Emission Spectrometry

Procedure

The basis of optical emission spectrometry (OES), also called atomic emission spectrometry (AES) or flame spectroscopy, is the following physical phenomenon: When energy is supplied to an atom, some of the electrons of this atom change their orbits. The energy supply can be carried out by means of an arc (spark spectrometer), with a flame or with a plasma. If the excited electrons return to their original orbit, a defined energy is emitted in the form of light of a certain wavelength. Therefore, a sample containing several

Fig. 7.18 Mobile, handheld X-ray fluorescence analysis (XRF) device. (Photo: Kurdewan, T., DHBW Stuttgart)

different elements produces light consisting of the wavelengths of each of these elements. By separating these wavelengths by means of a diffraction system, it can be determined which elements are present. The intensity of each wavelength is a function of the concentration of each element. These light intensities are measured, and a computer processes this information through stored calibration curves. The content of the alloy elements present in the sample can then be read directly in percent on the screen.

Equipment

Powerful, mostly fully automatic OES spark spectrometers or flame photometers are used in materials testing laboratories in the steel industry. Rugged, mobile OES spark spectrometers are mostly used on site in production, finishing and shipping for testing for mixed-up components and in the laboratory for rapid analysis. Figure 7.19 shows the use of a handheld spark spectrometer to identity checks (avoidance of material mix up) in the finishing of flat steel semi-finished products.

An example of the use of a spark spectrometer for the rapid analysis of different materials in a laboratory of a university is shown in Fig. 7.20.

Application

Optical emission spectrometry OES is used for the accurate determination of alloying and trace elements (trace analysis) with low atomic weights. Like the XRF analysis for low and high alloy steels, it is a fast and reliable analysis method.

Fig. 7.19 Use of a handheld spark spectrometer for checking for dentity checks during finishing. (Photo: BGH Polska Sp. z. o. o., Katowice)

> ▶ For routine production control in steelworks and further processing plants as well as in industrial research, other analytical methods are used in addition to the XRF and OES methods. These include, for example, the standardized methods of combustion analysis for the determination of carbon and sulfur, and the carrier hot gas extraction for the analysis of gaseous elements in steel, such as nitrogen, hydrogen and oxygen. These two analytical methods are also to be presented below.

7.2.4.3 Combustion Analysis

In combustion analysis, solid samples are burned or melted under oxygen or under a carrier gas. One can distinguish between combustion analysis for the determination of the non-metallic elements carbon and sulfur as well as combustion analysis with a carrier gas (carrier gas hot extraction) for the measurement of the nitrogen, hydrogen and oxygen.

Carbon-Sulfur Combustion Analysis

Procedure

The determination of the non-metallic elements carbon and sulfur in steel is carried out by combustion of steel chips in an induction furnace under oxygen flow. The weighing in of the sample quantities up to approx. 1000 mg with possible addition of additives is carried out in ceramic crucibles. During combustion, CO_2 and SO_2 are formed, from which even small amounts of carbon and sulfur can be determined by infrared absorption. The

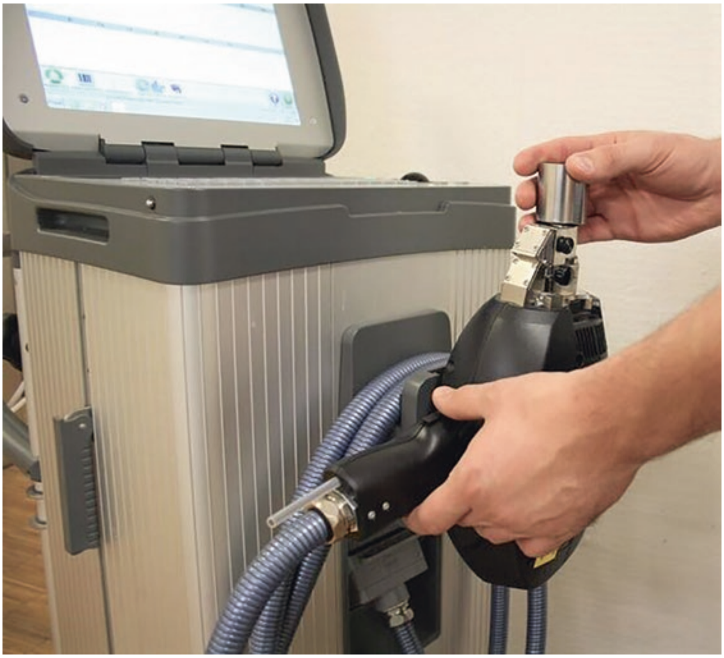


Fig. 7.20 Spark spectrometer for rapid analysis in a laboratory of a university. (Photo: Kurdewan, T., DHBW Stuttgart)

combustion, the analysis of the gas stream and the output of the results are carried out automatically. Figure 7.21 shows such a carbon-sulfur combustion analyzer in a steelworks laboratory.

Carrier gas hot extraction

Procedure

In the **c**arrier **g**as **h**ot **e**xtraction (CGHE) the analyzers work with a carrier gas, usually helium. In a graphite crucible, the samples are weighed up to about 5 g in the form of chips, powder or compact pieces. These are then inductively heated to very high temperatures up to 2700°C and melted. Depending on the gas content of the samples, gas streams are formed, the compositions of which are analyzed with respect to the elements nitrogen, hydrogen and oxygen. The sample preparation and measurement are also standardized for this process.

Equipment

Carbon-sulfur combustion analyzers can be found in labs, are designed for high temperature ranges and ensure precise measurement within seconds. As the name implies, carbon-sulfur combustion analyzers are used exclusively for the rapid determination of carbon and sulfur in

Fig. 7.21 Carbon-sulfur combustion analyzer in a steelworks laboratory. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

steel alloys. In addition, devices for the determination of the content of the gaseous elements nitrogen, hydrogen and oxygen utilising the method of carrier gas hot extraction are used.

▶ **Note**

In the practice of steel production, a distinction is made between the melt analysis and the piece analysis. These terms refer to the different sampling:

- *Melt analysis:*
  The sample is taken directly from the liquid melt in the laddle before casting (with a spoon or a dipping tube).
- *Piece analysis:*
  The steel sample is taken from a solid ingot, often also formed solid piece, e.g. casting ingot or semi-finished product.

Using the described analysis methods and the destructive testing methods, all data on the chemical composition and the mechanical-technological properties of a steel product are now available. However, a qualitative and quantitative description of the mostly invisible microstructures, as diverse and complex as they are, is also necessary in order to design the further manufacturing technology and to obtain a quality final product. This is now the task of metallography, and we will focus on the many non-destructive testing methods.

7.2.5 Metallography

▶ Metallography is the study of the microstructure of metals. Its purpose is to capture complex spatial structures of steel and to describe the microstructure both qualitatively and quantitatively. Obviously, this requires tools such as microscopes. The first useful microscopes appeared in the early seventeenth century. Then, in 1877, *Adolf Martens* (1850–1914) began targeted microscopic examinations of steel and iron. Today, optical microscopes are used for qualitative and quantitative evaluation of steel microstructures, as well as electron microscopes, such as scanning and transmission electron microscopes.

Procedure

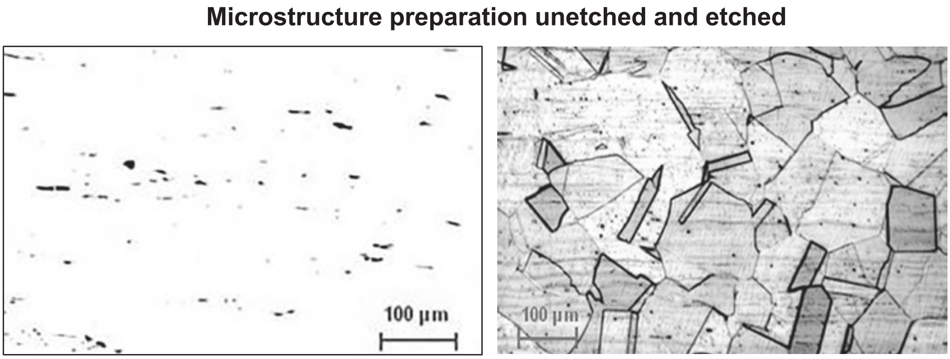
In order to make the microstructure of a steel sample visible using a microscope, the sample must be prepared. For this purpose, a cut is made along or across the sample and a representative, sharp-edged microsection is generated. During this sample preparation, the microstructure must not be changed by deformations, temperature influences, smears, breakouts or scratches. Figure 7.22 shows an example of a cross-section of steel wire sections, embedded in epoxy resin, finely ground and polished.

After grinding and polishing, dark spots can already be seen in the basic mass of the steel:

- *non-metallic inclusions, slag,*
- *pores, gas bubbles, blow holes,*
- *material separations and cracks.*

To contrast the structure (grain boundaries, phases), the specimen is etched. Depending on the steel quality and the test objective, different media (acids, alkalis, neutral solu-

Fig. 7.22 Cross-section specimen of steel wires embedded in epoxy resin. (Photo: Schlegel, J., BGH Edelstahl Lugau GmbH)



1.4305 – X8CrNiS18-9, longitudinal microsection unetched

1.4301 – X5CrNi18-10, longitudinal microsection etched

Fig. 7.23 Longitudinal microsections of austenitic steels, *left:* unetched, *right:* etched. (Micrographs: BGH Edelstahl Lugau GmbH)

tions, salt melts, etc.) are used. There is a distinction between grain boundary etching and grain surface etching. Figure 7.23 shows a comparison of the unetched and etched structures. In the unetched longitudinal microsection of steel 1.4305 - X8CrNiS18-9, the sulfide lines are clearly visible. In the etched longitudinal microsection of steel 1.4301 - X5CrNi18-10, on the other hand, the grain boundaries are highlighted.

Application

Metallographic examinations are usually carried out by means of macroscopy and microscopy.

Macroscopy

The observation is carried out with the naked eye or by means of reflected light stereomicroscopy at magnifications up to 50-fold. It serves to assess surfaces and fracture surfaces for overview purposes. Figure 7.24 shows, as an example, a classical transmitted light stereomicroscope with the recording of a surface section of a drawn bar made of 1.4718 - X45CrSi9-3. This bar sample shows, after hardening, a broken shell.

Microscopy

Microscopy means a microstructure examination with bright-field microscopes at magnifications up to 1000x. It is used to make phases, grain structure, grain boundaries and -sizes, impurities, voids, pores, cracks, etc. visible and to assess the heat treatment condition and the purity. Microscopy is also used to draw conclusions about the manufacturing process and error causes. An example of a modern bright-field microscope with computer-aided image analysis is shown in Fig. 7.25.

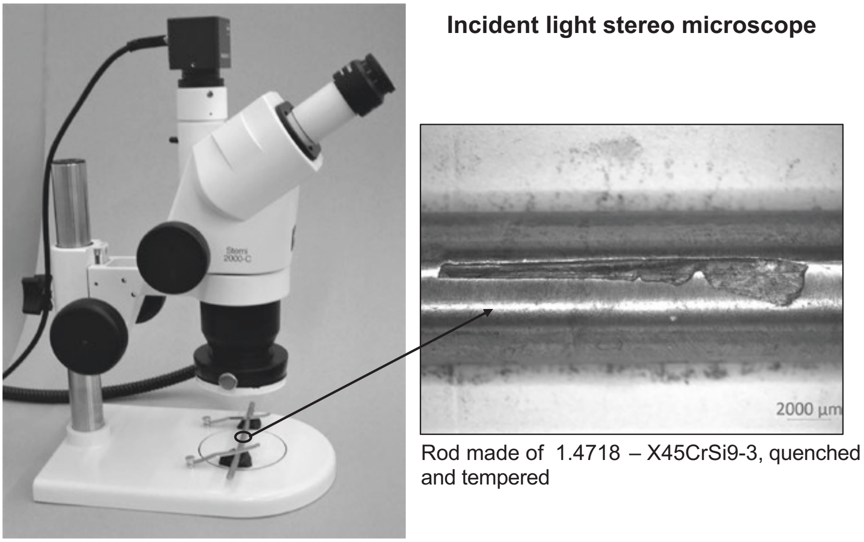


Fig. 7.24 Classic reflected light stereomicroscope with a recording of a surface section of a coated bar made of 1.4718 - X45CrSi9-3. (Photos: BGH Edelstahl Lugau GmbH)

Fig. 7.25 Bright-field microscope with computer-aided image analysis in a research laboratory. (Photo: Kurdewan, T., DHBW Stuttgart)

▶ Metallography, as a discipline of metallurgy, serves quality assurance, failure analysis and research and development. In addition to the classical steels, composite materials and new materials have to be metallographically examined more and more. Therefore, today the term materialography is often used instead of metallography.

7.3 Non-Destructive Testing

▶ Non-destructive testing (NDT) offers the advantage of being able to examine semi-finished products or components in the finished state and without damage, usually also automated. It is not necessary to remove samples and then to load them during the test until they break and destroy them.

Only in the last ninety years have methods for nondestructive testing been developed. They are used to detect surface and core defects using X-rays, radioactive rays, ultrasound, or magnetic flux. In addition, optical testing methods, partly with digital image processing, are gaining importance, taking into account the different surface conditions. Laser and holographic testing, acoustic emission testing, leak testing, microwave testing, and thermography are also used as very accurate, repeatable, and correlating nondestructive inspections to ensure the safety of components, structures, and machines during their use.

The following section presents the ultrasonic and eddy current testing methods primarily used for material testing of steel products, as well as the color penetration test. Finally, the visual and dimensional inspections used in production for manufacturing and acceptance testing are also mentioned.

7.3.1 Ultrasonic Testing

▶ With ultrasound (US) internal errors or irregularities can be examined in steel as in medicine (sonography). These internal defects or core defects and also near-edge defects (closed defects under the surface) have arisen metallurgically during steel production, the forming processes and during cooling processes. They comprise non-metallic inclusions such as slag particles, desoxidation products, cracks, core disaggregations, miscellaneous cavities, and similar defects..

Procedure

Ultrasound is sound waves with frequencies from 16 kHz, i.e. sound waves above the hearing range of humans (Beitz & Jarecki, 2013). They can be generated by piezoelectric ceramics under reversal of the piezoelectric effect. For this purpose, the ceramic is excited by applying an alternating voltage, causing vibrations and thus the emission of ultrasound. Ultrasound spreads directed like light. The reflection of sound waves at interfaces as well as the attenuation, i.e. the shading by an error, are used for error detection. This is done as follows:

The surface of the metallic test body is wetted with a coupling agent (e.g. gel, water or oil) and scanned with a test head that emits ultrasound. Internal interfaces (e.g. at a cavity, inclusion, crack) reflect the sound pulse differently than error-free material. After previous adjustment, the position and size of the error can be estimated from the echo.

The variants through-transmission and pulse-echo method are distinguished.

Through-transmission

In this US test method, a transmitter and a receiver opposite the material to be tested are used. Figure 7.26 shows this principle of through-transmission.

Pulse-Echo Method

A transducer serves as both a transmitter and a receiver. Figure 7.27 shows the principle of this pulse-echo method.

Equipment

Both testing methods can be used manually on individual products (parts), on rolled or forged semi-finished products, or also automatically in a production line on long products (e.g. bars, forged, rolled, round, raw, blasted, peeled or ground, polished). The US testing conditions such as scope of testing, scanning speed, scanning direction, requirements for the test body, geometry of the comparison bodies, adaptation of the testing heads, impact angle, sensitivity setting, determination of the sound path, etc. are standardized.

Manual US Testing

Figure 7.28 shows an example from practice, the manual ultrasonic testing of a rolled flat semi-finished product. The testing is carried out using the pulse-echo method. This

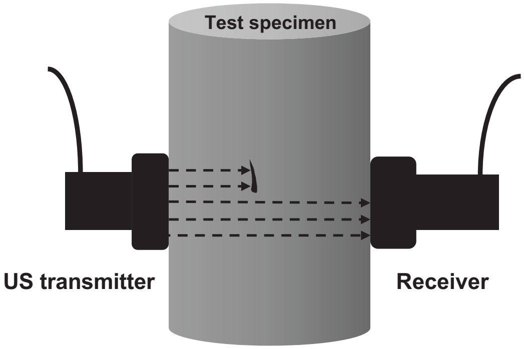


Fig. 7.26 Principle of the US test method through-transmission

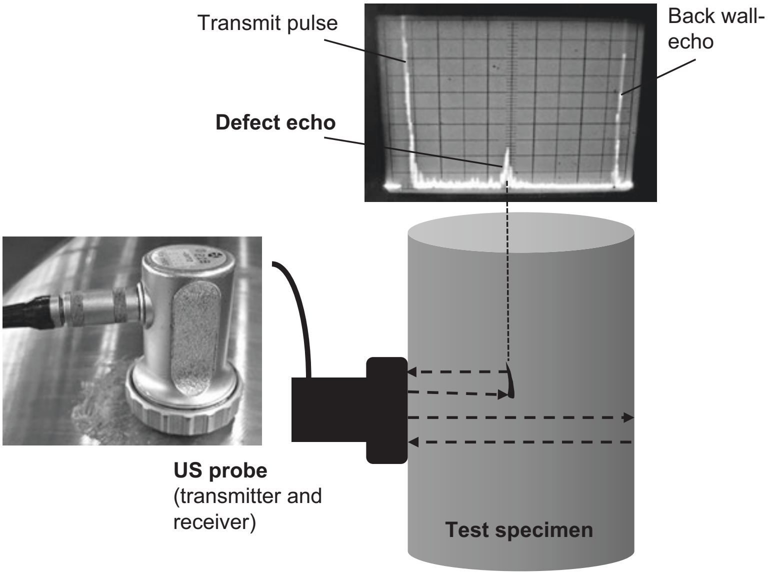


Fig. 7.27 Principle of the US testing according to the pulse-echo method. (Photos: Schlegel, J., BGH Edelstahl Lugau GmbH)

Fig. 7.28 US testing of rolled steel flat semi-finished product according to the pulse-echo method. (Photo: BGH Polska Sp. z. o. o., Katowice)

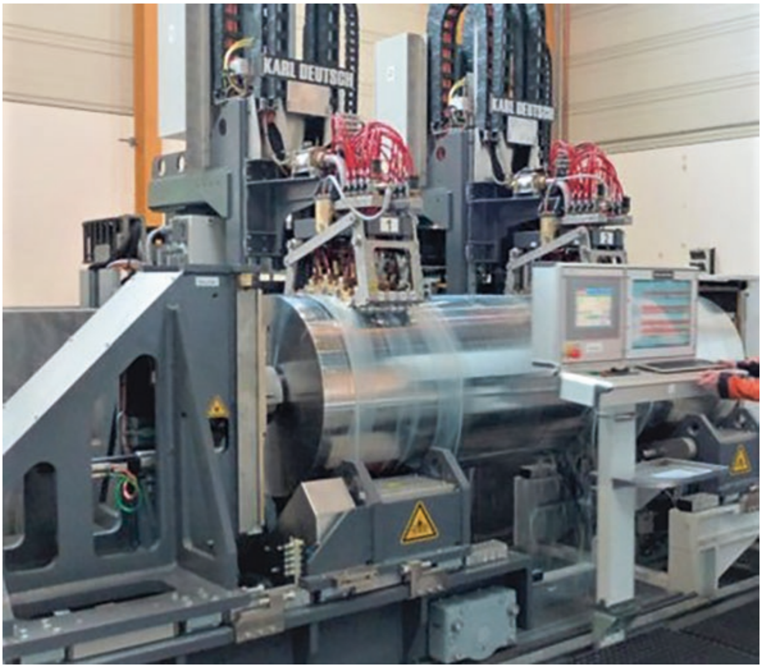


Fig. 7.29 Fully automated ultrasonic inspection system for round bars Ø 300 to 1000 mm. (Photo: BGH Edelstahl Siegen GmbH)

method has proven itself in the steel industry for testing for internal defects, in particular in rolled and forged semi-finished products and machined forgings.

Discontinuous, Automated US Inspection

With modern, automatically working US inspection systems, larger forged and machined, peeled or turned round parts are inspected. Figure 7.29 shows, as an example from practice, a fully automated US inspection system for round semi-finished products made of stainless steel in the diameter range 300 to 1000 mm.

Continuous, Automated Passage US Testing

With modern continuous testing facilities, for example, semi-finished products can be US-tested today with diameters of 10 mm up to more than 400 mm. Figure 7.30 shows a fully-automatic passage US testing facility for stainless steel semi-finished products with diameters of 100 to 400 mm and individual lengths of up to 18 m.

US testing facilities are also used for other product groups, such as square rods, sheets, plates, strips, pipes, solid and hollow shafts. These testing devices often use robot systems and various linear techniques to step-by-step scan the test body volumes. The automated passage US testing facilities are mostly equipped with probes that work according to the “phased-array technique”. This means that instead of a single probe, which acts as

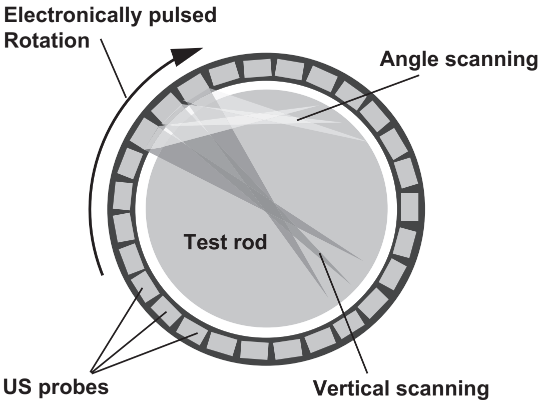
Fig. 7.30 Control panel of a fully-automatic US continuous passage testing facility for forged and peeled semi-finished products with a diameter of 100 to 400 mm. (Photo: BGH Edelstahl Siegen GmbH)

both transmitter and receiver, rotating around the rod-shaped test body, many probes are arranged in a fixed ring shape around the test bar. They are individually electronically activated so that a radial ultrasound scan is created via a grouped stepping process. This makes it possible to scan vertically and at an angle at the same time. With this electronically induced rotation of the sound beam, there is no mechanical rotation of the probes. Thus, in comparison to conventional ultrasound testing equipment, there is no wear of moving parts. Figure 7.31 shows, for understanding, a simplified principle representation of the phased-array technique, the so-called “pulsed ultrasound”. By the way, this US testing technique was derived from medical diagnostics and used for the first time in the steel industry about 30 years ago in pipe testing.

Application

The key question for the application of suitable US testing techniques is which errors can be detected and where the detection limits lie. Generally, core defects, near-edge non-metallic inclusions, pores and welded seams, i.e. internal defects that do not have to be open to the surface (but can be) are able to be detected by ultrasound. The position of the error and the direction of sound are decisive for the safe detection of a defect. Figure 7.32 shows typical defect positions, for example in a bar.

Fig. 7.31 Principle of the Phased-Array-Technique for US-testing of bars



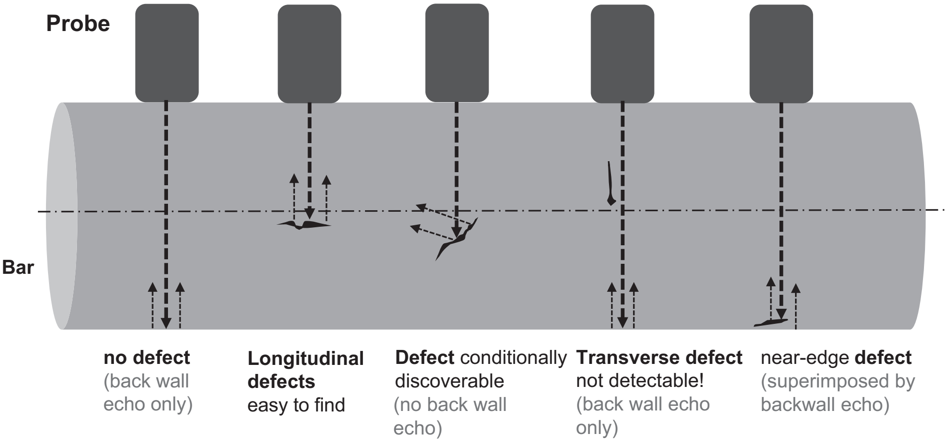
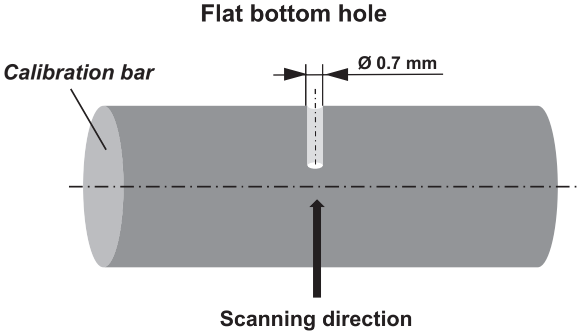


Fig. 7.32 Typical defect positions in a bar and their detectability in US testing

The US test is a comparative test. Therefore, the sensitivity of the system must be adjusted with so-called calibration or comparison bodies. These have similar acoustic properties and dimensions as the material to be tested. And they have defined, artificially generated errors in the form of small holes, cross holes, flat bottom holes or grooves. Their geometry such as diameter, depth and position are used to adjust the sensitivity. Figure 7.33 shows, for example, a calibration bar with a flat bottom hole with a diameter of 0.7 mm. This flat bottom hole (FBH) is referred to as a circular disk reflector (in the example with a diameter 0.7 mm) and indicates the defect size or sorting threshold of the now calibrated US testing system.

Fig. 7.33 Calibration bar with an artificial defect as a flat bottom hole with 0.7 mm diameter, suitable for the adjustment of automated passage US testing machines



In the practice of US testing, the smallest detectable defect sizes depend on the:

- *Heat treatment and microstructure*
- *Degree of deformation*
- *Surface condition*
- *Material* (sound attenuation is dependent on the chemical composition of the steel)

It should be noted that, due to the process, the ends of the bars are not testable.

Based on the current state of the art of US testing facilities, for example, the following minimum detectable defect sizes can be mentioned for bars under ideal testing conditions:

- *Bar Ø 10 to 30 mm: FBH 0.7*
- *Bar Ø 30 to 150 mm: FBH 1.0*
- *Bar Ø 150 to 400 mm: FBH 2.0*
- *Bar Ø 400 to 1000 mm: FBH 3.0*

For "black", that is oxidized semi-finished product, raw and rolled, a poorer coupling of the ultrasound is to be expected. This results in higher sound losses, and it is to be expected that the core defects will be less detectable. Currently, bars with a smallest diameter of approx. 8 to 10 mm can be tested. Development regarding the testing accuracy for smaller bar diameters in dependence on the surface quality (peeled, ground) is ongoing in different bright steel manufacturing companies.

7.3.2 Eddy Current Testing

▶ Eddy current is used to test for surface defects. In semi-finished steel products and components these comprise near-edge defects open to the surface that originate from the raw material, during forming, during heat treatment, during surface treatment, during machining, and possibly during storage and transport, i.e. local, crack- or hole-like defects such as cracks, tears, rolling, forging and drawing defects, other mechanical damage such as scratches, grinding furrows, etc.

Procedure

The eddy current testing is a classical electrical method for non-destructive material testing. It works for all electrically conductive materials. With a coil, an alternating magnetic field is generated. This induces a ring-shaped current flow (eddy current) in the test body without contact. Its density is influenced by existing defects (cracks) or "disturbed". With a second coil, this disturbance is registered and the defect is detected. The eddy current testing methodology can also be used for testing for mixed-up components, which, plant-specifically, is carried out as a sorting test of parts or often simultaneously next to the eddy current testing in automated in-line testing systems for long products. In addition, the test body is magnetized. In comparison to a reference sample, electrical and magnetic values, which depend on the hardness, the microstructure and the alloying constituents of the test body, are determined. If these values match those of the reference sample, there is no material mix-up.

This magnetically inductive testing method is also used for layer thickness measurement, for example of paint on sheets and strips.

Equipment

There is a variety of equipment for eddy current testing, both mobile units as well as stationary, automated, contactless production line testing facilities. The following is an example of how an eddy current testing facility for semi-finished products, e.g. round bars, works. With these facilities, three tests can be carried out in succession along a line on the running semi-finished product, e.g. round bars.

Eddy Current Testing for Transverse Cracks

This test is carried out using a stationary, feed-through coil that surrounds the test object. Figure 7.34 shows such a test arrangement schematically.

Eddy Current Testing for Longitudinal Cracks

This test is carried out using a rotating coil consisting of the exciter and receiver coils, see Fig. 7.35.

Magnetic Induction Mix-up Test

For this test, also referred to as Magnatest, a special fixed feed-through coil is installed in the automatic continuous feed-through testing machine (Magnatest).

Figure 7.36 shows these three mentioned testing methods, combined in line, using an example of an automatic eddy current feed-through testing machine for brigth bars.

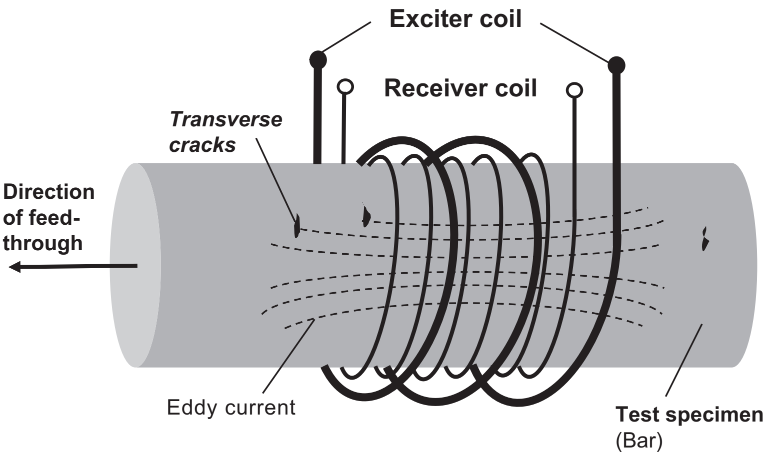


Fig. 7.34 Eddy current testing of transverse cracks using a stationary feed-through coil. (Graphic based on: Defectomat Institut Dr. Foerster GmbH u. Co. KG)

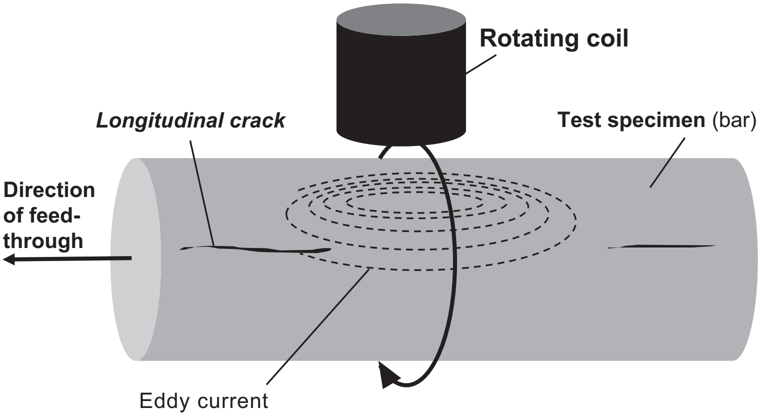


Fig. 7.35 Eddy current testing for longitudinal cracks using a rotating coil (probe). (Graphic based on: Circograph, Institut Dr. Foerster GmbH u. Co. KG)

Application

The eddy current method is generally suitable for all electrically conductive materials for surface crack and mix-up components testing, for testing the heat treatment condition and for layer thickness measurements.

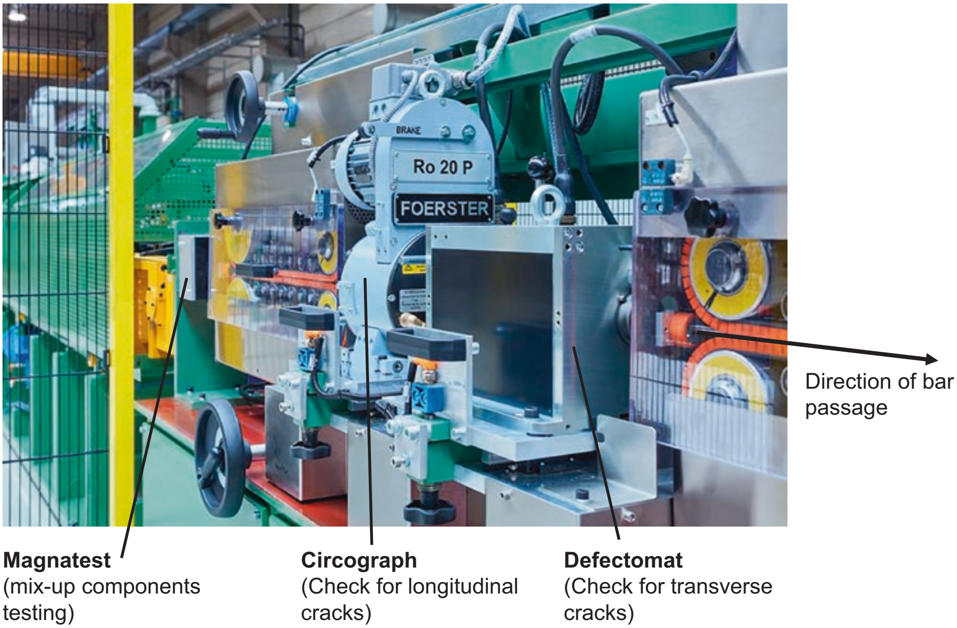


Fig. 7.36 Automatic eddy current feed-through testing machine for brigth bars. (Photo: Schlegel, J., BGH Edelstahl Lugau GmbH)

For surface crack testing, the defect detectability is dependent on the surface condition. Many smaller defects may be detected as a single defect. Therefore, the surface roughness (e.g. peeled, ground, polished for rods) has a great influence. Figure 7.37 shows, in a simplified manner, the defect detectability in eddy current testing of round stock in a pass. Defects that are open perpendicularly to the surface and do not or only barely run parallel to the surface are detected. Closed defects under the surface are not detected. Figure 7.37 shows examples of two extreme crack courses which illustrate the detectability of cracks. The left-hand crack shown, which runs almost perpendicular, is very well detectable with a depth of > 0.1 mm. The right-hand crack shown is not or only barely detectable because of the very small entry angle.

For the detection limits, i.e. the smallest crack depths that can be detected by eddy current testing depending on the surface conditions of the long products to be tested (round bars), the following limit values, as determined by the process, can be assumed:

- ***Crack depth > 0,1 mm:***
  Bars drawn, straightened, polished, Bars peeled, polished, Bars ground
- ***Crack depth > 0,2 mm:***
  Bars drawn, straightened

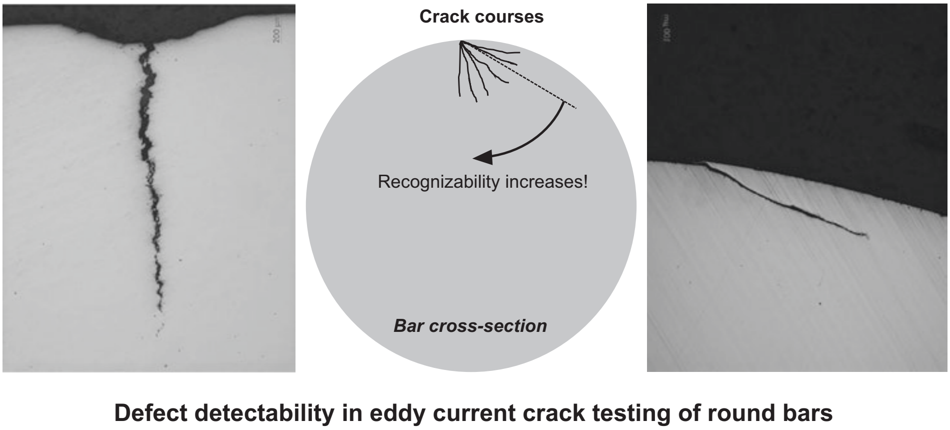


Fig. 7.37 Detectability in eddy current testing of bars. (Micrographs: BGH Edelstahl Lugau GmbH)

The straightness of the bars to be tested in the test line must be observed. This should usually be ≤ 1 mm/m. In addition, the ends of the bars cannot be tested for a length of up to 30 mm in eddy current testing.

Note

For the practice of bright steel production, it is recommended to always use the term "eddy current testing" in connection with the surface quality class according to DIN EN 10277-1:2008-06. This standard includes the technical delivery conditions for bright steel products. It takes into account that the test methods cannot always reliably detect all errors to 100% due to physical laws and conditions of use in practice. Based on this, a percentage of the delivery weight is allowed to contain defects above the specified defect limit, depending on the desired surface quality class. Figure 7.38 shows an excerpt from this standard for the product example bright steel round.

In addition to the eddy current testing method, there are the following other known methods for displaying cracks, folds, pores, also damage and other defects, that is, defects open to the surface:

- *optical methods*
- *color penetration methods*
- *magnetic particle inspection*

These methods should also be introduced briefly.

Surface quality classes for bright steel round

Product: Round	Surface finish class DIN EN 10277-1 (Table 10)			
	1	2	3	4
allowable defect depth	**max. 0.3 mm** for d ≤ 15 mm **max. 0.02 x d** for 15 < d ≤ 100 mm	**max. 0.3 mm** for d ≤ 15 mm **max. 0.02 x d** for 15 < d ≤ 75 mm **max. 1.5 mm** for d >75 mm	**max. 0.2 mm** for d ≤ 15 mm **max. 0.01 x d** for 20 < d ≤ 75 mm **max. 0.75 mm** for d > 75 mm	production-related crack-free
max. percentage of the delivery weight above the defined limits	**4%**	**1%**	**1%**	**0,2%**

Fig. 7.38 Excerpt from DIN EN 10277-1:2008-06—Tab. 10: Surface quality classes for bright steel round

7.3.3 Visual Inspection

> ▶ The visual inspection or visual testing (VT) is always an optical examination of a semi-finished product or component to be inspected in order to detect defects on the surface; and mostly at the end of a manufacturing process as a quality control measure. Visual inspections are also carried out on components that are already in use if required.

Visual inspection is divided into:

- *Direct visual inspection without aids* (Observing the test object with the naked eye)
- *Direct visual inspection with aids* (Meaning optical aids such as magnifying glasses, endoscopes, microscopes, mirrors)

For better defect detection, special lighting (different light colors, directed light or diffuse light) is always required.

Furthermore, the aforementioned standard defines direct and indirect visual inspection as follows: The direct visual inspection is carried out without interruption of the beam path between the test surface and the eye of the observer. In the indirect visual inspection the beam path is interrupted. A conversion of the light beam into another form of energy, e.g. into electrical information (camera), is carried out.

Special forms of visual inspection include, for example, the automatic optical inspection of components. The components to be tested are recorded photographically by computer and compared with a standard component. In this way, defects, including dimensional and form deviations, can be detected very quickly.

Typical errors that can be detected by visual inspection are mechanical damage such as scratches, cracks, ripples, notches, dirt deposits, assembly defects, burrs, also color changes (e.g. initial colors) and surface roughness.

Note
Visual inspections are carried out by people. This naturally results in a somewhat lower degree of efficiency compared to automated inspections. Fluctuations in concentration, performance pressure, fatigue, and also environmental influences cause a more or less large "slip-through" of undetected defects.

7.3.4 Penetration Test

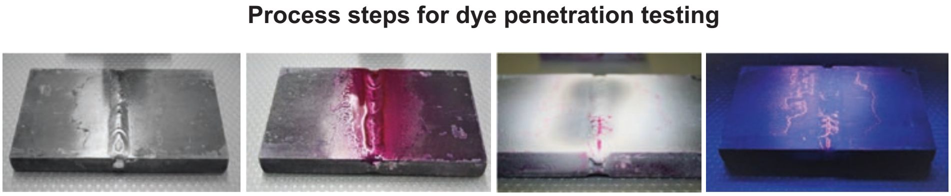
A candle is lit. There are enough occasions for this in life. And the candle burns, and burns. The wick is constantly soaking up with liquid wax. Similarly, porous bricks, textiles and paper can also become soaked with water, against the force of gravity. In very narrow tubes, crevices, pores and other cavities, liquids rise to the top. This phenomenon is known to us as the capillary effect (Schubert, 1982). Non-destructive material testing uses this effect as a indentation test to make surface cracks and pores visible.

Procedure

There is a distinction between color penetration testing in daylight with color contrast agents and fluorescent penetration testing under UV light with fluorescent penetration agents.

The individual process steps are clearly illustrated using the example of the examination of a weld seam by means of dye penetration testing, see Fig. 7.39.

The test body surface is cleaned (1) and covered with a penetrant (2). It penetrates into the smallest material separations open to the surface (cracks, pores, etc.). After another cleaning, a developer (3) is applied. The resulting contrast can be used to locate the defects under daylight or UV light (ultraviolet light), (3) and (4).



Process steps for dye penetration testing

1 – Initial sample with weld seam

2 – Sample with red contrast medium

3 – Sample cleaned, with white developer

4 – Sample under UV light

Fig. 7.39 Process steps in dye penetration testing on a weld seam specimen. (Photos: Kurdewan, T., DHBW Stuttgart)

Application

The penetration test is usually carried out manually on site directly on the test body, for example on rolled or forged semi-finished products, on die-forged parts or on machined parts, with cleaning agents, contrast agents and developers from spray cans. Only material separations that are open to the surface of the test body and into which the colorant can penetrate due to capillary action are made visible in this way. These are, for example, cracks, pores and other material separations down to one thousandth of a millimeter in width. However, the exact depth of the crack is not detectable or determinable.

This testing method can be used on all steels whose surfaces must be free of scale and rust. Often, the color penetration test is also used for the post-control of crack indications on automated in-line testing systems.

7.3.5 Magnetic Particle Inspection

▶ Another method for detecting cracks or pores on and near the surface is magnetic particle inspection, also called magnetic particle crack inspection or flux testing in practice, or fluxing for short.

Procedure

Magnetic crack testing is based on the principle of magnetic flux in ferromagnetic materials. By using test media that align in a magnetic field, cracks lying perpendicular to the current direction and surface-near defects are indicated by magnetic field disturbances. Fluorescent test media under UV light improve error detectability.

The test body surface is cleaned and then magnetized in partial areas or the entire surface. The magnetized area is then wetted with a carrier liquid, which contains smallest iron particles. At defect locations on or close to the surface, a stray flux (disturbed field path) forms. Here, the iron particles settle and make the defect visible, as shown in Fig. 7.40.

The components tested in this way must be demagnetized again after the test process. Magnetic fields remaining in the component can lead to restrictions in further processing, for example during welding or by adhesive forces during machining.

The different methods of magnetic particle testing differ in the way the test pieces are magnetized by means of yoke magnetization, current flow or field flow.

Figure 7.41 shows the principle of **yoke magnetization.** The analyzable magnetic field runs between two poles. Defects which are transverse to the magnetic field can be detected. In order to detect longitudinal and transverse defects, the yoke magnetization must be offset by 90° and carried out again.

The Fig. 7.42 shows the principle of **magnetization by means of current flow**. A pole is attached to each end of the workpiece to be tested and current is conducted between the

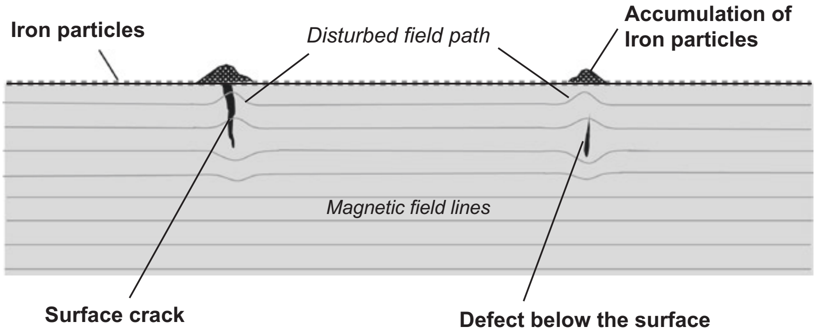


Fig. 7.40 Principle of the magnetic particle inspection

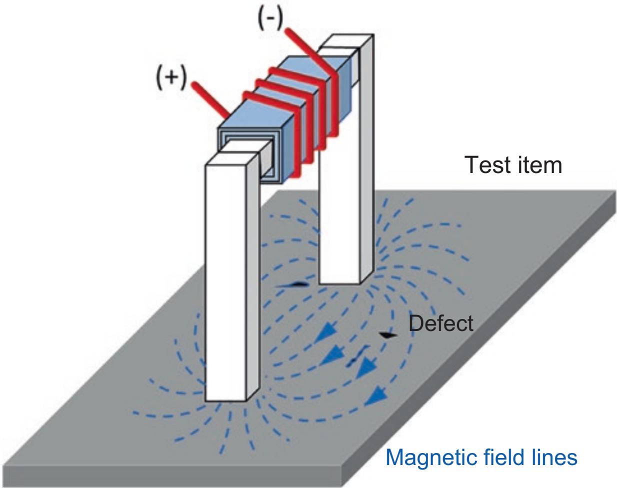


Fig. 7.41 Principle of yoke magnetization

two poles. This creates a circulating magnetic field transverse to the direction of current flow. Only longitudinal errors which run parallel to the direction of current flow can be detected.

For **field flow**, coil or cable windings are used, see Fig. 7.43. The field lines inside a coil or a cable winding run in a straight line and parallel to the coil axis. Only transverse defects, that is, defects running transversely to the coil axis, can be detected.

Fig. 7.42 Principle of current flow

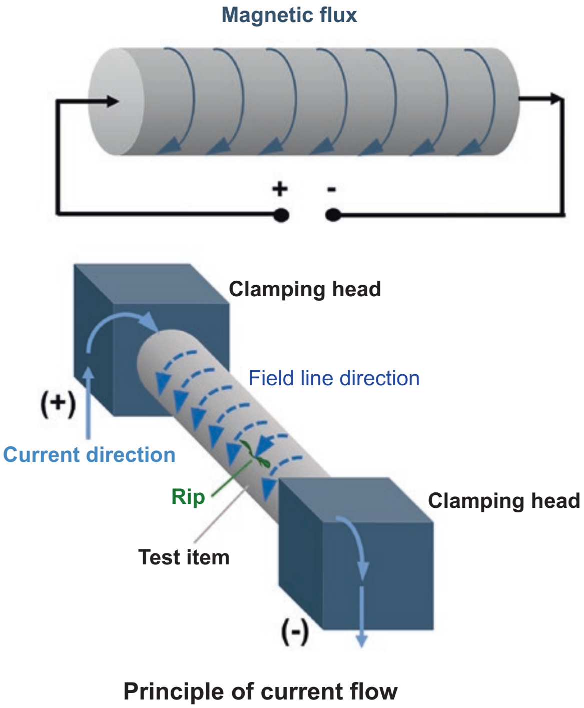
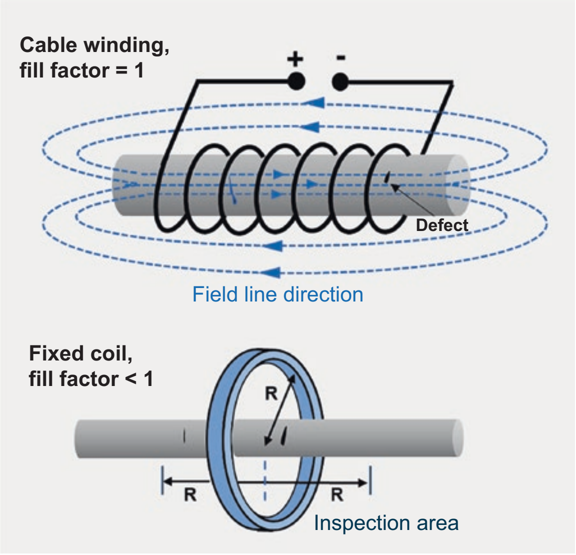


Fig. 7.43 Principle of field flow



▶ All magnetization techniques are based on the fact that flowing electric current generates a magnetic field. Using alternating current (positive and negative poles change with a high frequency), the surface of the component is only magnetized to a depth of a few tenths of a millimeter. When magnetizing with direct current (current flows between a constant positive and negative pole), the magnetic field also extends into the volume of the component. Defects in the volume or on the surface generate a leakage flux, which is indicated by the test device. As with the penetration test, the optical display of the cracks marked by the iron particles can be fluorescent in daylight or in the dark under UV or blue light.

7.3.6 Roughness Measurement

▶ Roughness meets us every day: rough hands after long work in the cold, rough paper, rough leather, roughened textile fabric or roughened surfaces for better adhesion or painting. Technically, roughness is a term used to characterize a surface quality, especially in the field of metallic materials. Depending on the state of the product after casting, forming, machining or after additional surface finishing, roughness can be very different. It is mainly influenced by processes such as polishing, rolling, grinding, lapping, honing, pickling, blasting, etching, vaporizing and coating, as well as by corrosion.

Both in terms of manufacturing and application, the surface quality of a product plays a special role for technical and optical reasons (sliding and visible surfaces). Roughness as an indicator for surface quality is considered and determined as the existing and measurable surface unevenness. The characterization of the surface roughness is carried out by taking a two- or three-dimensional profile of the surface to be examined. For this purpose, various contact and non-contact technologies and measuring instruments are available today:

- *Hand-held measuring instruments with stylus,*
- *stationary cutting edge measuring instruments,*
- *optical measuring methods.*

In profile-based methods, measuring devices with a stylus are used (profilometer). The stylus slides with its tip (probing needle) along a defined path on the surface of the test piece. This generates an electrical signal that the connected computer analyzes. The principle of this stylus method for measuring roughness is shown in Fig. 7.44. The devices used for this purpose are known under the name Perthometer.

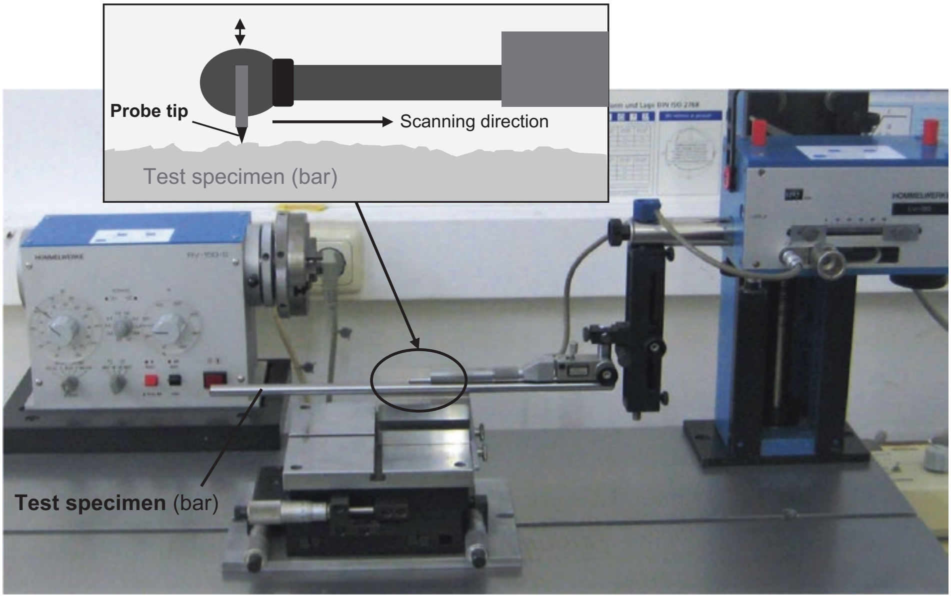


Fig. 7.44 Principle of the stylus method for measuring roughness on the example of a Perthometer from the testing laboratory of a bright steel manufacturer. (Photo: Schlegel, J., BGH Edelstahl Lugau GmbH)

Often, these scanning systems are used for a combined roughness and contour measurement. Various characteristic values are calculated from the scanned surface profile with the recorded heights and depths using standardized calculation methods. The relevant basic calculation principles can be found in the specialized literature. In practice, the following three characteristic values (in µm) are common:

- ***Roughness depth*** R_z

It is the mean of five extreme values of single roughness depths, recorded in five consecutive single measured sections of the roughness profile, see left graphic in Fig. 7.45.

- ***Mean roughness*** R_a *(also called mean roughness value)*

It is the arithmetic mean of all deviations of the roughness profile from the center line. Thus, this characteristic value R_a represents the average elevation relative to the ideal surface (zero line). The calculation is carried out from the sum of all surface areas, divided by the measuring length, see the graphic in the middle of Fig. 7.45.

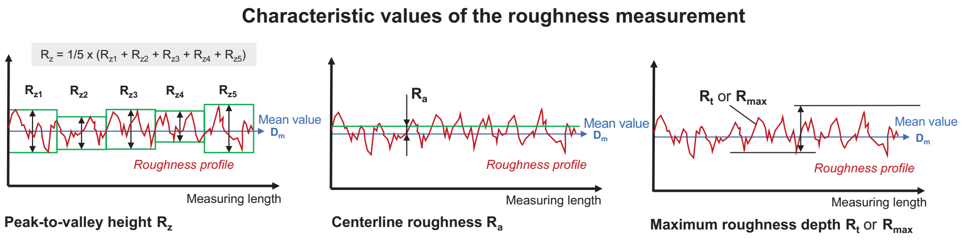


Fig. 7.45 Parameters of the roughness measurement: roughness depth, mean roughness and maximum roughness

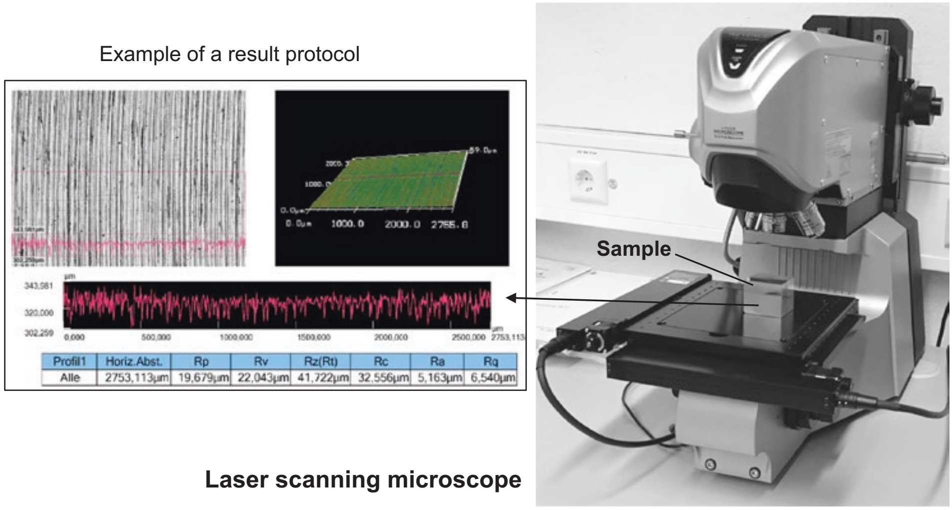
- ***Maximum Roughness R_t/R_{max}***

It is the vertical, maximum difference of the deepest and the highest profile amplitude within the measured length, see the right graphic in Fig. 7.45.

The execution of the roughness test is standardized, and the technically achievable roughness values can be found in various reference works. The ranges of the roughness values can be up to 25 µm for technical surfaces, depending on the condition or quality (Labisch & Weber, 2013). The decisive factor here are the manufacturing processes. In order to identify the surface quality to be achieved on the finished product, surface roughness values are therefore also specified in the manufacturing drawings in addition to the specification of the manufacturing process. This is usually done conceptually for three states of the workpiece surface:

- ***roughened:*** $R_a = 3.2$ to 25 µm (grooves are palpable and visible to the eye)
- ***planed:*** $R_a = 1.6$ to 3.2 µm (grooves are just barely visible to the eye)
- ***finely or. very finely planed:*** $R_a = 0.2$ to 0.8 µm (grooves are no longer visible to the eye)

In addition to the profile-oriented cutting edge method, surface-based non-contact 3D measurement systems are used for special requirements. The surface to be tested is scanned by a short-wave laser with a confocal 3D laser scanning microscope. Confocal means “having the same focus”. A “confocal microscope” does not illuminate the entire specimen, but only a part of it (a small light spot). The illumination is now rastered piece by piece over the entire specimen. This results in individual, sharply imaged areas, which are then assembled into an optical image with high contrast. The height resolution is 5 to 10 nm at most. In addition to line roughness values, topographical structures, contours and surface roughness values can be determined (https://steinbeis-analysezentrum.com/en/business/laboratory-equipment/confocal-laser-scanning-microscope-lext-ols4100-olympus/). Figure 7.46 shows such a confocal laser scanning microscope in a research laboratory with an example of a result protocol of a roughness surface measurement on a milled steel cube.



Profil1	Horiz.Abst.	Rp	Rv	Rz(Rt)	Rc	Ra	Rq
Alle	2753,113µm	19,679µm	22,043µm	41,722µm	32,556µm	5,163µm	6,540µm

Fig. 7.46 Confocal laser scanning microscope with a result protocol of a surface roughness measurement. (Photos: Kurdewan, T., DHBW Stuttgart)

7.4 Checking and Measuring

> In the practice of steel production and steel processing for forming or turning parts, in particular statements about concentricity, distortion, flatness/straightness, ovality/roundness and dimensions (diameter, length, width, angle) are required. For this purpose, various points in the production process are checked and measured. However, one should also correctly assess and distinguish the procedures “Checking” and “Measuring”.

Checking means comparing the test object with a “gauge” or a sample, e.g. checking a shaft diameter with a limit gauge or aligning a bar testing machine with a standard bar. The result is a clear statement: good or bad or ok or not ok, i.e. no specific measurement value.

Measuring is the scanning of a geometric dimension by means of a measuring device, such as measuring a rod diameter with a micrometer screw or with a vernier caliper. The result is always a specific measurement value.

Figure 7.47 shows the difference between checking and measuring.

Often, when determining specific dimensions, e.g. lengths, thicknesses, widths and diameters, the term dimensional measurement is used. However, this actually refers to measuring with different measuring instruments, such as hand-held measuring instruments, vernier calipers, micrometers, rules and tape measures. The execution of the measurement can be direct or indirect. With direct measurement, the actual measurement value is determined directly on the measured object, usually by contacting the measur-

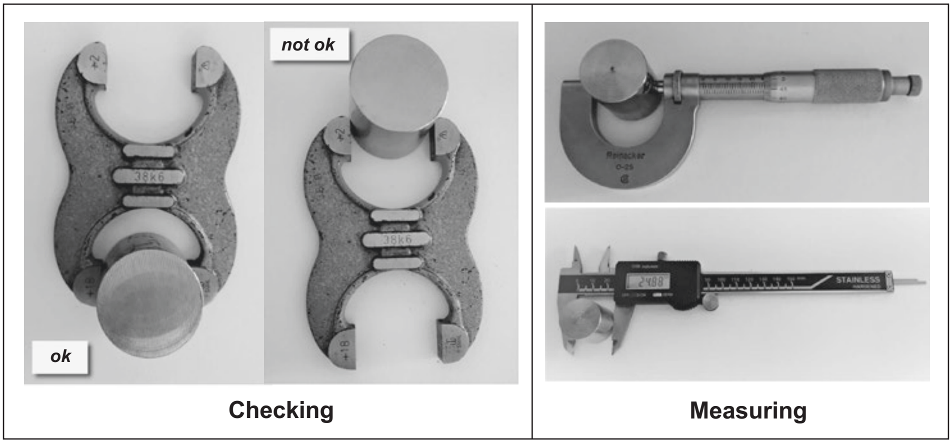


Fig. 7.47 Comparison of checking and measuring. (Photos: Schlegel, J.)

ing instrument with the measured object (test gauge, probe with scale or digital display). Often there is no possibility to measure directly on the measured object. Then another means (e.g. probe) is used to determine the desired dimension. With these, the dimension is taken (gauged) and then the dimension is determined by means of a measuring device (read out). For example, a dimension of a test piece can be taken with a vernier caliper. With a micrometer, the measurement value is then determined from the distance between the tips of the vernier caliper.

Gauges represent a specified dimension or a so-called reference standard for a certain geometric shape. They are used in production and especially during assembly. The following types of gauges are distinguished (see Fig. 7.48):

- ***Dimension Gauges***
  Dimension gauges are used as a gauge set, in which the measure increases from gauge to gauge, e.g. feeler gauges, measuring pins and gauge blocks.
- ***Form gauges***
  The form gauges enable the checking of, among other things, radii, angles, cones, threads by means of bevelled edge square, grinding gauges, radius gauges, thread gauges.
- ***Limit gauges***
  Limit gauges represent the permissible maximum or minimum dimensions for holes, shaft diameters and threads, e.g. limit plug gauges and caliper gauges. With these limit gauges, it can be checked whether the actual dimension of the component is within the permissible tolerance range.

Measuring and checking is only as accurate as the complex conditions during the check or measurement work allow:

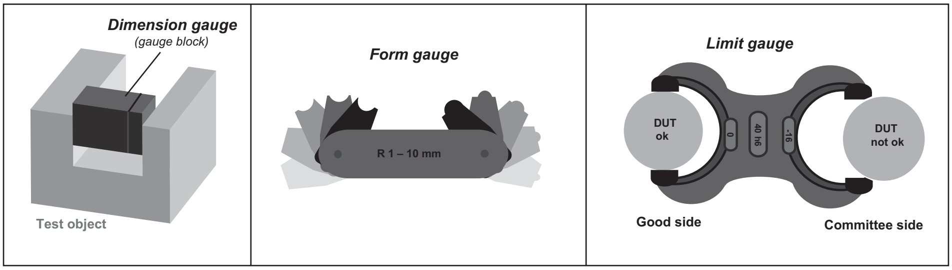


Fig. 7.48 The gauges types of dimension gauge, form gauge and limit gauge compared

- *Compliance with a defined reference temperature* (usually RT 20°C) for measuring tool, gauge and test body,
- *good lighting and visibility,*
- *cleanliness at the test or measuring point,*
- *calibrated measuring instruments,*
- *knowledge, vision and responsibility of the person carrying out the work.*

Other measuring and checking methods

> ▶ The presentation of important measuring and checking methods in the steel industry could not be carried out completely. There are so many fascinating developments and applications, see e.g. (Biermann, 2014), that a few more examples should still be mentioned.

Non-Contact Measuring

In cold rolling, strip thickness gauges are used which contribute to the inline control of the rollers and thus enable thickness tolerances in the micrometer range. Laser optical and confocal thickness sensors are used. Optical surface inspections are carried out automatically.

In-line laser diameter gauges ensure the narrowest diameter tolerances of bright rods during point-less grinding. These are coupled with the feed of the grinding wheels and thus guarantee the process-safe compliance with the desired tolerance ranges for the target diameters.

The control and monitoring of manufacturing processes is also possible with optical microphones. These detect ultrasound directly in the air. A coupling agent between the detector and the test body, as in conventional US testing, can be dispensed with. Such optical microphones can also be used for non-destructive ultrasonic testing of point-welded joints, composite materials and adhesive joints (Weinzierl, 2019).

In strand casting plants, hot and cold rolling mills, coating plants, in the production of steel pipes and in other areas of the steel processing industry, highly precise optical laser sensors are used for non-contact length and speed measurement.

Life Cycle Testing

In the case of permanent dynamic loads on components at certain temperatures, a drop in strength (creep) may possibly lead to failure of the component at a later stage. Therefore, short- and long-term tests for determining endurance strength (operational strength) are of crucial importance for safety-relevant structures, e.g. welded constructions.

Residual Stress Analysis

Steel also shows almost human behavior. It can remember. So, for example, a rod remembers that it once came from a wire ring which was straightened into a bar. When heat-treating (hardening) components made from such a bar via turning, distortion can easily occur. The cause of this is the mechanical residual stresses caused when straightening wire to bar. These must be minimized during manufacturing processes, for example by stress relief annealing. Whether this was successful can hardly be checked in a classical way, because residual stresses in the semi-finished steel or in components are internal, that is, coming from the inside. The material can be destructively tested by means of saw-cut, drill-hole or ring-core method. In this way, residual stress bearing material is machined away. The residual stresses released in this way deform the surrounding material. The degree of this deformation can be used to estimate the magnitude of the residual stresses. The non-destructive methods with X-ray systems and with electron backscatter diffraction using scanning electron microscopes or transmission electron microscopes are more exact.

Microstructure Analysis

Today, different contrast methods are available for the characterization of metallic microstructures: bright field, dark field, differential interference contrast (DIC), polarization contrast, and also fluorescence. Depending on the material, these methods ensure the detectability of the properties to be analyzed on the polished samples.

Modern quality control uses automatic image analysis software, for example, to determine grain size and distribution as well as pore analysis.

Novel digital microscopes combine the advantages of stereo and reflected light microscopes and can solve many measurement tasks with digital post-processing. Almost incredible, but true: A rapid technical development guarantees a look into the micro- and nanostructure of steels, and this even in 3D. For example, high-resolution field emission electron microscopes and atom probe microscopes are being employed.

Conclusion

Quality must be produced. The quality standard “zero defects” does not allow deviations. The goal is to prevent defects in advance. Only when defect-free production is not possible with the greatest effort, is it advantageous and necessary to detect the remaining defects as early as possible in the production process by means of the most modern methods and devices and to correct them immediately. Tests do not prevent defects from occurring, but with modern methods and devices they lead to an ever better detection of defects.

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Manufacturing Processes

8

▶ To produce a workpiece, a formed part, a component – in other words, a product that is precisely defined in terms of form, dimensions, dimensional tolerances, surface quality and mechanical-technological properties – various methods must be applied. The production of steel, the primary shaping (casting), the forming process including the necessary heat treatment processes and the testing were dealt with in the previous chapters. These methods are generally assigned to production technology, as are the further methods such as joining, coating and machining (mechanical machining such as turning, milling, planing/pushing, drilling, peeling, grinding). All of these methods of production technology are closely linked to the history of mankind. For example, there were already drill bits or fire drills in the Stone Age over 40,000 years ago. In the Bronze Age after 3000 BC, iron was then extracted and processed by casting, forging and fire welding. And from the middle of the eighteenth century, increasingly scientific methods were used to improve production technology and to develop new methods. Today, manufacturing is an important field of production technology and mechanical engineering, thus encompassing methods and facilities (tools, machining machines, etc.) for the production of products that are intended for the end user or that as semi-finished products still need to be processed further (Westkämper & Warnecke, 2010; Fritz, 2015). The following is an overview of the joining and coating methods of steel as well as the most important methods of mechanical machining.

J. Schlegel, *The World of Steel*, https://doi.org/10.1007/978-3-658-39733-3_8

8.1 Joining

▶ When considering this manufacturing process, childhood memories are awakened: always crafting, and with the metal construction kit you could screw together fascinating, also moving toys, e.g. a carousel; with Lego bricks put together great cars, buildings and figures or build ship and aircraft models made of wood and paper with all-purpose adhesive. And thus we have two or more solid bodies more or less permanently connected ("joined" or also assembled). These connections can be fixed and work well for the intended purpose, or they can be separable (screw connections). Through the adhesive or in the steel area by means of welding, inseparable, so-called material-joining connections can be made (Matthes & Riedel, 2003). There are also hardly or conditionally separable connections. In this case, however, the rivets have to be destroyed as connecting elements if a separation of the connection is necessary. The originally connected steel parts are not destroyed in the process. Similarly, soldered components can be "unsoldered" under certain circumstances.

The joining to be carried out in many diverse ways and in the steel industry is divided into material-joining, force-joining and form-joining connections.

8.1.1 Material-joining

Material-joining (substance-to-substance joining) include all types of connection with the steel material itself, i.e. welding, brazing and adhesive connections. They are not separable. Separation is only possible by destruction of the connecting means or the connection point. The example of the process ***welding*** makes this clear, see Fig. 8.1. At the connection point, the steel is locally, e.g. by means of an arc, heated to a high temperature and melted. With the welding wire (welding additive) new material is fed. There is an intimate, atomic bond in the weld zone, which has approximately the same properties as the steel parts to be joined. Modern welding processes are manual arc welding and automatic welding processes with high melting performance, such as submerged arc welding, gas shielded welding and electroslag welding.

Also, friction welding, a type of press welding, generates an intimate atomic connection between two materials in the joint zone.

Friction as a physical parameter always occurs between two solid bodies that are in contact and sliding against each other. The types of adhesive and sliding friction we feel and experience every day. The soles of our shoes adhere to the ground, otherwise we could not walk. And if, unexpectedly, this adhesive friction turns into sliding friction on a too smooth surface, it could also end painfully. Friction is always also associated with force. This force and the sliding speed between two parts to be connected have now been pushed to the extreme in friction welding so that local heating up to the plasticization of

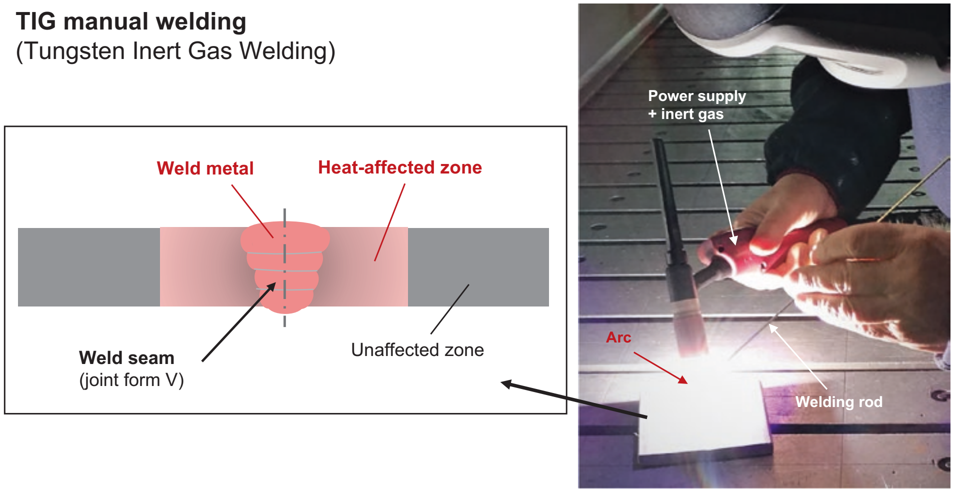


Fig. 8.1 Example of the generation of a material-joining connection: **T**ungsten-**I**nert**g**as-(WIG)-manual welding of stainless steel sheet. (Photo: Schlegel, J.)

the materials at the contacting surfaces occurs. The sliding movement is abruptly stopped and the parts are held in the desired connection position to each other under an additional pressure. They cool down and after the pressure is released, the joining process is completed. The advantages of this joining process are that no liquid phase is formed in the joint zone and a variety of different materials can be joined together (Witt, 2006).

The rotary friction welding is widely used. Here, a joining part must have a rotationally symmetrical shape. This joining part is rotated while the stationary part is pressed onto this rotating part. Figure 8.2 shows the principle of action of the rotary friction welding with a micrograph of the resulting joint zone of two steel parts. In the center of the micrograph, the steel beads pressed out of the joint zone and now protruding are clearly visible.

For special applications, “orbital welding” (joint parts are moved towards each other under pressure, like a sander) or “stir welding” (friction energy is not generated by moving joint parts, but by means of a special tool) are used.

Depending on the size and type of the parts to be joined (sheets, molded parts) and their materials, the friction welding methods are mainly used for the production of large-scale components in aircraft construction, space travel, shipbuilding, railway vehicle construction and also in the automotive industry. Smaller friction-welded components are used, for example, in container construction and medical technology.

Steel can also be soldered. The **soldering** as another material-joining process is primarily known from the field of electrical engineering/electronics for the production of electrical connections. In comparison to welding, when soldering the steel to be connected is not melted itself, but at lower temperatures a liquid phase is generated by

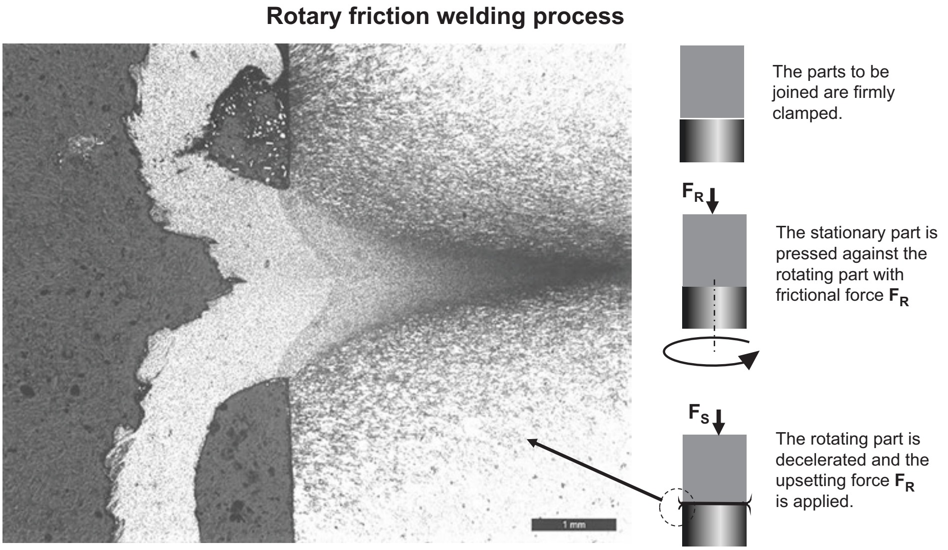


Fig. 8.2 Principle of action of the rotary friction welding. (Micrograph: Zilly, A, DHBW Stuttgart)

melting a solder. After the solder has solidified, a material-joining connection has been created. Soft soldering up to 450°C, hard soldering from 450°C and high-temperature soldering above 900°C are distinguished. The last of the mentioned processes takes place in a vacuum or under protective gas. The necessary heat is introduced electrically by means of a soldering iron, with the flame of a soldering torch, with hot air, hot steam, laser beam, by inductive heating, also by means of ultrasound, electron beam or arc.

In addition to soldering, mainly of pipes, arc welding is also used, especially in car body construction. Here, differently coated steel sheets (aluminized, galvanized, phosphated) have to be connected. The advantages of soldering come into play: The steel base material is not melted, the coating only evaporates locally, and due to the low thermal load, less distortion occurs as well.

In particular, in steel construction with thin-walled components (sheets, rolled profiles), in vehicle and aircraft construction as well as in plant and machinery construction, the process glueing is used. It is a very old joining process. Already 220,000 years ago, people used tree resins and tar to attach blades to shafts of weapons and tools. And today, adhesive bonds are indispensable in everyday life. Stamps stick to the envelope, plaster to the skin, windshields have also been glued for a few years, household appliances have many adhesive bonds and in medicine sensors are glued to the skin, wounds are glued and the stainless steel cannulas of syringes are glued into the plastic upper part. One- and multi-component adhesives, superglue, all-purpose adhesive, hot glue, adhesive tape, etc. Adhesives are used to repair and craft for many materials. The bondable adhesive bond is based on adhesion (ability to build up adhesive forces between the surfaces to be joined) and on cohesion (internal strength of the adhesive).

Most adhesives used for metal bonding are based on plastics. The selection of a suitable adhesive depends on the application profile, such as strength, dynamic loads, temperature conditions, chemical influences, etc. The adhesive joints require a design and surface preparation suitable for bonding (cleaning, defined roughness). This also ensures that the adhesive surfaces transmit the forces evenly. The advantages of bonding are that the joining parts, for example, do not require any drilling holes for screws or rivets, visually appealing connections can be produced and these with almost all materials. Usually, no thermal stress and thus no distortion occurs during bonding. However, it should be noted that the strength of the adhesive joint is not achieved immediately. The adhesive must first cure. It is only limited thermally and chemically stable. Compared to a weld seam, a glued connection in the joint zone contains a different material than the joining partners, namely the adhesive with its own strength. All these advantages and disadvantages must be considered when selecting the bonding process. Especially because of the possibility of lightweight construction, for example, also in agricultural machinery and plant construction, the motto "steel glueing instead of welding" is currently the goal of research work (Quitter, 2017).

8.1.2 Force-joining

The force-joining connections hold solely through the presence of forces. A compressive force (normal force) is applied perpendicular to the connecting surfaces. This creates such a strong adhesive force that shifting of the connecting partners is impossible and a secure connection is given. The friction clutch of a car works in the same way. It usually consists of two plates. These can be pressed against each other. The resulting friction resistance can transmit the rotary motion from one plate to the other. This state exists during driving, with the contact pressure being applied via a pressure spring. If the clutch pedal is now stepped on, the friction clutch is released, i.e. the contact pressure is removed. You press noticeably against the pressure spring. Now no rotary motion or torque can be transmitted from the engine to the gearbox and finally to the drive wheels. And sometimes it happens that the clutch is slipping. Then the clutch pedal was not stepped on completely. A small residual normal force acts still on the clutch plates. If the power connection is completely released by the loss of the normal force acting (here the clutch is fully stepped on), the connection is released. The classic example of this joining technique is the screw connection. After being tightened, it usually holds with a defined torque, since the friction in the threads prevents the screw from loosening under tensile forces. Screws can be less than one millimeter in size (e.g. watch screws), but also man-sized. And they are always easy to loosen, an advantage that ensures the screw connections a wide industrial application for the assembly and disassembly, for repairs, conversions, for separating and reusing components. Figure 8.3 shows, as an example,

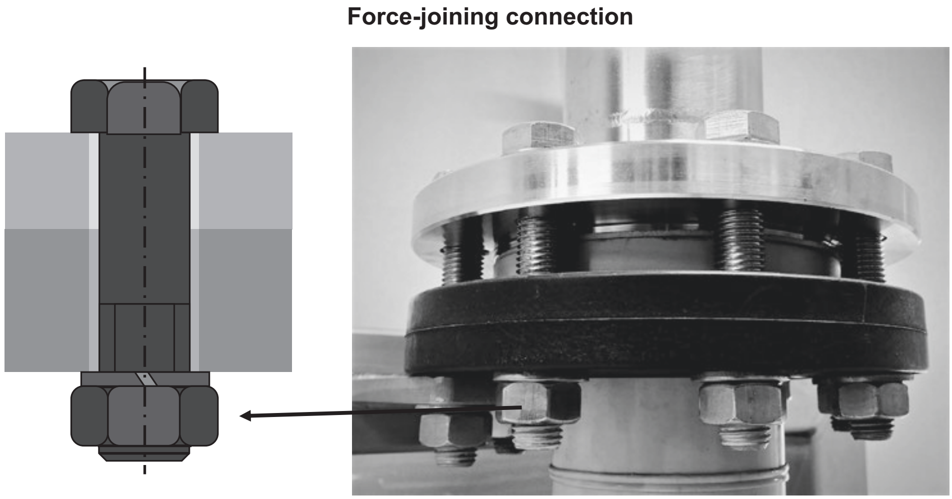


Fig. 8.3 Typical flange connection with screws.

a screw connection (through screws with locking rings and nuts), as it is used for the connection of pipelines by means of flanges in plant construction.

8.1.3 Form-joining

We close our clothing form-joining and securely with a zipper or Velcro, but also quickly releasably. With all these form-joining connections, the geometric shape of the parts to be connected is used, e.g. hooks and eyes, clamps, shaft-hub connections with keys, see Fig. 8.4.

Such a connection exists without force due to this geometric, form-joining interlocking of the connection partners.

The comparison of a force- with a form-joining connection is particularly clear with the example of lightweight hubbed shafts. For weight saving, they have hollow shafts. The individual cams are applied to these by force- or form-joining and force-joining. Figure 8.5 shows these connection variants.

The so-called "assembled camshafts" consist of tubular shafts onto which the individual cams are shrunk (friction fit). With the hydroformed (HF) camshafts the tubular shafts have been formed by internal high-pressure forming (HF – hydroformedsee Sect. 5.2.7: *Internal High Pressure Forming*) to the geometry of the oval inner contour of the cam. There is thus a form-joining and simultaneous force-joining connection.

Often, two components can only be joined by means of an additional connecting element. These are, for example, the already mentioned keys (feather keys). Also, pins, rivets and screws can act both form-joining and force-joining.

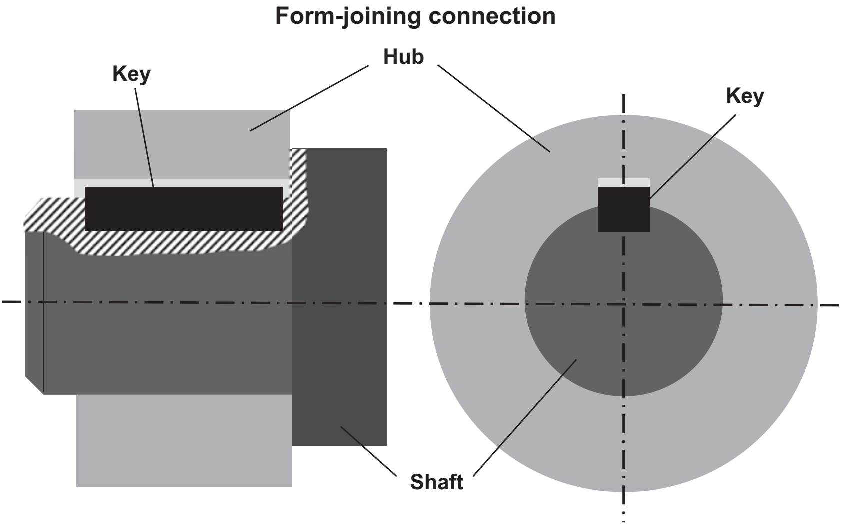


Fig. 8.4 Cross section of a shaft-hub connection, form-joining with key

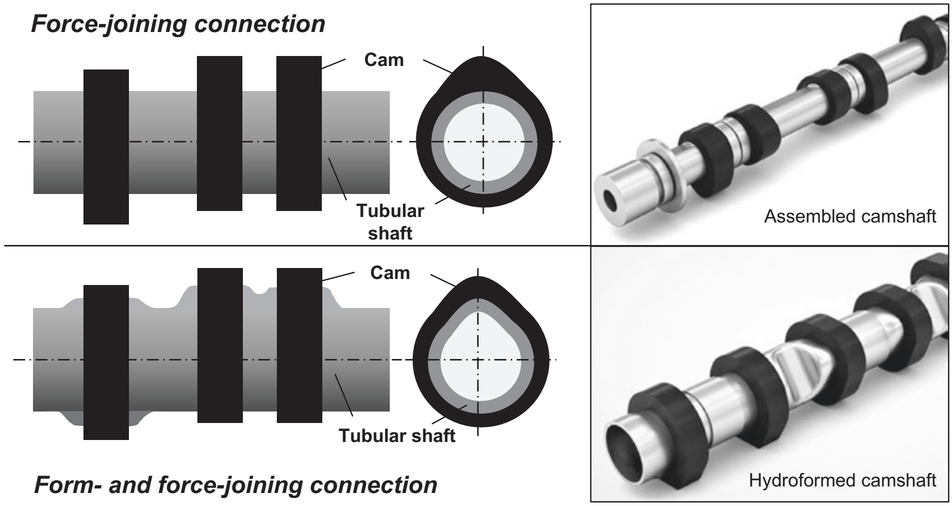


Fig. 8.5 Force-joining as well as form-joining and force-joining compared with the example of lightweight assembled camshafts. (Photos: Jansen AG, Oberriet, Switzerland)

8.1.4 Joining by Pressing, Casting, Forming

In addition to joining by the mentioned methods of welding, adhesive bonding, screwing and by using form-joining connections, there are other joining methods:

Joining by Pressing

In pressing, the parts to be joined and the necessary tools such as nails, screws, wedges, clamps and bolts are elastically deformed. The force fit thus generated prevents unwanted loosening. Typical of this type of joint are the press connections with excessive fit. Here the shaft always has a larger diameter than the bore of the part to be applied to the shaft, for example a gear. Therefore, this part must be pressed onto the shaft with force.

Joining by Casting

This process is suitable if a shaped part is to be supplemented with another part. This supplement is made with a formless, liquid or powdery substance. The additional substance can also flow into cavities of the base component to increase the strength. The process is distinguished by the pouring, cast around spraying, embedding, coating, galvanizing and sealing. Examples include the pouring of bearing shells into housings, the spraying of bushes, the vulcanization of wire braids, the pouring of rope ends or the coating, for example, of welding electrodes.

Joining by Forming

Both cold and hot forming processes can be used to join steel parts, e.g. beading, flanging, bending, lapping, notching, piercing and riveting. The probably oldest joining technique is joining of usually flat parts with solid rivets, see Fig. 8.6.

The solid rivet, a cylindrical bolt with a head, is inserted into the slightly larger bore of the steel parts to be connected and then the upset rivet head is cold-formed with hammer blows, thus creating a form-joining riveted connection. If a hot riveting (use of preheated rivets and hot forms of the upset rivet head) is carried out, the rivet shrinks during cooling, thus creating an additional force fit and a watertight connection. This advantage was used in the construction of large bridges, viaducts, high-rise buildings, towers, containers, locomotives and ships in the past. Figure 8.7 shows an example of a riveted steel

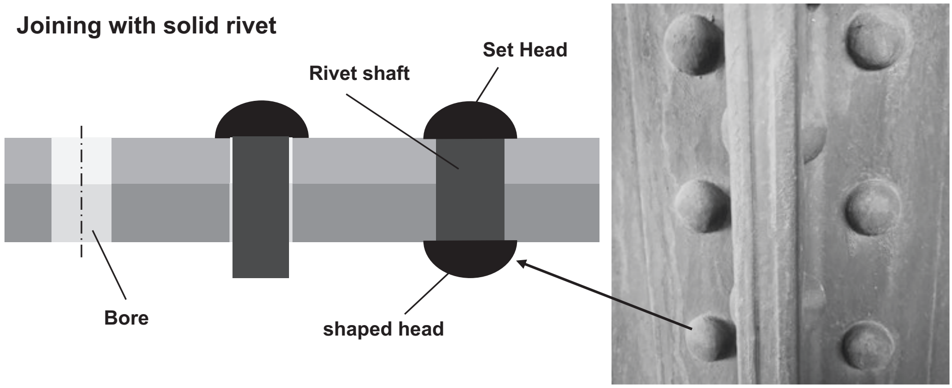


Fig. 8.6 Principle of joining with a solid rivet. (Photo: Schlegel, J.)

construction, the railway bridge “Viaduct Beckerbrücke” in Chemnitz. It was built in the same way as the Elbbrücke, the “Blue Wonder” in Dresden, between 1901 and 1909. With a total length of about 275 m, it is now a technical monument.

The most striking and world-famous steel construction is the Eiffel Tower in Paris. It was assembled from 18,038 steel parts with more than 2.5 million rivets between 1887 and 1889 and weighs more than 7300 t (weight of the steel construction, total weight over 10,000 t with a total height of 324.82 m) (see Fig. 8.8).

Classical riveted joints are today replaced to a large extent by modern welding processes. Nevertheless, the non-detachable, safe riveted joints for sheet metal parts are still used in aircraft construction and in steel construction for the production of vehicles. For this purpose, newer techniques have been developed, the details and applications of which cannot be discussed here. At least the different riveting processes should be mentioned:

- *Riveting with solid rivet, semi-hollow rivet, hollow rivet, closing ring rivet*
- *Blind rivets*
- *Punch rivets*
- *Hydrostamping rivets*

Fig. 8.7 Riveted steel structure of the railroad bridge “Viaduct Beckerbrücke” in Chemnitz

Fig. 8.8 Eiffel Tower in Paris. (Photo from Internet)

8.2 Coating

▶ Coating of semi-finished and finished products made of steel always has to do with a surface treatment, i.e. a structuring or modification, in order to specifically adjust property changes. These are supposed to achieve the protection and thus the securing of the service life of the product in industrial metal coating:

- Corrosion protection
- Protection against chemical influences
- Prevention or limitation of wear under mechanical stress
- Protection against radiation
- Protection against heat exposure

A defined coating (lubricant) also specifically enables the further processing of the steel semi-finished product, for example by means of cold forming. If a calcareous layer is applied to a freshly cleaned and etched steel surface, this is referred to as a lubricant carrier coating. If a steel construction is galvanized in a dipping bath, this is referred to as a coating for corrosion protection. And even the application of a paint layer to a steel surface represents a coating. The optical effect, and thus the attractiveness of a product, can be the reason for such a special surface coating.

These diverse coating variants should first be classified according to several criteria:

- ***Condition of the material to be coated***
  (base material, also called substrate).

- ***Coating material***
  Examples: plastic, metal, enamel, paint, other.

- ***State of the coating material to be applied***
  Gas:
  This includes the processes PVD—physical vapor deposition from the gas phase as well as CVD—chemical vapor deposition.
  Liquid:
  Examples of applying material in liquid form: lacquering, spraying, enamelling.
  Dissolved:
  This includes coating processes such as zinc galvanizing, nickel plating, electro-plating, phosphating.
  Solid:
  Coating materials in the solid state are applied, for example, during welding, powder coating and sputtering (spraying).

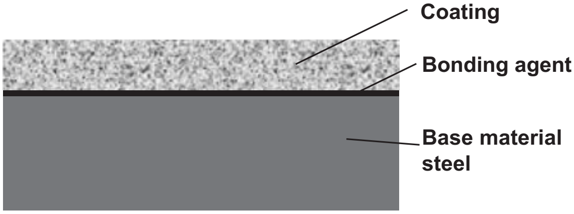
Coating processes
Chemical, mechanical, thermal or thermomechanical processes are used, for example vapor deposition, spraying, dip coating, rolling. Depending on the process and the application, a thin layer, a thick layer or several contiguous layers are applied. For this purpose, the steel surface is always prepared, cleaned, possibly roughened and provided with an adhesion promoter. Figure 8.9 shows the structure of a coating on steel in a simplified way.

The following is a brief overview of the most important methods for corrosion protection and achieving decorative surfaces of steel, primarily concerning metallic and non-metallic coatings.

Temporary Rust Protection and Special Surface Treatments of Steel

For short-term, temporary surface protection during storage and transport of steel products, there are various options:

Fig. 8.9 Structure of a coating on steel



- *Application of mineral oils, waxes, fats or clear lacquers* by spraying, brushing by hand or by means of electrostatic coating
- *Generation of corrosion-inhibiting coatings by dipping*
- *Passivation*

The latter is usually carried out after a cleaning process in a dipping bath for the chemical generation of a passive oxide layer on steel parts.

Oxidizing (Blue Glowing)

The steel product is annealed at about 800 to 900°C in an oxidizing atmosphere (blue glowing). This forms a bluish iron oxide layer which protects the surface from corrosion. This annealing also leads to the reduction of internal stresses in the workpiece (https://en.wikipedia.org/wiki/Bluing_(steel)). The corrosion protection effect can be further improved by a post-treatment with oils or waxes. This oxidizing, known in everyday life as “bluing”, is mainly used by weapon manufacturers.

Browning

When browning small steel parts, such as fittings, measuring tools and weapons, are cleaned and then dipped into hot, alkaline solutions with an oxidizing effect. This creates thin, black or dark brown oxide layers, which can in turn be treated with oil or wax. This process is used in machine and tool construction as well as in the manufacture of weapons.

Phosphatizing

In this process (phosphate conversion coating), the cleaned part or the steel semi-finished product is dipped or sprayed with a solution of various phosphates (zinc, manganese or iron phosphate)(phosphated). A firmly adhering, grey phosphate layer forms on the surface, which protects the steel from chemical influences. It is porous and forms a good “anchor” for subsequent coatings. Phosphate layers also have good sliding properties. This is advantageous for cold forming of steel (https://en.wikipedia.org/wiki/Phosphate_conversion_coating).

Chromating

In the dipping bath, chromic acid acts on the steel surface and forms chromic acid salts there. In this chemical process, the base material steel is also etched. The resulting chromate layer provides a good passivation protection layer or acts as an adhesive for a further, usually metallic coating.

8.2.1 Non-Metallic Coatings

Coatings on steel surfaces made of non-metals are distinguished according to the coating materials into inorganic and organic coatings, plastic coatings as well as paints and lacquers.

Inorganic Coatings

For example, cement mortar linings are used as internal protection for gas and water pipes. Coatings made of enamel provide an effective protection against corrosion and wear for steel parts. The sliding properties, chemical resistance and optical appearance are also improved. The enamel is applied as a molten base enamel, a glassy-silicate material, and in several top layers, usually by dipping. This is followed by enamel firing. Typical examples of enamelled steel parts can be found in the household: the pots and bathtubs (in the past more common than today). Technical enamel is used for the lining of acid-resistant containers, pipelines, storage tanks and other apparatus in chemical and pharmaceutical process engineering.

Organic Coatings

This includes, for example, bitumen as corrosion protection for steel pipes, or hard or soft rubber layers applied by vulcanization as protection against chemical stress.

Plastic Coatings

For corrosion protection, plastic coatings on steel have become important in various variants today. In particular, steel strip is provided on one side or both sides with plastic film after intensive pre-cleaning, partly with zinc primer and after applying adhesive layers. In addition to corrosion protection, decorative films also create color effects, for example for architectural elements for facade cladding. Furthermore, plastics can also be used in powder and paste form or in liquid form for coating, provided that a very clean, fat-free steel surface is available.

Paints and Varnishes

Painting of steel parts for industrial use is usually carried out automatically by spraying, powder coating, casting, rolling or dipping. The following processes are decisive for a high-quality coating: cleaning, applying a primer, applying the paint layer usually in several thin layers and finally drying the coating.

In particular, the steel strip coating with paint is today the most widely used coating process for surface finishing. Both variants, the film and paint coating, are referred to as “coil coating”. The application areas summarized in the overview of Fig. 8.10 are to be mentioned for these strip coating processes.

8.2.2 Metallic Coatings

▶ On surfaces of low- and high-alloyed, non-corrosion-resistant steels, metallic coatings are often used for corrosion protection. The most well-known is galvanizing; but also coatings of tin and aluminum or of their alloys are common. In order to also increase wear resistance, hard alloys (chromium, cobalt, nickel alloys) are used for the coating. Depending on how these metallic coatings are produced, one distinguishes:

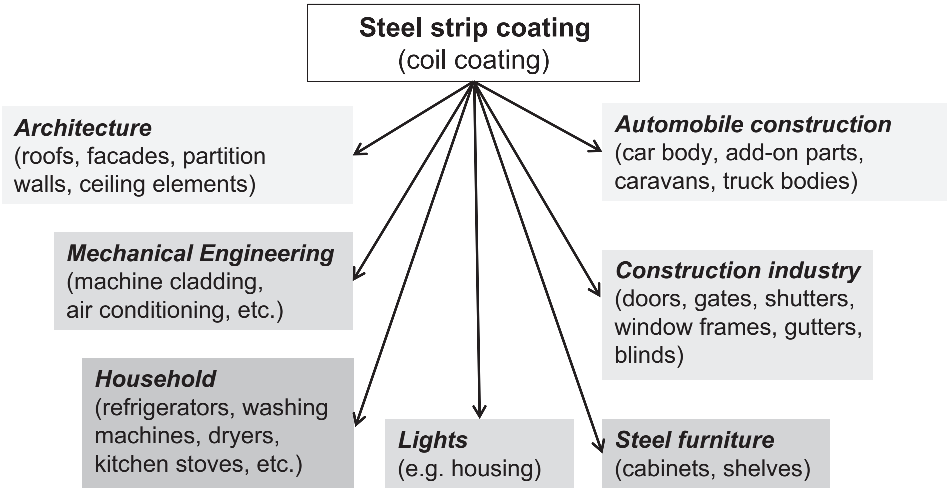


Fig. 8.10 Overview of the application areas of steel strip coating ("coil coating")

- *hot dip coating* (hot-dip zinc galvanizing, tinning),
- *electrolytic metal deposition* (galvanizing),
- *thermal spraying* (metal spraying, flame spraying),
- *vapor deposition* (sputtering),
- *mechanical application by plating* (rolling plating, explosive plating).

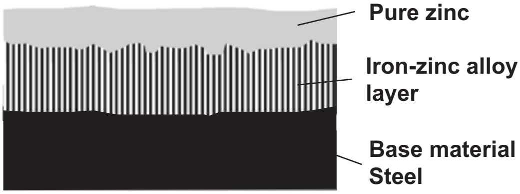
These coating methods are introduced below.

8.2.2.1 Hot Dip Coating

Zinc-coated steel, also known as galvanized steel, comes in many different forms in everyday life and is also easily recognizable by its gray, crystalline surface: poles for street lighting, signal systems and electrical power lines, fences, gates, gratings, guardrails on roads and highways, substructures for canopies, staircases, bridge construction, other load-bearing structures for industrial plants, container construction, etc. Most of these structures or their individual parts are made of unalloyed quality and construction steels and are dipped into a molten zinc bath. With this galvanizing, steel-zinc-diffusion layers (transition layers) first form on the surface. A thin layer of pure zinc remains after the steel part has been removed from the zinc bath and excess zinc has been removed by dripping, blowing or scraping. Figure 8.11 shows a typical layer structure after a hot-dip coating.

For the galvanizing of steel semi-finished products (steel strip or steel wire), continuously operating galvanizing plants are used. By welding the coils together, work can be done with endless strip or wire. These plants combine dip galvanizing in the melting bath with the annealing of the steel semi-finished product. So these plants consist of

Fig. 8.11 Typical layer structure after a hotdip coating of steel with zinc



a pass-through furnace, the zinc melting bath, a drawing device with the possibility of adjusting the zinc layer thickness (nozzle stripper, mechanically acting stripper), cooling and the winding station. The steel strip or steel wire usually dips obliquely into the bath with the molten zinc (melting temperature approx. 460°C), is deflected (deflection roller or deflection stone in the zinc bath) and pulled vertically upwards. With the regulation of the through-flow speed and the adjustment of the used scrapers, the desired zinc layer thickness can be set. Figure 8.12 shows schematically the structure of a continuously working dip galvanizing plant in comparison to a piece galvanizing plant.

Typical zinc layer thicknesses in continuous hot-dip galvanizing are in the range of 7 to 25 µm. In batch galvanizing, layer thicknesses can be up to 150 µm and more. The technology of strip galvanizing has been further developed so that galvanized steel strips, due to the adherent and deep-drawable zinc layer, are now standard for car body construction. In addition to this application, galvanized steel is in demand as a strip, flat steel, narrow strip, bent part, also perforated, mainly in machine and plant construction, in architecture (façade and ceiling elements, lightning protection) and in the household industry.

High-strength, galvanized steel wires are used as ropes, for example for Bowden cables, crane ropes, for lifting devices, as bracing wire for fencing, for wire mesh fences, as barbed wire, as support ropes for cable cars, for facade design, etc.

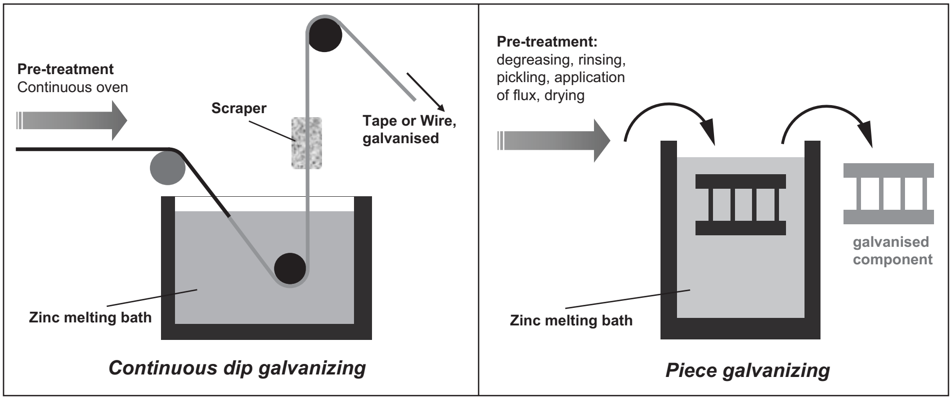


Fig. 8.12 Structure of a continuously operating galvanizing line in comparison to a piece galvanizing bath

In addition to zinc plating, aluminum or zinc-aluminum coatings are also applied to steel by the molten metal plating process.

8.2.2.2 Electroplating

Electroplating is an electrolytic metal coating, that is, an electrochemical deposition of metals on steel. This process is based on a discovery by *Luigi Aloisio Galvani* (1737–1798). In 1780, he noticed that during experiments with frog legs, they twitched when they were touched with two electrodes made of different metals. This effect was named after him: galvanism (muscle contraction by electricity). And *Alessandro Volta* (1745–1827) recognized that this effect was caused by the different metals that, in combination with an electrolyte, generate a voltage. For a metallic coating, this electrochemical working principle is used as follows, see Fig. 8.13: In a bath there is an aqueous solution with metal ions (electrolyte) and electrodes. The anode (positive pole) consists of the coating metal, e.g. copper, zinc, chromium or nickel. When a direct current is applied, metal ions are detached from this anode. These are positively charged and now migrate to the negative pole (cathode) in the electrolyte. Since this negative pole is connected to the workpiece or the workpiece is switched to the negative pole, the metal ions deposit relatively evenly on the surface as a metal coating.

In order to achieve a adherent, metallic coating, the workpiece to be coated must be pretreated to obtain a clean, fat- and oxide-free surface. The achievable layer thicknesses during galvanizing are in the range of approx. 2 to 25 μm and are thus lower than during dip coating.

There are various methods of galvanic coating in use for piece or continuous strip coating, with alkaline or acidic electrolyte baths and with different pre- and post-treatments. Chromium plating was and is used for a wide range of applications, for example for surface finishing of vehicle parts. Bumpers, trim, wheel rims, hubcaps, everything

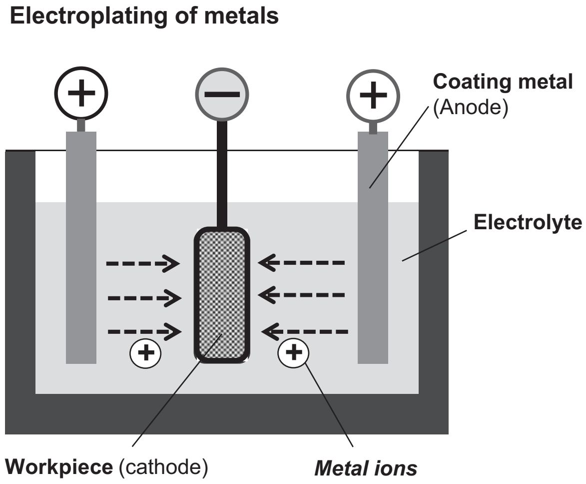


Fig. 8.13 Principle of galvanic deposition of metals

that was possible was and is chromed. This was a particularly beautiful tradition in the 1960s to 1980s. Beautiful chrome models were created, today sought-after classics on the vintage car market. Figure 8.14 shows, for example, a car over 50 years old with a lot of chrome trim.

Nickel plating, zinc plating, tin plating, and coating of small parts with precious metals such as gold and silver are today's industrial coating methods for a variety of applications. Many components such as cable-hose connections, screws and nuts, ball valves, fittings, press buttons, etc. are nickel-plated because nickel is very resistant to air, water, diluted acids and bases. And gilding and silvering are the classical methods of the jewelry and cutlery industry.

8.2.2.3 Thermal Spraying

In this coating process, a melted or softened metal is sprayed onto a steel surface with high acceleration energy. The metal droplets are pressed into the surface irregularities, partly also welded layer by layer. After cooling, a metallic top layer with good adhesion is formed. The coating material is used in the form of metallic powder or wire. The arc, plasma beam, fuel-oxygen flame, laser beam or preheated gases are used as energy carriers for thermal spraying. Based on this, today there are a variety of methods for many applications in industrial use. Figure 8.15 shows an overview of methods for thermal spraying of metals onto steel.

Fig. 8.14 Detail of a chromium model, an over 50 year old classic car. (Photo: Schlegel, J.)

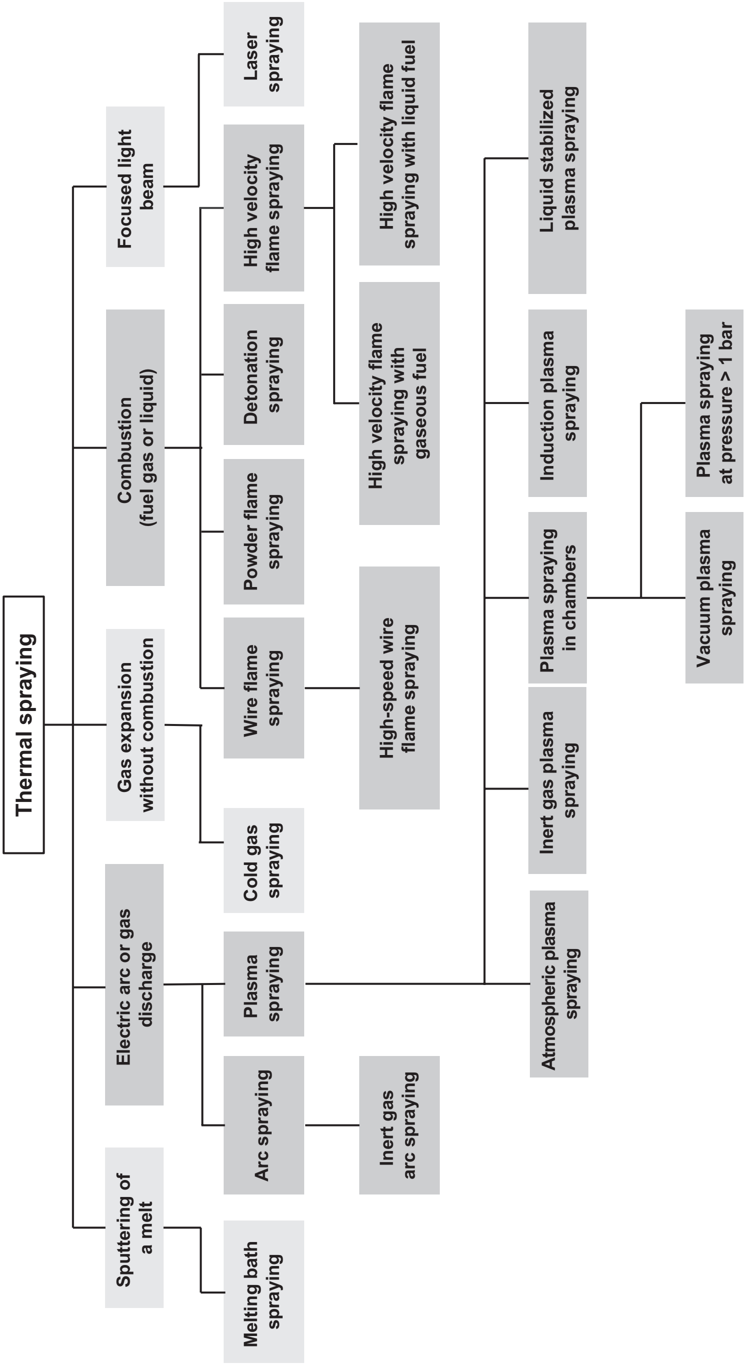


Fig. 8.15 Overview of methods for thermal spraying of metals onto steel

Selected coating methods that are widely used today include:

Flame spraying
The metal powder is sprayed using a burner and simultaneously fused with the base material.

Plasma spraying
As with flame spraying, only using a plasma burner, metal powder is sprayed onto a component. Figure 8.16 shows the principle of plasma spraying with metal powder. Protective gases used include argon, nitrogen, hydrogen, helium, etc.

Arc spraying
In arc spraying, for example in so-called spray galvanizing, the continuously fed coating metal (a zinc wire) is melted in an arc. With gas (air, nitrogen or argon), the fine droplets formed are applied to the steel surface. There the coating metal adheres and forms a good corrosion protection layer.

Laser surface cladding
Metal powder or welding wire is melted by means of a high-energy laser and applied to the component at the same time. Laser surface cladding has proven itself, for example, as a coating technique for the repair of machining tools, for the generation of wear-resistant and functional layers.

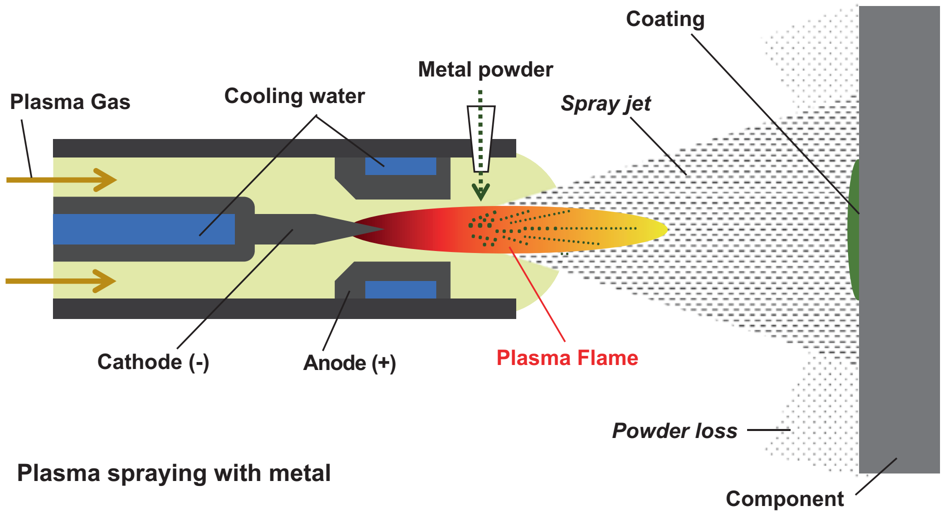


Fig. 8.16 Principle of plasma spraying with metal powder

▶ **Note** All metal spraying processes cause only a small thermal load on the component to be coated, so that even very large areas or large components do not distort during coating. The surface improvements achieved with the thermal spray coatings on steel in terms of wear and corrosion protection as well as friction and sliding properties are, inter alia, in demand in the automotive, paper and printing industries, in the aerospace industry, in the waste industry, in machine and plant construction. In addition, thermal metal spraying is preferred for the repair or regeneration of worn large tools such as sinks, dies and press tools, for example for car body parts.

Interesting are new applications for the generative production (3D printing) of larger, more complex components using thermal metal powder spraying.

8.2.2.4 Vaporization (Sputtering)

The term "sputtering" comes from "atomization", a physical process in which atoms are released from a solid (coating material, called target) by bombardment with ions. They go into the gas phase and are then deposited on the steel surface of the component to be coated (called substrate). This vaporization of metallic layers takes place in different plants under vacuum and plasma. Figure 8.17 shows a simplified representation of the sputtering process.

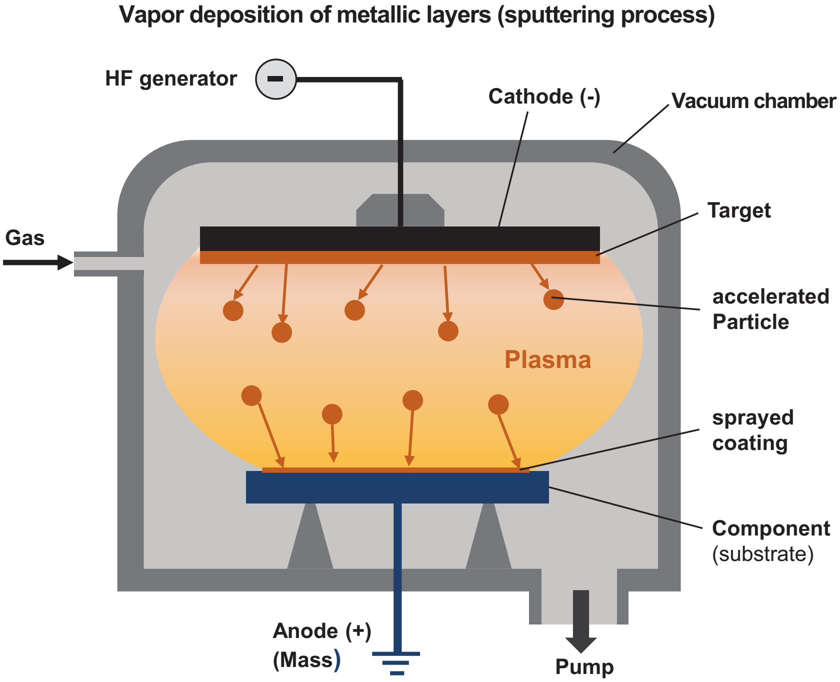


Fig. 8.17 Representation of the sputtering process

The sputtering of metal layers on steel is today a standard coating process with which a great variety of metals, e.g. titanium, tungsten, nickel, nickel alloys, aluminum, precious metals, but also non-metals can be applied to steel components. The sputtered layers are in comparison to the mentioned spraying or dipping layers very thin and are mostly used for optical surface refinement, e.g. for the production of mirrors, car headlights, car rims, etc.

8.2.2.5 Plating

Plating refers in metal processing to a process in which a base material is provided with one- or two-sided metal coatings. Of course, these should enter into a firmly adhering connection with the base material, which is created by a combination of high pressure and temperature action (directly during the plating process or during a subsequent heat treatment). Plating creates so-called composite metals, e.g. a plated steel strip with a copper coating.

The following techniques are available today for plating of steel products:

- *Rolling* (see also Sect. 5.2.4.2: *Rolling processes*)
- *Explosive forming* (use of the explosive force to form various metals)
- *Electroplating* (electrochemical process)
- *Welding*
- *Casting*

▶ As with the other coating processes, the goals of plating are increased corrosion protection, increased surface hardness, improved sliding properties, and also a beautiful appearance. And always the intended use as well as the size and shape of the steel product to be coated (component or semi-finished product) determine the selection of one of the described methods.

8.3 Machining

▶ After metallurgical production, the first shaping by casting and forming, including heat treatment and testing, the raw or semi-finished material obtained must be brought into the desired finished form. For this purpose, special tools are used for the "machining" or "abrasive" processes. These cause a continuous or discontinuous, massive or only superficial material removal from the steel semi-finished product, from a forged part or other workpiece. The result is a targeted change in shape and surface, which is accompanied by this volume loss. Below is some information about machining processes.

8.3.1 Basics

The following main machining processes are distinguished:

Turning

- *Longitudinal turning*
- *Profile turning with profile tool*
- *Form turning* (by means of adapted tool path)
- *Thread turning*
- *Plane turning*
- *Cross cutting turning* (cutting off turning)

Milling

- *Profile milling* (longitudinal and round profile milling)
- *Rolling milling with profiled milling cutters*
- *Plane milling*
- *Freeform milling*

Peeling

- *Bar peeling* (rotary peeling)
- *Wire peeling* (rotary peeling, draw peeling)

Planing, Pushing

Grinding

- *Outer, inner round grinding*
- *Flat grinding*
- *Profile grinding*
- *Point-loss grinding*
- *Face grinding*
- *Cutting off grinding*

Drilling

- *Drilling with spiral drills*
- *Deep hole drilling*

Countersinking

Fine machining

- *Reaming*
- *Lapping*

- *Honing*
- *Reaming*

EroEroding

Machining bar ends

Cutting

- *Shearing*
- *Sawing*
- *Cutting grinding*
- *Thermal cutting*

▶ First, an overview and tips on chip formation, machinability, tool materials and machining equipments.

Chip Formation

When a tool cutting edge penetrates the steel workpiece, there is first an elastic and plastic deformation. When exceeding the maximum "sustainable" tensile stress of the steel, the chip is removed in the shear plane. Depending on the given workability of the steel (ductile or brittle) and depending on the machining parameters, different types of chips occur, such as tear-off, shear or flow chips. Figure 8.18 shows some chip shapes that can occur, for example, when turning.

Chips that do not damage the tool and workpiece, allow high surface quality, can be transported easily and quickly, and do not endanger safety are favorable. Very long chips can become jammed, block chip removal, and cause increased tool wear, often also tool breakage.

Fig. 8.18 Examples of chip shapes. (Photos: Schlegel, J.)

The tension parameters that can be set on the machining equipment and adapted to the machining task are:

- ***Cutting speed and feed***
  These parameters determine the cycle time, thus the output and tool wear. They must be reduced in case of poor machinability.
- ***Cutting depth***
  It is the chip removal that is limited by the machine performance, the size (stability) of the workpiece and the tool used.

In all machining processes, these manufacturing parameters vary depending on the tools used with different cutting tool geometries. These geometries are characterized as follows:

- *Defined surfaces*
  These refer to the chip, main clearance, side clearance, and angle of these surfaces to each other and to the cutting surface of the workpiece.
- *Cutting*
  The main and side cutting, the chamfers and cutting corners are to be distinguished.

Figure 8.19 shows a simplified representation of the working surfaces during machining.

Machinability
The machinability characterizes the complex property of a material to be machined under certain conditions. This is influenced by the microstructure components in the

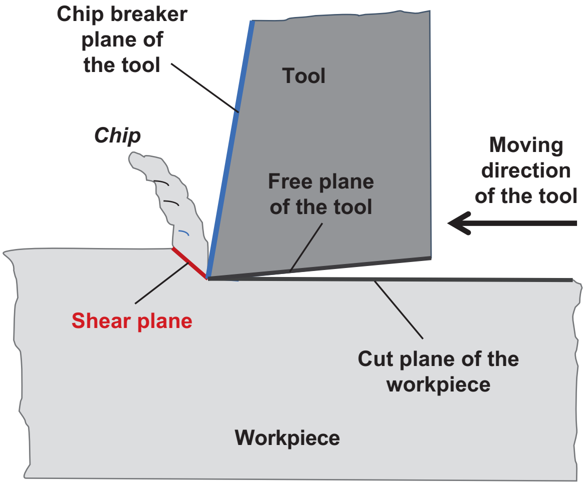


Fig. 8.19 Simplified representation of the working surfaces during machining

steel, such as ferrite, cementite (Fe_3C), pearlite (phase mixture of ferrite and cementite), austenite, bainite (intermediate microstructure between pearlite and martensite) and martensite (hardened microstructure). In particular, the sulfur content plays an important role in terms of chip formation. Sulfur is only slightly soluble in steel and forms stable sulfides. Above all, the desired manganese sulfide has a positive effect on machinability, resulting in short-fractured chips and thus a better surface quality. However, too high sulfur content deteriorates the purity and the mechanical properties of the component to be machined (see Sect. 3.3.2: *Solid Elements, Non-Metals – Sulfur*).

The tool material (wear resistance), the thermal conductivity of the workpiece to be machined, thus the speed of removal of the resulting friction heat, as well as the cooling and lubricating agent (water-oil emulsion) used are also of importance. In all machining processes, these influencing variables are very complex and often difficult to assess in practice. Usually, an evaluation is made according to:

- *Service life or tool wear*
- Cutting force (influences wear and energy consumption)
- Surface quality (roughness, shine of the machined part)
- *Contour, dimensional accuracy*
- *Chip form*

For this purpose, tables with standard values for machining a diverse range of steels with different tools can be found in technical literature. Likewise, many steel producers publish so-called 'data sheets' for their steels that contain specifications for parameters which guarantee optimal chip removal.

Tool Materials

One distinguishes cutting materials, which form the cutting part of a machining tool with a geometrically determined cutting edge, e.g. a turning tool, drill, milling cutter or peeler, or grinding media, which cause the material removal with an undefined cutting edge, e.g. as a grinding wheel or abrasive paper.

High demands are placed on the hardness, temperature and wear resistance, bending strength and toughness of the tools. For almost every machining operation, including heavy machining, hard machining, dry machining and high-speed machining, there are suitable metallic, ceramic or composite cutting materials:

Tool Steels

They no longer play a role in high-performance machining today.

High-Speed Steels

These steels, also called HSS, for example the classical HSS quality 1.3343—HS 6–5-2 C, are used preferably for drills, milling cutters, reamers and taps, often also with surface coating (see also Sect. 2.4.3: *Tool steels – high-speed steels*).

Cast Hard Alloys

These hard alloys based on cobalt-chromium were introduced in the USA in 1907 as "Stellite".

Hard Metal

Hard metal is a sintered composite of a soft cobalt binder phase with hard, embedded carbides. This special tool material is mostly used for coated wear improvement, e.g. as indexable inserts. Figure 8.20 shows two examples of typical shapes of hard metal indexable inserts for turning.

Cutting Ceramics

Cutting ceramics have only been used for steel machining since 1950 as an oxide, non-oxide or mixed ceramic.

Superhard Cutting Materials

For special, difficult machining cases, boron nitride or diamond tools are used.

Machines

Since the 3rd millennium BC, the fiddle drill has been known, an evolution of the fire drill (whirl drill), which was set in rotation between the hands. The rotation of the drill could be accomplished with a bowstring, which was wound once around a wooden or bony rod and attached to the ends of a flexible branch. Figure 8.21 shows the handling of such a fiddle bow. For the first time, a tool was no longer moved by hand, but with

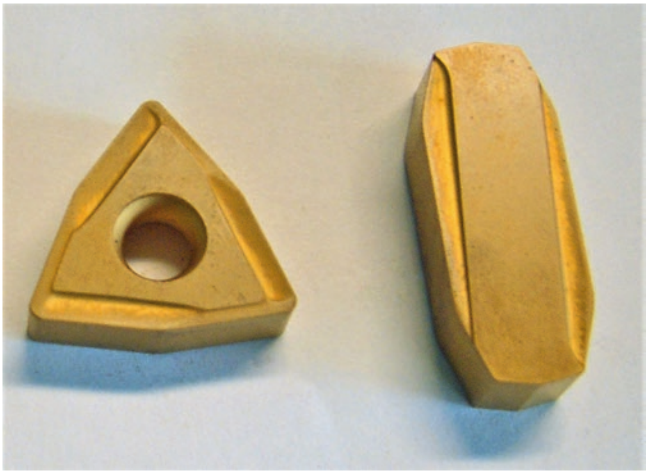


Fig. 8.20 Carbide indexable inserts for turning. (Photo: Schlegel, J.)

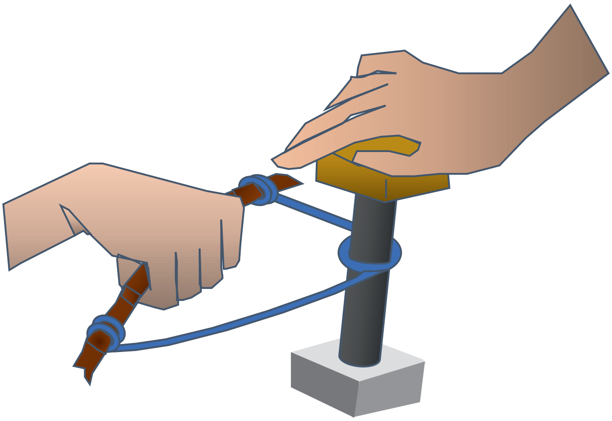


Fig. 8.21 Handling of a fiddle bow

a special device. Thus the probably first tool machine was created, suitable for drilling; and horizontally arranged also for turning or lathing.

With the industrialization in the late eighteenth century, the machining equipment was significantly improved and equipped with new drives (transmission drive with water, later with steam power, finally the single drive with electric motor). Today, the most diverse machines are used for the countless machining techniques for the continuous machining of semi-finished products or for the individual machining of workpieces, also for maintenance parts and test bodies. Increasingly, machining centers for complete machining (e.g. turning-milling machines, turning-drilling-milling or turning-grinding centers) are used, of course computer-controlled as CNC universal machines.

The following explanations are limited to an overview of the most important machining processes turning, milling, peeling, planing/milling, grinding, drilling, finishing, eroding, separating and some methods for machining of bar ends.

8.3.2 Turning

▶ Mainly rotationally symmetrical, i.e. round parts are machined by means of the classical turning process. Modern CNC turning machines enable the production of high-precision, even complex contours. For very small turned parts, e.g. for watches or medical technology, one speaks in Switzerland and also in France of Décolletage. By turning, the ends of round bar stock can also be machined (e.g. planing, centering). Turning is a very old machining process and, together with drilling, milling and grinding, belongs to the most important machining processes of machining technology.

When turning, the material removal is carried out by means of a firmly clamped, rotating workpiece-guided tool (turning tool), which performs the feed and advance movements. The main cutting movement of rotation is carried out by the workpiece to be machined. The cutting data here are the cutting speed (rotation), the feed and the cutting depth. Figure 8.22 shows this principle of machining by turning.

The following **tools for turning** of steel products are used:

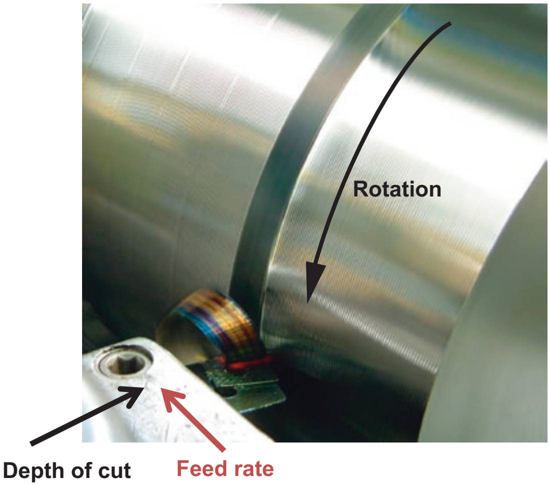
- *Holders with tungsten carbide indexable insert* for external and internal turning, grooving (high material removal, thus coarse material machining up to near final dimension) and facing (low material removal, final dimension setting with high surface quality)
- *Holders with tungsten carbide cutting insert*
- *Holders with profile indexable insert, e.g. for threading*
- *Turning tool made of tool steel*

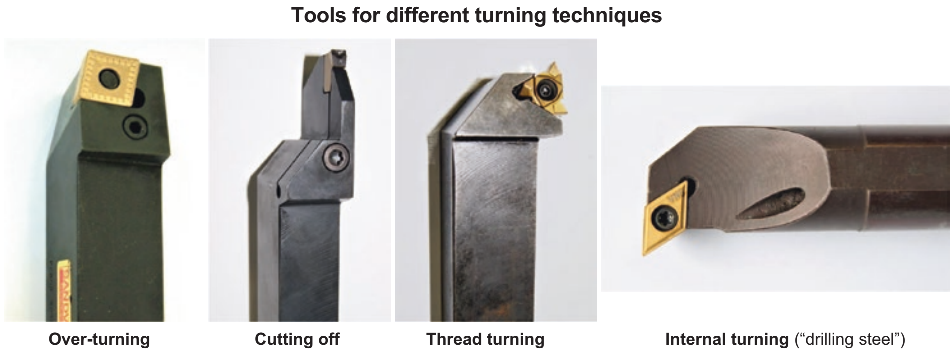
Figure 8.23 shows examples of tools for different turning techniques.

The **machine tools** for steel turning can be divided into three types:

Conventional turning machines (engine lathes, universal lathes)
The tool movements are carried out by means of manual operation. These types of machines are mainly suitable for single production. Figure 8.24 shows such an older lathe with manual operation, which is used by a craft business for metal processing.

Fig. 8.22 Principle of machining by turning. (Photo: Schlegel, J.)





Tools for different turning techniques

Over-turning **Cutting off** **Thread turning** **Internal turning** (“drilling steel”)

Fig. 8.23 Turning tools for over-turning, cutting off, threading and internal turning. (Photos: Schlegel, J.)

Fig. 8.24 Conventional lathe with manual operation. (Photo: Schlegel, J.)

Automatic turning Machines

The tool movement takes place automatically by means of curve or computer control (e.g. CNC short and long turning machines). These automatic turning machines are suitable for single and series production. Figure 8.25 shows a classical CNC turning machine for machining forged parts.

Figautomatic turning machines 8.26 shows a CNC long-turning machine for machining long-forged parts for body presses (tension anchors) with lengths up to 18 m and diameters up to 1440 mm.

Machining Centers

There are various machining techniques in a complex machine, for example turning, drilling and milling. Figure 8.27 shows an example of a CNC machining center.

Turning is a very widespread and extremely versatile standard machining process for steel products: from special turned parts for hobbyists, from precision turned parts for the automotive industry, medical technology, machine and plant construction, from long turned parts such as propeller shafts for shipbuilding, from complex turned parts such as cold-rolled parts, flanges, hollow parts, from over-turned semi-finished products (rods) and machined forgings to micro-turned parts for the electronics industry. Not all applications can be listed here.

Fig. 8.25 CNC turning machine. (Photo: Schlegel, J., BGH Edelstahl Siegen GmbH)

Fig. 8.26 CNC long-turning machine for parts up to 18 m in length and with diameters up to 1440 mm. (Photo: Schlegel, J., BGH Edelstahl Siegen GmbH)

Fig. 8.27 CNC machining center. (Photo: Schlegel, J., BGH Edelstahl Lippendorf GmbH)

8.3.3 Milling

When milling the material is removed from a stationary workpiece with a multi-edged, rotating tool (milling cutter). The many cutting edges are not always in engagement.

Depending on the direction of rotation and the feed, the concurrent and opposed milling are distinguished. Figure 8.28 shows a schematic comparison of these milling variants.

The following **milling tools** are used:

End mills, circular, slot, groove, prism, shank, disc, slit, roller, angle, radius, tooth form cutters made of solid carbide or with carbide indexable inserts. Figure 8.29 shows, as an example, a solid carbide end mill and a cutter head with indexable inserts clamped in place.

The **milling machines** can be used in three technically different variants:

Conventional milling machines

These types of milling machines are controlled manually or mechanically. Often, they are used as combined drilling and milling machines.

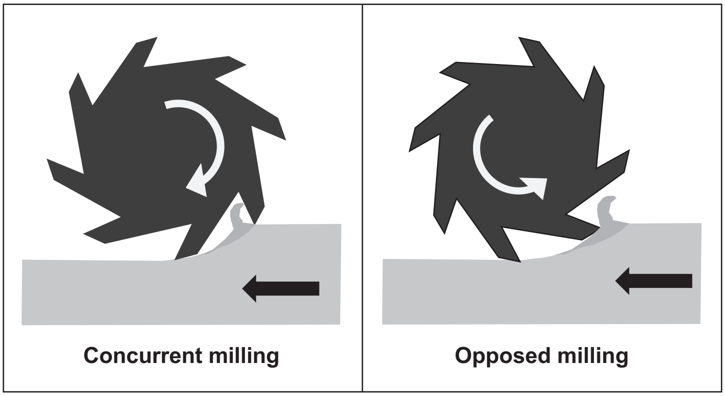
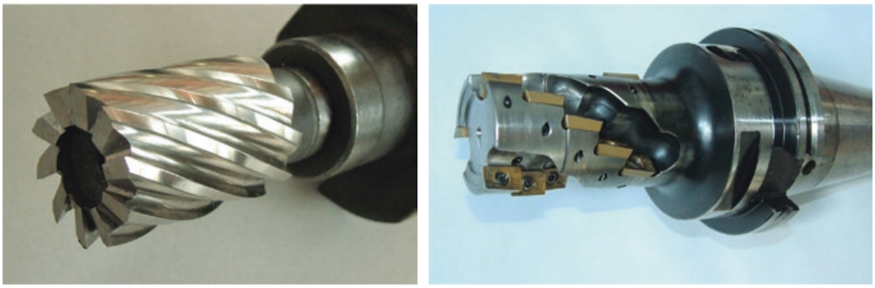


Fig. 8.28 Comparison of the variants of concurrent and opposed milling


Solid carbide end mill

Cutter head with indexable inserts

Fig. 8.29 Solid carbide end mill and cutter head with indexable inserts clamped in place. (Photo: Schlegel, J.)

CNC-controlled milling machines

CNC milling machines today have up to 11 axes of movement. Figure 8.30 shows, for example, the milling of a spherical piece on such a CNC milling machine.

High-performance-milling centers

These are used in combination with other machining processes such as turning and drilling in a plant, for example as turning-milling centers.

The milling of steel products is also very common, just like turning: planing and contouring or profiling milling, also of the most difficult contour shapes according to customer requirements, milling of grooves, recesses, etc. on forged workpieces, milling of hollow bodies for power plant construction, milling of valve blanks and other molded parts for machine and plant construction, milling of gear parts, of all kinds of turned parts up to the milling of micro precision parts for medical technology.

8.3.4 Planing, Pushing

In these processes, chips are removed from the steel workpieces with special machining tools, the planing or pushing cutters, which have a geometrically predetermined, specific

Fig. 8.30 Milling of a spherical piece on a CNC milling machine. (Photo: Schlegel, J., BGH Edelstahl Siegen GmbH)

cutting geometry. This always results in flat surfaces. The difference between planing and impact refers to the relative movement, thus the cutting movement between the tool and the workpiece. Thus, when planing, the workpiece to be machined is moved along the stationary plane iron. At the end of the material removal, the workpiece must be retracted (empty or return stroke). Then the workpiece is moved laterally by a chip width and the cutting movement is carried out again. With impact, this process is reversed, i.e. the cutting movement over the workpiece is carried out by the impact chisel. Figure 8.31 shows this work process schematically when planing and pushing.

Milled surfaces show the typical parallel machining marks. The achievable roughnesses depend on the feed, the material, the cutting geometry and the depth of cut. Today, the machining processes of planing and pushing are increasingly being replaced by milling. It allows shorter production times with higher surface quality.

8.3.5 Peeling

Peeling of fruit and vegetables or of coniferous trees after felling is common. Raw, rolled or long-forged steel is also peeled as rod or wire half-finished product to remove the oxide or rolling skin as well as possible defects (surface cracks). This creates a bright half-finished product with the customer-desired surface quality (dimensional accuracy, roughness, roundness) or as a pre-stage for a subsequent grinding process.

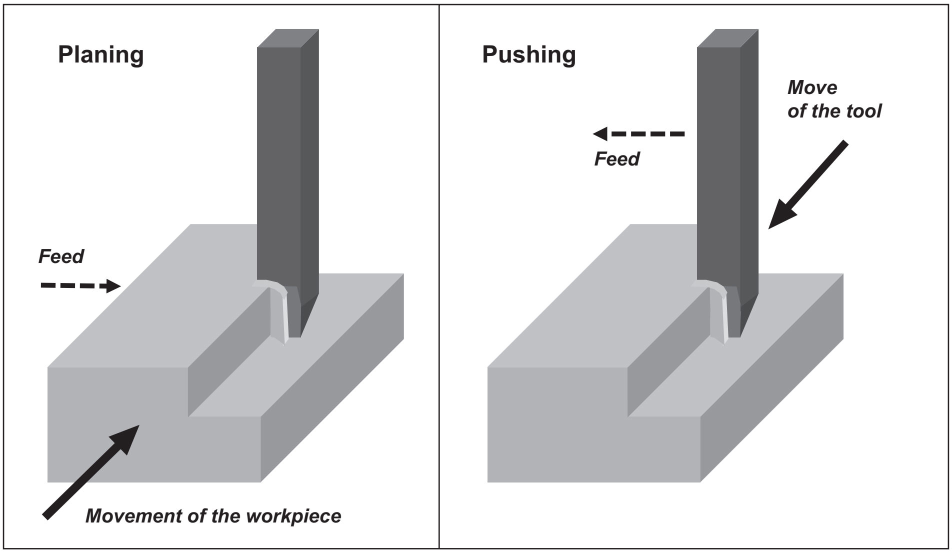


Fig. 8.31 Comparison of the work processes when planing and pushing

In the broadest sense, peeling means removing the outer layer or shell from an object or workpiece. For this purpose, a special peeling tool (knife, draw blade, peeling head) is used. Today, two main variants and corresponding plants for the continuous peeling of steel half-finished products are used:

Rotary Peeling

As the name suggests, with rotary peeling a continuous machining with a tool (peeling head) rotating around the workpiece (bar or rod stock) is achieved. This tool has one or more cutting edges that are constantly engaged. Such a peeling head consists of several holders (usually four), which are equipped with carbide inserts and arranged in rotating cassettes. Figure 8.32 shows, as an example, a four-fold bar peeling tool with four holders, each with one indexable insert.

A modern bar peeling machine for long-forged bars in the diameter range 160 to 610 mm is shown in Fig. 8.33.

Draw peeling

When drawing the product to be peeled (wire) is pulled through a fixed, closed, circular peeling tool. This results in a continuous, superficial material removal (see Sect. 5.2.9.1: *Wire drawing* as well as Fig. 5.68).

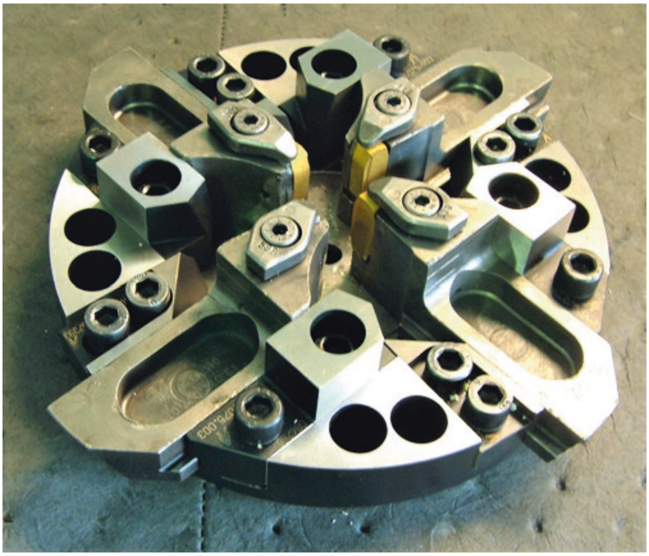


Fig. 8.32 Four-fold bar peeling tool. (Photo: Schlegel, J., BGH Edelstahl Lugau GmbH)

Fig. 8.33 Modern bar peeling machine for long-forged bars in the diameter range 160 to 610 mm. (Photo: BGH Edelstahl Siegen GmbH)

8.3.6 Grinding

Grinding is a machining or a superficial material removal with a mostly rotating, multi-edged tool with geometrically undefined cutting edges, which are not constantly in use, see Fig. 8.34. It can also be assigned to the finishing processes.

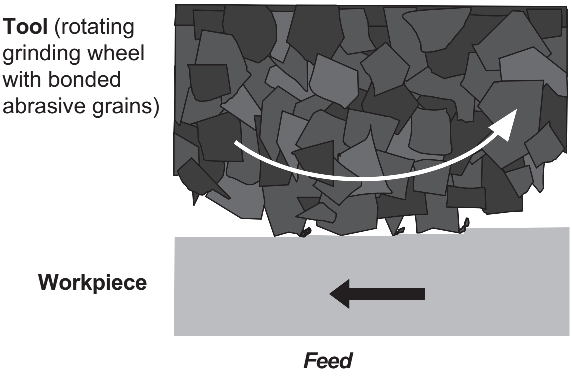


Fig. 8.34 Principle of the manufacturing process grinding

The following types of grinding are distinguished:

- *Plane, flat, round or profile grinding of workpieces* (single machining)
- *Round grinding of long products* (continuous in pass)

The Fig. 8.35 shows examples for plane and cylindrical grinding.

For the continuous round grinding of bars, the centerless grinding process is used. The rotationally symmetrical workpiece (round bar) to be ground is not clamped between two holding points in the grinding machine as is the case when grinding individual parts. The workpiece is located between the grinding wheel, the regulating wheel and the support rail. It is therefore not fixed and can be fed through centerless by the regulating wheel. Together with the support rail, the regulating wheel supports or presses the workpiece against the grinding pressure of the grinding wheel. In addition, the regulating wheel regulates the rotational speed of the workpiece and causes the workpiece to be fed by an inclination. Figure 8.36 shows this operating principle of continuous centerless grinding.

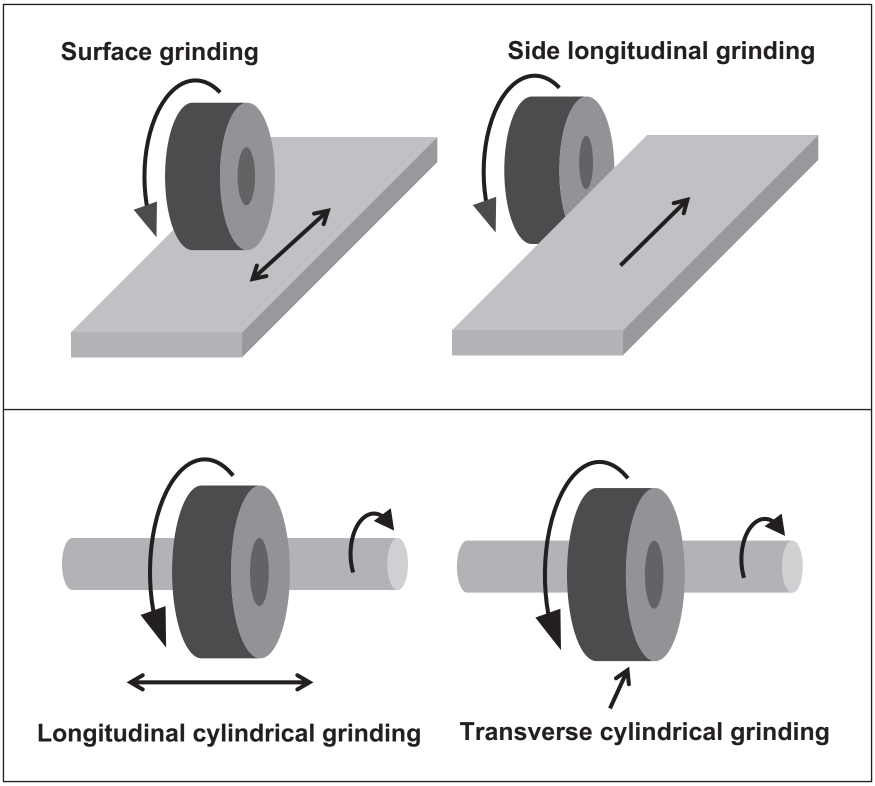


Fig. 8.35 Examples of grinding variants, *from left to right:* surface grinding, longitudinal grinding, longitudinal and transverse cylindrical grinding

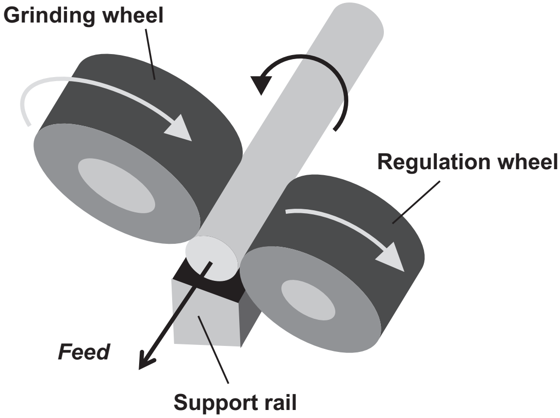


Fig. 8.36 Operating principle of continuous centerless grinding

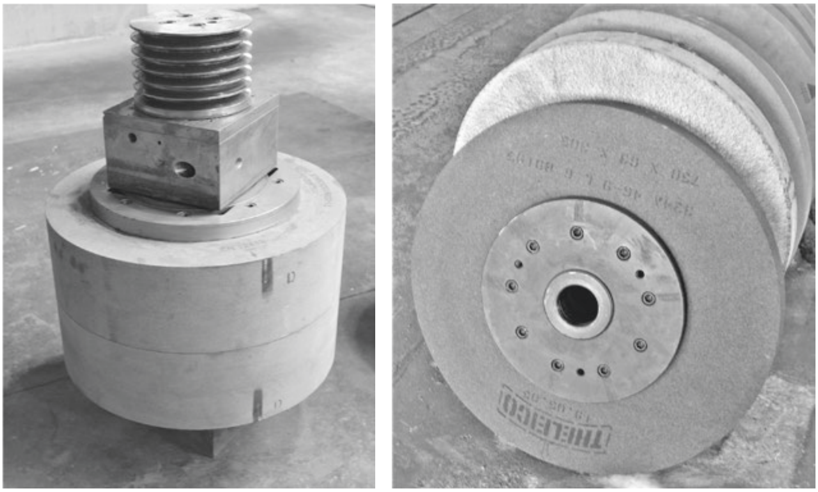
The following very complex-looking grinding parameters must be observed:

- *Grinding allowance* (roughing, finishing)
- *Speed of the grinding wheels*
- *Feed rate*
- *Grit of the grinding wheels*
- *Dressing intervals*
- *Condition and setting of the support rails* (also called guide lines)
- *Grinding agent* (grinding emulsion)

In addition, the straightness and surface condition of the bars to be ground affect the grinding result during through-feed grinding. Here, in practice, in the case of blank steel production, surface roughnesses with center roughness R_a max. 0.4 µm or averaged roughness depths R_z max. 4 µm can be achieved.

The grinding tools used are grinding grains (corundum with the compound Al_2O_3 or silicon carbide), which are bound in synthetic resin, ceramic, metal, galvanic or rubber, and depending on the grinding task are used in different forms as grinding discs, cutting discs, grinding bodies, grinding belts or grinding paper. Figure 8.37 shows, for example on the left, a grinding disc prepared for use in centerless grinding, and on the right grinding discs for round grinding of workpieces, which are clamped and ground between the tips in a universal round grinding machine.

The grinding methods range from cutting material pieces (cutting grinding), rough and fine machining of surfaces (surface grinding, cylindrical grinding), profile grinding (sting grinding), fine grinding (honing, lapping) to sharpening of cutting tools and the production



Grinding disc for centerless round grinding

Grinding disc for external cylindrical grinding between centers

Fig. 8.37 Examples of different types of grinding discs

of polished specimen for metallographic examinations. For these numerous and diverse tasks different grinding devices are used as well. Depending on the design and control, the following are distinguished:

- *Hand grinding machines*
- *Surface grinding machines*
- *Grinding systems for centerless continuous grinding of bright bars*
- *Belt grinding machines*
- *Turning and grinding centers*

The following illustrations show three types of grinding machines:

- A *centerless continuous working through-feed grinding machine,* arranged in a grinding line (chamfering, pre- and finish grinding as well as checking the bars in a diameter range of 5 to 10 mm, with inline laser diameter measurement) – Fig. 8.38,
- A *universal cylindrical grinding machine* is used, for example, for grinding a bearing journal of a cold rolling mill between centers – Fig. 8.39,
- A *grinding device with grinding belts* for grinding of peeled steel wire – Fig. 8.40.

The field of application for grinding is very diverse. Whenever a turning or milling operation is not or only difficult to carry out, for example with difficult to machine materi-

Fig. 8.38 Centerless continuous working through-feed grinding machine in a grinding line for bar diameters of 5 to 10 mm. (Photo: Schlegel, J., BGH Edelstahl Lugau GmbH)

Fig. 8.39 Grinding a bearing journal of a cold rolling mill on a universal cylindrical grinding machine. (Photo: Jeibmann, J., Photographik, Dresden)

als (hardened steel parts, hard metal), and when very high demands are placed on the surface quality, even with very complex parts, grinding methods are used. In addition to the precision machining of pre-turned workpieces or the through-feed grinding of raw rods, various grinding techniques are used in the steel-producing industry for grinding

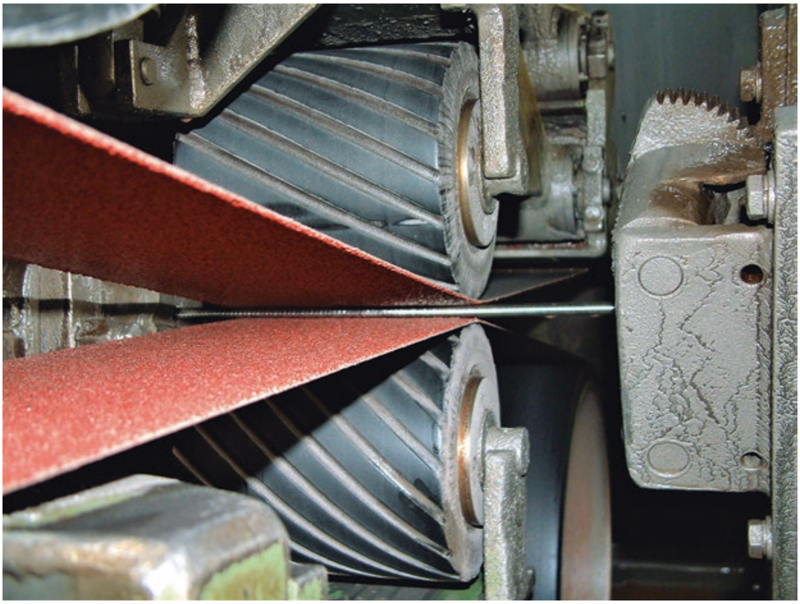


Fig. 8.40 Belt grinding of peeled steel wire. (Photo: Schlegel, J., BGH Edelstahl Lugau GmbH)

steel-cast blocks as raw material preparation before forming, for intermediate grinding of semi-finished products before final forging or hot rolling, and for band grinding of bars and wire.

8.3.7 Drilling

▶ Already during the time of the Neanderthals (approx. 200,000–40,000 BC), pierced shells and animal teeth were worn as jewelry. Later, pierced bones and antlers were added. Stone drilling marks the Neolithic period (transition from hunter-gatherer cultures to sedentary farmers about 12,000 years ago). The drilling technique of that time was interesting. “False” holes were created as double-cone holes by striking indentations on both sides. The “real” holes were made as solid or hollow holes with rotating tools. These holes usually ran in a V-shape, as the drill head made of ivory, hardwood, stone or animal teeth quickly became worn.

The machining process of drilling today takes place with drill bits rotating around the longitudinal axis on stationary workpieces. All cutting edges of the single or multi-edged, rotating drill bit are constantly in engagement. This creates cylindrical depressions (passages, holes) or internally profiled holes (e.g. internal threads) in the workpieces to be machined, i.e. always internally lying cavities. The resulting machining is similar to that of other machining techniques. However, it must be noted that the shank of the drill is moved along the already finished inner wall of the hole.

Different materials require different types of drill bits, for example, universal bits, metal spiral bits, concrete bits with tungsten carbide cutting edge, flat end mill bits, stepped bits, sheet metal bits, deep hole bits, thread bits, or profile bits. The most commonly used tool in this regard is the spiral drill bit (König & Klocke, 2008). All drill bits consist of a shaft and a head. The shaft transfers torque, guides the drill bit head, allows for the removal of drilling debris, and the inflow of coolant. The drill bit head with its wear-resistant cutting edge is responsible for the feed during the advance. Spiral or helical drill bits for steel are centering themselves through the tip and are made of chromium-vanadium steel, high-speed steel, or, for extreme applications, tungsten carbide. Deep hole drill bits are aligned with the cylindrical surface of the hole being drilled. Other types of drill bits include solid drill bits and core drill bits for larger diameters. Figure 8.41 shows various types of drills: a conventional spiral drill bit, a spiral drill bit with a tungsten carbide insert, a spiral drill bit with a tungsten carbide head, a two-lip deep hole drill bit, a solid drill bit head with a diameter of 120 mm and tungsten carbide indexable inserts, and a drill bit head with a diameter of 280 mm for core drilling. By the way, the two-lip drill bit has a hollow shaft and two openings on the cutting surfaces. The coolant (drilling emulsion) is fed through these. The drilling debris and coolant are discharged through the groove in the drill bit shaft.

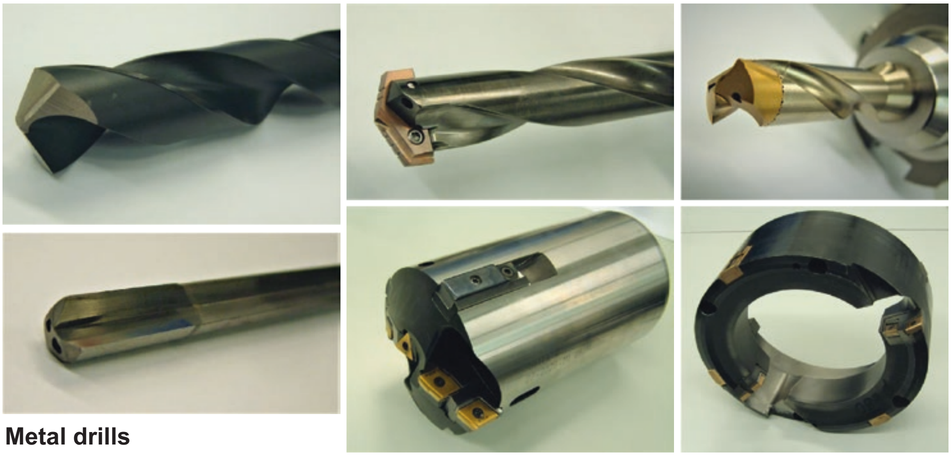


Fig. 8.41 Metal drills, *top:* conventional spiral drill, spiral drill with tungsten carbide insert, spiral drill with tungsten carbide head, *bottom:* lip drill, solid drill head Ø 120 mm and drill head Ø 280 mm. (Photos: Schlegel, J.)

The **machines for drilling** steel can be distinguished as follows:

Hand drill machines

Typical hand drill machines are present in almost every household and indispensable for a do-it-yourselfer. These hand drill machines are used for drilling in steel as well as in wood, concrete and other materials.

Drilling machines

These include the table and floor-standing drill machines and the universal drill machines, which are mostly equipped with a CNC control today.

Drilling benches

Drilling benches are horizontally aligned drilling machines for processing mostly very long steel products.

Machining Centers

For the machining process of drilling in combination with turning and/or milling, today's most modern CNC machining centers are in use.

With classical metal cutting drilling, various tasks are fulfilled:

- Drilling into the solid material, reaming, blind-hole or through-hole drilling, countersinking
- Deep hole drilling
- Fine machining (reaming)

Steel products that receive a drilling operation and usually also turning and milling operations can by no means be listed in full. Only a few examples should be given: hollow bars, various machined parts (milled, turned, drilled), e.g. sun shafts for wind turbines, planetary gear parts, flanges, parts for the automotive industry, for machine and plant construction, for aerospace, for power plant construction, chemical plant construction, for thermal power plants, etc. Figure 8.42 shows, for example, turned and drilled parts for machine construction.

Drilling also includes sinking and reaming as post-processing techniques for already produced holes. When sinking, holes are deburred or provided with a defined cone-shaped and cylindrical enlargement. Figure 8.43 shows these possible forms of cone-shaped and cylindrical sinking.

The tools used are the countersinks or counterbores (cone or profile countersinks) made of high-speed steel or hard metal.

To improve surface quality as well as form and dimensional tolerances, holes are often subsequently finished with a reamer (reaming). Only a small amount of material is removed, i.e. the enlargement of the bore diameter is very small.

Fig. 8.42 Turned and drilled parts for machine construction. (Photo: Schlegel, J.)

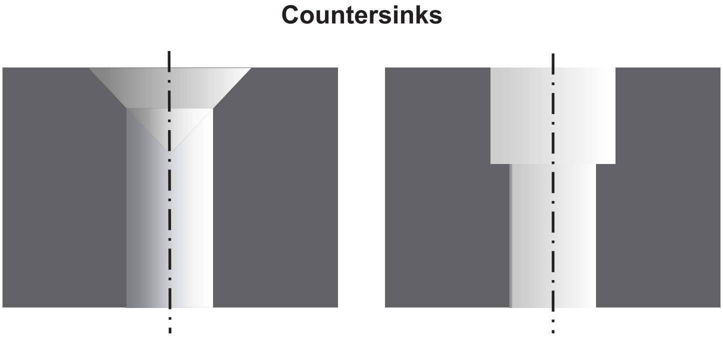


Fig. 8.43 Sink forms: cone-shaped and cylindrical

Laser drilling can be considered as a special process of machining steel, since no chips are produced. The laser beam heats the material to the point of melting and vaporization. Precisions of up to one micrometer are possible. Therefore laser drilling can be used for small holes from a diameter of 40 µm where this is simply not possible with mechanical drilling. For example, laser drilling is used for the insertion of nozzle channels in diesel and gasoline injectors utilised in injection technology for combustion engines.

A very special drilling process is electrical discharge machining (EDM). It is mainly used to generate the starting holes for a subsequent wire drilling (Sect. 8.3.8: *Electrical discharge machining*).

8.3.8 Electrical Discharge Machining

▶ Sometimes when taking off clothes made of synthetic fibers, small light arcs appear. You can hear a slight crackling and also feel it. The clothes had been electrostatically charged and now discharged again. This effect can be increased by applying high electrical voltages so that targeted sparks occur, which are already more than just painful and show a destructive effect where the sparks jump. It was *Joseph Priestley* (1733–1804) who first discovered this destructive effect of electrical discharges in 1770. Of course, it was not exactly desired in many switchgear operations. Only in 1943 did scientists come up with the idea of deliberately exploiting this effect for controlled material removal. It took until 1955 before a first tool machine for spark eroding was introduced and came into industrial use.

Today the following methods based on electrical discharge machining (EDM), also known as spark machining or spark eroding, are used: sinker EDM, hole drilling EDM and the spark-eroding cutting (wire-cut EDM).

Sinker EDM

On sinker EDM (electrical discharge machining) machines, the electrically conductive workpiece to be machined is positioned in a bath of non-conducting liquid, called the dielectric. The tool, usually a copper or graphite block, has the negative geometric shape that is to be machined into the workpiece. Now the workpiece is switched as the anode (negative charge) and the tool as the cathode (positive charge). With a targeted discharge technology (voltage, current, discharge intervals, pause intervals), sparks are generated in the gap between the tool and the workpiece (usually about 0.004 to 0.5 mm), which lead to a removal, melting and vaporization of material from the workpiece. Figure 8.44 schematically shows this principle of operation of sinker EDM.

Sinker EDM is used where complicated, deep and narrow contours are to be produced in a tool made of tool steel, including hardened steel, e.g. for moulds for plastic injection moulding, cutting dies and matrices for machine and plant engineering.

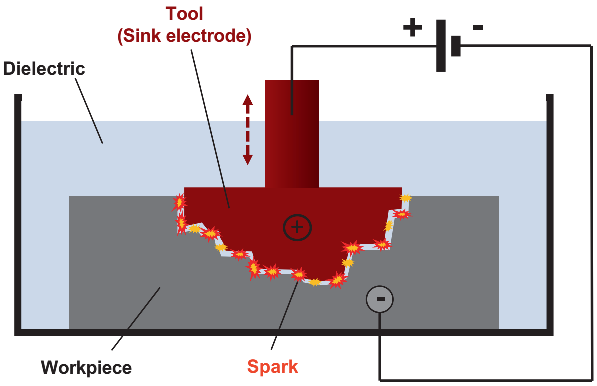
Hole drilling EDM

Hole drilling EDM can be regarded as a special application of sinker EDM. Copper or graphite tubes in the diameter range from 0.13 to 3 mm are used as sinker tools. These are constantly replaced due to wear. The main purpose of hole drilling EDM is to create the start holes in the workpieces for subsequent wire-cut EDM. Therefore, the EDM machines used are also called start hole drilling machines.

Wire-cut EDM

In wire erosion, an electrode in the form of an almost infinitely long wire is used which is constantly pushed forward. This allows various shapes to be cut out of a steel work-

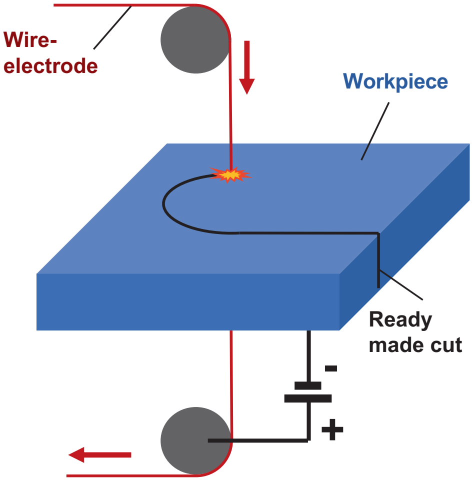
Fig. 8.44 Principle of operation of sinker EDM



piece with a high degree of precision by means of electrical discharge machining. For this reason, this process also belongs to the group of cutting processes. Figure 8.45 shows the principle of operation of wire-cut EDM schematically.

Messing, copper, tungsten or steel are used as material for the wire electrodes with diameters of approx. 0.02 to 0.33 mm. All conductive materials, preferably tool steels, can be machined independently of their hardness due to the process, whereby very small cutting widths and sharp-edged contours with high dimensional accuracy are created. It must be noted that classical building steels complicate the erosion process because of

Fig. 8.45 Principle of operation of wire-cut EDM



their low homogeneity and their impurities. Semi-finished products with the tendency to deform during machining may possibly not be eroded.

8.3.9 Fine Machining

▶ Fine machining is always the last machining step in order to achieve an improvement of the dimensional and shape accuracy as well as the surface, e.g. in terms of improved sliding properties. Only a very minimal material removal from the surface takes place. This includes the methods of lapping, honing, reaming and polishing. The presented methods of grinding as well as wire and sinker EDM can also be assigned to fine machining.

Lapping

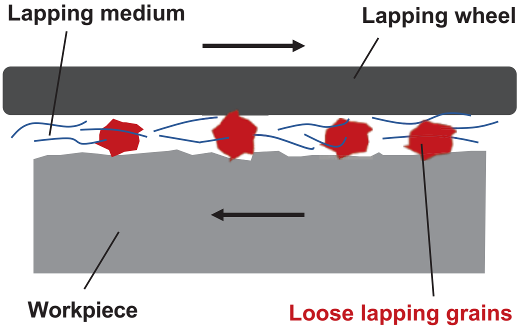
When lapping, instead of using abrasive grains that are bound together tightly, like when grinding with grinding wheels, loose grains (lapping powder) are used. These grains are mixed with a paste or liquid (lapping medium). The smoothing of the workpiece surfaces in multiple directions is done mechanically, often by hand, using a lapping disc. Figure 8.46 shows the working principle of lapping schematically.

There is a distinction between plane, parting, round, screw, roll and profile lapping. These smoothing processes are particularly suitable for machining very hard surfaces, e.g. in gear pumps or injection nozzles, i.e. where the smallest dimensional and form tolerances of a few micrometers are required.

Honing

The honing process is used to machine flat and cylindrical inner surfaces (bores). The honing tools are self-aligning and self-centering. The honing of cylinder inner surfaces of combustion engines and hydraulic components is commonly known. Figure 8.47 shows a schematic view of honing with a tool (hone).

Fig. 8.46 Working principle of lapping



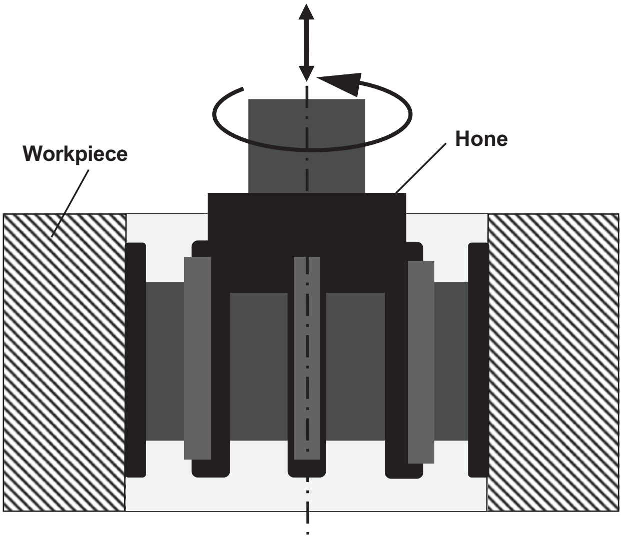


Fig. 8.47 Working principle of honing with a honing tool (hone)

Reaming

Fine machining by turning with multi-toothed tools in a straight, helical or circular cutting motion is referred to as reaming. The reaming tools (reamer) for external reaming and reaming needles for internal reaming are pulled along the outside of the workpiece to be machined or through an existing borehole. The reamers have geometrically determined cutting edges with integrated gradations for the depth of cut. They are mostly made of high-speed steel and often with a titanium nitride coating. Figure 8.48 shows the reaming of a bore with a reaming needle schematically.

The methods of plane, cylindrical, screw, profile and form reaming are distinguished according to the shape of the workpieces to be machined. In addition, there are the special methods of turning and chain reaming. The mentioned methods can be used as wet, dry, hard or high-speed reaming. Reaming is used where the desired contours cannot be generated by turning and milling and the highest dimensional accuracy and surface quality are required (e.g. for gears, wrench keys, grooves in machine components).

Polishing

▶ After washing, wax is usually applied and then polished nicely. Our car shines like new again. Of course, the aluminum and chrome surfaces are also polished to a high gloss. This is done with special pastes or liquid polishes, the composition of which also depends on the condition or degree of wear.

This smoothing process is used to improve the surface quality of steel components in terms of favorable sliding friction and improved optics. Mechanical polishing and electro-polishing

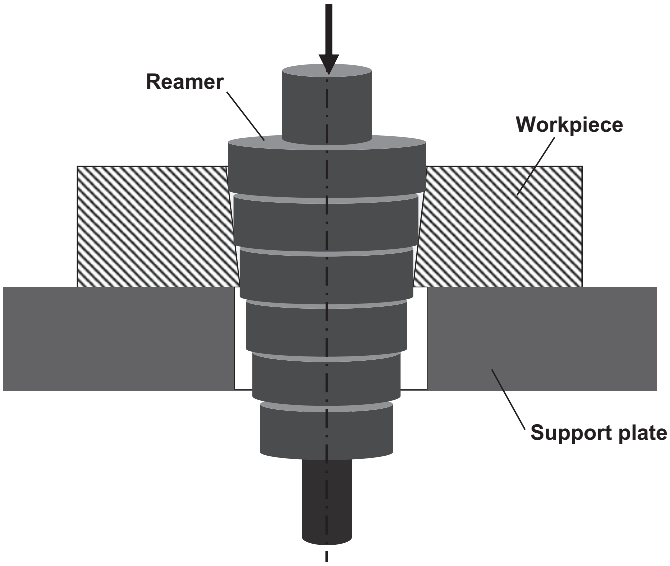


Fig. 8.48 Reaming of a bore with an internal reamer

and plasma polishing are distinguished. The classical *mechanical polishing* is done mechanically or by hand with a polishing tool (polishing disc) and polishing powder in a paste. The starting condition of the surface to be polished, the contact pressure and the polishing speed of the polishing tool are decisive for the polishing result. In industrial production, polishing is usually automated with rotary transfer machines or robot technology.

In *electropolishing*, the material is removed from the surface to be polished electrochemically in an electrolyte under voltage. The *plasma polishing* is similar to electropolishing, but higher voltages are applied. As a result, a plasma film forms around the workpiece, which can remove the roughness peaks. Areas of application for electropolishing are, for example: facade panels, jewelry (decorative appearance), pipeline construction, container construction and tanks for the food industry, medical technology (surgical instruments), parts for the aerospace industry. Electropolishing is also used in metallographic laboratories for microsection preparation for microstructure examinations.

8.3.10 Machining Bar Ends

▶ **Note** In the blank steel fabrication (manufacturing of bright bars with tight tolerances and highest surface quality) an additional special machining of the rod ends according to customer specification is carried out. This includes machining techniques such as cutting, deburring, turning, centering and chamfering, used individually or in combination. The customers are manufacturers of turned parts and use CNC long-turning machines. For them, bars with a defined bevel are important for a smooth, automatic feeding of the bright bars from the bar feeders into the guide bushings of the turning machines.

Based on this, the following this chamfering or beveling of bar ends will be presented.

Chamfering

Chamfering off the ends of bars is done with a chamfering tool in a way that is roughly comparable to sharpening pencils. Figure 8.49 shows the principle of operation for chamfering with a tool head that has two cutting edges made of hard metal indexable inserts.

The results are geometric shapes of the bars as planned and chamfered, chamfered, and centered and chamfered, with different possible chamfering angles. Figure 8.50 shows three practical examples from bright steel production.

For all methods of machining bar ends, saw blades, saw bands, cutting-off grinding discs, turning chisels, center drills and special end milling cutters, e.g. rotating end milling cutters, are used as tools. Therefore, the bright steel works are equipped with the following machines: jig saws, band saws, cutting-off grinding machines, lathes and end milling machines for single-sided or double-sided end milling, also semi-automated and combined inline with surface inspection machines.

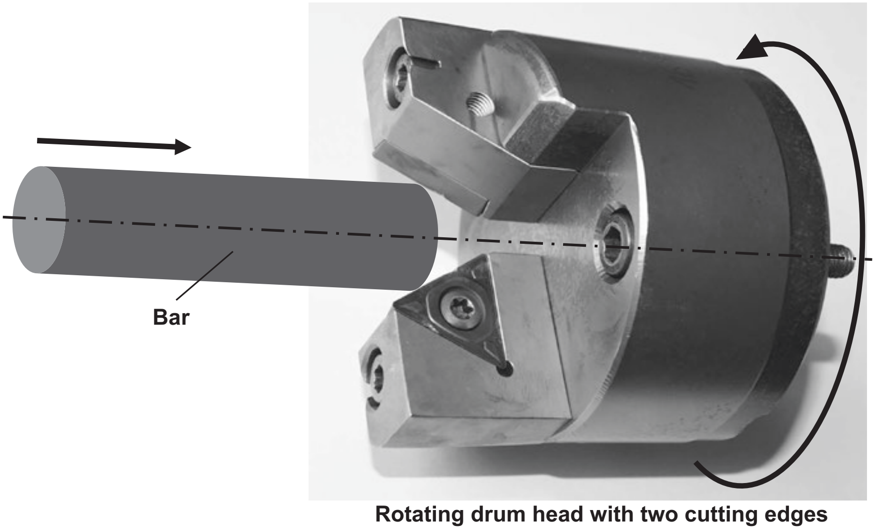
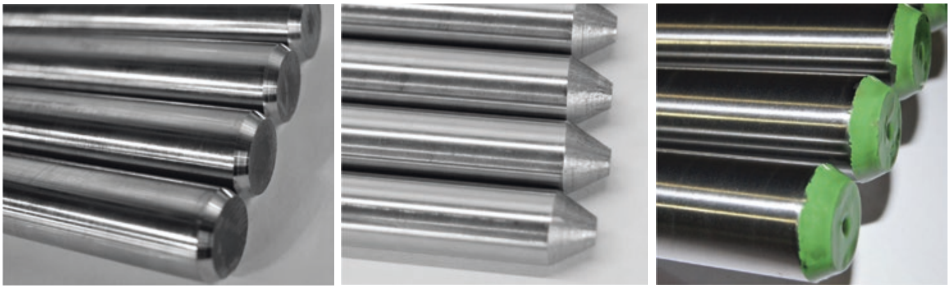


Fig. 8.49 The principle of operation for chamfering the ends of bars. (Photo: Schlegel, J., BGH Edelstahl Lugau GmbH)



Bars peeled, ends chamfered at 45°

bars ground, ends 30° pointed

Bars, ground, ends planned, chamfered and centred with colour marking

Fig. 8.50 Examples of executions of bar ends, *from left to right*: peeled bars, ends chamfered; ground bars, ends pointed; ground bars, ends planed, chamfered and centered with color marking. (Photos: Schlegel, J. BGH Edelstahl Lugau GmbH)

8.4 Cutting

▶ We experience and carry out cutting processes every day. Salad and vegetables, hair, fingernails and toenails, paper, wood, plastics and metals for DIY and craft work, trees, hedges and much more is cut. And this always leads to a local destruction or cancellation of the material cohesion. The original cross-sectional shape is not changed. Various tools and cutting techniques are used for this. Whether with material loss or chip free, cold or hot, manually, mechanically or automatically, the cutting takes place almost everywhere, even in the production of steel products. Starting with the shearing of scrap into suitable sizes for filling the electric furnaces, the shearing of the rolled, still hot semi-finished product (separation of head and foot), the out separation of test material for material testing, the removal of non-quality-compliant, e.g. uninspected bar ends in the bright steel production, the cutting of customer-specific semi-finished lengths in service centres, the generation of exact cut surfaces for welding connections up to the cutting of wire pieces in turning machines (escomatic machining) for the production of precision turned parts.

The following cutting methods are to be distinguished:

- *Cutting of steel parts without producing chips in a mechanical way*: Shear cutting (power shearing)
- *Cutting in a mechanical way by producing chips with geometrically determined cutting edge*: Turning (turning off), sawing (band, circular sawing)
- *Cutting on a mechanical way by producing chips with geometrically undetermined cutting edge*: Cuttoff grinding

- *Cutting by stripping or removal of particles in mechanical, thermal or chemical ways*: Water jet cutting, torch cutting, melting cutting, spark eroding

The following should be presented as a focus Procedures Shearing, *Sawing*, Cuttoff grinding, *Waterjet Cutting* and Thermal Cutting.

8.4.1 Shear Cutting

One distinguishes between shear or knife cutting, biting (for example with the pliers or the side cutter), breaking, tearing and splitting. For **shear cutting** in smelting works, drum, crank or pendulum shears are used. Figure 8.51 shows the principle of action of shear cutting on the example of the hot shear of a rolled square billet at the end of a blooming mill.

In production lines for long products (rod and wire), so-called flying shears are used. These carry out the shearing process in motion, adapted to the through-put speed of the long product. Flat products (steel strip) must be trimmed and also cut transversely. This is done with circular knife shears and length-cutting shear plants.

An interesting mechanical separation process is high-speed cutting. Similar to a karate fighter who can break bricks, a wood board or a stack of concrete slabs with his

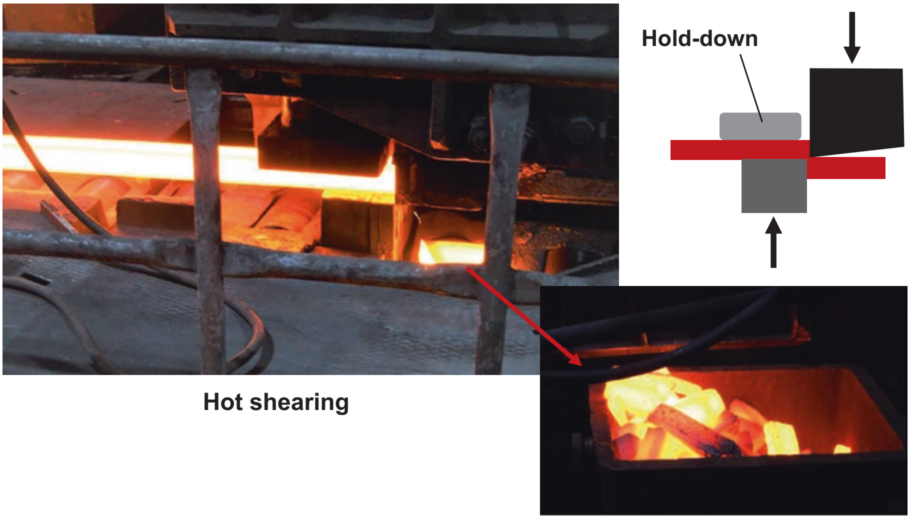


Fig. 8.51 Principle of action of shear cutting on the example of the hot shear of a rolled square billet at the end of a blooming mill. (Photo: Schlegel, J. BGH Edelstahl Freital GmbH)

bare hand, the cutting tool is accelerated impulsively here. With up to approx. 10 m/s, the material cutting then takes place "karate-like". Figure 8.52 shows this cutting technique.

Compared to classical separation, this process, also called "High-Speed-Impact-Cutting (HSIC)" or "adiabatic" separation, offers advantages especially for medium and large quantities of almost all materials such as extremely short cycle times, almost flat and burr-free cut surfaces, no burr and no chips.

8.4.2 Sawing

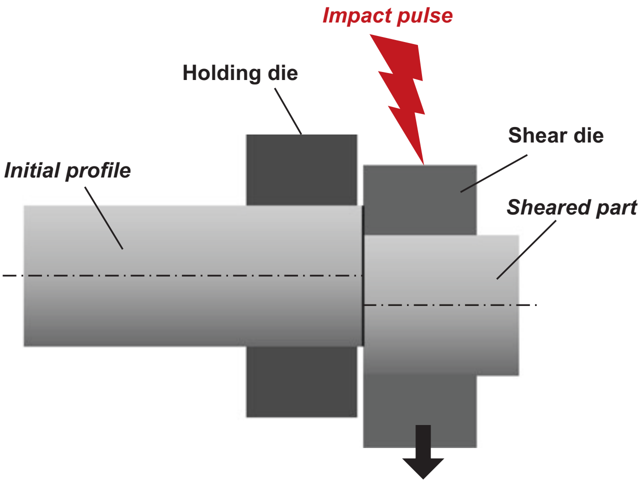
▶ Sawing is an ancient method that was already used in the Stone Age for woodworking. Since the industrial metalworking, steel parts are sawed in particular in mechanical engineering. For this purpose, new cutting materials (high-speed steel, hard metal) were implemented in the 1970s. From now on sawing could also be very precise and productive and be used for finishing.

Sawing is a material-removing manufacturing process in which a tool, a reciprocating hacksaw, a band saw or a rotating circular saw, is used to cut slots and separate the workpiece by removing chips. Figure 8.53 shows the sawing, for example, with a circular saw and a band saw.

8.4.3 Cutoff Grinding

In comparison to the sawing process (cutting with defined blades/saw teeth), cuttoff grinding is a machining process with undefined cutting edges. The tool used is a rapidly

Fig. 8.52 Working principle of high-speed cutting



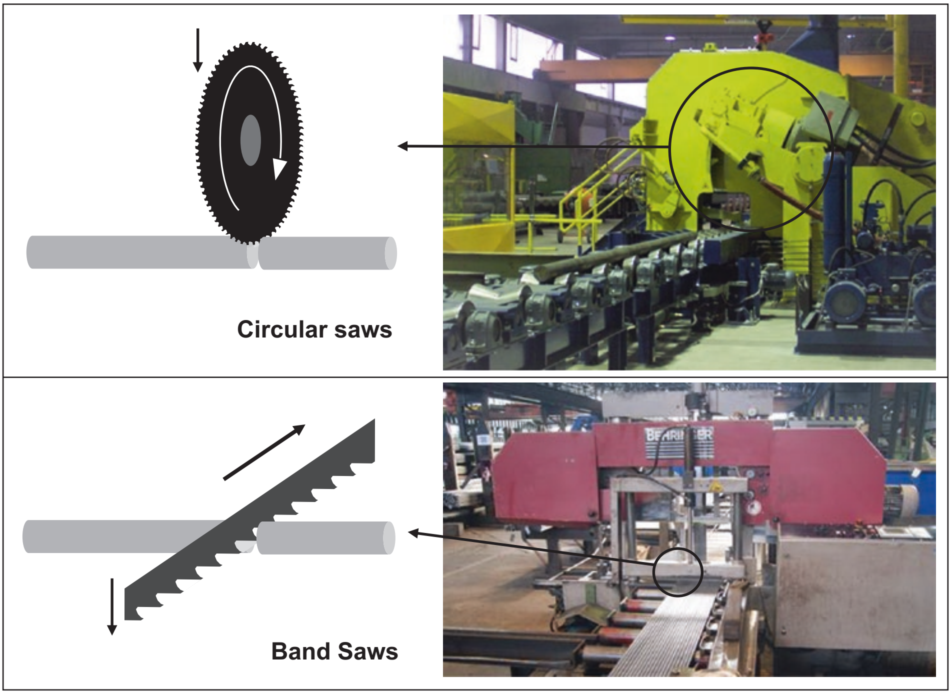


Fig. 8.53 Cutting with a circular saw and a band saw. (Photos: Schlegel, J., BGH Edelstahl Siegen GmbH and BGH Edelstahl Freital GmbH)

rotating cutting or grinding wheel made of very hard corundum (aluminum oxide) and silicon carbide, for particularly hard steels also made of boron nitride and diamond. The cuttoff grinding process is used when classical sawing of high-strength, hardened steel profiles is no longer economically feasible.

Depending on the requirements, different cutting wheels and machines are used for cuttoff grinding. The well-known angle grinder is particularly versatile and flexible. With this electrically powered hand machine, also called cutting grinder or Flex, hard metals can be easily and quickly ground and cut. Figure 8.54 shows this using the example of cutting an angle profile made of stainless steel. In the steel semi-finished product manufacturing companies, high-performance cutting grinding machines, partly automated, are used for cutting round and profile semi-finished products.

Dry or wet machining is possible with all cutting methods that involve chip removal. The resulting frictional heat during sawing and cutting must be dissipated with the chips that are removed. It is advantageous to cool and remove the hot chips and grinding particles by means of a coolant and flushing the workpiece. This is not necessary with water-jet cutting.

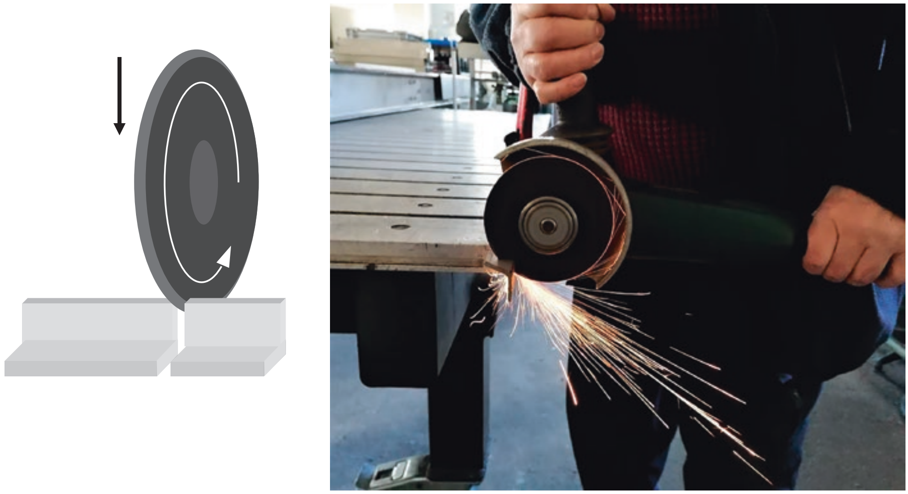


Fig. 8.54 Cutting a stainless steel profile using a cuttoff grinding wheel. (Photo: Schlegel, J.)

8.4.4 Water Jet Cutting

▶ The water jet is known from mining in the early twentieth century. It was used to remove gravel and clay layers and in gold mines to separate the gold veins from stones and earth, later also to clean casting pieces. From the end of the 1960s, water jets were used to separate composite materials in aircraft construction. When powdered hard particles were added to the water jet as an abrasive agent, the industrial use began as a special manufacturing process for deburring, cleaning surfaces and separating different materials (Schulze 2015).

The cutting with water jet is based solely on the high pressure with which the jet hits the workpiece. This causes the smallest particles to be chipped off. In the industrial practice of metal cutting, pressures between 1000 and 6200 bar and exit speeds of about 900 to 1000 m/s are used (Schulze 2015). Figure 8.55 shows the principle of operation of water jet cutting on the example of a high-pressure CNC water jet cutting machine for cutting out steel samples for material testing in a stainless steel plant. This plant works with a water pressure of 3800 bar at an exit speed of 3600 km/h (1000 m/s).

Water jet cutting machines consist of water treatment, high-pressure generation with pumps and jet generation by means of a nozzle with a diameter in the range of 0.1 to 0.5 mm. The working or cutting pressure determines the achievable cutting depth (Risse, 2012). When water jet cutting, the workpiece is not thermally stressed. Very fine and complex contours can be cut, resulting in a slightly oblique cutting edge. Water jet cutting without the addition of abrasives, the so-called pure water jet cutting, is mainly used

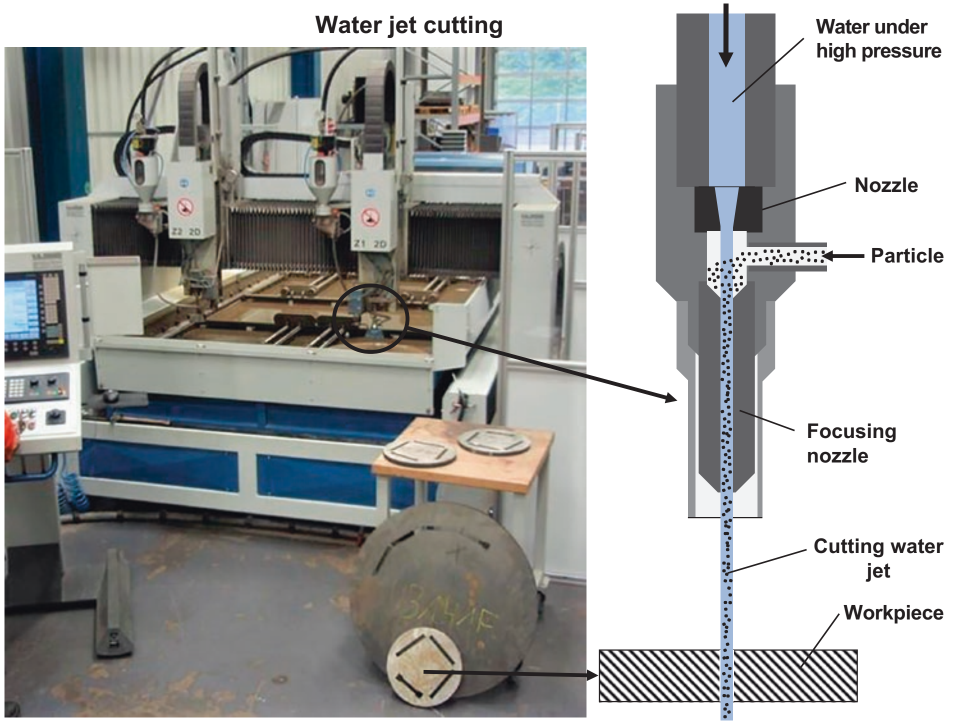


Fig. 8.55 Water jetcutting with a high-pressure CNC waterjet cutting machine for cutting out steel samples for material testing in a stainless steel plant. (Photo: BGH Edelstahl Siegen GmbH)

for soft and tough materials such as plastics, textiles, rubber, foam, paper and food. Hard and very thick workpieces can only be cut with an abrasive water jet (water jet with the addition of powdered, hard sand). This applies to materials such as stone, bulletproof glass, ceramics, marble and metals. Water jet cutting is possible for steels with thicknesses up to 50 mm (Schulze, 2015).

8.4.5 Thermal Cutting

▶ In addition to shearing, sawing, cuttoff grinding and water jet cutting, thermal cutting methods are also available. These include torch cutting, melting and sublimation cutting. These cutting methods will be presented below.

Torch cutting

Torch cutting, also known as oxy-fuel gas cutting or oxy-acetylene cutting, is a process that involves the use of a fuel gas and oxygen to cut metals. This is done by heating the metal to its ignition temperature and then using a stream of oxygen to cause it to burn.

This cutting with a flame is a widely used, economical process that can be used to cut steel thicknesses of up to 1000 mm. However, the quality of the cut edges or surfaces is only moderate. Figure 8.56 shows the principle of operation using the example of oxy-fuel cutting of a forged round bar.

Stationary torch cutting machines (oxyacetylene cutting machines) and mobile hand-held cutting torches are used. With these relatively small and light devices, very flexible and fast cutting tasks can be carried out, e.g. in workshops, on construction sites, during the dismantling of steel structures, during the scrapping of various machines, plants and other steel parts, also from ships, etc. Laser cutting is also used for special tasks, e.g. for processing thick sheets.

Melting Cutting

In melting cutting the cutting process takes place in two partial steps. The workpiece is melted locally at the separation point. With a gas jet, this liquid melt is hurled out of the separation gap in the form of droplets. This happens, for example, during laser melting, plasma or electron beam cutting. The advantage is that, as a result of the gas used (nitrogen or argon), almost oxide-free cutting edges are produced. Therefore, melting cutting, preferably laser melting cutting, is used where workpieces have to meet high optical requirements without further work. All fusible materials, especially highly alloyed steels, can be cut. Figure 8.57 shows the principle of action of laser fusion cutting in compari-

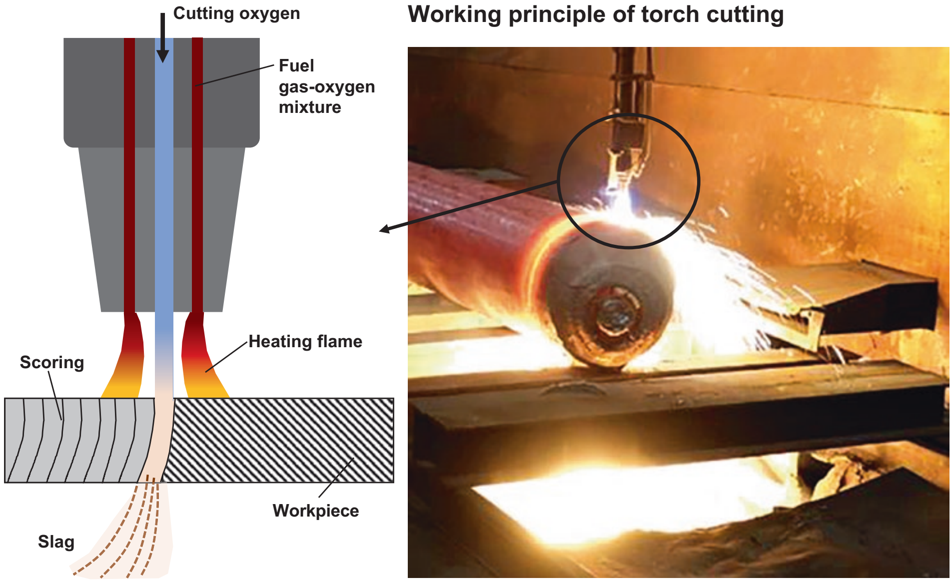


Fig. 8.56 Cutting of a round bar by means of oxyacetylene(torch) cutting. (Photo: Schlegel, J., BGH Edelstahl Lippendorf GmbH)

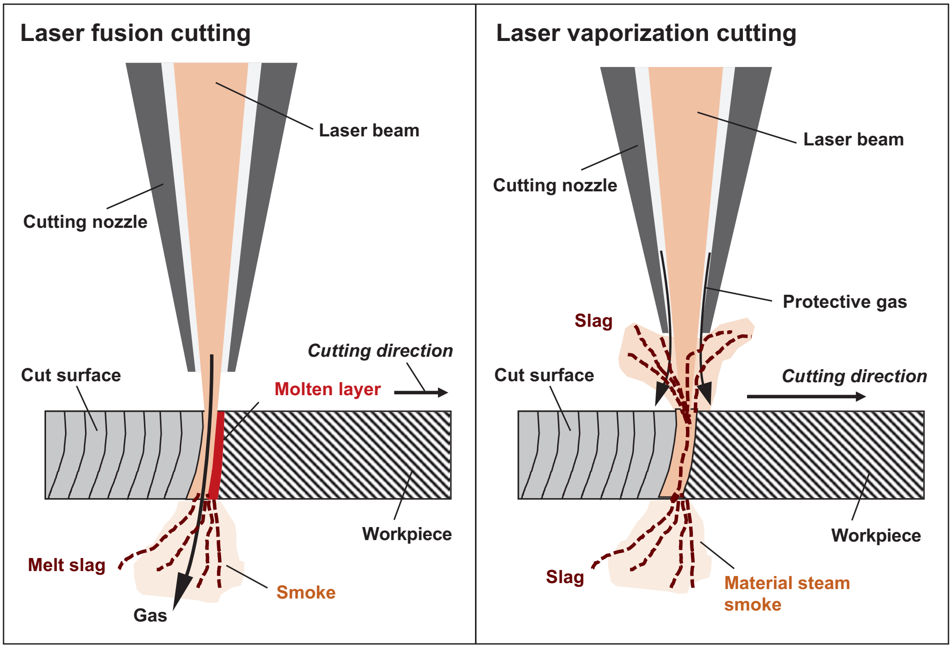


Fig. 8.57 Comparison of the laser fusion and laser vaporization cutting of steel

son to a similar cutting process, vaporization cutting. Here, the material of the workpiece is vaporized at the point to be separated by a laser beam. This vapor hurls the still molten material out of the separation gap upwards and downwards. A process gas (nitrogen, argon or helium) is used to keep the cutting surface oxide-free. This vaporization cutting process is used especially for thin and sensitive workpieces. Complex contours can be produced with high accuracy and high-quality cutting edges.

Conclusion

The machining process **cutting** is used by the steel-producing industry:

- *in the semi-finished product adjustment before further processing as well as for the production of finished lengths,*
- *in the bright steel production (bar) for the production of fixed lengths or bar lengths according to customer requirements,*
- *for service purposes, i.e. for the production of customer-specific cuts,*
- *for sampling purposes in preparation for material testing.*

Often, for technological reasons, the separating process also includes additional machining of the semi-finished product edges or the ends of the rods, e.g. by planing, chamfering and centering. And in the further processing industry, the separation process is used in many ways. Steel can be separated or cut in very different ways. But not every cutting process is also suitable for every steel and for every cutting task. For example, as a do-it-yourselfer, you have already noticed that, for example, very thin sheet steel is difficult to saw. The thickness, the steel quality and the thermal load capacity of the workpiece, the cutting task (coarse, fast cuts, for example when shredding scrap or precise, narrow cuts in toolmaking), economic reasons and also environmental conditions play a major role in the selection of an appropriate cutting process.

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9

Finishing

▶ Hardening and tempering of bars leads to the desired strength properties, but the bars are usually slightly crooked. The further processing by centerless grinding requires "straight" bars. The customer, a manufacturer of precision turned parts, also requires very straight bars. So they have to be straightened. Rolled billets sometimes have cracks on the surface. These could intensify during further processing by cold forming, so they should be removed before this forming. Samples have to be taken for process-accompanying quality control after the various processing steps. Cutting edges have to be deburred and the products have to be labeled for safe identification. This list could be extended even further. Everything that happens during and at the end of the production line in the steel-producing and processing industry is assigned to the finishing (adjustment) (Hiersig, 1995). The term adjustage comes from the French "adjuster" and means something like aligning, i.e. making or putting in order. Various post-processing steps are necessary for this. These are based on the product (material, delivery condition and geometry) as well as on the requirements for further processing or for the application.

The finishing usually includes the following steps:

- *Cutting to achieve the dimensions desired by the customers* (see Sect. 8.4: *Cutting*)
- *Machining the cutting edges, the billet and bar ends* (deburring, chamfering, see Sect. 8.3.10: *Machining bar ends*)
- *Straightening to secure the requirements for straightness*
- *Surface treatment* (cleaning, coating) and *removal of surface defects*
- *Sampling for quality control* (in-process and final inspections)

J. Schlegel, *The World of Steel*, https://doi.org/10.1007/978-3-658-39733-3_9

- *Signing, color marking or stamping for clear identification of the product*
- *Intermediate storage*
- *Completion* (assembly)
- *Packaging and shipping*

Often, heat treatment is also assigned to the adjustage area in companies. Below, only some of these adjustagework can be presented with examples of product-related applications, particularly for semi-finished steel, such as surface treatment, straightening, completion, packaging and shipping.

9.1 Surface Treatment

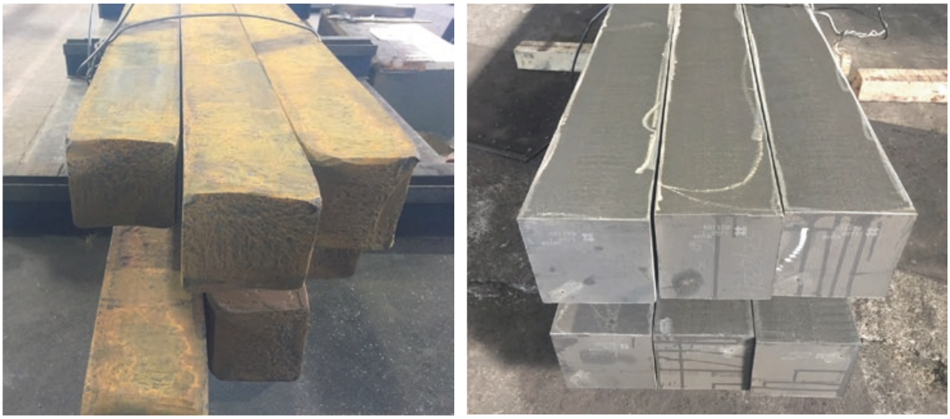
The work included in the adjustment to treat surfaces is based on the steel intermediate product (type, shape and size: e.g. a forging, a bar of steel or a rolled wire, a rolled profile, a tube, a strip or a sheet), the type of further processing and also the conditions during final use as a finished component. Methods such as cleaning, brushing, pickling, polishing, blasting, peeling, grinding, deburring and coating are used.

A surface treatment with a defined mechanical surface removal by blasting, peeling, grinding (see Sect. 8.3: *Machining*) is carried out, for example, on cast ingots and on already rolled billets made of crack-sensitive steels. The aim is to remove oxide layers as well as to clean or grind out defects (repair grinding), to remove surface defects caused by rolling and forging as well as to prevent the propagation of cracks during subsequent further forming. Figure 9.1 shows, for example, the cleaning effect by blasting of rolled square billets which, after heat treatment by quenching in water, had a slightly oxidized surface. In addition, the edges were ground.

Figure 9.2 illustrates the surface treatment by means of grinding round continuous casting billets immediately before further hot rolling to wire. In addition, a locally ground out defect on a round billet is shown, which was generated by hand with an angle grinder.

Cleaning, for example chemically by pickling, electrochemically in a galvanic bath, or mechanically by brushing, is used in particular to remove dirt and lubricant residues from the surface of drawn wires, bars, pipes or profiles, and to remove rolling, drilling, grinding emulsions from semi-finished products and machined parts. In this way, contamination of the furnaces and adhesion of burned-out lubricant residues on the product can be avoided during a heat treatment process. Fat-free, clean surfaces are also required for a subsequent coating.

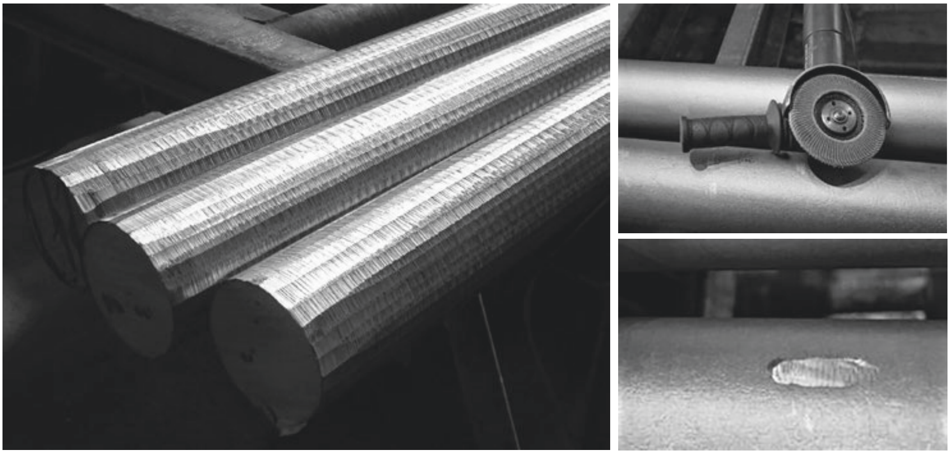
In both stainless steel production (cutting, aligning bars), sheet metal cutting, generally in the cutting of products, but mainly in the mechanical processing of workpieces in the metal processing industry, burrs (sharp edges, fibrations) are formed by material displacement. These represent a danger of injury and, under certain circumstances, also



Square, rolled, raw, heat treated,
after quenching in a water bath

Square, rolled, raw, heat treated,
after blasting, edges ground

Fig. 9.1 Example of a surface treatment by blasting: Cleaning of rolled square billets after heat treatment and quenching in water. (Photos: Schlegel, J., BGH Edelstahl Freital GmbH)



Continuous casting billets, machine ground over

Round billets, blasted and
with ground out defect

Fig. 9.2 Machine-ground continuous casting billets, prepared for further hot rolling, as well as blasted round billets with a locally ground out surface defect. (Photos: Schlegel, J., BGH Edelstahl Freital GmbH)

impair the further processing or function of a finished component. The **deburring** and rounding of sharp edges can be carried out mechanically, chemically or, more recently, by plasma treatment, depending on the product.

In the adjustment, a coating of semi-finished product, e.g. drawn wire, which is to be further processed into screws by cold forming, is carried out under certain circumstances. This wire is provided with a sliding lubricating film by dipping, spraying or brushing, which in combination with the lubricant minimizes friction and thus tool wear during cold forming. And a coating is also carried out with suitable corrosion protection agents in order to prevent corrosion during storage and transport.

In addition to the technologically justified cleaning of the semi-finished product surfaces and the securing of a desired corrosion protection, quality assurance measures also play a role in the adjustment. For example, testable surfaces must be created for hardness, mix-up, surface and core defect tests.

9.2 Straightening

The manufacturing stages of forming, heat treatment, machining and also separating, joining and coating processes can also lead to the products becoming deformed or distorted. Internal stresses, unwanted unevenness, bends, wave-like deformations and thus also dimensional deviations occur. However, industry is increasingly demanding tighter tolerances. Therefore, between the manufacturing stages and at the end of production, the semi-finished products such as rolled, forged and drawn bars, pipes, profiles, flat steel, wire, sheets, blanks, waves, spindles, rails, precision turned parts, cold-stamped parts, welded structures, etc. must be straightened. This can be done with a lot of experience and a good eye by hand with light hammer blows on the anvil or on a straightening bench, similar to how straightening is still often done in craft-oriented, smaller businesses today. It is a forming process in which products are straightened by a slightly plastic change in shape. Pressure is applied against the curvature and a slight bending is generated. The main dimensions of the item to be straightened do not change within the tolerance limits. After the pressure is released, the part to be straightened is straight or it has to be stressed again. The material properties remain unchanged, except that, in particular in the surface-near area, stresses are introduced by the straightening process. Only the required straightness should be improved or, at the customer's request, process-reliably set by such a bend forming process. Figure 9.3 shows the straightening process in a simplified way with a representation of the compressive and tensile stresses as well as the fiber course in the workpiece to be straightened.

A constant result can be achieved with a fixed bend forming by using machines and also in continuous processing. Modern straightening machines detect by means of sensors the geometries before, during and after the straightening and adapt via an NC (numeric control) the height and position of the bend forming to the measured deviations.

For straightening of different steel products, different methods are used, which are mainly characterized by linear movements (straightening, bending) or by rotating tool

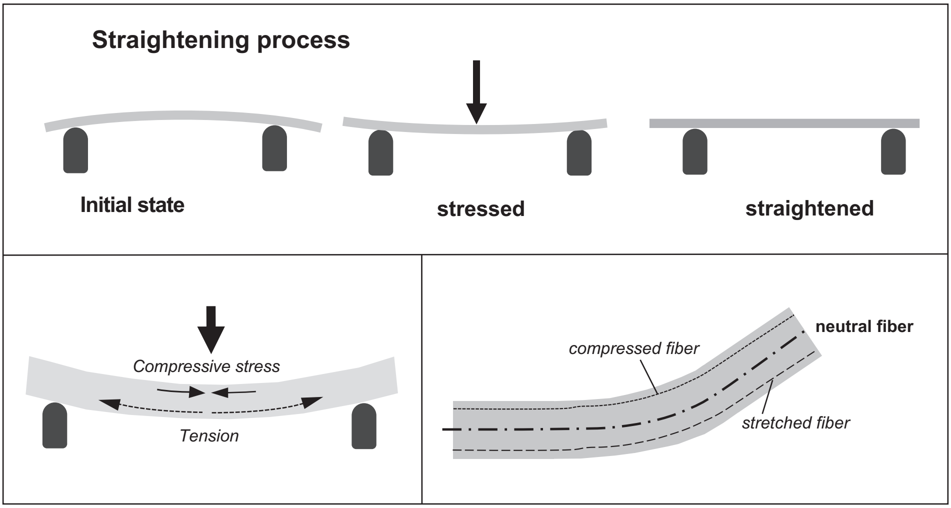


Fig. 9.3 Straightening process with representation of the stresses and fiber course in the workpiece to be straightened

movements (roll straightening), carried out discontinuously in individual steps or continuously. Figure 9.4 shows a comparison of these alignment methods.

The **stretching** is used for aligning bends in round bars, profiles or pipes. Plastic deformations of 1 to 2% are realized through tensile forces. Stretching is also used as an alternative to rolling for strip material. For this purpose, defined areas are unwound from the coil, clamped and stressed with tension beyond the stretching limit.

In **bending and straightening** a stamp presses on the workpiece to be straightened, which is fixed on two supports. This process of "free bending" can be carried out several times, always in a different orientation of the workpiece, until the desired straightness of the long product, usually round bars, is achieved. For example, using an automatically operating 10-MN-fine straightening press, long-forged semi-finished products with a diameter of 120 to 350 mm can be straightened to a straightness of 3 mm at a bar length of 16 m, see Fig. 9.5.

There are various techniques for continuous straightening, such as roll straightening in different variants according to Fig. 9.4 as well as the special processes of rotation straightening and straightening with straightening nozzles.

Roll straightening The straightening process of bars and pipes takes place by means of several, axially parallel, profiled rollers, of sheets or band by means of smooth rollers in roller straightening machines.

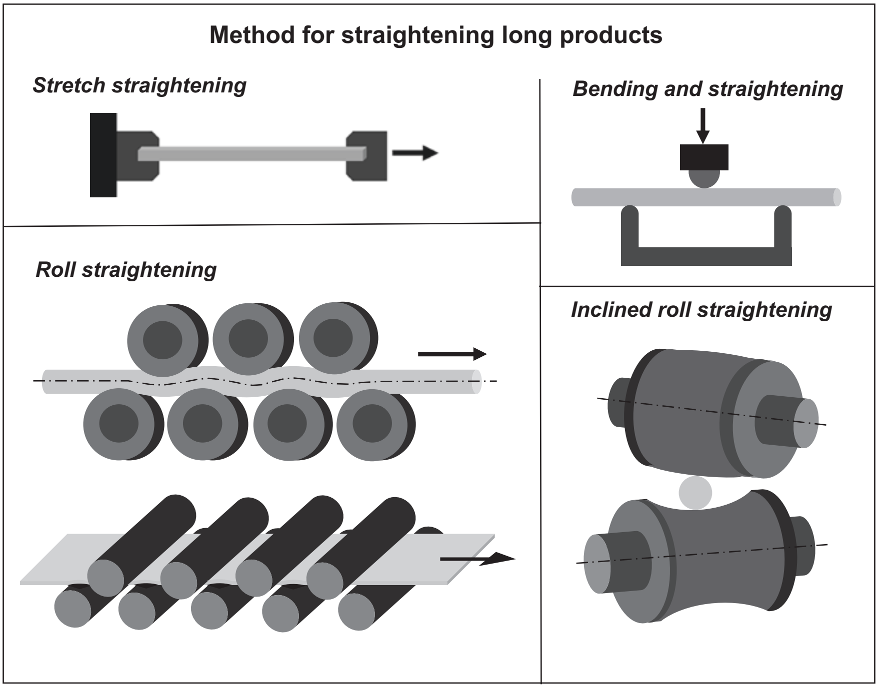


Fig. 9.4 Comparison of methods for straightening long products

Inclined roll straightening Inclined roll straightening means that the workpiece is guided between inclined arranged, concave and convex profiled rollers and is straightened. There are straightening machines with two or more rollers (up to 10 alignment rollers) in use.

Rotation straightening This straightening method (so called spinner-type straightening), used mainly in the production of bright steel, consists of several straightening jaws offset from each other and adjustable. These rotate in the straightening machine as a unit (alignment rotor) parallel to the workpiece axis. Figure 9.6 shows this straightening technique using a rotation straightening machine from the practice of a bright steel manufacturer. This machine is used to straighten wire, which is inserted in the form of a wire ring. The straightening result is a straightened wire, which is cut into individual bars of fixed length (3 m as standard) in the machine. In practice, this manufacturing step is called “straightening of wire to bar”.

Straightening with straightening nozzles Compared to the straightening rotor with adjustable jaws, this process uses several nozzles which are movable and rotatable perpendicular to the axis of the object to be straightened. The length-cutted bar rotates during the straightening process. Figure 9.7 shows this straightening process, which is used for fine straightening, for example in a so-called “automatic straightening and cutting-off line” for drawing and straightening wire and cutting the straightened wire to bars.

Fig. 9.5 Bending and straightening of forged round stock with an automatic 10 MN fine straightening press. (Photo: BGH Edelstahl Siegen GmbH)

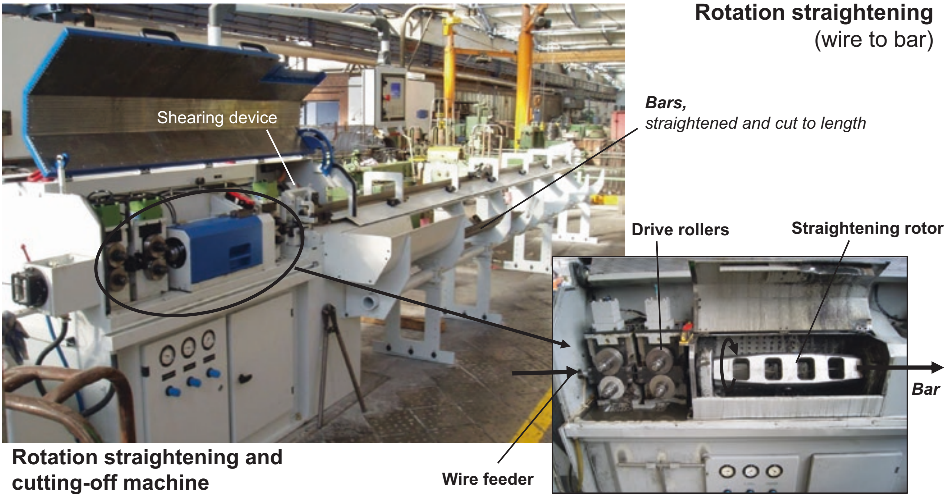


Fig. 9.6 Rotation straightening on the example of a rotation straightening machine for straightening wire to bar. (Photo: Schlegel, J., BGH Edelstahl Lugau GmbH)

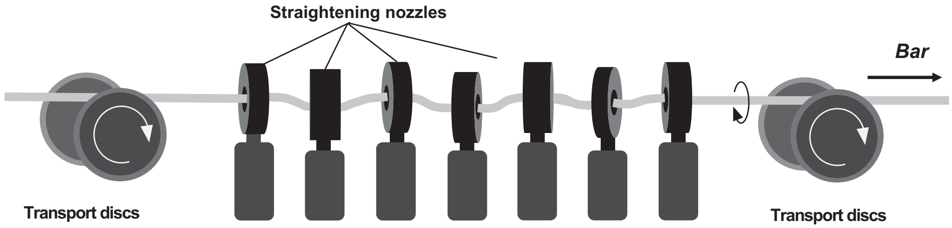


Fig. 9.7 Straightening of rods with straightening nozzles

The straightening methods described represent an important manufacturing step within the process chain for the production of bright bars from wire stock material in the bright steel production. Typical achievable straightness deviations are 0.5 to 1.0 mm/m.

9.3 Completion, Packaging and Shipping

The work in finishing shops includes all necessary work steps according to customer order to prepare the products for shipping and the assembly of the necessary documents. Depending on the product type (semi-finished product or machined finished part), this includes:

- the *packaging* (bundling and weighing),
- the *labeling* (stamping, labeling, marking),
- the *acceptance of the finished products* (e.g. by external assessors and testing organizations),
- the *creation of documents* (delivery papers, test certificates, customs declarations, etc.).

Typical facilities for completion and finishing the products are transport facilities, weighing facilities, storage facilities, bundling facilities for rings, bars, pipes, profiles, winding wire as well as tools and aids for labeling the finished products (signing and stamping facilities, color and barcode marking technology) as well as the necessary IT technology for documentation.

The **final inspection** and the **release of the products** include, in addition to the dimensional, quantity, weight and visual inspections, the mix-up check and the material tests specified according to the customer order. The results are documented in manufacturer’s certificates enclosed. This is particularly important for both the manufacturer’s own technological and logistical processes and for the subsequent processing of the products by the customers and their customers up to the final application, thus with regard to a clear identification and traceability of the products (product liability).

Now that the steel products are ready, that is, packaged, checked and released, packaging occurs according to customer requirements and taking into account, for example, weight restrictions, the emptying of trucks with a crane or forklift, crate sizes, and possibly the need for seaworthy packaging for overseas transport. A packaging, also called "emballage" in commercial terms, is therefore the deliberately applied, easily removable wrapping of a product (cargo). The packaging should protect the cargo from environmental influences, damage, contamination and loss, as well as the people associated with the cargo, e.g. from injuries, while also allowing a durable, safe labeling of the cargo. Packaging can consist of different materials, often specially developed only for packaging purposes. Packing aids are used primarily for sealing the packaging, e.g. binding wire, steel band, plastic band, jute, as well as for padding, e.g. foam. Figure 9.8 shows a mosaic of different types of packaging for different products made of steel.

The effort for packaging can vary greatly. No packaging, only bundling with binding wire or straps, is for example common with concrete rods and mats. Also larger, machined forgings are only mounted on Euro pallets, sometimes wrapped in shrink film. The higher the quality of the steel and the higher the surface quality, the more sophisti-

Fig. 9.8 Packaging types for various steel products. (Photos: Thyssenkrupp Steel Europe AG, Schlegel, J., BGH Edelstahlwerke GmbH)

cated the packaging. Therefore bright bars, ground, polished are always delivered packed in wooden boxes, wrapped in corrosion protection film. Since packaging also burdens the environment, its ecological balance must be considered. Alternatives are to be sought with regard to material, function, durability and disposal costs. The reuse, recycling and disposal of packaging are regulated in the Packaging Ordinance. This regulation also applies to steel products. In addition, special packaging regulations for export must be observed.

The finished products are now handed over to the shipping department within the company, while the so-called "ready to ship" message is generated in the company's internal order management systems. Figure 9.9 shows two examples of shipping departments for semi-finished products (bar material and bright bars).

Finally, the transport to the customer takes place. The Incoterms (**In**ternational **Com**mercial **Terms**), i.e. the international trade clauses created by the International Chamber of Commerce, must be observed in the trade in goods. These regulate the manner of delivery and specify who (supplier or customer) bears which transport and insurance costs and where the transfer of ownership of the product to the customer is to take place.

The semi-finished goods manufacturers, who produce semi-finished raw materials and semi-finished products such as plates, sheets, strips, bars, profiles, pipes and wire according to the product definition (Kurz et al., 2009), mainly supply the further processors, such as turning shops, stamping shops, cold upsetting plants, bending shops, i.e. the manufacturers of finished parts. The semi-finished goods manufacturer delivers directly to the customer as needed (customer order). In a special delivery variant, the semi-finished goods supplier first stores his goods on site at the customer in a special warehouse. This is called a consignment warehouse. The customer now takes the raw material for his production from this warehouse in a timely manner. These withdrawals are notified to

Automatic shipping store for round bars

Shipping store for bright bars

Fig. 9.9 Shipping departments for bar material and for bright bars made of stainless steel. (Photos: BGH Edelstahl Siegen GmbH; Schlegel, J., BGH Edelstahl Lugau GmbH)

Warehouse of a stockist and trader of stainless steels and metals in bar form

Fig. 9.10 View into the warehouse of a stockist and trader for stainless steels and metals in bar and wire form with small dimensions and tightest tolerances. (Photos: L. Klein SA, Biel/Bienne, CH)

the supplier, and if the minimum quantity is not met, this consignment warehouse must be refilled.

A second customer base for semi-finished product manufacturers are stockists, traders or service centers. They take over the storage of a certain range of steel and other metals in different semi-finished product forms, the cutting and packaging in small and very small quantities according to customer wishes, as well as the technical advice and delivery service regionally and internationally. In this way, the specific need for high-quality special steels is also covered in the most diverse product forms that a semi-finished product manufacturer could not deliver alone. This is, for example, important for companies in the automotive industry, aerospace, medical technology, electrical engineering and watch industry. This is understandable when considering how many crowns for mechanical watch movements of wristwatches could be made from a 3 m long, ground rod of wear-resistant watch steel. The watch manufacturer therefore only needs very small quantities of a few kilograms and these of special stainless steels that only a specialized stockist can provide. Figure 9.10 shows a view into the modern warehouse of such a stockist, who offers services for customers from the watch industry and medical technology in particular.

Conclusion

With the transfer of the goods to the customer, the individual orders and the production processes necessary for them are completed; however, internal processes at the manufacturer continue. In all steps, including the adjustment work, metallic and non-metallic, solid and liquid, recoverable or non-recoverable residues and internal waste, e.g. slag, cinder, scrap, sludge and filter dust arise. Collecting, classifying, preparing, recycling or disposing of these substances must be carried out under ecological and financial aspects. These important processes will also be presented in Chap. 10: *By-products and Waste*.

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By-products and Waste

10

▶ *“Where there’s sawdust, there’s wood being cut!”*
This old saying is indicative of many life situations. It combines the positive (sawing – being active), that is, the process of creating something new, with the negative (sawdust – waste), which inevitably results from such a process. The emergence of the negative has reasons and is partly even legally conditioned, but this does not release anyone from perceiving it and deliberately minimizing it. This also applies to all metallurgical processes of steel production, further processing by hot and cold forming, heat treatment, machining and adjustment work. Various materials, waste, emissions and also recyclable materials arise in these manufacturing processes.

10.1 Basics

The terms **by-product** and **waste** refer to different substances that are not always clearly delimited in practice. According to today’s understanding, both by-products and waste are accompanying results of manufacturing processes, but not the goal of these processes. A substance that is used further without further preparation or processing is considered a by-product.

Waste, colloquially often referred to as garbage, in Swiss as Kehricht and in Austrian as Mist, includes no longer needed residues or leftovers in solid, liquid or gaseous state. Their further use is regulated by the waste and recycling law by the classification into particularly hazardous, i.e. dangerous waste, up to the non-hazardous waste not requiring supervision. At the same time, waste suitable for recovery (recyclables) and waste for disposal are distinguished. Today, more environmentally friendly solutions, the avoidance and utilization of waste have priority. The following order results in the handling of waste:

J. Schlegel, *The World of Steel*, https://doi.org/10.1007/978-3-658-39733-3_10

- *Avoidance* (e.g. prohibition of environmentally harmful substances)
- *Preparation for reuse*
- *Recycling* (utilization)
- *other utilization* (e.g. for energy generation)
- *Disposal* (landfilling)

Different substances are required for the production of steel products:

Melting, secondary metallurgy, casting, remelting:
High-oven gas, bile gas, smoke gas, filter dust, slag, refractory eruption, scrap
Hot forming (rolling, forging, pressing, extrusion, etc.):
Coarse scale, dust, oil, lubricant, scrap
Cold forming (drawing, deep drawing, stamping, bending, etc.):
Used lubricants (solid lubricants, emulsions, oils) and cleaning agents (e.g. from ultrasonic baths), scrap
Pickling:
Pickling residues, used chemicals (acids and alkalis), exhaust air
Cleaning:
Sludges, chemicals, contaminated water, dusts, exhaust air
Heat treatment:
Scales (from water and oil quenching tanks), dusts, scrap, exhaust air
Surface treatment (peeling, grinding, coating, etc.):
Worn tools (grinding wheels, hard metal, etc.), scrap, chips, grinding and polishing sludge, used cleaning agents, residual paint, plastic waste
Machining:
Scrap, chips, used oils and emulsions, hard metal, other worn tools, exhaust gases
Material testing:
Scrap (chips, destroyed samples), cleaning agents, used grinding, polishing and etching agents from metallography, residues of epoxy resin
Finishing:
Scrap, chips, used cleaning and packaging materials (waste wood, plastic waste)
Other:
Recycled paper, electrical and electronic waste, waste wood, used tires, absorbent and filter material (e.g. oil-soaked rags), plastic waste, hall sweepings, old paint and lacquer

This incomplete list alone makes it clear how important it is to pay attention to such negative side effects during the production process. With projects for the treatment of waste and the recovery of valuable materials, the potential for an environmentally and economically sensible utilization is constantly being expanded. Figure 10.1 shows an overview of the material flows in a steel mill with an attached rolling mill and forge, taking into account an environmentally friendly treatment, preparation and utilization of the waste.

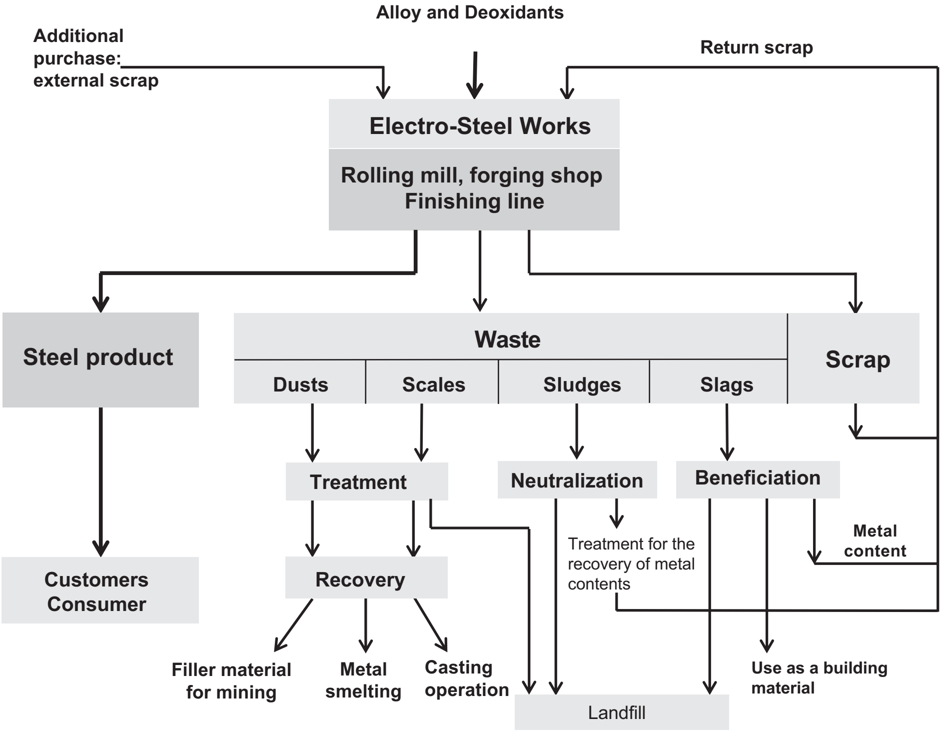

Fig. 10.1 Material flows in a steel mill with an attached rolling mill and forging shop (simplified)

▶ Below, only the most important by-products and waste that inevitably arise during steel production and processing are to be considered, such as exhaust gas, scrap, slag, refractory material, scale and liquid waste.

10.2 Exhaust Gas

Exhaust gases arise as gaseous by-products in processes of matter transformation. Without purification, they contain pollutants that are harmful to the environment and human health. The best known and most discussed pollutants are CO_2 and NO_x in the exhaust gas of combustion engines. And even the amounts of CO_2 in the exhaust gas of blast furnaces are a challenge for steel producers. Despite the increasing use of scrap and the development of alternative reduction processes (see Sect. 11.2: *Steel in the Future*), the production of crude steel in the blast furnace dominates. The iron is present in the ore as an oxide, that is, bound with oxygen. Coke is used, which provides the necessary heat for melting during combustion and reacts with the oxygen of the iron ore to form carbon dioxide CO_2. It is mixed with other gases (carbon monoxide, nitrogen and hydrogen) as a flammable blast gas derived from the blast furnace and subjected to a multi-stage purification. This includes a dry coarse cleaning, a wet cleaning and a fine cleaning with special filters. The cleaned gas is collected in a gasometer and then used again for firing the hot blast stove (preheating the air blown into the blast furnace), as heating gas in rolling mills, for steam boilers and district heating as well as fuel for gas engines. And with the conversion of the blast furnace gas into so-called synthesis gases, important precursors for the production of methanol, ammonia or polymers can be provided. And from these, in turn, synthetic fuels, fertilizers and plastics can be produced (Schmies, 2020).

The flue gases generated during the operation of blast converters and electric furnaces, as well as during the post-treatment and remelting processes of steel, are not usable as heating gases. For environmental protection reasons, they must be cleaned in flue gas cleaning plants (e.g. filter plant with dry filter). The deposited filter dusts are externally recycled or disposed of. Dust removal plants are also used in surface finishing (surface maching of billets, grinding). Special cleaning lines (filters, air washers) are used for exhaust air cleaning of pickling baths, galvanizing baths, galvanic coating plants and other plants that pollute the exhaust air chemically (e.g. polymer baths for quenching, cleaning baths).

10.3 Scrap

▶ The German term “Schrott” (scrap) is derived from the Lower Rhine word “Schrot” defining a “cut piece”. And also the scrap collect (in German “Schrotteln”) is due to the *“rags, bones, iron and paper, the ragpicker is here!”*. With this mocking song, the children often accompanied the scrap collector 90 years ago. With handcarts, horse-drawn carts, later with trucks, they drove along the streets and collected especially metal junk of all kinds. But soon this activity fell away in the advanced industrial countries. Industrial companies now took over the collection, processing and recycling. Often ridiculed and despised in the past, recycling has now gained enormous economic importance.

Recycling of scrap metal is probably the oldest example of recycling in human history. We can assume that with the beginning of the metal ages (the Bronze Age began about 2000 years BC) recycling already played a major role. Even back then, not every piece of work succeded, and a few broke here and there. Because the metal was very valuable, it was used again and again.

Today, against the background of increasingly scarce metallic raw materials, the achievable product quality and process efficiency, scrap has become an extremely valuable secondary raw material and is primarily the starting material for electric steel mills for the production of high-quality steel products. In 2019, for a world production of 1875 million tons of crude steel (Germany produced approximately 40 million tons), approximately 40% scrap was used (http://stahl-online.de—Statistics).

Figure 10.2 provides a view into the scrapyard of an electric steel mill with scrap boxes for the sorted storage of defined scrap groups.

Without scrap there is no new steel—economically and ecologically there is no alternative to scrap recycling today, because sustainability, resource efficiency, recycling and environmental balance are indispensable challenges with societal-social aspects in the production of materials and products due to their effects on humans and the environment. And steel, the most widely used and universal material in the world, has a leading position here. In an eternal cycle, steel is created from scrap, as often as desired and above all without loss of quality. The recycled steel is absolutely equivalent to the steel originally produced from ore (blast furnace-converter route). This multi-recycling can be simplified by taking into account the primary production of steel from ore: *Ore – pig iron – steel – steel product – use – scrap – electric steel – steel product – use – scrap – electric steel – steel product – use – scrap – etc.* Figure 10.3 shows this eternal cycle of steel in a simplified way.

Compared to the production of steel from scrap, the production of steel from ore requires more than twice as much energy. And an electric steel mill produces about 80% less greenhouse gases compared to a blast furnace-converter steel mill (Bünder, 2020).

Fig. 10.2 Scrapyard of an electric steel mill. (Photo: Schlegel, J., BGH Edelstahl Siegen GmbH)

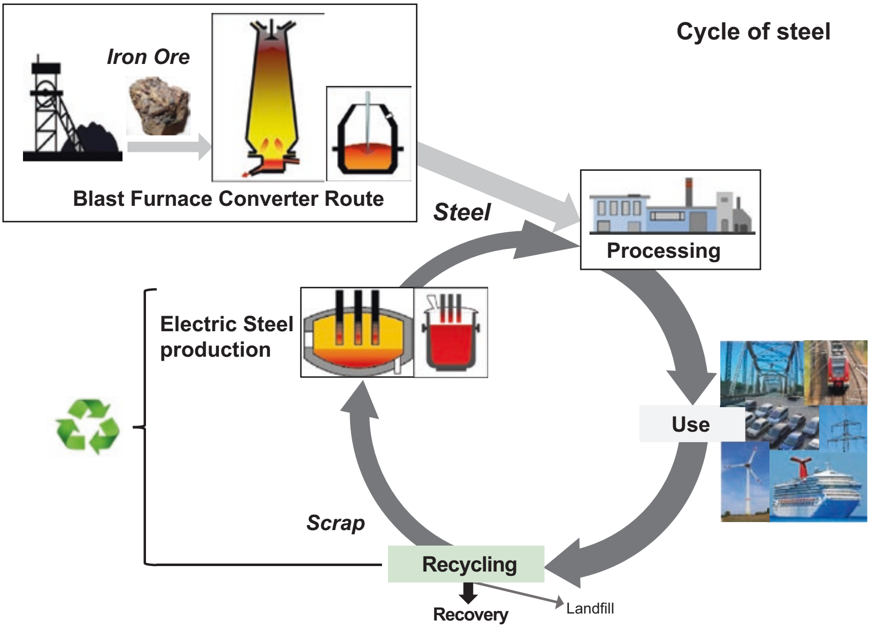

Fig. 10.3 The eternal cycle of steel in a simplified representation

Therefore, the melting of scrap has been carried out for a very long time and is today referred to with the modern term **recycling**. A high analytical agreement between the scrap and the steel alloy to be produced also saves alloying elements. Based on this, the ecological balance of steel, with its theoretically infinite number of life cycles, can only get better because with each new cycle the environmental impacts decrease. Thus, scrap steel also becomes the most important raw material for future high-tech products.

Almost the entire world's scrap is recycled. It is important to distinguish between different types of scrap. These can include up to 40 specifications for collecting and sorting, which are tailored to the intended use. The criteria for this are laid down in the European Scrap Directory for Iron-containing Scrap. These include, among other things::

- the *size of the scrap parts* (e.g. for scrap type 3: max. 150 × 50 × 50 cm with min. 6 mm material thickness),
- the *scrap starting material* (e.g. sheet metal scrap).
- the *chemical composition.*
- *the degree of contamination* (e.g. foreign matter, such as dirt, plastic, packaging),
- the *metal* (pure metal or mixture of different metals).

The scrap value and the recycling potential of the scrap metal are also determined depending on the scrap type and quality. In principle, the arriving scrap is first tested for

Fig. 10.4 Mobile XRF device in use for the quick detection of the chemical analysis of steel scrap. (Photo: Schlegel, J., BGH Edelstahl Siegen GmbH)

radioactivity by the recycling companies. This is followed by a screening and an unmixed storage as a result of testing with analytical devices (e.g. with mobile XRF devices) and a sort-pure storage. Figure 10.4 shows the use of a hand-held, mobile XRF device (see Sect. 7.2.4.1: *X-Ray Fluorescence Analysis*) for the quick detection of the chemical analysis of the delivered scrap.

The scrap is finally delivered to the steel mills in a customer-friendly manner. Upon arrival at the steel mill, before storage in scrap boxes, a check for radioactivity is carried out again. In addition to this purchased scrap, an electric steel mill also processes scrap that is technologically generated internally in its own steel mill and in the connected rolling mills, forge shops and other processing operations. The proportion of this so-called return scrap can amount to up to 40% of the total scrap consumption. Figure 10.5 shows typical return scrap from a hot rolling mill, a forge, the rod production and the machining for this purpose.

10.4 Slag

Slags (as a general term also called ironworks slags) always arise as residues in high-temperature processes with liquid pig iron, raw steel or steel. They consist of glassy or crystalline non-metallic mixtures of substances that consist of basic and acidic oxides (Hasse & Brunhuber, 2001). Slags take over important tasks in metallurgical processes such as binding of the non-metallic components from the melt in connection with the

Fig. 10.5 Examples of return scrap, *from left to right:* hot-rolled ends of billets, sawed-off parts of forged square and hollow profiles, cut-to-length peeled bars, chips from turning. (Photos: Schlegel, J. BGH Edelstahl Freital GmbH)

additives, the covering of the melting bath surfaces, thereby protecting or preventing reoxidation of the steel melts. Based on this, the formation of slags as thin as possible is deliberately initiated by targeted addition of additives. Depending on the production route, the blast furnace slag, the steelworks slag, the electric furnace slag and the secondary metallurgical slag arise. Figure 10.6 shows an overview of these types of slag.

In electric steel mills for the production of stainless steel, the slags arising from the electric furnaces and during secondary metallurgical treatment are also called “stainless steel slags”.

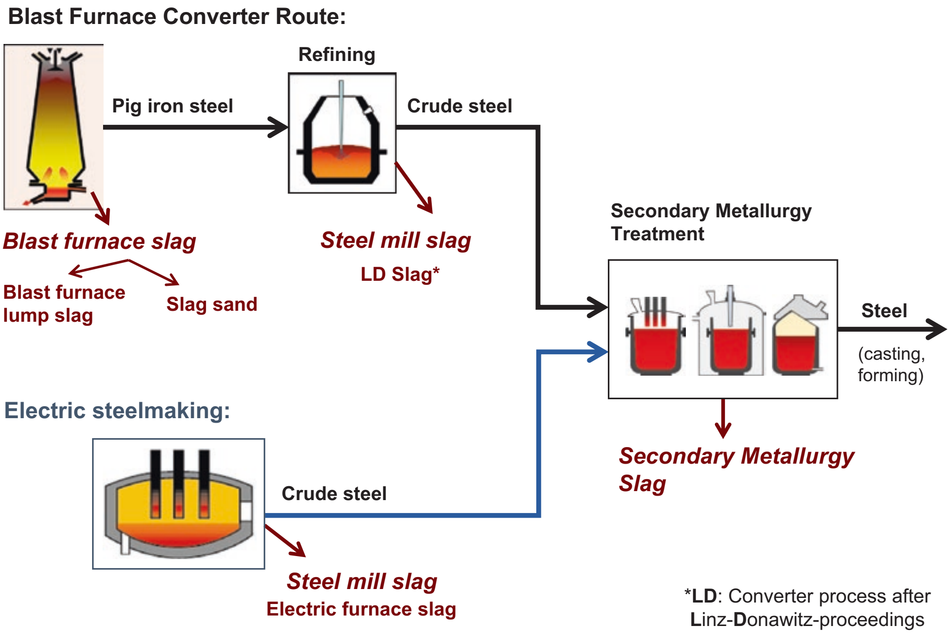

Fig. 10.6 Overview of the types of metallurgical slags in steel production

The slag that forms in a liquid state floats on the surface of the smelt bath because of its low density and can be easily separated or skimmed off the melts of pig iron (crude iron), raw steel, or steel in the furnace. This process is called skimming. Figure 10.7 provides a view into an electric steel mill where raw steel (crude steel) melt is being skimmed.

After skimming, a different cooling and processing takes place. Quick cooling of the blast furnace slag in water results in granulated slag (glass-like blast furnace sand). With a slow cooling in beds (pits—tipping points for slag), crystalline blast furnace lump slag is formed. Figure 10.8 shows such a discharge of blast furnace slag into a bed for a slow cooling.

Spent slag remains as a solid slag cake even after the remelting processes ESR and PESR. This slag was used in the liquid new state to specifically clean the steel to be remelted (see Sect. 4.3.2: *Remelting Processes*).

Slags are valuable raw materials for a variety of uses. For example, depending on their composition, blast furnace slag is used in the form of finely ground blast furnace sand as an additive for cement, as a rock fraction in road and path construction, for the production of fertilizers, as slag stones for paving, as slag wool for thermal insulation or as a blasting agent. For these uses, an elaborate preparation of the slags is carried out, such as defined cooling, breaking, sieving and classifying, removal of metallic

Fig. 10.7 Skimming a raw steel melt in an electric steel mill. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

Fig. 10.8 Discharge of blast furnace slag into a slag pit for a slow cooling. (Photo from the Internet)

components and of impurities. The electric furnace slag is also prepared as a special grain fraction in asphalt mixtures, base layers and paving sand. The achievable fine and coarse grain sizes have rough, porous surfaces and high hardness, which results in the particularly good load-bearing and compressive strength of the layers produced from them. Figure 10.9 shows, as an example, the use of prepared electric furnace slag as a base layer for road construction.

▶ The sustainability of the raw material slag, its environmental compatibility and the reduction of the landfill share, thus the preservation of natural resources, are the driving aspects for the constant search for new utilization possibilities.

10.5 Other Raw and Waste Materials

▶ The waste balance of steel-producing and processing companies contains a number of other liquid and solid substances in addition to slag and scrap, such as refractory materials, scales, sludges, dusts, emulsions, oils, fats, chemical residues, grinding wheels, also electronic waste, hall sweepings, lacquers, paper and contaminated textiles. The assignment of these substances to

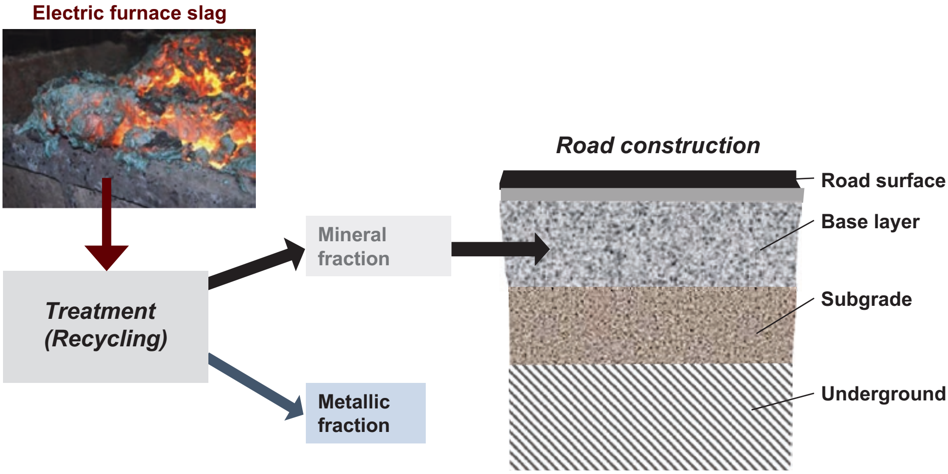

Fig. 10.9 Use of pretreated electric furnace slag as a base layer for road construction. (Photo: Schlegel, J., BGH Edelstahl Freital GmbH)

material and also energetic utilization or to disposal takes place according to legal regulations. Many of these substances can be converted into other products or reused as raw materials. This also applies to refractory materials, scales and liquid wastes.

Refractory Materials

Refractory materials are ceramic products for use at temperatures above 600°C, for example known as fireclay, silica and magnesia. They consist mainly of oxides such as silicon dioxide, aluminum oxide, magnesium oxide, calcium oxide, chromium oxide, zirconium oxide and silicon carbide and carbon in different compositions, which are determined by the applications. In the steel industry, refractory material is needed in large quantities for the lining of blast furnaces and converters, the melting of electric and induction furnaces, the treatment vessels, the transport and casting laddles, for example, for the lining of tapping spouts and distributors, for the lining of preheating and heat treatment furnaces as well as supporting cast material for the uphill ingot casting.

Figure 10.10 shows examples of refractory linings and coatings: melting vessel of an electric arc furnace, distributor for a horizontal continuous casting plant and pot annealing furnace.

The selection of suitable refractory materials and their service life are determined by the operating temperatures (firing or melting temperatures), the process media and operating modes of the lined plant. The most modern, longest lasting refractory products and technologies (brick lining, gunning) are used in blast furnaces. These can produce 7000 to 12,000 t of pig iron daily and must last for years, today even for 20 years, before a repair and relining with refractory material (called relining) is necessary. In contrast, the

Fig. 10.10 New refractory linings *from left to right:* melting vessel of an electric arc furnace, distributor for a continuous casting plant, pot annealing furnace. (Photos: Schlegel, J., BGH Edelstahl Freital GmbH)

ceramic lining of the casting frames for the increasing ingot casting must be renewed after each casting. Figure 10.11 shows the refractory breakout after ingot casting and the relining with tubular refractory bricks.

Raw iron emptying laddles and steel casting laddles mainly serve to transport raw iron from the blast furnace to the converter steel mill or raw steel from the electric arc furnace to the cupola metallurgical treatment. These laddles are also used for metallurgical process steps (fine treatment) at the same time; so they also have to meet these requirements with regard to the refractory lining. Figure 10.12 shows, as an example, the lining (consumed and renewed) of a steel casting ladle in an electric steelworks. This ladle is used both for the transport of the liquid raw steel from the electric arc furnace to the ladle treatment plant, and for the treatment of the raw steel in this plant (degassing under vacuum, see Sect. 4.3: *Post-treatment of steel*) as well as for the pouring of the liquid steel into ingots (rising block casting).

Refractory material to be disposed of is produced as a result of the mentioned wall linings and coatings. This material is usually sorted on site by external service providers, then forwarded to an unmixed processing and utilization, partly landfilled.

Scale

Scale is also often referred to as “sinter” or “cumbustion”. At high temperatures (glow or preheating temperatures for hot forming), a more or less thick layer of iron oxide forms on the surface of steel products under the influence of oxygen. Depending on the type of formation, glow, forge or rolling scales are distinguished. Figure 10.13 shows examples for this: glow scales on preheated forging blocks and hot forging scales during free forging.

Depending on the steel quality and the temperature-time regime during preheating or heat treatment without protective gas, the scale layers adhere to the surface to different degrees. In many cases, they must be removed immediately before forming in order to not roll or forge them in. The steel is cleaned. For this purpose, the scale washers have proven themselves. The scale is blown off obliquely with a water jet under high pressure, usually with 100 to 400 bar, via nozzles. Local cooling, breaking and evaporation effects occur.

Fig. 10.11 Refractory material breakout after ingot casting and new lining of the mold frame with tubular refractory bricks. (Photos: Schlegel, J., BGH Edelstahl Siegen GmbH)

For example, the water that suddenly evaporates blows off the scale, which is then rinsed off by the remaining water. Today, such hydromechanically acting scale washers are used in particular on hot-rolled strip rolling mills, but also on rolling mills for plate, wire and profiles. Scale washers are also increasingly used in fully automated forging lines, e.g. for drop forging of precision parts such as connecting rods, gears, etc. for quality reasons.

Scales are collected, delivered to an external treatment and reused for many applications. The constituents of the scales, the stable iron oxides Fe_2O_3 and Fe_3O_4, are coveted raw materials for the iron and steel industry. They are also used, inter alia, as iron black pigments for glass coloring, as iron oxide red for rust protection paints, as a polishing agent for glass, metal and precious stones, and as an additive for ceramics, cement and other building materials.

Liquid Wastes

Waste oils, fats, emulsions, sludges, color residues, chemicals (acids, alkalis, solvents), wastewater from cooling circuits, etc. are produced in steel mills, during forming, dur-

Fig. 10.12 Steel casting ladle, melt charge size approx. 42 t, *left:* in use for transporting raw steel to the laddle metallurgical (fine treatment) plant, *right from top to bottom:* lining worn out, new lining installation and finished ladle. (Photos: Schlegel, J., BGH Edelstahl Freital GmbH)

ing mechanical processing, during heat treatment processes with oil, polymer and water quenching baths, during cleaning with ultrasonic baths, during pickling, during coating, during finishing and maintenance work, and also during material testing, etc.; that is, everywhere where liquids are used for cleaning, cooling, lubricating, coating, separating and protecting (from corrosion). The treatments (cleaning, filtering out metallic fractions, neutralization, etc.) are correspondingly diverse and carried out with different effort, in order to recover as many recyclable materials as possible from the liquid wastes and to send as few materials as possible to landfill. Figure 10.14 shows as an example of practice a central grinding media preparation plant in a grinding shop for the production

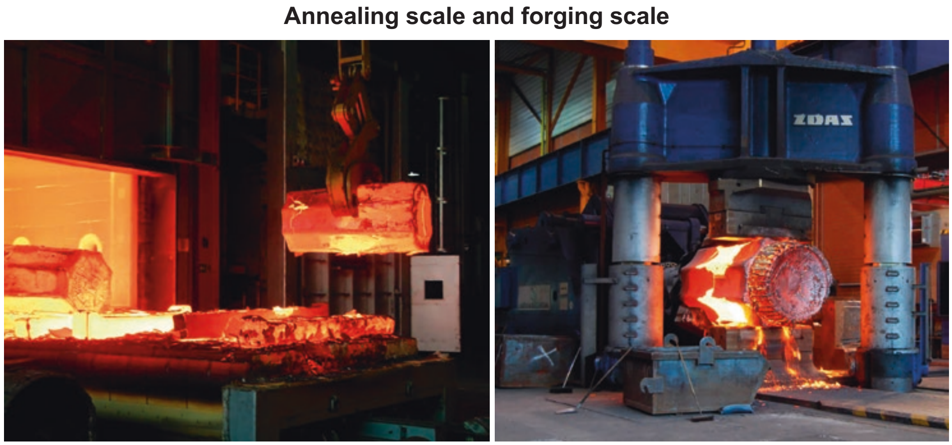

Fig. 10.13 Glowing scale on preheated forging blocks and flaking scale during open die forging. (Photos: Schlegel, J., BGH Edelstahl Siegen GmbH)

Fig. 10.14 Example of a central facility for filtering used grinding emulsion in a bright steel grinding plant. (Photos: Schlegel, J., BGH Edelstahl Lugau GmbH)

of bright, ground bars made of stainless steel. This plant serves to filter the used grinding emulsion from the connected grinding machines. The filtered grinding sludge contains metallic fractions, ceramic materials from grinding wheels, residues from forming by drawing (oils, soaps) as well as coolant. The disposal of these filtered grinding sludges for further environmentally friendly treatment takes place externally in containers. There are also legal regulations for this, in particular taking into account any dangerous components that may be present in the liquid wastes (see European Waste Catalogue [EWC]).

Conclusion

With the advancement of technology, substances or ingredients of waste that were previously considered harmless are increasingly being classified as “critical”. For example, the Regulation concerning the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) is aimed at protecting human health and the environment by restricting the use of certain dangerous substances. Therefore, a sensitive approach to waste is generally required, both where it is generated in production, during internal transport, during storage, treatment and recycling.

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Steel in Everyday Life

11

▶ Steel has an impressive, over three thousand year long history and has proven itself as a special material for industry, architecture, medicine, military technology, household and leisure industry, for environmental protection, energy technology and also for art. Steel is the material that everyone knows today and that accompanies everyone in life. And when products made of another material are used (e.g. made of plastic, wood, ceramic, light metal), they are usually processed with steel tools. Many examples illustrate this presence of steel in our lives. With the motto *"Did you know …?"* we would like to raise interest in some particularly interesting steel applications with a focus on stainless steel and perhaps also achieve an "Aha" effect when reading (topics in no particular order!).

Did You Know That Stainless Steel 1.4301 has Something to Do With the Bomb-Proof Memory of Germany?

We are talking about our cultural memory spanning more than 1400 years of history. For at least 500 years, this history should be preserved for posterity and be fully protected from destruction by wars, fire or natural disasters. It is stored in an atomic bomb-proof manner in the Barbara Tunnel near Freiburg im Breisgau: 400 m below ground, it is the best-protected place in Germany. In this "Central Safekeeping Site of the Federal Republic of Germany", historical documents, files, documents and contracts are stored as copies on microfilm. This is where you will find the coronation charter of *Otto the Great* from 936, the Golden Bull of 1356, manuscripts by *Goethe, Schiller* and *Kafka,* scores by *Bach,* but also the original edition of the Basic Law of the Federal Republic of Germany (Flyer: Information from BBK).

J. Schlegel, *The World of Steel*, https://doi.org/10.1007/978-3-658-39733-3_11

And what does this have to do with stainless steel? A lot, because the barrels in which the films slumber are made of it, particularly of the stainless steel 1.4301 - X5CrNi18-10, the well-known corrosion-resistant V2A steel. These barrels are produced by deep drawing without welding seams. Each barrel can hold approximately 21,100 m of polyester microfilm as a storage medium. When storing, the barrels are first climatized. They are then sealed airtight with one lid, one copper ring and screws each. Figure 11.1 provides a view into the Barbara Tunnel with the stainless steel barrels stored in this way.

More than 1 billion copies are safely stored on 31,000 km of microfilm today, and 1.5 million are added every year. Thus our descendants will be able to read the stored information and they will only need a magnifying glass and a light source. And for stainless steel 1.4301 this application is very special because it is unique and very important for German culture and history.

Did You Know That There are "Self-Healing" Stainless Steels?

"Self-healing" refers to steel's ability to react to surface injuries and heal them. What is self-evident with human skin also happens with some types of stainless steel. If steel is exposed to a corrosive environment (moist air, chemical vapors, salt water) or if mechanical damage is caused to the surface (scratches, grinding marks), iron oxide can form. The steel rusts, or it doesn't. In the latter case, a passivation layer was present that

Fig. 11.1 Barbara Tunnel with stored stainless steel barrels. (Photo: Straube, B., BBK – Federal Office for Civil Protection and Disaster Assistance, Bonn)

slowed down or prevented corrosion. Rust- and acid-resistant steels have this phenomenon. With a steel containing more than 12% chromium, a thin invisible chromium oxide layer forms on the surface, preventing further oxidation. If this layer is mechanically damaged, bare steel comes into contact with the corrosive environment. Quickly, "self-healing" creates a new oxide layer—the passivation is perfect again. Beautiful examples of this are the classic corrosion-resistant steels, such as those used for cutlery and kitchen utensils, in swimming pools, for railings, outdoor lighting, sculptures, furniture parts, lamps, jewelry, art objects, etc. Figure 11.2 shows, for example, a balustrade with posts and handrail made of a standard stainless steel.

If no spontaneous passivation occurs, then it is a normal steel. Under certain circumstances, this steel can rust on the surface. This forms a brown layer of iron oxide, which does not stop further oxidation. So this steel rusts further and further.

Did You Know That Stainless Steel 1.4305 Has an "Oscillating" Meaning for Many People?

With oscillating or swinging, that is, a continuous repeating movement, you can have fun like swinging at the fun fair, or also accomplish something useful, e.g. brushing your teeth. The history of the toothbrush is interesting to read on this subject. Already in the Stone Age, people used thin branches to clean their teeth. Targeted dental care is

Fig. 11.2 Parapet on a balcony with handrail and posts made of stainless steel 1.4301 - X5CrNi18-10. (Photo: Strzelczyk, R., Strzelczyk Edelstahl-Verarbeitung, Rossau)

detectable from around 5000 BC. In ancient Egypt, there was already toothpaste made from finely ground pumice and wine vinegar. In our latitudes, every Germanic who thought highly of himself carried a leather bag at his belt containing bone cleaning sets with toothpicks and ear spoons. From 1500, the first toothbrushes with bristles from domestic pigs were known in China. In German-speaking countries, toothbrushes with horsehair were available from around 1600. However, they were too soft and therefore ineffective, according to the father of modern dentistry, the French doctor *Pierre Fauchard* (1678–1761).

In 1789, Englishman William Addis (1734–1808) founded the first company to produce toothbrushes from cow bones and bristles. However, they were very expensive and remained a luxury item for only a few. It was not until cheap nylon was used for the bristles that the toothbrush became a mass-produced item. The first electrically powered "oscillating" toothbrush was patented in 1880. The mass market introduction was achieved in 1954 by the Swiss company Broxo with the Broxodent, which only performed elliptical oscillations. Later there were further developments, including: rotating brushes, piezo-electric sonic toothbrushes, 3D toothbrushes with oscillation and pulsation, brushing teeth with position and pressure detection, and app support.

All modern toothbrushes must have replaceable brush heads because they wear out the quickest. They are placed on the driver shafts protruding from the devices. These shafts are made from the stainless steel 1.4305 - X8CrNiS18-9. Figure 11.3 shows a modern electric toothbrush with the driver shaft clearly visible.

Did You Know that You Can Shoot a Steady Ball with a Special Steel?

Meaning "Boule" (from French *la boule,* the "ball"), known in Germany as a general term for leisure ball games, called "Boccia" in Italy. Already Greek doctors, including *Hippocrates of Kos* (460–370 BC), recommended for health strengthening a game with

Fig. 11.3 Electric toothbrush with two replaceable brush heads. (Photo: Schlegel, J.)

stone balls. And in the second century AD, the Greek scholar *Julius Pollux* documented a game widely spread in the Roman Empire, in which balls were thrown at a brick. This could be the origin of Boule. In the Middle Ages, the Boule game was especially popular in France. During the World Exhibition in Paris in 1900, Boule competitions were also held. After that, especially France vacationers brought this game to Germany.

Boule is a popular pastime today that is played in many variations in public places, sports halls, gardens, or on the beach. The range of balls made of plastic, wood, carbon steel or stainless steel (austenitic nickel-chromium alloys) is correspondingly diverse. Figure 11.4 shows boule balls made of stainless steel with the target ball used in the game.

With different surface finishes, e.g. chromed, satin-finished, polished or milled, these boule balls are produced as leisure and also as competition balls. Balls with diameters of 71 to 80 mm, with 650 to 800 g weight and with a hardness of approx. 350 HV (Droß & Hausmann, 1998) are common. The boule player wants to place his ball exactly to hit a target ball or to hit away an opponent's ball. For this purpose, his thrown ball should not rebound (rebound effect). To achieve this, the balls have a special structure inside, which today can even be produced by 3D printing. So: a beautiful, round and healthy application for stainless steel!

Did You Know that Since Its Invention, Stainless Steel has Inspired Architects and Today it is Used in Construction for New Applications?

With fascinating looks, weather-resistant, mechanically durable, low-maintenance and easy to care for, stainless steel proves itself to be sustainable in construction (leaflet 875: stainless steel, 2015). This makes stainless steel buildings the most unique and interest-

Fig. 11.4 Target ball and boule balls made of stainless steel. (Photo: Schlegel, Chr.)

ing, the Chrysler Building in New York, the Petronas Towers in Kuala Lumpur, the Burj Khalifa in Dubai, or the new One World Trade Center in New York. Figure 11.5 with the Petronas Towers in Kuala Lumpur, 442 m high, completed in 1999, shows the glossy facade designed with stainless steel.

Stainless steel is used for corrosion-resistant reinforcement of concrete and masonry, for visual, solar, fire and burglary protection, for climate-regulating claddings on facades, also for so-called "media facades" (wire mesh with integrated LEDs). But also roof coverings, brackets for photovoltaic systems, parapets, handrails, escalators, doors and gates are made of corrosion-resistant stainless steel. Today, these steels can be found throughout the spectrum of architecture in extremely diverse versions as panels, fabrics, braids, grids, profiles, bars, screws, clamps or ropes. In addition to matte, brushed, glossy or colored surfaces, increasingly innovative coatings are used, e.g. with lotus effect, against graffiti and fingerprints. Decorative or invisible as a durable, universal building material, the non-rusting stainless steel hardly sets any limits on design, functionality and sustainability in construction.

Did You Know what Stainless Steel 1.4542 has to Do With the Dandy Horse by Drais?
In the direct sense, of course, nothing, because the invention of *Karl Freiherr von Drais* (1785–1851) more than 200 years ago is history (Dodge, 1997). His wooden dandy horse or swiftwalker marked the beginning of individual mobility. Figure 11.6 shows a

Fig. 11.5 The Petronas Towers in Kuala Lumpur. (Photo from the Internet)

historical illustration of this dandy horse from the patent application of February 17, 1818 by Karl Drais (No. 896, “vélocipède”).

It was a long way to the modern road and touring bikes, mountain bikes and e-bikes, also lined with curious, sometimes accident-prone designs, such as the cast-iron old-fashioned high wheels. However, these high wheels already had a pedal construction that allowed considerable speed to develop because of the large front wheel. The safety risk of the high bike was only minimized with the breakthrough of the chain-driven rear wheel of *John Kemp Starley* (1854–1901). These new “safety bicycles” developed quickly into the today’s standard bike with the typical triangular frame construction, the “diamond frame”. This was invented in 1890 by *Thomas Humber* (1841–1910). Later, pneumatic tires, modern braking and lighting technology and the gearshift were added. In this way, the classic bicycle finally emerged, as shown in Fig. 11.7 as an example.

And today the bicycle is an attractive, reliable means of transport and a much sought-after sports equipment. The variety of shapes and the materials used for modern bicycles and E-bikes is great. The corrosion-resistant stainless steel stands out visually and also in terms of its properties. It is the 1.4301 - X5CrNi18-10, which as a cold-rolled tube frame or used for spokes, rims, pedals, axles, gearshift and chain gives the bicycle comfort and durability. And the mentioned 1.4542 - X5CrNiCuNb16-4, a heat treatable, non-rusting steel, is used for rivets that connect the chainrings to the cogwheel.

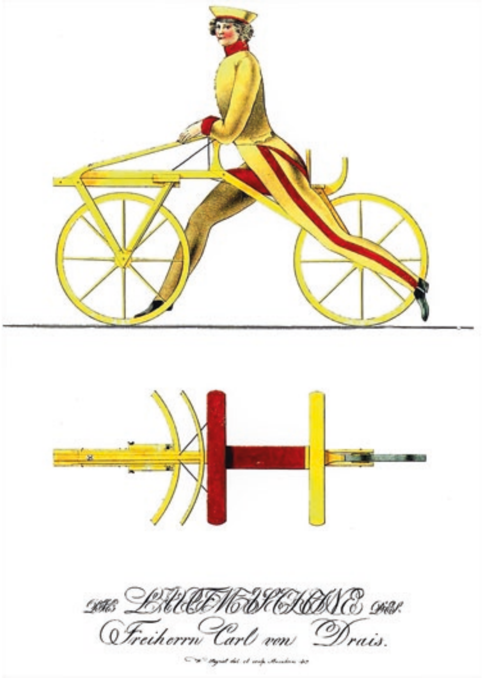


Fig. 11.6 Dandy horse around 1817 by *Karl Freiherr von Drais,* illustration from the Internet (https://en.wikipedia.org/wiki/Dandy_horse)

Fig. 11.7 A classic bicycle with a triangular frame. (Photo from the Internet)

Mr. *von Drais* could not have guessed that even stainless steel would help make the bicycle so popular.

Did You Know that Origami can also be Made of Steel?

Origami is known as the ancient art of paper folding (Japanese *oru* - “fold”, *kami* - “paper”). This results in a three-dimensional complex structure made from a sheet of paper.

After paper was invented in China around 100 BC, it came to Japan in 610 AD through Buddhist monks. There, mainly ceremonial paper folding gained importance. European paper folding art developed in the sixteenth century, starting in Egypt and Mesopotamia (Casanova, 2020). At first, only a few forms were known, including the most widespread, classic folding of a crane, as shown in Fig. 11.8.

Soon, more complicated models could be folded that people previously thought impossible. Everyone will remember folding paper airplanes as children and flying them around the living room, or making them now for the children and grandchildren. That, too, is origami art.

For many applications, complex folding structures are today manufactured from sheet metal using multidirectional folding techniques. These thin-walled “high-tech origami” structures offer more resistance to mechanical loads than solid components. This saves weight and costs (lightweight concept). In other words, a deliberately wrinkled construction is more stable than a smooth one. Attractive façade elements, heat exchanger plates or core structures in sandwich panels are examples of this. Figure 11.9 shows a section of such a sandwich panel with a relatively simple folding geometry. This was made from the deep-drawing steel DC04 - 1.0338 as a welded construction.

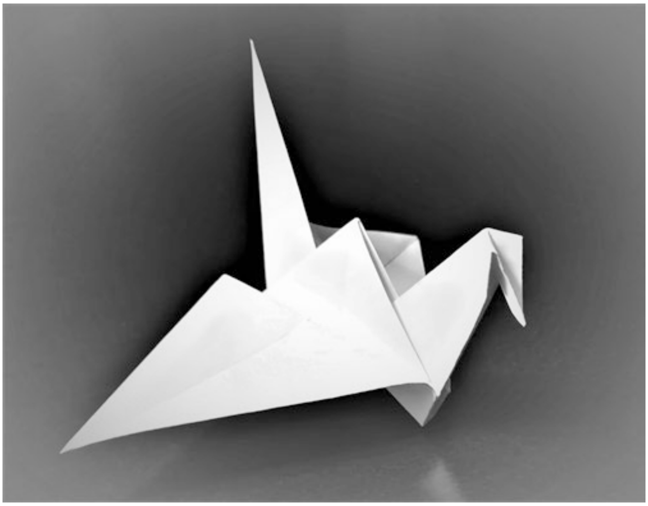


Fig. 11.8 Classically folded origami crane made of paper. (Photo: Schlegel, J.)

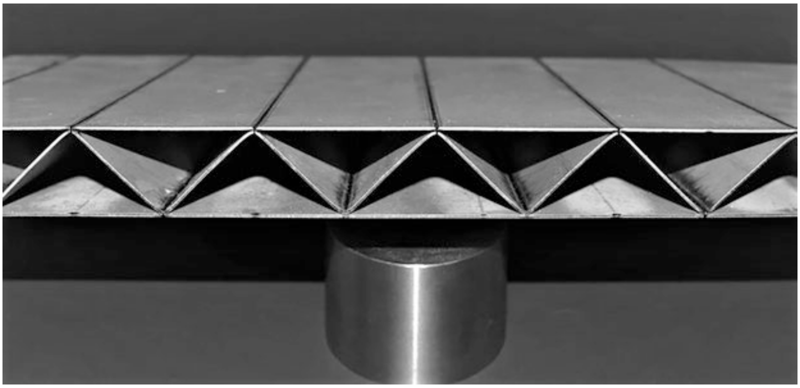


Fig. 11.9 Detail of a sandwich panel, manufactured as a welded composite with a folding geometry. (Photo: Schneider, M., Institute of Forming Technology, University of Stuttgart)

In particular, folded core structures appear promising for sandwich composites. There are projects and manufacturing approaches for this, for example at the Institute of Forming Technology at the University of Stuttgart (Schneider et al., 2016; Schneider & Liewald, 2018). The project goal is the production of pre-structured three-dimensional folding structures as "bulk good" from thin sheet, e.g. made of unalloyed, soft steel DC04 - 1.0338. Potential areas of application for such steel-steel sandwich composites are in shipbuilding, aircraft construction, railway engineering and the construction industry.

Fold structures are also known from stainless steel sheets, e.g. from 1.4301 - X5CrNi18-10 or 1.4404 - X2CrNiMo17-12-2 with thicknesses of 0.8 to 3 mm for everyday objects such as bowls, boxes, shelves, tables, chairs, high-quality parts for sailing yachts, for toys or for exclusive works of art. It is already surprising how exact, sharp-edged, complex spatial structures can be folded from mathematically calculated sheet metal cuts without distortion and without welding or screw connections (Hoffmann & Trautz, 2013). Today, the return of origami paper folding to modern steel forming and manufacturing technology is fascinating for the ancient art.

Did You Know that Stainless Steel can also be a Lot of Fun?

Stability, functionality and especially beauty are the reasons why more and more manufacturers of sports equipment are using stainless steel. Using this steel it then goes up and down rapidly, for example down the ski slopes into the valley. The new competitors to the classic downhill skiing, such as snowbiking and snowboarding, promise a great sports experience. The material stainless steel with smooth surfaces (low friction, high speeds), with sufficient high strength even at low temperatures and with reliable corrosion resistance usually plays a “supporting” role, for example as a material for skis (Herrling Press Release Stainless Steel Rust-free). Ski bikes with skis made of stainless steel are coming up strong. As on a motorcycle, the driver steers it while sitting by shifting weight. The completely stainless steel sleds also allow for carefree descents. And the more classy and sporty a ski has to be for carving, the more stainless steel is used for stabilization in the form of steel caps or as a ski surface.

If there is no snow, you can experience year-round tobogganing on all-weather toboggan runs. Numerous other attractions made of stainless steel can be found not only in leisure and water parks. The classic summer toboggan runs in trough form as well as dry and water slides in various designs provide fun and excitement. Figure 11.10 shows an example of such leisure attractions made of stainless steel.

Flying is also possible as a leisure activity: with the electrically powered Wie-Flyer, the “pilots” themselves are responsible for their travel speed. Up to 30 km/h are possible. In the so-called “witch’s broom”, you let gravity work for you in the downhill sections. In the uphill sections, a circulating rope is used as an “accelerator”, which moves the gondolas catapult-like to the peak. The latest driving pleasure amongst others from Wiegand is the CoasterKart, whose vehicles are driven by linear induction motors. The use of corrosion-resistant stainless steel guarantees a long and safe life for all these attractions.

In this way, the material stainless steel has also opened up particularly sporty and attractive areas of application, which offer a lot of fun.

Did You Know that There is “Steel Soap”?

Everyone knows unpleasant odors on their hands after preparing fish or peeling and chopping onions or garlic. Not to mention nicotine and mouth odor, sweat and shoe odor. To eliminate them and not use any chemicals or any means is easy today, without witch-

Fig. 11.10 Attractions made of stainless steel in a leisure park. (Photo: Josef Wiegand GmbH & Co. KG, Rasdorf)

craft. There are handwashing brushes, stainless steel in the form of soap, also deodorants, body sponges, lollipops as special “stainless steel odor killers” in various forms. And they last a lifetime. Figure 11.11 shows an example of such a stainless steel soap, as can be used in the kitchen or bathroom.

If you touch a piece of stainless steel with your skin, similar to washing your hands with soap, an oxidation process is triggered in connection with water and air, i.e. a chemical process. The stainless steel only acts as a catalyst here to destroy the relatively stable and long molecule chains of the aromatic hydrocarbon compounds (odour molecules). And it really works: unwanted odours are effectively neutralised and not, as with various perfumes and deodorant sprays, just masked by other odours.

Did You Know that the Demand for Kegs is Increasing?

No, no typo – kegs are meant “small barrels”. They were developed as reusable barrels made of stainless steel for industrial filling and germ-free storage of beverages, especially for beer. Introduced in 1964 in Great Britain, they were and are particularly interesting and popular for beer with the usual sizes of 5 to 50 L. They are increasingly popular with partygoers and catering services. Made of the non-rusting stainless steels 1.4301 - X5CrNi18-10 and 1.4571 - X6CrNiMoTi17-12-2, they fit well with the general trend of sustainability (Klinkhammer, Information SCHÄFER Container Systems).

Fig. 11.11 Stainless steel soap as an odor neutralizer in a handy oval shape, size: 90 × 50 × 20 mm. (Photo: Schlegel, J.)

Stainless steel kegs can be used for up to 30 years, cleaned hygienically by machine and recycled 100%. The taste of beer and all other drinks is not affected by multiple use. Beer can be tapped simply, safely and germ-free. Figure 11.12 shows kegs and a sectional model thereof.

Kegs withstand a multiple of the operating pressure of 3 to 7 bar. On the top of the small barrels is the valve (keg head), on which the tap head is attached. This leads the propellant (carbon dioxide or nitrogen) from an external container to the keg. The over-

Fig. 11.12 Stainless steel kegs, left a sectional model. (Photo: SCHÄFER Container Systems, Neunkirchen)

pressure in the barrel drives the beer out through the tap. This prevents foaming. With the tap closed, further storage of the remaining beer is ensured. So a quite meaningful and tasteful application of cylindrically shaped stainless steel. Cheers!

Did You Know that Many Watches Shine with Stainless Steel?

We mean the watch cases.

The first pocket watches built from the early fifteenth century usually had cases made of gold and silver alloys. Such pocket watches were still in use until the twentieth century (Kahlert, 1990). With the first wristwatch made in 1810 by the Swiss watchmaker *Abraham Louis Breguet* (1747–1823), both the technical and the material development towards the modern wristwatch began.

Yellow gold, platinum, titanium, aluminum, high-tech ceramic, stone, wood, and plastic are materials from which watch cases are now made in different designs. But above all, the gloss that can be achieved by polishing and the noble appearance have led to the fact that stainless steel is now used most often as a case material for wristwatches. Initially, the classic non-rusting stainless steel 1.4301 - X5CrNi18-10 was used. However, the modern and extremely high demand for polishability today is the reason why specially developed stainless steels with a defined, narrowly limited chemical composition and highest purity are used. An example is the steel 1.4435 - X2CrNiMo18-14-3. It underwent a very elaborate metallurgical production and multiple remeltings. From this steel, blank bars for watch cases and for smaller watch components, such as crowns, are manufactured. Figure 11.13 shows a watch case made of stainless steel for a modern wristwatch. So now, in the truest sense of the word, wristwatches of well-known watch brands also shine with stainless steel cases.

Fig. 11.13 Wristwatch with stainless steel case. (Photo: Schiess, C., Cenic Watches & Parts, Biel, Switzerland)

Did You Know that Velcro Closures are Also Made of Stainless Steel?

Many innovations have been and are being copied from nature (biomimetics). Even the ubiquitous Velcro has a "natural" model: the cocklebur, a plant from the family of Asteraceae. It forms small, spherical fruits that have many spikes with tiny hooks. These cling tenaciously to the fur of animals, and also to the clothing of humans, thus ensuring the dissemination of the seeds. When the Swiss inventor *George de Mestral* (1907–1990) had to remove the many cockleburs from the fur of his dog and from his pants after a hunting trip, he came up with the brilliant idea of constructing a releasable fastener. In 1951 he patented his invention under the name Velcro, derived from French *velours*—"velvet" and *crochet* "hook". His company Velcro Industries brought the first Velcro closures to the market in 1955. The simple closing and opening, repeatable many times by means of the hook-eye principle, made them so successful. As a replacement for shoelaces and buttons, as well as for the attachment of bandages, cufflinks and prostheses, they quickly found a wide range of applications.

Classic Velcro connections consist of two plastic strips and are only limitedly resistant to heat, chemicals and disinfectants. For some applications, they are also much too weak. New Velcro closures made of stainless steel spring band 1.4310 - X10CrNi18-8 with punched connection geometries have been developed for use in hot environments in particular. These are well suited for contact with chemicals and for very high holding forces, e.g. in the air conditioning, ventilation and automotive industries. Figure 11.14 shows, as an example, the Velcro fastener "Metaklett".

The construction of "Fixx-Itt" from 1.4301 - X5CrNi18-10 (Merkel, 2009) is also interesting. On a carrier plate, many approximately 1.0 mm big wire pins with "spherical heads" are positioned. They are formed by laser. This connection technology developed by the Bremer Institute for Applied Beam Technology GmbH is schematically shown in Fig. 11.15. It offers great potential for the medical technology and automotive industry (Brüning & Vollertsen, 2014).

Did You Know What a "Bähschnitte" has to Do With A Corrosion- and Heat-Resistant Bending Wire?

A "Bähschnitte" is a German colloquial term for a roasted slice of dark bread. By removing moisture, this bread becomes more durable and has a nice aroma. The ancient

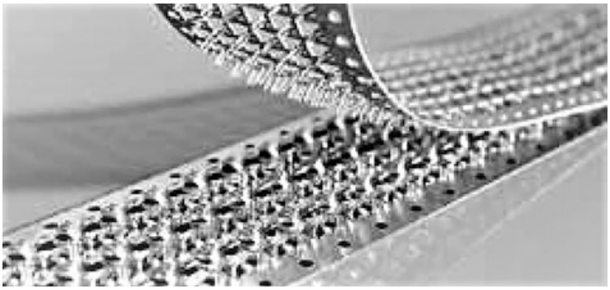


Fig. 11.14 Velcro fastener made of stainless steel: "Metaklett" by HÖLZEL Stanz- und Feinwerktechnik. (Photo: Hölzel Stanz- und Feinwerktechnik GmbH + Co. KG, Wildberg)

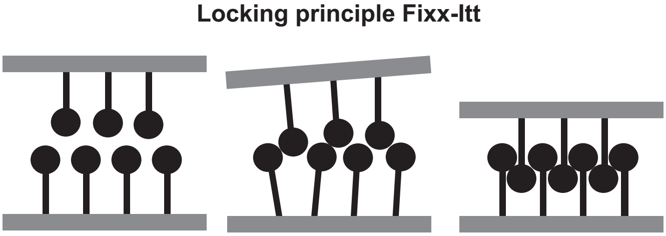


Fig. 11.15 Schematic representation of the locking principle of the Fixx-Itt Velcro fastener made of stainless steel. (Based on: Wire / Wire: Velcro fastener made of stainless steel, Bremer Institut für angewandte Strahltechnik GmbH [Bias], Bremen)

Egyptians and Romans knew this too. It was roasted over an open fire, on hot stones or on oven walls.

Today, toast is very popular and has been known in Germany since the 1950s as an upscale and practical bread meal with the typical light bread. Various toast machines are used: In 1910 there were electrically operated roasting machines, after *Albert L. Marsh* (1877–1944) invented a chromium-nickel alloy (Chromel – 90% nickel, 10% chromium) for heating conductor wires in 1905. These alloys are used to manufacture the heating coils.

Improvements in the turning of the toast slices and the automation of the devices were decisive for an exciting development from the plug-in, hanging, folding, rotating and carousel toasters to the flat-bed, pop-up and convection toasters. The hygienic, corrosion-resistant and heat-resistant stainless steels 1.4301 - X5CrNi18.10 and 1.4404 - X2CrNiMo17-12-2 in the diameter range from 0.8 to 5.0 mm were and are used. They are used to produce the holding grids of the plug-in toasters as well as the conveyor belts moving in the convection toasters. Figure 11.16 shows a classic plug-in toaster as an example. The heating spirals switched on during toasting are clearly visible.

Fig. 11.16 Classic plug-in toaster. (Photo: Schlegel, J.)

When inserting or sliding, the toast slices are only in contact with these stainless steels for a short moment and very close to the heating elements. This creates the beautiful roasting or toasting effect. A toast to that!

Did You Know that There are Steels that have to Rust First Before They Don't Rust Anymore?

Rust forms on unprotected steel surfaces by oxidation with oxygen in the presence of moisture. Except for the well-known corrosion-resistant steels, such "weathering" still causes great damage worldwide.

Special steels with low levels of chromium, copper, nickel and phosphorus initially rust in a normal way, forming a barrier layer of sulfates and phosphates under the slightly rusted surface. This slows down further corrosion. Expensive surface protection, e.g. by galvanizing and/or applying protective paints, can be dispensed with. Such a weather-resistant steel was patented for the first time in 1926 by the United Steelworks AG in Düsseldorf and sold under the name "Union-Stahl". After the Second World War, constructions with this steel were no longer pursued. It was not until the 1960s that it was rediscovered and used again in Europe, now under the trade name "COR-TEN-Steel", derived from the words "corrosion resistance" and "tensile strength". Such a weather-resistant steel was also produced in the former GDR. Called "KTS 30/45" and melted in a Siemens-Martin furnace, this steel was mainly used for high-voltage grid pylons.

The euphoria was initially over in the early 1980s. Since the 1990s, these steels have been used again more intensively in the construction sector (façade elements), in industry and in bridge construction, taking into account their special features. The rugged rust-brown surface is certainly a matter of taste, but it has also motivated many artists to create interesting art objects. Figure 11.17 shows an example of a large-scale sculpture made of weather-resistant steel by the Chemnitz artist Michael Morgner.

Did You Know that Stainless Steel Can Be Moved Up and Down Quickly, Obliquely, in a Curved Shape, and Also in a Straight Line?

We are talking about passenger conveyor systems: elevators (lifts), escalators (moving walkways), and boarding bridges (travelators).

The birth of the modern elevator can be traced back to the mid-nineteenth century in the United States. The mechanic *Elisha Graves Otis* (1811–1861) invented a safety catch device for elevators and founded the Otis Elevator Company. Now the upper floors of skyscrapers could be reached comfortably and safely. And they became higher and higher and faster: With 20 m/s (72 km/h!), the world's fastest passenger elevator today rushes 440 m into the sky at the Chow Tai Fook Centre (a skyscraper in Guangzhou, China).

As early as 1859, a US patent was issued for a staircase with moving steps (rubber inclined belt with wooden boards). After the World Exhibition in Paris in 1900, esca-

Fig. 11.17 Sculpture „Spannung” made of weatherproof COR-TEN steel by *M. Morgner,* Chemnitz. (Photo: Schlegel, J.)

lators were increasingly installed in department stores and underground railways. For example, on 11 July 1925, Germany’s first escalator went into operation at the Cologne department store of the Leonhard Tietz AG. Today, Germany’s longest free-standing escalator leads over 58 m to the Ruhr Museum on the Zollverein Coal Mine Industrial Complex. Figure 11.18 shows a typical example of an escalator with a lot of stainless steel in a shopping centre.

If the movable treads do not form steps, but a flat surface, it is a travelator, colloquially called “treadmill”. This can be executed horizontally, slightly inclined and arched. The world’s first travelator was used at the World’s Fair in 1893 in Chicago. With a length of 3.5 km, this “road of the future” was also presented at the World’s Fair in Paris in 1900. And from 1954 the first public travelator moved the passengers in the Pavonia Terminal of the Jersey City train station in the USA.

Modern travelators today shape the image of airports, train stations and supermarkets. All three “moving” structures have one thing in common: the use of high-strength and corrosion-resistant steel for robust technology with a great look. Shiny claddings of the

Fig. 11.18 Escalator in the shopping center Havelpark Dallgow. (Photo: Schlegel, Chr.)

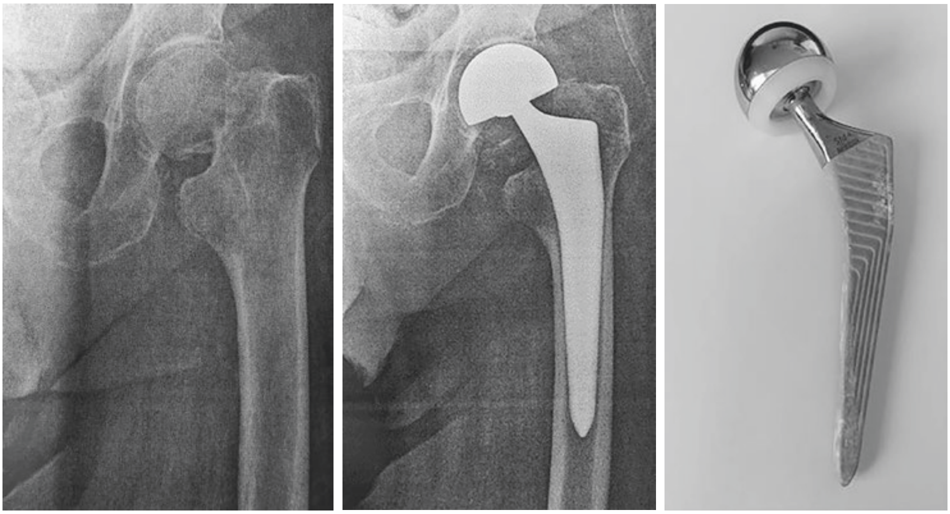
cabins invite you to get in. And handrails, railings, display boards, etc. always convince with easy-care surfaces, also resistant to aggressive cleaning and disinfecting agents.

So again an interesting, moving application example, especially for the corrosion-resistant stainless steel.

Did You Know that Everyone in Life Never Wants to have Anything to Do With a Special Steel?

And if it should ever come to that, then one is very happy that there is a steel that is highly corrosion-resistant, very wear-resistant and also biocompatible. This pertains to the special stainless steel 1.4441 - X2CrNiMo18-15-3, known as implant steel. It is melted several times according to a special technology, produced in a highly pure form and has to meet specific approval conditions for medical applications.

As the term “implant” from the Latin “to plant within” expresses, this steel is implanted in various forms in the human body, to remain there forever or at least for a while. It has the medical task of replacing or supporting certain body functions. We then speak of an implant enclosed in the body, an endoprosthesis, if it takes over a replacement function. The endoprosthesis is completely surrounded by body tissue, must not trigger any unwanted reactions with the tissue and the body fluids and must also be



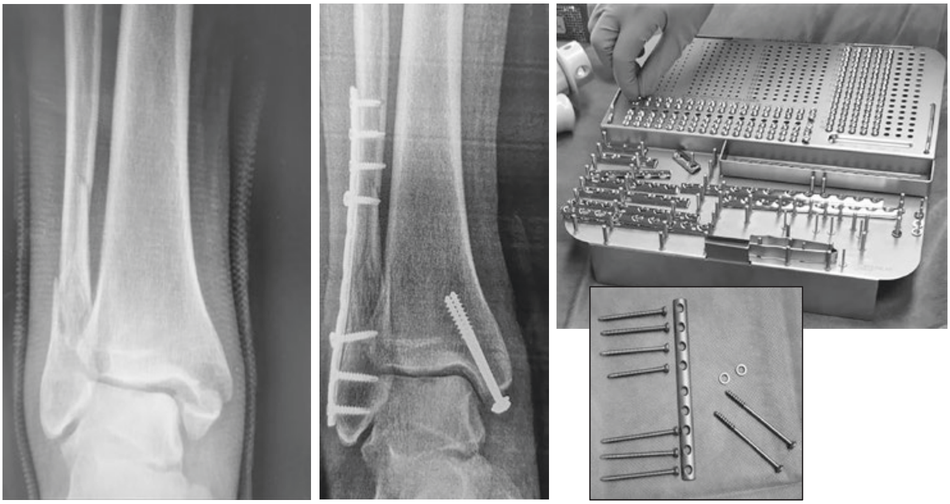
Hip joint prosthesis after a fracture of the neck of the femur

Fig. 11.19 Use of a hip joint prosthesis after a fracture of the femoral neck. (Photos: Bogenschütz, C., Zollernalb Klinikum gGmbH, Balingen)

biofunctional, i.e. ensure a firm contact with the bone. Classic examples are hip and knee joint prostheses, which are highly stressed mechanically in the body. In addition to the special steel 1.4441 mentioned, cobalt-based alloy CoCr28Mo6, pure titanium, titanium alloy TiAl6V4, ceramic materials and polymers are used for this purpose. If allergic reactions are to be expected due to nickel and chromium, titanium and titanium alloys are selected. However, otherwise the implant steel offers the best strength and wear properties for the load-bearing, alternatingly stressed prosthesis parts. Figure 11.19 shows, for example, the use of a hip joint prosthesis after a fracture of the femoral neck.

And for the alignment and fixation of fractures (osteosynthesis), the implant steel is used in the form of plates, screws, wire and nails. This is shown in Fig. 11.20 using the example of the fixation of a tibia and fibula fracture.

In addition, steel 1.4441 is used for a variety of surgical instruments. The demand for this is increasing. The population is getting older, and medical progress ensures good everyday mobility well into old age. So the implant steel, but also many other corrosion-resistant, well disinfectable steels find a wide, extremely useful application in medical technology. And if by chance the case should arise that one needs medical help oneself, then one can rely on these steels and the skill of the medical personnel.



Fixation of a tibia and fibula fracture

Fig. 11.20 Fixation of a tibia and fibula fracture using a plate and screws. (Photos: Bogenschütz, C., Zollernalb Klinikum gGmbH, Balingen)

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12

Steel in the Future

▶ Steel is and remains material number 1. This was not foreseeable at the beginning of the Iron Age more than 3000 years ago. After such a long, eventful time of steel production and application, one would actually assume today that the "forgeable iron" is well researched in terms of composition and properties. This is a fallacy! The material steel is not yet exhausted. Every year, around 200 steels are improved according to customer requirements and around 50 new ones are invented (Köthe, 2011).

Steel Still has a Lot of Potential

Whenever it comes to creating more powerful, lighter, longer-lasting, and safer components and systems at no additional cost, while also being more energy-efficient, sustainable, and durable, steel is the material of choice today and in the future. In the exciting competition among all materials, demand is growing, and the variety of steel alloys and properties is increasing. Long-term steel development therefore focuses on innovative alloy concepts, such as weight-reduced steels, ultra-high-strength steels, high-strength and simultaneously super-ductile steels, high-temperature resistant, ultra-fine-grained steels, as well as steels with bone-like properties, steels for offshore technologies, glass-like steels, superplastic steels, shape-memory steels, so-called "surface-functionalized" steels, multi-functional steels, nano-intelligent structural alloys, self-healing steels, steels for 3D printing, and much more. The "alloy design", i.e. the creation of a tailor-made alloy model, is initially carried out on the computer. Even phase transitions can now be simulated on the computer. This saves time and expensive laboratory tests. Using quantum mechanics, the properties of such modeled, not yet created steels can even be estimated. The basis for this are the deep insights into the atomic crystal structures of steel that are already possible today using microprobes (Raabe, 2011).

J. Schlegel, *The World of Steel*, https://doi.org/10.1007/978-3-658-39733-3_12

Steel Turns Green

Sustainability and thus environmental and climate protection are today indispensable challenges also for the material steel (Neugebauer et al., 2013). And precisely here does steel have an outstanding position with its eternal cycle: steel is produced from scrap, any number of times and above all without loss of quality. But steel also has a large CO_2 footprint. There are still no blast furnaces without coke to produce steel CO_2-neutral from ore. Technically this is conceivable. New technologies are under development and also being tested on a small scale. But it will take a few years until possible alternatives will revolutionize the currently dominant raw iron production by iron ore reduction in the blast furnace. Direct reduction with hydrogen and natural gas as well as melting reduction with hydrogen are possible, for example hydrogen plasma melting reduction, whereby the hydrogen must be produced with renewable energy (Schenk & Lüngen, 2016). Emissions (CO_2 emissions trading) will become very expensive from 2021. That is also why there is a constant optimization of technologies and steel production plants in the steel industry and at the same time a gradual transformation into a climate-neutral steel production (Schulz, 2019).

The future of steel has begun!

The proportion of recyclable scrap, perfectly separated, cleaned and shredded, will increase in the future. This also requires a rethinking of sustainable alloy design, that is, materials that are more durable and meet multiple requirements and are easily recyclable. And if the design of the components is further optimized in connection with the material steel, the overall ecological balance during application can be further improved.

Conclusion

The past centuries have been characterized by a change in the use of materials. New materials were added, others lost importance. This development will certainly follow a similar pattern in the future and will also apply to the numerous steel alloys. And steel in the future is not a discontinued material, but will continue to play a very important role and constantly open up new applications.

Much has been written about the world of steel, by no means everything. Steel still offers a lot of untapped potential and the future with steel will certainly be more interesting than the present.

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Timeline of Iron and Steel

13

In Sect. 4.1: From the History of Steel, important milestones in the history of iron and steel production are described. It is the aim of the timeline in Fig. 13.1 to place these in chronological order in comparison with social and technical events. This timeline was created based on a chronicle contained in Lietzmann and Schlegel (1992) and has been significantly extended up to the present day.

J. Schlegel, *The World of Steel*, https://doi.org/10.1007/978-3-658-39733-3_13

Iron and Steel Timeline

Social and technical events		Chronicle of iron production and processing	
Assumption: Beginning of mankind 8 - 5 million years ago in Africa			
2.6 million years ago	**Stone Age (earliest epoch in human history)**		
after 10,000 BC	Development of agriculture and animal husbandry	after 10,000 BC	Fiddle drills (fire drills) are known Likely beginning of the processing of solid found metals such as gold, silver, copper and meteoric iron Copper known in the oldest cultures
6000 - 5000 BC	**Copper Age in the Near East**	5000 BC	First indications of the use of wire made of precious metals
5000 BC	**Copper Age in Southern and Central Europe** In China and Egypt use of sulfur for bleaching textiles, as medicine and for disinfection		
3000 BC	**Copper Age in Northern Europe**	**around 3000 BC**	**Probably first metallurgical production of iron in Asia Minor, production of iron blades in Iraq** Tin used as admixture to copper (bronze)
after 3000 BC	**Bronze Age in the Near East**		
1950 BC	*Hammurapi (1728-1686 BC),* the 6th king of the 1st dynasty of Babylonia, mentions iron in his laws.	2200 - 1550 BC	Lead known in the early Bronze Age
		around 1910 BC	Gold wire produced by drawing
1800 - 600 BC	**Bronze Age in Central and Northern Europe**	1800 BC	Iron jewelry and iron tools in Phoenicia (narrow strip of land on the eastern Mediterranean coast of the present-day states of Israel, Lebanon and Syria)
		since 1400 BC	Iron known in Cyprus Beginning of the use of iron in Egypt
		from 1300 BC	Hittites (small Asian people of antiquity) supply iron to Egypt. Iron known in Persia.
1100 BC	**Hallstatt period (A)** older pre-Roman Iron Age in Europe, divided into time epochs	1100 - 1000 BC	Philistines (people who inhabited the coast of historical Palestine) know iron weapons.
1000 BC	**Hallstatt period (B)**	since 1000 BC	Iron swords in Greece, bronze and iron among the Illyrians (tribes that lived in antiquity in the western Balkan peninsula and southeastern Italy). Iron anvils for forging
850 BC	**Hallstatt period (C)**	around 800 BC	Roman Empire is the largest producer of copper. Iron utensils used by the Etruscans (people who lived in north central Italy)
800 BC to 700 AD	**Roman Empire**		
750 - 700 BC	**Beginning of the Iron Age in Europe**	**from 770 BC**	**Earth trough furnaces for iron ore reduction** **Use of iron in China (shaft furnace)**
650 BC	**Hallstatt period (D)**	650 BC	Iron known as chariot wheel fittings
500 BC	**Beginning of the La Tène period** (Epoch of the younger pre-Roman Iron Age)	**since 500 BC**	**Iron mining and processing in Sudan,** **Beginning of iron smelting in the Siegerland region (Germany)** Findings of first drawing tool (die) made of iron from San Zeno (Tyrol)
230 BC	Steam blower, bailer chain with water wheel, threaded spindle, Bronze leaf springs (copper-tin alloy) known	around 400 BC	Gauls have iron long swords.
100 BC	Paper in China	200 - 100 BC	Damascus steel for sword blades

Fig. 13.1 Timeline of iron and steel

		Turn of the times	
		67	Iron chain bridge at King-Tung-Fu in China
		100	**Iron production and processing among the Germanic tribes**
200 - 400	**Start of the use of hard coal in smelting and forging processes**	300	Iron wire drawing tool found in France
		310	Iron column of Dehli
		around 500	**Production of forgeable steel in China**
		700	Beginning of the nail industry in Belgium
around 800	**Beginning of the development of forging** (metal fittings for doors and chests)	800 - 1050	Dies from iron from the Viking Age in Norway
		900	First evidence of a waterwheel driven hammer mill
1000 -1250	***Romanesque***		
		1003	Drawing of an Osemund hammer (Märkisch Osemund: very soft, easily forgeable iron)
1096 - 1099	First crusade		
1120	Manuscript "Schedula Deversarium Artium" (Directory of the technical arts) by the Benedictine *P. Theophilus (1070-1125).*	1147	Damascene armorers come to Solingen
			Lump furnaces (precursor of today's blast furnaces)
1165	Fair in Leipzig mentioned for the first time		
from 1200	Growing of the cities, organization of the crafts in guilds	from 1200	Increasing use of hammer mills
		from 1240	Forged sheet iron in Bohemia (tinplate)
about 1250	*A. Magnus (around 1200-1280)* produce elemental arsenic (As).		
1250 - 1500	***Gothic***		
from 1350	Production of firearms	**about 1320**	**Oldest hammer mill in Germany**
		from 1350	Use of water power for shock drawing
		1363	Wire smiths and needlers in Nuremberg
			First blast furnaces
after 1400	First pocket watches		
1492	**Discovery of America**		
	Transition from the Middle Ages to modern times	1495	*L. da Vinci (1452-1519)* designs a sheet metal rolling mill.
		1497	*A. Dürer (1471-1528)* draws an iron rolling and cutting mill.
1500 - 1650	***Renaissance***		
		1500	*L. da Vinci (1452-1519)* designs a turbine driven rolling machine for conical lead and iron rods, describes for the first time an experiment to determine the tensile strength.
1517	*M. Luther (1483-1546)* proclaims his theses.		
1524 - 1525	Great German Peasants' War		
		since 1500	Hand-driven pocket rolling mills for window lead
		1536	Start of tinplate production in Saxony
1556	*G. Agricola (1494-1555): Book "De re metallica" appears,*		
1567	German version G. Agricola "Vom Bergkwerck XII Bücher".		
1600 - 1750	***Baroque***		
		from 1600	Water power for rolling mills
	Heyday of iron forging	1624	Wire drawing introduced in Sweden
1618	Beginning of the Thirty Years' War	**from 1627**	**Process for converting iron into steel**
1669	*H. Brand (1630-1692)* discovers phosphorus (P).		
1676	*R. Hooke (1635-1703)* notes that stress and strain are proportional up to the elastic limit.	1705	Strip iron rolling mill (quarto) by *Chr. Polhem (1661-1751)*
		1709	**Hard coal used for pig iron production in England.**
1723	*Czar Peter I (1672-1725)* establishes the Mining and metallurgical school in Ekaterinburg.		

Fig. 13.1 (continued)

1725 -1800	***Rococo***		
		1734	**First manual on ferrous metallurgy**
		1735	**First coke blast furnace in England**
		1740	*B. Huntsman (1704-1776)* produces crucible steel for the first time in Sheffield.
1743	First zinc smelter in Bristol, England.		
1751	*A. F. Cronstedt (1722-1765)* presents pure nickel (Ni).		
1765	Founding of the Freiberg Mining Academy		
1766	*H. Cavendish (1732-1810)* discovers hydrogen.		
1767	*J. Watt (1736-1819)* constructs a steam engine.		
1770 - 1830	***Classicism***		
1750 - 1850	**Industrial Revolution in England**		
1770	*J. Cook (1728-1779)* lands of the east coast of Australia.		
1771	*C. W. Scheele (1742-1786)* discovers nitrogen (N) and oxygen (O).		
1774	*J. G. Gahn (1745-1818)* reduces elemental manganese (Mn).		
1775	Clausthal mining school founded		
	A. L. de Lavoisier (1743-1794) discovers carbon (C).		
1781	*P. J. Hjelm (1746-1813)* produces elemental molybdenum (Mo).		
1782	*J. M. von Reichenstein (1740-1825)* discovers tellurium (Te).		
1783	*F. de Elhúyar (1755-1833) and J. J. de Elhúyar (1754-1796)* produce metallic tungsten (Wo).		
1784	*J. Watt (1736-1819)* invents the steam hammer.	**1784**	*H. Cort (1740-1800)* introduces puddling process (transformation of pig iron into wrought iron) in England.
1784	*J. Wikinson (1728-1808)* builds the first iron ship.		
1789	*M. H. Klaproth (1743-1817)* discovers zirconium *(Zr).*		
1791	*W. Gregor (1761-1817)* discovers titanium (Ti).		
		1795	*J. Bramah (1748-1814)* obtains patent for the first hydraulic press.
1796	*J. S. Tennant (1761-1815)* discovers diamond as a carbon modification.	1796	First coke blast furnace in Germany (Royal Steelworks Gliwice).
1796 - 1815	Napoleonic Wars		
1798	*L. N. Vauquelin (1763-1829)* isolates chromium (Cr).		
1800 - 1830	***Empire***		
1801	*C. Hatchett (1756-1847)* discovers niobium (Nb).	**from 1800**	**Beginning of the application of scientific methods in metallurgy**
	A. M. del Rio (1764-1849) discovers vanadium (V).		
1802	*A. G. Ekeberg (1767-1813)* discovers Tantalum (Ta).		
1803	*M. H. Klaproth (1743-1817), J. J. Berzelius (1779-1848)* and *W. von Hisinger (1766-1852)* isolated cerium (Ce) as an oxide.		
1808	*Sir H. Davy (1778-1829)* obtained calcium (Ca) for the first time.		
from 1810	Abolition of the compulsory guild system in Prussia.	from 1810	Cold-rolled tinplate (tinned steel sheet)
	Founding of manufactories		
1810	First wristwatch by A. L. Breguet (1747-1823)		
	J. L. Gy-Lussac (1778-1850) and *L. J. Thénard (1777-1857)* chemically detected sulfur (S).	**1811**	**Fr. Krupp (1787-1826) founds cast steel factory in Essen.**
1817	*J. J. Berzelius (1779-1848)* discovers selenium (Se).	1817	*D. Uhlhorn (1746-1837)* designs a toggle press.

Fig. 13.1 (continued)

1820 - 1840	***Biedermeier***		
		from 1820	**Improved puddle iron rolling mills in England** Ingot rolling mills in England
1824	*J. J. Berzelius (1779-1848)* discovers silicon (Si), describes the elementary elemental character of boron (B) and produces zirconium (Zr).	**1824**	**Introduction of the puddling process in Germany**
1825	*H. C. Ørstedt (1777-1851)* manufactures aluminum (Al).		
		1826	**First blast furnace in Westphalia**
1828	*P- M. A. Lebeau (1868- 1959)* produces pure beryllium (Be). *A. Bussy (1794-1882)* produces pure magnesium (Mg).	1828	*J. B. Neilson (1792-1865)* blows hot air into the blast furnace instead of cold air. Start of use of hot blast stoves.
1831	*M. Faraday (1791-1867)* discovers electromagnetic induction. *J. von Liebig (1803-1873)* produces metallic titanium (Ti) from ore.		
from 1831	Development of iron shipbuilding		
1835	First German railroad Nuremberg-Fürth	**1835**	**Rolling of the first railroad tracks in Germany.**
		1839	*J. Nasmuth (1808-1890)* builds a steam hammer.
		1848	**Development of the I-shaped beam in France**
		1849	Introduction of steel mould casting in Bochum *by J. Mayer (1813-1875).*
1851	First world exhibition in London		
1854	*R. W. Bunsen (1811-1899)* produces pure chromium (Cr).		
1855	Foundation of the Iron and Steel Institute in Philadelphia.	**1855**	*H. Bessemer (1813-1898)* invents the bessemer converter for refining.
		1859	Lead-hardened steel wire ("patent wire")
1860	*Ph. Reis (1834-1874)* invents the telephone.		
		1861	**50t steam hammer "Fritz" in operation (Krupp company)**
		1863	*H. C. Sorby (1826-1908)* uses the microscope for the first time to examinate metals.
		1864	**Siemens-Martin process introduced**
1870 - 1871	Franco-Prussian War	1870	*A. Thyssen (1842-1926)* founds steel mills in Mühlheim, Germany.
		from 1870	Use of diamond drawing dies
1871	Paris Commune		
1871 - 1900	***Founding period***		
1871	Foundation of the German Empire		
		1875	Painting "Iron Rolling Mill" by *A. v. Menzel (1815-1905)*
1877	*A. Wöhler (1819-1914):* "Memorandum on the Introduction of a State recognized state-approved classification of iron steel". **Start of steel standardization**	1877	First German armor plate rolled
		1878	**Thomas steel according to Thomas-Gilchrist process,** developed by *S. Thomas (1850-1885)* and *P. C. Gilchrist (1851-1935).* *E. W. Siemens (1816-1892)* designs the first electric melting furnace.
		1885	Invention of the cross-rolling of tubes by *R. Mannesmann (1856-1922)* and *M. Mannesmann (1857-1915).*
		1888	**First German reversible duo ingot rolling mill (blooming mill).** Flat-die cross-rolling introduced
		1889	**Continuous tube rolling mills in USA**
		1890	*P. L. T. Heroult (1863-1914)* invents the electric arc furnace.
1892	Invention of the diesel engine		

Fig. 13.1 (continued)

1895 - 1910 Art Nouveau			
1895	*C. Linde (1842-1934)* develops method for gas seperation.		
		1897	**First rolling mill driven by electric motor** (Berlin cable plant Oberspree, Germany)
1900	World Exhibition in Paris	**1900**	*F. Taylor (1856-1915)* introduces high speed steel.
	J. A. Brinell (1849-1925) invents a hardness tester.		**Continuous rolling mills with horizontal and vertical duo rolls**
		1902	**Introduction of the universal beam mill**
		1904	*P. L. Heroult (1863-1914)* develops the melting of scrap with the energy of the electric arc - beginning of electric steelmaking.
		1907	*W. D. Coolidge (1873-1975)* produces tungsten wire as light bulbs.
1910	Electrically operated toasting devices		
1911	*Atomic* model by *E. Rutherford (1871-1937)*		
		1912	**V2A steel** (stainless steel) patented by *E. Maurer (1886-1969)* and *B. Strauss (1873-1944).*
1913	*Assembly line* by *H. Ford (1863-1947)*		**Beginning of the era of stainless steels**
1915	Theory of relativity by *A. Einstein (1879-1955)*		
	Theory of plasticity by *R. v. Mises (1883-1953)*	1923	**Tungsten** carbide developed by Osram and presented in 1927 at the Leipzig Fair.
1925	Germany's first escalator in Cologne (Tietz department store)		
		1926	Union steel (weather-resistant steel) patented by Vereinigte Stahlwerke AG.
1928	Color television by *J. L. Baird (1888-1946)*	**from 1928**	**Start of industrial use of vacuum melting process**
1929	Quartz watch by *W. M. Marrison (1896-1980)*		Use of hard metal drawing dies
		from 1930	**Electro-slag remelting (patents in USA)**
1931	Electron microscope by *E. Ruska (1906-1988)*		
	Nuclear fission *O. Hahn (1879-1968)*	**1932**	Patent granted for a weather-resistant steel alloy, later further developed and named COR-TEN steel.
1937	World economic crisis		
1941	Computer Z3 by *K. Zuse (1910-1995)*		
1942	Nuclear reactor		
1950	Niobium (Nb) established as the official name for columbium.	**from 1950**	**Oxygen blast converter process (Linz-Donawitz)**
1951	*George de Mistral (1907-1990)* invents the Velcro fastener.		
1954	Solar cell	1954	**AOD converter for oxygen freshening** **A**rgon-**O**xygen-**D**ecarburization
	Market launch of electrically powered toothbrushes		
	First public moving sidewalk in Jersey City station, USA		
1960	First ruby laser in USA by *Th. H. Maimann (1927-*2007)		
		from 1960	**RH process (Ruhrstahl-Heraeus process)** **COR-TEN steel in Europe** **Remelting processes (ESR, PESR, VAR, electron beam, plasma remelting)**
1964	Kegs (small barrels) made of stainless steel in Great Britain		
1967	Color television starts in Germany		
		from 1970	**Continuous casting increasingly displaces ingot casting**
		1975	**Maraging steels,** martensitic hardenable steels with a high nickel content and high strength
			Midrex process (direct reduction of iron ore) patented
		1977	65 MN closed-die forging press - the largest in the world.
			Axial feed cross rolling developed
		1980	**Duplex steels,** austenitic ferritic steels with approximately equal proporties of ferrite and austenite

Fig. 13.1 (continued)

		from 1980	**Discontinuation of Thomas steel production** Metal powder injection molding is used industrially.
1983	The American *Ch. Hull (born 1939)* invents three-dimensional Printing of workpieces (3D printing)	**1985**	**Bake hardening steels,** deep drawing steels with strength increase through heat treatment at 200 °C. **High strength IF steels** with interstitial free ferritic matrix (in interstitial sites no atoms of alloying elements are intercalated).
1990	**Reunification of Germany** Start of the commercial phase of the Internet	**1990**	**Isotropic steels,** ultra pure, ferritic deep drawing steels **DP steels** (dual phase steels) - steels with a structure of ferritic matrix with an island-shaped martensitic second phase, resulting in a low yield strength with high tensile strength.
		after 1990	**Two-roll strip casting of steel** **Internal high-pressure forming**
		1993	**Shutdown of the last Siemens Martin furnace in Brandenburg/Havel, Germany.**
1995	DVD as a digital audio storage medium	**1995**	**TRIP steels,** ferritic-bainitic steels with retained austenitic and with transformation-induced phase transformation-induced plasticity and with increased ductility. **TRIP/TWIP steels,** high alloy austenitic CrNiMn steels with transformation- or twinning-induced plasticity and with high strength and ductility. **PM steels, partially martensitic steels with ferrite** **CP steels,** complex phase steels with martensite, bainite and ferrite.
1999	Beginning of the age of mobile communications		
		Turn of the millennium - 2000	
		2000	**Press hardening** (controlled hardening of sheet metal parts in the hot forming die)
2001	Online encyclopedia Wikipedia founded.		
2002	Introduction of euro cash		
		2003	**Shutdown of the last German bottom-blowing converter at the new Maxhütte steel mill, Sulzbach-Rosenberg**
2010	First tablet computer from Apple	**2010**	**TRIPLEX steels,** phase steels with martensite, austenite and carbide as well as with high strength and ductility.
		2012	**Q&P steels** (Quenching & Partitioning), martensitic steels with retained austenite, with high strenght and ductiliy.
		2016	**AMC steels,** high alloy, austenitic martensitic steels with carbides and Q&P treatment
		constantly::	Further development of steelmaking processes with the aim of CO_2-free steel. Development of new steels and special materials.

Fig. 13.1 (continued)

References

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Glossary

3D printing A term used for all manufacturing processes that, without a tool, create a three-dimensional object layer by layer under computer control. The terms “additive manufacturing”, “generative manufacturing” or “rapid technology” are also common. Typical materials for 3D printing are plastics, resins, ceramics and metals.[1]

Abrasive cutting *see “Water Jet Cutting”*

The process of water jet cutting with abrasive additives in the form of powdery hard particles in water.

Accompanying element It is not an alloying element, but an element that can unintentionally enter the steel via the scrap or as an accompanying mineral in the ore and must not exceed a maximum concentration.

Adhesive There is much to glue in everyday life. We connect material-locking parts made of different materials with different adhesives. This joining process is used in addition to welding and brazing in the steel processing industry.

Adiabatic cutting *see “High speed cutting”*

Aging brittleness Increase in hardness and brittleness of steel during aging due to precipitation processes.

Aging As with humans, aging processes can also occur in steel, i.e. changes in properties over a longer period of time, such as an increase in hardness and strength while decreasing elongation. Mainly nitrogen and carbon are the causes.

Aging Final step of the heat treatment process “precipitation hardening” which is carried out after solution annealing and quenching. The present supersaturated microstructure state is usually excited at temperatures of 150 to 190 °C to form the desired precipitates for an increase in strength.

AHS steel (engl. **A**dvanced **H**igh **S**trength Steel) *see “Carbon steel”*

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[1] Definitions and explanations of technical terms, special expressions, common terms and abbreviations from the practice of steel metallurgy, steel processing and material testing (source, among others: Wegst, C. & M. Wegst (2019). *Stahlschlüssel-Taschenbuch,* Verlag Stahlschlüssel Wegst GmbH).

J. Schlegel, *The World of Steel,* https://doi.org/10.1007/978-3-658-39733-3

Alitizing Surface coating with aluminum by diffusion during annealing of steel workpieces in aluminum powder, dipping in liquid aluminum bath or spraying of liquid aluminum.

Alloying Element Chemical element that is deliberately added (alloyed) to a metal in order to specifically adjust or improve certain material properties.

Amorphous Microstructure state without shape. An amorphous metal does not have a regular crystal structure, but the atoms are arranged irregularly, as is typical for glass.

Annealing color Color that the steel assumes during annealing (tempering) in normal atmosphere (without protective gas), i.e. during heating to a specified annealing temperature. Depending on the temperature, steel shows characteristic annealing colors.

Annealing on speroidal cementite Variant of the soft annealing, whereby lamellar cementite (Fe_3C) in the microstructure is formed into a spheroidal shape to improve the formability and machinability of the steel.

Annealing scale *see "Scale"*

This scale form arises as combustion when steel products are annealing in air.

Annealing temperature Temperature at which the steel is to be glowing in the annealing furnace depending on the steel composition and the heat treatment to be carried out.

Annealing to best strength Variant of soft annealing. Today this process is referred to as "annealing to a certain hardness".

Annealing to best structure Variant of soft annealing. This treatment is an annealing to a pure Ferrit-Pearlit-structure, also known as "Pearlitizing".

Annealing diagram The course of hardness and tensile strength of steels at increasing annealing temperature, from which the necessary annealing temperature can be taken according to the desired hardness, also called "tempering diagram".

Annealing *see "Heat treatment"*

Heating, warming up and cooling of workpieces in order to achieve defined properties, thus a subfield of heat treatment.

Anvil block A heavy part made of steel, cast iron or concrete, to which the anvil of machine hammers is attached and which is intended to cushion the impact of the hammer.

Anvil cap Interchangeable, flat insert without a deepening for forging, sometimes used in practice as a term for forging dies with form deepenings.

Anvil A practically shaped block of steel, cast or forged, and the basic tool of forging: the anvil, on which the glowing forge piece is formed with hammer blows.

AOD-Converter Plant for the post-treatment of steel (ladle metallurgy). With an argon or nitrogen – oxygen mixture, which is blown into the liquid steel melt via nozzles in the bottom of a converter, decarbonization of the steel takes place above all. Therefore the name AOD: **A**rgon-**O**xygen-**D**ecarburization.

Arc furnace (AF) *see "Electric **A**rc-**F**urnace"*

Arc spraying Thermal process for surface coating, e.g. hot-dip galvanising, in which the coating metal in wire form is melted continuously in an arc and sprayed onto the steel surface with a gas in the form of fine droplets.

Atomic emission spectrometry (AES) Fast and reliable analytical method for low- and high-alloyed steels and in particular for the alloying elements with low atomic weights, used in steelworks laboratories. AES is also called "**o**ptical **e**mission **s**pectrometry" (OES) or "flame spectroscopy". The basis is the phenomenon that atoms emit light of a defined energy when supplied with energy. The atoms of different elements in the steel also produce light with different wavelengths. This is used for analysis. The energy supply can be carried out by means of an arc (spark spectrometer), with a flame or by means of plasma.

Atomizing Powder metallurgical process for the production of powder by atomizing liquid metal melts.

Austenite Metallographic designation for the face-centred cubic lattice (lattice structure) in iron or steel. The phase also known as "gamma-iron" occurs in pure iron above 911 °C and is not magnetizable. It is stabilized by austenite-stabilizing alloying elements such as nickel, carbon, cobalt, manganese and nitrogen at higher and/or lower temperatures. Sometimes in practice the austenitic steel is also called austenite.

Austenitic steel Has the austenitic, face-centred cubic lattice microstructure, even at room temperature or from room temperature up to melting temperature. This is achieved by the alloying elements such as chromium, nickel, manganese, molybdenum and cobalt. Pure austenitic steels do not show $\gamma \rightarrow \alpha$ transformation, so they are not transformation hardenable.

Austenitizing In transformation hardening, the steels are heated to temperatures above the transformation point. This transforms the ferritic into the austenitic microstructure. This heating to set a fully transformed austenitic microstructure is called "austenitizing". Then the quenching is carried out to form a martensitic hardening microstructure.

Autogenous cutting Thermal separation process, also known as "flame cutting" or "torch cutting". A cutting flame and a sharp oxygen jet are used to burn the steel in the cutting zone.

Automatic turning machine Automated, CNC-controlled machine for the chip-removing machining process of turning to produce rotationally symmetrical turned parts.

Axial-feed cross rolling *see "Cross-rolling"*

Process of cross-rolling by means of driven disk-shaped or wedge-shaped rolling tools, which can be moved towards each other in the radial direction. In the rolling gap formed in this way, the rotationally symmetrical workpiece is set in rotation and a groove is rolled in. This is defined when the workpiece is moved into the workpiece axis. In this way, for example, shafts or profiled hollow parts can be flexibly and automatically generated.

Bainite A microstructure in carbon-containing steels, named after the US metallurgist *E. C. Bain* (1891–1971), which forms at temperatures and cooling rates between those of the microstructures pearlite or martensite, therefore also referred to as "intermediate phase microstructure".

Base Steel Unalloyed steels for requirements for which no special measures are required during steel production, such as steels for ironware, wire mesh, railings and fences.

Batch analysis *see "Melt charge"*

The result of the chemical composition of a melt charge determined in the steelworks laboratory, documented in the test certificate for this charge.

Batch annealing furnace A heat treatment facility in the form of a stationary chamber (batch furnace), electrically or gas-heated, at normal atmosphere, also with protective gas or under vacuum possible heat treatments.

Baumann hammer A hardness tester that can be used very conveniently on site and has a dynamic plastic effect. A test ball is suddenly struck with spring force onto the surface of the workpiece to be tested. The size of the resulting impression is measured and serves as a measure of the hardness.

Bear Powerful and very heavy, like a bear, this tool processes the workpiece as the upper movable part of a die-forging press or as the upper and lower anvil of a counterblow hammer as if it were a bear.

Bearing metal Not steel, but alloy with low hardness made of lead, tin, antimony, copper or cadmium for use in plain bearings.

Bend forming A workpiece is formed (bent) chipless with help of bending stresses, especially known in sheet metal forming. Methods include free bending, deep drawing, rolling, bending and rolling. Straightening by bending is also a bending process.

Bending tensile test *see "Bending test"*

Bending test Destructive testing method used to determine the formability of cold-formed or cold-formed and heat-treated samples, such as sheets, strips, strips and wires, which are stressed by repeated bending by 90° until they break. The number of bends that the sample has withstood is a measure of its formability.

Bending test Method of destructive material testing, also called "Bending tensile test", whereby a geometrically defined test speciment is exposed to a number of deflections and various material parameters are determined from the bending force and the achieved deflection values, such as the stress-strain line during bending (similar to the stress-strain curve during the tensile test).

Bessemer converter Looks like a pear, but is much larger and represents a pear-shaped, tiltable furnace with a refractory lining to treat liquid pig iron (refining: burning of carbon, silicon, manganese and other elements). For this purpose, compressed air is blown into the pig iron from below through the bottom. Therefore, these onverters are also referred to as "bottom-blown converters". Smaller Bessemer onverters hold up to 1 t, the large ones up to 8 t of pig iron.

Bessemer process *see "Bessemer-Converter"*

Process developed by *H. Bessemer* (1813–1898) around 1855 for the mass production of steel: Raw iron still in liquid form coming directly from the blast furnace is filled into a tilting converter and "bottom-blown" with compressed air.

Bimetal The name already refers to the fact that it is a metal consisting of two layers of different metals, usually in sheet and strip form. Since the two metals have different thermal expansion coefficients, one also speaks of "thermobimetal". When heated, this bimetal bends. This effect is used for temperature-dependent controls, for example in temperature switches in irons, coffee machines, toasters or kettles, as well as in cooling water thermostats in motor vehicles.

Blast converter Pig iron from the blast furnace contains unwanted impurities such as carbon, silicon, sulfur and phosphorus. These can be removed by blowing oxygen into the liquid pig iron. This process is called "blowing" and is carried out in tiltable vessels, the blast converters.

Blast furnace gas Furnace gas that is constantly produced during the blast furnace process (reduction of iron ore) as a combustible gas made up of nitrogen (45 to 60%), carbon dioxide (20 to 25%), carbon monoxide (20 to 30%) and hydrogen (2 to 4%).

Blast furnace lump slag Forms when the liquid slag from the blast furnace cools slowly in beds (cooling areas, pits).

Blast furnace slag sand Fine-grained, glassy by-product of pig iron production in the blast furnace, produced by rapid cooling of blast furnace slag and grinding, also called *"slag sand"* and used, inter alia, as an additive for cement, as a rock fraction in road and path construction, for the production of fertilizers, for slag stones and as a blasting agent.

Blast furnace slag *see "Ironworks slag"*

Residue from the high-temperature process in the blast furnace.

Blast furnace stove Installation with combustion and storage space, in order to heat fresh air using waste heat and by means of combustion of slag gas, and supply it to the blast furnace as "hot wind".

Blast furnace – converter route Classic way of primary steel production: reduction of iron ore in the blast furnace and refining of pig iron in the converter to crude steel.

Blast furnace Large-scale metallurgical plant for the production of liquid pig iron from iron ore by means of a continuous reduction and melting process.

Blasting Not the plurality of a beam like sunbeams is meant, but a process of the surface technology, in which by means of compressed air, pressure liquids, electrostatic fields or centrifugal wheels blasting agents are highly accelerated on the surface to be processed and there cause a material removal or a solidification.

Bloomery furnace A small, shaft-shaped kiln (height up to 1.2 m, diameter up to 70 cm) made of clay and stones for reducing iron ore with wood charcoal („blooemry process"). Depending on the size of the kiln and the process, a cast iron with an uneven carbon content and slag residues of a maximum weight of 50 kg could be produced, while the slag ran out of the kiln after it was opened.

Bloomery process *see "Bloomery furnace"*

Smelting (reduction) of iron ore with wood charcoal, wood or peat in a small shaft kiln at temperatures of 1100 to 1350 °C, with air being supplied by a bellows. This smelting process, called “bloomery process”, was already used by the Celts, Romans, Germans and other peoples in Europe from about 700 BC.

Blooming mill Rolling stand with two rolls for shaping cast and forged ingots, usually operated in reverse, i.e. with decreasing roll gap (upper roll is moved closer), rolled forward and back again.

Blow hole Hollow space formed in castings during cooling and solidification due to the shrinkage of the material volume.

Blue annealing *see “Blueing”, “Annealing”*

Blue break test *see “Macroscopic Purity”*

Standardized standard method for testing steels for macroscopic, non-metallic inclusions (“macroscopic purity”). For this purpose, an unbent sample is broken at 300 to 400 °C. Steel runs blue at these temperatures, but not the existing inclusions, which are often already visible with the naked eye or visible under low magnification and can be classified according to standardized guidelines.

Blue brittleness When annealing at a temperature at which the steel turns blue, steels with a higher carbon content can become brittle and thus have reduced toughness and also lower cold formability. Therefore the name “blue brittleness”, which can occur in the temperature range from 200 to below 400 °C.

Blueing *see “Annealing Color”, “Annealing”, “Tempering”*

The blueing can also be understood as the annealing of the steel after hardening. During this heat treatment, different colors occur on the steel surface as a result of oxidation, depending on the annealing temperature. These are also used specifically for beautiful color designs of steel parts, for example in the watch industry. As a result, steel parts that have been slowly brought up to about 300 °C turn blue with a cornflower blue shimmer.

Boilers steel For boiler and pressure vessel construction suitable, unalloyed to highly alloyed, high-strength and heat-resistant steel.

Bottom-blown process *see “Bessemer process”, “Oxygen refresh in the AOD converter”*

In this process, air, an argon or a nitrogen-oxygen mixture is blown through openings in the bottom of the converter to refresh liquid pig iron or liquid raw steel.

Box calibrated rolls Rectangular box shape that is cut multiple times side by side in the rolling paths of rolls that are used, for example, in a block rolling mill for rolling square or rectangular billets.

Bright steel production Bright steels are steel long products which, by means of a surface treatment and a cold forming or by a machining, have a flat, smooth, blank surface and thus a very good workability, a good dimensional accuracy and are also suitable for a subsequent coating. The bright steel production includes the processes such as pre-treatment by pickling or peeling, forming by drawing, straightening, grinding and polishing.

Brightfield microscope The opaque sample to be examined is not tested by radiographic inspection, but directly in the direction of observation, often by the objective itself.

Brightfield stereomicroscope As a special type of brightfield microscope with two objectives, it offers a three-dimensional impression of the examined object.

Brinell hardness test HB Method for hardness testing, developed in 1900 by Swedish engineer *J. A. Brinell* (1849–1925). A tungsten carbide ball is pressed into the sample surface with a defined test force and the round impression is measured as the hardness HB.

Brittle *see "Brittleness"*

Brittleness A material property that refers to a brittle fracture behavior with no or almost no plastic deformation under shear stress. Brittle steels break immediately without elongation at the achieved tensile strength. Hard materials such as ceramics, glass, carbides and nitrides show similar brittle fracture behavior, as well as diamond.

Broach *see "Broaching"*

Machining tool for broaching, mostly used as a one-piece tool for diameters up to 150 mm in broaching machines.

Broaching needle *see "Broaching"*

An elongated, slightly conical tool for broaching, which is pulled through the workpiece bore to be machined by means of a broaching machine.

Broaching In the transferred sense of "removing something from the way" or "making free", broaching refers to a process of "making free" surfaces (external broaching) or bores (internal broaching) by means of various tools from unevenness, i.e. to improve the surface quality. Surface roughness values of R_t between 1.6 and 25 μm can be achieved.

Bulge test Method for determining flow curves in the two-axis stress state of sheets that are clamped on all sides, loaded with oil pressure, and bulged until they break. The flow curve is determined from the oil pressure in correlation to the bulging state.

Burnishing Creating a very thin protective layer of approximately 1 micron thickness on the steel surface in order to reduce corrosion. This is done by submerging the workpiece in an acidic or alkaline solution or in a salt melt. This produces black iron oxide layers.

Caliber sequence *see "Roll calibration"*

Not the usual classification of the outer diameters of projectiles and the inner diameters of the barrels of weapons is meant by the term "caliber", but the geometric shape of profiled rolls, used in block and profile rolling mills for steel long products. And the sequence of individual forming steps during the rolling passage of the material to be rolled successively through several differently profiled ("calibrated") rolls is called "caliber sequence", such as an alternating sequence of oval and round calibers.

Carbide former *see "Carbide"*

Chemical elements such as tungsten, molybdenum, vanadium, cobalt, chromium and titanium, which are added to the steel with carbon to form carbides.

Carbide Binary chemical compound of carbon with another element, which can be metallic (e.g. tantalum carbide TaC) or salt-like (e.g. calcium carbide CaC_2).

Carbon steel A term used for a particular type of steel, which can be misleading in practice, because every steel has carbon as the most important alloying element in addition to iron. The correct modern high-strength, unalloyed steels are meant, also called "C-steel" or "AHS steel" (**A**dvanced **H**igh **S**trength Steel). These include, for example, some cold work steels such as knife steels.

Carburizing agent Agent are used for carburizing workpieces and can be solid, liquid or gaseous, e.g. carburizing powder, salt melt or enrichment gas (hydrocarbon).

Carburizing In order to increase hardness, steels with a low carbon content can be carburized, i.e. enriched with carbon at high temperatures. For this purpose, a carbon-rich environment with carburizing agents is required. Carburizing is often also called "cementation".

Carrier gas hot extraction Standardized method for determining the concentrations of gaseous elements such as nitrogen, hydrogen, and oxygen in steel.

Case hardening depth *see "Case Hardening"*

Depth of hardness from the surface onwards in a case-hardening process, e.g. in induction hardening.

Case hardening steel A non-alloy or low-alloy steel with carbon contents of 0.10 to 0.25% by mass, thus not suitable for heat treatment. Therefore, workpieces made of carbon steel are "inserted" into a carbon-containing atmosphere, heated to temperatures between 880 and 1050 °C and thus carburised on the surface. Only then is hardening and tempering carried out.

Case hardening A process for surface hardening which comprises the steps of carburising, hardening and tempering of the steel.

Cast iron Iron-carbon alloy with a high carbon content of more than 2 mass-% (steel: less than 2 mass-% carbon).

Casting and rolling process *see "Two-Roll Strip Casting"*

Method for continuous strip casting, in which the liquid steel passes from above, between two rollers rotating in opposite directions and cooled, begins to solidify in the nip and is drawn off in strip form with a thickness of max. 6 mm.

Casting band Band that circulates at the bottom of a casting machine and on which liquid steel is poured from a feed system and solidifies to form a strip about 10 mm thick. Sometimes in practice the product, i.e. a continuously cast strip, is also referred to as a casting band.

Casting machine Machine for casting metals, e.g. a casting machine with a casting band or a die casting machine (melt is fed into a casting chamber under high pressure).

Casting powder Powdered mixture of mineral raw materials such as, for example, calcite, feldspar, fluorspar as well as soda and technical silicates, used in foundry factoies for lubrication, in order to avoid adherence of steel to the mould wall, for setting an even heat transfer between steel and mould, for protecting steel against reoxidation, for absorbing non-metallic inclusions from steel and for thermal insulation of the molten steel surface.

Casting Transferring a metal melt from the liquid to the solid state by pouring it into a mould in which solidification takes place. Since the first solid, machinable form is produced by this pouring and solidification after steelmaking, casting belongs to the manufacturing process “primary shaping”.

Cementite Phase in the iron-carbon system with the composition Fe_3C (iron carbide).

Centerless continuous grinding Machining (grinding) of the outer surface of round workpieces such as shafts, bolts, rods and needles, whereby the workpiece is rotated on a guide rail through point-less round grinding machines between the grinding wheel and the regulating wheel.

Ceramics The term “ceramics” encompasses a variety of materials, with fired clay in the form of beautifully designed objects being perhaps the best known and having a very interesting history to tell. The “industrial ceramics” of various compositions, including silicates, oxides, carbides, nitrides, and borides, have been developed for a number of technical applications, such as cutting ceramics for machining metals, coatings for heating elements, cutting nozzles for laser and waterjet cutting, ceramic powders for coating metals, or refractory materials for high-temperature applications in melting and heat treatment furnaces.

Cermet Term comes from **cer**amic and **met**al for a very hard composite material consisting of a metallic matrix (binder phase of niobium, molybdenum, titanium, cobalt, chromium, etc.) with embedded ceramic particles (mainly aluminum oxide, zirconium oxide).

Chamfering Bars are tapered or chamfered like pencils with a taper tool. Tapers with defined angles and lengths are produced according to customer requirements.

Chamfering Creating a beveled surface on workpiece edges, e.g. at the ends of bars with beveled tips and a defined bevel angle.

Charging opening of a blast furnace Opening at the top of a blast furnace, through which the blast furnace is charged with coke and a mixture of metal-containing ores and additives and from which the blast furnace gas (tapping gas) is also drawn off.

Charpy impact test Testing method for assessing the toughness properties of steel under multiaxial or impact loading, developed by *A. G. A. Charpy* (1865–1945), also known as the “Charpy test”. A notched specimen, fixed on two supports, is broken by means of a pendulum impact device. The amount of energy absorbed by the specimen from the fall of the pendulum hammer is calculated from the comparison of the original drop height with the swing-through height of the pendulum hammer and quantifies the notch impact toughness of the tested specimen.

Charpy test *see “Notch impact test”*

Chemical Analysis *see “Batch analysis”*

It comprises all methods for determining the composition of substances, i.e. the alloying constituents in the case of steel, and both qualitatively (Which elements are contained?) and quantitatively (proportion in mass-% of the respective elements). In practice, the "chemical analysis of a steel" also refers to the compilation of the results in the form of the test certificate.

Chill mould Reusable permanent mould into which metal melts are poured, cooled there and thus take on the mould shape, such as moulds for casting.

Chip type Chip shape that arose as a result of the formation of the chip, by which the machining process can also be judged, such as tear-off chip, shear chip or flow chip.

Chip Particle mechanically removed from a workpiece to be machined.

Chrome plating Production of chrome coatings on metal objects, for example by means of galvanic coating.

Chrome steel In colloquial usage, steels are referred to as "chrome steels" if they have a high alloy content of chromium. Chromium acts as a carbide former in steel. Very hard chromium carbide particles are formed in the structure, which increase wear resistance. The hot strength, heat and corrosion resistance are also improved. And steels with more than 12 to 13% chromium do not rust. So from 1912 with the V2A steel the era of the stainless chromium-nickel steels and many other steels began, such as the ferritic chromium steels, the austenitic chromium-nickel steels and also the chromium-molybdenum steels (special austenites).

Chromium plating (Chromating) A surface finishing process for the formation of chromate layers on metals by dipping in chromic acid baths. The chromate layer formed in this way provides a good passivation protection layer or acts as a good adhesive for a further, usually metallic coating.

Circular curved continuous strand casting Continuous casting process in which the solidifying strand exits vertically from a mold and is then deflected in a curved manner into the horizontal (arched strand casting).

Circular disk reflector *see "Flat bottom hole"*

Artificial error size in the form of a small flat bottom hole in a calibration piece (reference body) for setting the sensitivity of ultrasonic testing systems.

Coating Applying a adherent, thin or thick layer to a workpiece surface.

Coefficient of expansion (α in K^{-1}) Commonly referred to as the "coefficient of thermal expansion", "thermal expansion coefficient" or simply "expansion factor", it is the material property that describes the change in dimensions with temperature changes. The "linear expansion coefficient α" is predominantly used as the relative change in length with a change in temperature in units of per Kelvin (K^{-1}).

Coil Term used for a wound band or a wound wire (often also called "spool").

Coil-coating Term for "continuous coil coating", as it is used mainly for steel and aluminum band for one- or two-sided coating with lacquer and plastic.

Coining Press forming using contoured stamps that press more or less deep contours into a workpiece when force is applied. The term coining already refers to a high surface quality, uniformity and exact contours or dimensional accuracy. The best known application is the coining of coins and medals.

Cold brittleness Brittle behavior, for example of forged components at room temperature, which is related to segregations in the microstructure and caused by phosphorus during solidification of the steel melt.

Cold forging A variant of forging metals in general at room temperature, whereby self-heating of the forging material to approximately 150 °C can occur due to the forging energy.

Cold forming Plastic deformation of metals at room temperature or at temperatures far below the recrystallization temperature, so that cold hardening occurs depending on the degree of deformation.

Cold Hardening Increasing impairment of plastic deformation at room temperature by obstacles in the microstructure (e.g. grain boundaries impede dislocation motion during glide), the strength of the material increases, the toughness and formability decrease. For further deformation, increasingly higher forces must be applied until this is no longer possible from an engineering point of view or the workpiece breaks.

Cold isostatic pressing Powder metallurgical process for compressing metal powder to a “green preform” by means of isostatic pressing.

Cold rolled strip Beverage cans made of tinplate, a cold-rolled and galvanized steel sheet with thicknesses of 0.1 to 0.5 mm, are the best-known products made of cold rolled strip. Today, cold rolling mills with single-stand or tandem rolling lines produce cold rolled strip with thicknesses below 1 mm and widths exceeding 2 m from hot rolled steel strip.

Cold working steel Tool steel for machining other materials at room temperature, with no higher temperatures than 200 °C occurring.

Color penetration test *see “Penetration test” or “Dye penetration test”*

Non-destructive testing for surface defects (cracks, pores) that uses capillary forces to make such defects visible in daylight with color contrast agents.

Combustion analysis Standardised method for carbon and sulphur determination in steel.

Combustion Oxide layers on steel surfaces caused by very high temperatures (melting temperatures, annealing or preheating temperatures for hot forming) under the influence of oxygen. There is a loss of material due to burning, gassing, sputtering, slagging or scaling. If steels are exposed to high temperatures during use, it is important to know their scaling resistance, i.e. up to what temperatures no combustion (scaling) occurs on the surface. These temperatures range from 750 to 1250 °C for heat- and scaling-resistant steels.

Composite material A material made of two or more materials with different properties, also called “compound”.

Compression degree Decrease in height caused by pressure forming during forging.

Compression test Reversal of the tensile test with respect to the direction of force, since instead of tensile forces, compressive forces are used to determine the flow curves of brittle materials, such as cast iron. The test is carried out on metallic materials with cylindrical specimens (“cylinder crushing test”).

Compression yield point Load limit in a compression test, up to which a material can withstand a compressive stress without beginning to deform plastically in a permanent manner, comparable to the yield strength in a tensile test.

Compression Pressure forming for the plastic deformation of materials, which leads to a decrease in height and width.

Compressive forming Plastic deformation of materials under the action of compressive forces, such as rolling, forging, hammering, pressing, deep drawing, extrusion.

Compressive strength Resistance of the material to applied compressive forces.

Concrete steel Reinforcement (strengthening) in concrete structures, also called “reinforcing steel”, “armouring iron” or “monier iron” in the past. In Germany, concrete steel with the characteristic yield strength of approx. 500 N/mm^2 is predominantly used.

Concurrent milling *see “Milling”*

Milling process with a milling cutter rotating in the feed direction of the workpiece.

Confectioning Work mostly at the end of a production, assigned to the finishing, which includes the product division or portioning, the cutting of customer-specific cuts and special types of packaging.

Confocal microscope Special light microscope that does not illuminate the entire preparation of the test piece at once, but scans the test piece with small sections of a small light spot. The complete image is then generated in the computer.

Consignment stock A term for a supplier’s warehouse that is located at the customer’s premises or in the vicinity thereof. The stored goods remain the property of the supplier until the customer withdraws goods from this warehouse. Only at this point does the delivery with invoicing to the customer take place. According to the consignment contract, the supplier is obliged to continuously replenish this consignment warehouse in order to ensure a minimum stock level.

Continuous rolling mill A rolling mill with several rolling stands arranged in line one behind the other, which enable continuous rolling with several individual cross-section reductions, such as in the case of continuous wire rolling.

Continuous slab casting Continuous casting from one strand, usually using the arched continuous casting process, and subsequent cross-cutting into individual slabs.

Continuous strand casting Continuous casting process for the production of semi-finished products made of metal in different formats.

Continuous strip casting Continuously cast thin strip directly from the steel melt as raw material for cold rolling. The very short and fast solidification of the steel melt results in a very fine-grained structure. The two-roll casting process and the casting process using a casting band are distinguished.

Converter slag *see “Steelworks slag”*

A type of slag that is produced when pig iron is refined to steel in an LD converter (**L**inz-**D**onawitz-Converter), also known as an “LD slag”.

Converter A vessel with a refractory lining for the reception and treatment of liquid pig iron or steel, also known as a "crucible" or "melting vessel". The classic steelmaking process is the basic oxygen converter for reducing carbon in pig iron.

Cooling bed Although it has the same effect, it is not cooling bedding: the storage area for very hot products, for example, immediately after continuous casting, forging or hot rolling, with gradual further transport of the cooling products.

Corex process *see "Smelting reduction"*
A two-stage "smelting reduction process" for producing pig iron from iron ore. It combines the process of direct reduction (pre-reduction of the iron ore to sponge iron using non-coked coal) with a subsequent melting process (final reduction) to produce pig iron that is comparable to that from the blast furnace process.

Corrosion resistance The property of materials to resist corrosion. Corrosion-resistant (stainless) steels do not rust because they form a protective passive layer with a chromium content of min. 12 mass-%

Corrosion The term derives from the Latin "corrodere" – to decompose, to erode, to gnaw. It is an ubiquitous chemical reaction of the material with the environment, i.e. with its reducing or oxidizing media, such as seawater, acids, bases, salts, and occasionally also under the simultaneous action of mechanical stress. With steel, rust (iron oxide) forms in this process.

Corten steel Weather-resistant, corrosion-resistant steel that forms a dense barrier layer of sulfates and phosphates that adheres to the underlying red rust layer and protects against further corrosion; trade name "COR-TEN steel".

Counterblow hammer Machine hammer in which the lower ram (anvil) is not rigidly mounted, but always moves up in the same rhythm when the upper ram moves down. Thus, the forging product is hammered on both sides.

Crack Locally limited material separation (defect), present in the metal after metallurgical production like slag, non-metallic inclusion or decarburization, formed during further processing by internal and/or external stresses like rolling doubling, transverse crack, notch, heat treatment defect, welding defect or machining crack, etc., i.e. all defects that, if not detected, can eventually lead to crack propagation and component damage during use due to long-term loading.

Creep modulus *see "Creep"*

Creep number *see "Creep"*

Creep rupture strength *see "Creep rupture test"*
Material property, determined in a creep test, which states how much stress the material can withstand at a certain temperature without suffering damage.

Creep rupture test Test procedure for determining the material behavior at constant test temperature above room temperature and constant tensile force. The results are parameters such as the creep time upto the rupture, the creep strength and creep limit.

Creep A time- and temperature-dependent, plastic deformation of components that occurs under constant load. The characteristic value for this is the "creep modulus" or the "creep number". This material behavior, which can occur under certain circumstances, must be taken into account in mechanical engineering and construction in order to avoid damage.

Critical cooling rate In hardening, the material-dependent cooling rate that is at least necessary to form the martensite structure. The “upper critical cooling rate” represents the longest cooling time or the lowest cooling rate to achieve 100% martensite, and the “lower critical cooling rate” is the shortest cooling time and thus the highest cooling rate at which martensite first appears.

Cross Rolling Generic term for rolling processes that allow forming and profiling of rotationally symmetrical preforms transversely to their axis using wedge-shaped tools. This forming can take place between two axially parallel, counter-rotating rolls, then the terms “cross wedge rolling” and “round cross rolling” apply. In “flat cross rolling”, two plates with wedge-shaped profiling move parallel to each other in opposite directions, up and down, in order to form different diameters at any point on the preform. A special variant of cross rolling is “axial feed cross rolling”.

Cross wedge rolling *see “Cross rolling”*

Crystal defects *see “Lattice defects”*

Crystal lattice *see “Lattice”, “Crystal”*

Crystal nucleus Very fine particle that, in a metal melt, acts as a nucleus to facilitate crystallization.

Crystal recovery A similar process to what we experience in the sauna: the breakdown of internal tensions. In steel, this happens as the elimination of the consequences of plastic deformation, with no new formation of the structure, that is, no recrystallization. The grain shape and size remain unchanged.

Crystal twin Crystal form made up of crystals of the same chemical composition and structure that are joined together and resemble each other like twins.

Crystal Solid material consisting of three-dimensionally periodic, always constant structural units (cells with lattice structure), with the smallest subunit called the “elementary cell”. Well-known beautiful crystals are from quartz, single crystals from silicon or sugar crystals.

Crystalline State of solids that has arisen through crystallization.

Crystallite *see “Crystal”, “Grain”*

Crystallization rate Rate at which a crystal grows after nucleation during solidification (temperature decrease), depending on the mobility of the atoms, which decreases with cooling.

C-steel *see “Carbon steel”*

Curie temperature Material-specific temperature that marks the reversible transition from ferromagnetic to paramagnetic state. For example, iron is only ferromagnetic up to 768 °C. Above this Curie temperature, it loses this property and is paramagnetic.

Note: A ferromagnetic material is strongly attracted by a magnet, but a paramagnetic one is only very weakly attracted.

Cut grinding Machining process for cutting workpieces by means of rapidly rotating cutting or grinding discs.

Cutting ability The property of how well the blade of the used cutting tool (knife) cuts in use, depending on the cutting material, the sharpness and grinding geometry, not to be confused with the "edge holding property".

Cutting ceramic *see "Indexable inserts"*

Ceramic material used as a cutting material in the form of indexable inserts for milling cutters, turning tools, drills, etc.

Cutting geometry Geometric design of the cutting surfaces (wedge surfaces) on the cutting part of a machining tool, which causes the material removal and on which the chips slide.

Cutting material Material from which the cutting edge of a machining tool is made, such as hard metal, cutting ceramic, boron nitride or diamond.

Cutting A process for separating material using scissors, knives or biting tools (pliers, side cutters).

CVD "**C**hemical **V**apor **D**eposition" – a process for depositing thin layers of metals by chemical vapor, for example for microelectronic components or for hardening tools (drills, cutting tools) by applying titanium nitride layers.

Cylinder compression test *see "Compression test"*

Damascene steel A steel made of several layers of different steel grades with different chemical compositions, forge welded, that shows polished and etched decorative patterns and has been produced in Europe for more than 2000 years, for example for kitchen and hunting knives.

Deburring In every machining process like turning, milling, drilling, stamping, also during cutting often sharp edges with burr occur due to material displacement. During deburring these are removed, because they can impair the function of components and also lead to injuries. This deburring can be done mechanically by means of brushes, files, sinking drills, milling cutters, grinding tools, high-pressure water jets, thermally e.g. by explosion deburring, chemically by etching, electrochemically by means of electrolysis and also by means of ultrasound.

Décolletage Turning in the micro range for the production of precision parts for the watch industry and medical technology. The term "Décolletage" is mainly used in Switzerland and France.

Deep drawing Classical tensile-compressive forming of sheets by means of a drawing punch and a drawing die.

Deep hole drill Drilling tool that self-centers during drilling and is used to produce very long holes with a length-to-diameter ratio of more than 15 × D in deep hole drilling machines, e.g. lip drill.

Deformation A deforming, distorting of a solid material by external force, often accompanied by irreversible plastic deformation, as can occur, for example, in an uncontrolled way in a car crash. In the practice of forming technology, deformation is often equated with "forming".

Dendrites Oriented solidified crystallites with a fir-tree-like structure.

Denitrogenation agent A chemical element, that binds nitrogen from the steel melt.

Deoxidation *see "Deoxidizing agent"*
Procedure of steel metallurgy to bind the oxygen released during cooling of the steel melt by means of additives and thus to avoid cavities in the casting. These additives are referred to as "deoxidizing agents".

Deoxidizing agents Are deliberately added to the steel melt in order to bind the oxygen released during cooling of the steel melt. These are elements that have a strong affinity for oxygen, such as aluminum and silicon.

Destructive testing A general term for all material testing methods that require a sample to be taken from the semi-finished product or workpiece being tested, that carry out analyses and microstructure examinations on the samples, or that simulate characteristic loads that occur in practice during use, which ultimately lead to the damage or destruction of the test specimen.

Desulfurization Removal of sulfur from steel melts to avoid segregations (formation of sulfides) as well as to improve the purity of the steel. Processes for this purpose are, for example, the pre-desulfurization of pig iron in the transport ladles before use in the converter or the ladle metallurgical post-treatment of the raw steel produced in the electric furnace in VD, VOD or AOD plants.

DH process *see "**D**ortmund-**H**örde-**Process**"*

Die forming *see "Die forging"*

Die forging Press forming with moving tools, the dies, which have the to be produced form partially or completely as a negative form.

Die A tool in various designs for hot and cold forming as well as machining of metals, usually made of hot and cold working steel or hard metal, such as press, stamping, forming and drawing dies.

Diffusion annealing *see "Segregations"*
Heat treatment process to reduce microstructure inhomogeneities or concentration differences in the workpiece by diffusion. The terms "homogenization annealing" and "equalization annealing" are also commonly used.

Diffusion We encounter it in everyday life, and it is even vital. For example, gas exchange in the lungs and thus the oxygen supply to our body takes place by means of diffusion. It is a movement of particles (atoms, molecules, ions) that is not caused by external forces, but by temperature-dependent concentration differences. In steel with its lattice structure, diffusion means the exchange of atoms and ions that takes place when the steel is heated. This can take place inside as "volume diffusion" or at interfaces as "surface diffusion". The result is always a compensation of the concentration differences in the microstructure.

Digital microscope The examination object is viewed using a built-in image sensor via a monitor (digital camera instead of an eyepiece). Advantages of digital microscopes are higher magnifications, better picture quality, easy operation and picture storage.

Dimensional gauge Gauge with a measure that has already been set in advance to check this measure on the workpiece, using several measures with increasing measures, such as final dimensions or parallel dimensions.

Direct extrusion *see "Forward extrusion"*

Direct reduction *see "Midrex process"*
A process for the direct reduction of iron ore without blast furnace and without coke. Natural gas is used as a reducing agent, converted into hydrogen and carbon monoxide. The product is a porous sponge iron that must be melted in an electric furnace. The "Midrex process" is particularly well known for smaller steel mills.

Direct visual inspection Viewing the test object or the test surface directly with the naked eye without an aid, such as a magnifying glass.

Dislocation *see "Lattice defects"*
Disturbance (lattice defect) in a crystal lattice, distinguished in "step dislocation" and "screw dislocation".

Distortion Unwanted dimensional and shape changes of workpieces.

Drag roll *see "Roll drawing"*
Non-driven, profiled roll, used as a roll pair during rolling, for example for profiling round wire.

Draw cone In wire drawing multiple wet machines driven rotating shaft with several drawing discs of different diameters, which exerts the pulling force on the wire by friction.

Draw die Tool with a trumpet-shaped draw channel for drawing of wire, rod or tube.

Draw peeling die *see "Peeling"*

Draw peeling Method for peeling of wire, wherein the wire is drawn for material removal by a fixed draw peeling die.

Drawing bench A device for drawing bars or pipes.

Drawing box Container for receiving solid, powdery lubricant, such as drawing soap, or liquid lubricant, such as oil, directly in front of the drawing tool on drawing machines.

Drawing channel Cylindrical, trumpet-shaped bore in drawing tools.

Drawing die geometry *see "Drawing channel"*
Shape and dimensions of the drawing channel in drawing dies with an inlet zone (inlet angle), forming zone (drawing angle), guide zone and inclined run-off zone.

Drawing die Tool for drawing bars, pipes or deep drawing.

Drawing drum Vertically or horizontally arranged, rotating cylinder, which transmits in drawing machines on the drawing product the necessary pulling force by friction and on which the drawing product can be wound to the coil.

Drawing iron An iron or steel rod with a series of conical holes of different diameters, formerly used as a tool for wire drawing.

Drawing punch Punch of a deep drawing machine, which brings the necessary forming pressure on the sheet to cause it to flow through the drawing die.

Drawing roll Cylindrical tool with several drawing discs, mostly in steel-ceramic composite construction, driven to apply the drawing forces during wire drawing or the "drag roll" used in pairs during roll drawing, which is not driven, to wire profiling.

Drawing sequence Sequence of individual forming steps to be carried out one after the other in wire or deep drawing.

Drawing tool Forming tool for drawing-press forming such as rod, wire, tube drawing or deep drawing.

Drawing A forming process in which a starting rod is drawn through a conical opening in a drawing tool (die), tapered and lengthened.

Drawing Drawing-extrusion-forming process in which the drawing material (wire, rod, profile, pipe) is drawn through a conical or trumpet-shaped narrowing hole in the drawing tool (drawing die, drawing channel) and thereby reduced in cross-section. Dry drawing agents (stearates) or wet drawing agents (oils, soap emulsions) are used.

Drawing-press forming Plastic forming process of materials under the action of tensile and compressive forces, whereby drawing forces are applied in the forming zone of the forming tools, resulting in compressive forces that cause the forming, such as drawing, deep drawing and pressing.

Drill EDM *see "Wire eroding"*

Special method of die-sinking EDM to create the starting holes necessary for wire EDM.

Drilling *see "Machining"*

Machining process for producing through-holes, blind holes and centring holes with the aid of rotating tools that have geometrically defined cutting edges and are constantly engaged (drills).

Dry drawing *see "Drawing"*

Cold forming by drawing with dry lubricant, e.g. powdered stearate.

Ductile *see "Ductility"*

Ductility The ability of a material to deform plastically and permanently under shear stress before breaking. The opposite of this is brittleness.

Duplex steel Two-phase steel with a ferritic-austenitic microstructure.

Durability Term from materials science describing the lifetime of a component, i.e. the maintenance of strength without damage under static and dynamic loads during use.

Dynamic recrystallization *see "Recrystallization"*

Breakdown of lattice defects in crystals and reformation of the structure by nucleus formation and grain growth during deformation, usually hot forming.

Earth hole furnace A furnace with a simple design, used in nature for iron ore reduction. This type of furnace marks the beginning of the metallurgical extraction of iron from ores more than 3000 years ago.

Earth trough furnace *see "Earth hole furnace"*

Eddy current crack detection *see "Eddy current test"*

Eddy current test Classic electrical method for non-destructive, contactless testing of surface defects in semi-finished products and components made of electrically conductive materials, using eddy current, the density of which is influenced or "disturbed" by existing defects (cracks).

Eddy current Eddy current in the form of a closed vortex, induced in a conductor by means of a magnetic field.

Edge holding proberty The resistance of a cutting edge of a cutting tool to wear, that is, how long this edge remains sharp and "cuttable".

Elasticity modulus (E in N/mm^2) *see "Hooke's law"*

Material constant that describes the linear elastic behavior, as it occurs, for example, in the tensile test up to the yield strength (linear increase in stress-strain). The "Hooke's law" applies here (strain depends linearly on the applied stress). In practice, the terms "E-modulus", "tensile modulus", "elasticity coefficient" or "strain modulus" are also used.

Electric furnace slag *see "Steelworks Slag"*

A type of slag that is produced in electric steelworks during the production of high quality steel in electric furnaces and during secondary metallurgical treatment.

Electrical Discharge Machining (EDM) Controlled material removal from metallic workpieces by spark discharge, also called "spark eroding".

Electrical sheet Cold-rolled sheet (also strip) made of an iron-silicon alloy with defined magnetic properties, which is used in the form of cut and stamped laminations for use in magnetic cores for dynamos, electric motors, transformers, relays, coils, meters, etc. From this, one speaks of transformer or core sheets as well as dynamo or motor sheets.

Electrical steel A high-quality steel produced from scrap in an electric arc furnace of an electrical steelworks.

Electric-arc furnace Melting furnace, in practice often **EAF** (**E**lectric **A**rc **F**urnace) called, used mainly for the production of new steel alloys by melting scrap steel. This is done by means of an arc that is ignited between the scrap in the furnace crucible and the current-carrying electrodes. Electric arc furnaces are also used as melting reduction furnaces for melting ferroalloys and for remelting sponge iron in iron ore direct reduction processes, such as the Midrex process.

Electro-compressing A special forming process (upsetting process) in which a partial section of a rod is inductively heated and simultaneously compressed. The classical example of this locally restricted material accumulation is the upsetting of valve heads on inlet and outlet valves for car combustion engines.

Electrolysis A process in which a chemical process (redox reaction) is forced by electrical energy from a DC (direct current) power source. This principle is used, for example, to obtain hydrogen, aluminum and chlorine, and to deposit metals from a solution, in order to create metal layers, as is the case, for example, in chromium plating.

Electrolytic metal coating A process of electroplating or galvanizing, in which metal coatings are deposited electrochemically in an electrolytic bath on metal workpieces (substrates). If they are metal coatings, one speaks of "electroplating".

Electron beam cutting *see "Melting Cutting"*

Electron microscope A microscope that uses electrons to image the interior or surface of objects. Since the matter wave of the fast electrons used is much shorter than the wavelength of visible light, much higher enlargement can be achieved, currently about 0.1 nm.

Electroplating *see "Electrolytic Metal Coating"*

Electropolishing An electrochemical machining process (electrochemical smoothing) used to create very smooth surfaces. The machining, that is, the reduction in surface roughness, is usually carried out under direct current in an electrolyte bath, with the workpiece to be treated being connected as the anode.

Electro-Slag Remelting (ESR) A metallurgical process for the production of steels with high purity and almost defect-free structure. The remelted, that is, to be purified steel ingot (continuous casting, forged or rolled ingot) is used as an electrode in the remelting plant ("consumable electrode"). The liquid slag used cleans these steel droplets. In a water-cooled crucible, a new ingot solidifies.

Elementary cell *see "Crystal lattice"*

The smallest unit of a crystal lattice with spatially arranged atoms, such as the cubic-space-centred lattice (α-iron).

Enameling Dishes, pots, pans, advertising signs, formerly also house numbers and bathtubs, these are the objects that we know well in enameled form. But email is also in demand in industry as a protective layer. The application of such layers of silicates and oxides usually on metal is called enameling. For this, email slip is applied wet (dipped, sprayed, flooded or poured) to the clean, grease-free surface and fired at 800 to 900 °C.

Endurance strength The load limit that a dynamically, for example, vibrating loaded material can withstand over time without showing signs of fatigue or failure, also known as "fatigue limit", "endurance limit" or "fatigue strength".

Endurance test Method for determining the fatigue strength or the time strength and endurance of materials and components, developed by *A. Wöhler* (1819–1914). The results of several tests are the Wöhler curves, which are used for the calculation and proof of operational safety.

Engineering steel A steel suitable for construction, in particular for steel and machine construction, low in carbon and usually unalloyed or low-alloyed.

Equalizing annealing *see "Diffusion annealing"*

Erichsen cupping test Testing procedure in metal processing for determining the deep-drawing capability, thus the cold formability of sheets and strips. Very high demands are placed on these, e.g. in order to be able to produce demanding car bodywork shapes by means of deep drawing. The deep-drawing test simulates such a deep-drawing process by pressing a spherical punch hydraulically into the sheet. The depth of penetration achieved up to the formation of cracks is considered to be a measure of the deep-drawing capability.

Escomat Term (trade name) for a special turning machine, in which the material is fed as a ring or rod. The turning is not carried out as with conventional lathes, but the fed material is fixed and machined by means of tools rotating around this material.

ESR *see* "**E***lectro*-**S***lag*-**R***emelting*"

Eutectic point *see "Eutectic"*

Eutectic Phase equilibrium, in which eutectic alloys have a clear melting point, the so-called "eutectic point", such as pearlite of the iron-carbon system at 0.80 mass% carbon with the melting temperature of exactly 723 °C.

Evaporation coating Process for the production of very thin, metallic coatings. The coating material is vaporized into the gas phase under vacuum and plasma and then evaporated onto the steel surface to be coated. This method is also known as "sputtering", which comes from "atomization".

Excenter press Mechanically driven press for cutting, stamping, deburring and bending operations. The rotation of the shaft is converted into a vertical lifting movement by means of an eccentric shaft and a connecting rod.

Exhaust Gaseous waste products, usually referred to as "combustion gases", which arise in processes of material transformations.

Expansion alloy Alloys with a controlled thermal expansion with linear expansion coefficients of close to zero to approximately 12×10^{-6}/K within a certain temperature range. Such an expansion characteristic is a condition, for example, for use in bimetals, in parts for measuring instruments, thermostats, X-ray tubes, and in lighting technology.

Explosive forming Variant of high-energy forming by means of a pressure wave generated by the explosion of explosives, e.g. explosive blanking, explosive welding.

Extrusion *see "Strand extrusion"*

This name comes from the Latin "extrudere" – to push out, to push out. Solid materials are continuously pressed through a shaping opening (die) to form a strand.

Fall hammer A type of machine hammer, in which the hammer bear falls by its own weight in free fall on the material, to be forged and causes the forming (hammering). The lifting of the bear can be carried out in various ways, formerly by means of water power, later with steam, today electrically, with compressed air or spring force.

Fatigue crack *see "Material fatigue"*

Fracture of workpieces under overload due to prolonged alternating stress, such as vibrations.

Ferrite former Elements that are added to the liquid steel to form the space-centred cubic phase ferrite in the mixed crystal and to stabilize or restrict the austenite range, such as chromium, molybdenum, vanadium, aluminum, titanium, niobium, tantalum, zirconium.

Ferrite Metallographic designation for the space-centred cubic phase (lattice structure) in iron or steel. The phase also known as "alpha-iron" occurs in pure iron from room temperature to 911 °C and is ferromagnetic. Sometimes in practice the ferritic steel is simply called ferrite.

Ferritic steel The steel with ferritic, space-centred cubic crystal modification and this is retained up to the melting point. A transformation of ferrite into austenite during heating does not take place. This is caused by the ferrite formers. Therefore, ferritic steels cannot be hardened by heat treatment.

Ferromagnetic Materials are ferromagnetic if they also show residual magnetism (remanence) without an external magnetic field, i.e. they behave magnetically according to common language usage. In particular, iron, nickel and cobalt are ferromagnetic in pure form (easy to check by holding a magnet).

Filter dust Residue in the form of dust separated from smoke gas cleaning plants (wet or dry filters).

Final drawing Last forming step in drawing (single drawing), usually carried out specifically to adjust defined properties by cold working or as a polishing pass with drawing oil to improve surface quality.

Final heat treatment Heat treatment carried out at the end of a production process.

Fine grain formation *see "Fine grain steel"*

The formation of fine, many very small grains in the structure during the solidification of the steel melt. This happens when many nuclei are present and the solidification takes place quickly, so that hardly any grain growth can take place. Small grains in the structure mean a higher strength. During recrystallizaion nuclei formation and grain growth also take place. A fine-grained structure can be influenced by parameters such as deformation degree during hot forming or recrystallization temperature.

Fine machining Generic term for manufacturing processes used to produce workpieces with the highest surface quality and dimensional accuracy, such as honing, lapping, grinding, polishing, electrochemical machining, ultrasonic machining, wire and sinker EDM.

Fine treatment Not to be confused with fine machining. In steel metallurgy, fine treatment refers to those processes used for post-treatment of raw steel that are used to produce the desired steel alloy (chemical composition, purity). The desired alloying elements are alloyed in special aggregates, the melt is homogenized, remaining traces of carbon, sulfur, or other elements are removed or reduced. These processes are also known as "ladle metallurgy" or "secondary metallurgical treatment".

Fine-grained steel Engineering steel with a fine-grained structure, low in carbon (max. 0.2 mass-% carbon), mostly low-alloyed, with good strength and weldability, used for heavily loaded welded structures such as crane jibs.

Finishing In steel, rolling and pressing plants, finishing means "putting in order" the products with various post-processing steps such as cutting, straightening, surface treatment, often also heat treatment, machining of cut edges, sampling and testing, packaging, signing, storage, completion, etc.

Fire welding Ancient method for connecting forge parts, which are almost heated to melting point in the forge fire, in the doughy state welded together by hammering.

Flake formation Unsightly and unwanted milk souring in coffee flocks out. Similarly unsightly in larger workpieces when cooling after a hot forming can form flakes.

They are just as unwanted material separations or tears in the core, which are caused by hydrogen outgassing. This flaking can be avoided by alloy additions, an adapted forming with delayed cooling or by a subsequent “flack free heat treatment” (heat treatment to give the hydrogen an opportunity to diffuse out of the already formed flakes again).

Flame refining furnace *see “Puddle furnace”*
Furnace facility for the refining of raw iron from the blast furnace by means of the puddling process, also called “puddle furnace”.

Flame refining stove *see “Puddle furnace”*

Flame spectroscopy *see “Optical emission spectroscopy”, “Spark spectrometer”*
Method for determining the chemical elements in steel, based on the spectroscopic examination of the light emitted by a flame from the elements of a steel sample. This light is examined according to wavelength and intensity and assigned to the individual elements by comparison with calibration curves.

Flame spraying Thermal coating process in which, for example, metal powder is melted by means of a burner and additionally sprayed onto the workpiece to be coated with compressed gas or compressed air. There it melts with the surface of the workpiece for the purpose of wear and corrosion protection. The processes “powder flame spraying” and “plasma flame spraying” are known.

Flat bottom hole In comparison to the conventionally produced blind holes with a pointed bottom, a flat bottom hole has a flat, even bottom. This is, for example, important if such a flat bottom hole is to serve as a defined, artificial error for the calibration of the test sensitivity of ultrasonic testing systems.

Flat die cross rolling Cross rolling process with two profiled flat dies moving in opposite directions, between which a rotationally symmetrical preform, e.g. for drop forging, can be produced.

Flow curve *see “Flow stress k_f”*
Representation of the relationship between degree of deformation and yield stress as a function of material, forming temperature and forming speed.

Flow stress (k_f in MPa or N/mm^2) *see “Formability”*
Outer force that is required per unit area to achieve, maintain and thus achieve a permanent deformation by plastic flow of the material.

Flowability *see “Mould filling ability”*
The ability of a molten metal to flow into and fill a mold, as characterized by its flowability. It describes how well the liquid melt fills the mold and transfers the geometric shape to the casting.

Flue gas Smoke-emitting gas, visible as smoke from pipes, such as chimneys, that enters the atmosphere from furnaces, boilers, fireplaces, steam generators, and also from the operation of converters, electric furnaces, and post-treatment and remelting plants, which cannot be used as heating gas and must be cleaned in flue gas cleaning plants for environmental protection reasons.

Fluorescence test *see "Magnetic particle inspection"*
Method for detecting cracks or pores on and near the surface of workpieces, based on the principle of magnetic flow. By using test media that align themselves in the magnetic field, defects lying transverse to the direction of flow are indicated by magnetic field disturbances. Fluorescent test media under UV light improve defect detectability. In practice, this test method is also called "magnetic particle testing".

Flying cutter Installation for the cutting, cross-cutting, chopping of ingot castings, brambles, bands, bars and wire inline during the manufacturing process, i.e. the cutters are moved synchronously with the speed of the product to be cut and carry out the cutting process.

Force-joining connection The name characterizes the connection technique: By means of force (friction), components are connected, as in a friction clutch.

Foreign atom Atom of another element (impurity) in the lattice of the host crystal, incorporated as an exchange atom or interstitial atom.

Foreign phase Steel is polycrystalline, made up of individual crystal lattices that can have irregularities (lattice defects). Such lattice defects represent foreign phases as three-dimensional defects (volume defects), such as pores, inclusions or precipitates.

Forging degree λ in % Degree of forming, calculated from the change in the initial to the final cross-sectional area during forging.

Forging die Forming tool, two- or multi-part with negative hollow form for die forging.

Forging machine *see "Long forging"*
A machine for forging long round semi-finished products with hammers working against each other.

Forging Generic term for the classical hot forming process of metals between two tools such as a hammer and an anvil, carried out manually or industrially.

Form gauge Gauge with a pre-determined form, in order to check this form on the workpiece, e.g. radii, angles, cones or threads.

Form matrix Forming tool with a round or profiled through-bore, whose geometric profile is transferred to the workpiece during a forming process, e.g. drawing die, press die (flow press, extrusion press die).

Formability Maximum achievable deformation. Materials with a high degree of formability are easily deformable.

Formability The property of a material to be deformed permanently by external stress.

Forming capacity *see "Formability"*

Forming degree Degree of the cross-sectional decrease or change achieved during forming, calculated and referred to differently depending on the forming process, e.g. decrease, forging degree, rolling degree, length change, stretching, stretch degree, compression, compression degree, widening, widening degree.

Forming force Force that is applied to the forming machines in order to carry out the forming of a certain workpiece. It is important to note whether the force is introduced directly into the forming zone as in rolling and forging, or applied indirectly as in drawing and deep drawing.

Forming resistance *see "Forming resistance"*

Forming speed Speed at which the forming takes place, e.g. during hot rolling or pressing at a slower speed than during cold rolling or hammering.

Forming strength *see "Flow stress"*

Material-dependent stress required to initiate and maintain a permanent deformation in the uniaxial stress state.

Forming work The necessary physical work for the forming of a certain workpiece with a defined volume, depending on the material (flow stress), from which the workpiece consists, and on the degree of forming to be achieved.

Forming *see "Plastic forming"*

Deliberate geometric change of an existing raw or workpiece form into a new form, whereby depending on the process differently acting forces cause permanent shape changes without dissolving the material cohesion and changing the volume, also called "plastic forming" and to be distinguished from an unconscious, uncoordinated "deforming".

Form-joining connection With the snap or Velcro fastener, we close form-joining and safely, also quickly releasably, our clothing. The geometric shape of the parts to be connected is used to establish the connection. This is done, for example, in the metal industry by means of hooks and eyes, clamps, shaft-hub connections with keys.

Forward extrusion Variant of extrusion, where the billet exits the die in the direction of movement of the ram, also called "direct extrusion".

Friction welding *see "Rotary friction welding"*

Friction between two contacting and sliding surfaces generates heat. This effect has been pushed to the extreme in friction welding so that local heating up to the plasticization of the materials at the contacting surfaces occurs. If the sliding movement is abruptly stopped and pressure is applied, the parts are "materially joined" in the joint zone. "Rotary welding" has a wide range of applications.

Friction wheel spindle press *see "Spindle press"*

A device for pressure forming (pressing) that functions like a spindle press. The up-and-down movement of the spindle with the press tool is generated by means of a friction wheel construction. The spindle has a flywheel at the top, which is set in rotary motion by friction in each case by one of the rotating two discs on an axially displaceable, electrically driven shaft. And depending on the direction of rotation, the spindle moves up or down.

Functional Material In contrast to a construction or structural material, the function is in the foreground during use, such as an iron alloy used as a magnetic material for electric motors.

Galvanizing with zinc Process for surface finishing of metallic workpieces with zinc.

Galvanizing *see "Electrolytic Metal Coating", "Electroplating"*

Electrochemical deposition of thin metallic coatings on workpieces in an electrolytic bath.

Gas carburization *see "Carburization"*

Carburizing of steel workpieces with a low carbon content in a hydrocarbon-containing atmosphere (gaseous carburizing agent) at high temperatures.

Gas nitriding *see "Nitriding"*
A process for thermally nitriding the edge of steel workpieces, which is carried out at temperatures of 500 to 530 °C under slight overpressure in an atmosphere that provides nitrogen (ammonia).

Gauge In engineering, it is the term for a handy measuring device (reference standard) in order to compare a desired state with the actual state of the test object, e.g. with form, dimension, drilling and limit gauges.

Glass hardness It is not the hardness of glass that is meant, but in connection with the hardening process, the very high hardness produced after quenching, so that the steel behaves brittly, almost like glass.

Grain boundary *see "Grain"*
Boundary between grains of different crystal orientation, visible in the microstructure as a two-dimensional lattice defect by means of chemical etching.

Grain formation *see "Recrystallization"*

Grain growth Given sufficient energy input (temperature) and after completion of a crystal recovery and recrystallization, grains (crystallites) grow at the expense of smaller ones. A coarser grain results. In theory, this process could continue until a single crystal has formed.

Grain refinement *see "Microalloyed steel"*
Creating a microstructure with finely distributed, very small grains in steel by means of an appropriate heat treatment or by microalloying, i.e. alloying only a few percent by mass of alloying elements, in order to have many nuclei of crystallization in the steel melt, which contribute to a fine-grained microstructure during solidification and increase the strength of the steel.

Grain Part of the microstructure of polycrystalline metals with a certain crystal orientation or structure and composition, also called "crystallite", arises during solidification or recrystallization and grows until it comes into contact with other grains with different orientations but the same crystal structure. The resulting boundary between the adjacent crystalline grains is called a "grain boundary".

Greenling A porous preform produced by powder metallurgy by cold compaction (pressing) of metal powder, which must be subjected to a subsequent sintering process (compaction and solidification by diffusion) to produce a dense molded article (up to 99% density).

Grinding Fine machining process that causes a superficial material removal by grinding tools such as grinding wheels and belts containing bonded grinding grains.

Gripping condition In rolling, the condition that the rolled material is moved in between the rolls, that is, "gripped" and thus can be rolled at all. This is the case if the pulling friction force component is greater than the normal force component acting in the opposite direction.

Ground sample Sample prepared for a metallographic examination, finely ground (longitudinal or transverse grinding) and usually etched to make the structure visible.

Ground surface A workpiece can be ground, that is, it has been machined by means of a grinding process. But it can also mean the short form for a "grinding test" as it is used in metallography for sample preparation in order to create micrographs.

Hammer coining Coin stamping with the hammer. The coin blank is placed on a fixed lower die, an upper die is placed and then the coin smith strikes the upper die with the hammer. The engraving of the two dies is then impressed into the coin blank.

Hammer forging *see "Hammer mill"*

Both the forging process with a hammer and the earlier hammer mills with water-powered hammers can be understood under the term "hammer forging".

Hammer mill Term for the craft workshops for the production of wrought iron (iron hammer) known from the thirteenth century, which used water-powered hammers, but also the term for today's industrial companies, which with hammers (drop hammers, pneumatic hammers, air hammers) produce various formed parts freely or in the die.

Hammering Forming with a hand or machine hammer, whereby, in comparison to pressing, a high forming speed per hammer blow is exerted on the forge material (hammered).

Hard alloy Highly wear- and corrosion-resistant metallic materials based on iron, nickel or cobalt with a content of hard phases of up to 50 mass percent.

Hard material A hard material, even extremely hard, such as metal carbides, nitrides, oxides or diamond, rarely made of ceramic, used as an additive for metal composites, such as hard metals or cermets.

Hard metal draw die Hard metal with a trumpet-shaped draw channel in a steel housing as a forming tool for wire, rod and tube drawing.

Hard metal A powder metallurgically produced composite material consisting of a cobalt binder phase with small hard material particles (carbides) embedded in it, thus slightly tougher than pure hard materials, but harder than tool steel and at the same time more brittle than steel, used as a cutting material for tools such as turning tools, drills or milling cutters as well as for forming and stamping tools.

Hard manganese steel *see "Manganese steel"*

Hardening steel Hardenable high-quality engineering steel with a carbon content of 0.2 to 0.7 mass-%, mainly with manganese, chromium, molybdenum and nickel alloyed.

Hardening *see "Cold hardening"*

Increase in strength by plastic deformation.

Hardening Methods of increasing the resistance (hardness, strength) of materials by deliberately influencing or changing the microstructure through "transformation hardening", "precipitation hardening" or "cold working".

Hardness HB *see "Brinell hardness test"*

Hardness HRB *see "Rockwell hardness test"*

Hardness HRC *see "Rockwell hardness test"*

Hardness HV *see "Vickers hardness test"*

Hardness Hardness is the measure of a material's resistance to indentation, scratching or abrasion. Its determination is therefore usually carried out with statically acting indentation methods.

Hearth bogie furnace Electric or gas-heated industrial furnace system for preheating to warm forming temperature and heat treatment of large, heavy steel parts, e.g. cast blocks for forging, consisting of a chamber furnace which is charged by means of a hearth bogie when the door is open.

Hearth refining process *see "Siemens-Martin process"*

Process for producing steel by treating liquid pig iron in a flat hearth to reduce the carbon content and simultaneously remove unwanted impurities. The necessary oxygen is added in the form of scrap and ore, and heat is supplied from the outside. The best-known metallurgical refining process (purification of pig iron) is the "Siemens-Martin process".

Heat treatment Generic term for all treatments of materials using heat, in the case of steel the treatment of semi-finished steel products and solid components with thermal, thermochemical or thermomechanical effects in order to improve or achieve certain properties.

Heating conductor material Their task is not to conduct heat, but to generate heat from electrical energy. For this purpose, they have a relatively high specific electrical resistance, which results in heat being generated inside these heating conductors when an electrical current flows through them. In addition, they are resistant to ignition, which is why they are used as heating wires in devices such as kitchen stoves, hotplates, washing machines, dishwashers, kettles, toasters, hair dryers, heaters, flow heaters, soldering irons, immersion heaters, seat heaters, etc.

Heating spiral *see "Heating conductor material"*

Heating conductor wire bent into a spiral shape, usually insulated or protected in ceramic moldings (pipes) for heating elements.

Heating Temperature increase by means of electrical or gas-heated furnaces or inductively, e.g. for heat treatment or preheating for subsequent hot forming.

Heavy metal "Heavy" metal, such as lead, copper, zinc, tin, iron, etc. with a density above 5.0 g/cm^3 (steel has a density of 7.85 to 7.87 g/cm^3 depending on composition).

High energy forming *see "Explosive Forming", "Hydroelectric Forming", "Hydro-Impulse Forming", "Magnetic Forming"*

Tensile-compressive forming of a workpiece with a sudden impulse, whereby the plastic deformation into a contoured tool takes place with a very high energy and very high forming speed.

High speed cutting steel *see "High speed steel"*

High speed steel **H**igh **S**peed **S**teel (HSS), a high-strength, high-alloy tool steel, alloyed with the carbide-forming elements tungsten, molybdenum, vanadium, chromium and cobalt, suitable for machining tasks with high cutting speeds, therefore also the common terms "high-speed steel", "high-performance high-speed steel" or "high-performance cutting steel".

High-performance cutting steel *see "High-speed steel"*

High-performance high-speed steel *see "High-speed steel"*

High-quality engineering steel *see "High-quality steel"*
Term for hardening, case hardening and nitriding steels that are used where components have to withstand high static and dynamic loads in service.

High-quality steel slag Occurs in metallurgical plants during the smelting of scrap to produce high-quality steels.

High-speed cutting Similar to a karate chop, the cutting process is carried out with a tool that is impulsively accelerated, also called "high speed impact cutting (HSIC)" or "adiabatic cutting".

High-speed forming *see "High energy forming"*
Plastic deformation is carried out impulsively with a very high deformation speed.

HIP *see "Hot Isostatic Pressing"*
Abbreviation for metal powder compaction and sintering by "**H**ot **I**sostatic **P**ressing".

Homogeneous structure Homogeneous quality of all structural components in spatial arrangement.

Homogenization annealing *see "Diffusion annealing"*

Homogenization *see "Diffusion annealing"*
Something unify, make the same, equalize concentration differences, that is also done during homogenization annealing of steel by diffusion.

Hone Tool for the round honing of boreholes, provided with honing stones.

Honing Fine machining process for almost all materials, carried out as the last machining to improve dimensional and form accuracy as well as surface quality, e.g. on cylinder running surfaces of combustion engines.

Hood type annealing furnace A plant for heat treatment of steel products, which are stacked on a solid base and enclosed in a removable hood in normal atmosphere, in protective gas or under vacuum.

Hooke's Law *see "Elasticity modulus"*
Describes the linear-elastic behavior typical for metals (deformation proportional to the applied load) below the yield point, discovered in 1676 by *R. Hooke* (1635–1703). The corresponding proportionality constant is the elasticity modulus (E-modulus).

Horizontal continuous strand casting Procedure for the continuous casting of strands (round, square) with horizontal solidification of the strand from the mould.

Hot forming *see "Recrystallization temperature"*
Generic term for all forming processes of metals carried out above their recrystallization temperature, such as forging, hot rolling, extrusion, hot forming.

Hot isostatic pressing (HIP) A powder metallurgical process for compaction and sintering in one process step, in which metal powder is compressed isostatically in a flexible, evacuated envelope in a heated chamber at temperatures up to 1150 °C and pressures up to 100 MPa under protective gas.

Hot-rolled strip Strip produced by hot rolling, with thicknesses of 0.8 to 25 mm, mainly used as raw material for cold rolling.

Hot-working steel Alloyed tool steel that can withstand temperatures of up to 600 °C during machining of other materials.

HSS *see "High speed steel"*

Hydroforming process Deep-drawing process for sheets, in which the shaping does not take place as in deep drawing with a drawing die, but by means of a liquid under high pressure. This forms the sheet into the inner contour of the mold in all directions.

Hydroforming *see "High energy forming"*

The pressure wave generated by an electrical discharge in a liquid (water or oil) is used for shaping.

Hydro-impulse forming *see "High energy forming"*

The pressure pulses or pressure waves necessary for shaping are generated in a liquid medium using a projectile or a falling weight.

Hydrostatic extrusion Extrusion process in which the punch does not apply the pressing force directly to the block to be shaped, but indirectly via a working medium (water or oil) in a press chamber (recipient). The resulting high hydrostatic pressure (up to 20,000 bar) surrounding the block on all sides presses the block out through the die to form a strand.

Impact Hardness tester *see "Baumann hammer", "Poldi hammer"*

Testing device that causes a sudden, impact-plastic impact of a test ball on the test surface by means of spring force or hammer blow.

Implant steel Highly corrosion-, very good wear-resistant and biocompatible steel, mainly used for load-transmitting, alternately stressed prosthesis parts as well as for plates, screws, nails and wire for fixing bone fractures, e.g. the well-known implant steel 1.4441 – X2CrNiMo18-15-3.

Implant An artificial material remaining in the body permanently or for a short time to replace or support bodily functions.

Inclined roll straightening A method for straightening long products using inclined rollers that are arranged obliquely to each other, concave and convex profiled in straightening machines with one pair of straightening rollers or up to 10 straightening rollers.

Inclusion mixed crystal The name says it all: it is a crystal which is mixed from atoms of at least two or more elements. In this process, the atoms of one element (foreign atoms) are included between the lattice points in the lattice gaps of the other elements (host lattice).

Incoterms Abbreviation from **In**ternational **Co**mmercial **Terms,** international trade clauses drawn up by the International Chamber of Commerce for Trade in Goods, which regulate the manner of deliveries and specify who – supplier or customer – is to bear which transport and insurance costs and where the transfer of ownership of the product to the customer is to take place.

Indirect Strand Extrusion *see "Reverse Strand Extrusion"*

Indirect Viewing Method for viewing a test object, whereby the beam path is interrupted and a conversion of the light beam into another form of energy takes place, e.g. into an electrical information (camera-based examination).

Ingot segregation *see "Macrosegregation"*

Inner High Pressure Forming Process for forming hollow parts in a closed forming tool by means of a liquid internal pressure. For this purpose, an emulsion is poured into the hollow space of the preform to be formed (pipe), this is sealed with sealing stamps and the internal pressure is increased to up to 30,000 bar. The plastic forming (enlargement) begins, whereby the inner contour of the forming tool is assumed. For example, pipes can be selectively enlarged.

Interchangeable cutting insert Powder metallurgically produced from hard metal, cermet, boron nitride, diamond or cutting ceramic with several cutting edges for machining, interchangeable and multiple times usable by turning into another position in the tool holder.

Intercrystalline Corrosion Type of corrosion that starts from the surface and runs along grain boundaries in the microstructure, also called "grain break-up".

Intermediate annealing *see "Intermediate heat treatment"*

Intermediate heat treatment Heat treatment of semi-finished products or workpieces that is carried out between processing steps, such as the soft annealing between cold forming steps during wire drawing.

Intermediate phase microstructure *see "Bainite"*

Interstitial site A space between the lattice sites occupied by atoms, used by other atoms of alloying elements (inclusion mixed crystal).

Iron-carbon diagram Equilibrium diagram for the iron-carbon system that shows the corresponding phase compositions as a function of carbon content and temperature.

Ironware *see "Basic steel"*

Bars, flat products and other shaped parts made of basic steel, e.g. available in hardware stores for railings, handrails, door and gate fittings, for forge work, etc.

Ironworks gas *see "Blast furnace gas"*

Gaseous by-product of ironworks blast furnace process, consisting of carbon dioxide, carbon monoxide, nitrogen and hydrogen and discharged as a combustible gas from the top of the blast furnace.

Joining A manufacturing process for joining two or more solid parts (components) without or with an additive (e.g. adhesive), permanently, releasably or only conditionally releasably (e.g. rivets), whereby the connection can be material-, form- or force-joining.

Jominy test *see "Quenching test"*

Killed poured steel This steel has almost no pores and shrinkage in the casting structure, because it was "killed" before casting. Deoxidizing agents such as silicon or aluminum were added to the melt. These elements bind the oxygen released during casting, that is, during the cooling of the melt. This prevents gas bubbles from forming, which would lead to pores in the casting block.

Knife steel *see "Carbon steel"*

Carbon steel suitable for knife blades.

KOR-TEN steel *see "Corten steel"*

Ladle metallurgical treatment *see "Secondary Metallurgical Treatment"*

Treatment of the liquid crude steel coming from the converter or electric arc furnace in special aggregates. The desired alloying elements are charged, the melt is homogenised, any remaining carbon, sulphur or other elements are removed and the desired casting temperature is set. This post-treatment of the crude steel to produce the desired steel, ready for casting, is also called "ladle metallurgy", "fine treatment" or "secondary metallurgical treatment".

Ladle trailer *see "Torpedo wagon"*

Ladle Like in the kitchen, a container that is always confronted with high temperatures. In steel metallurgy, ladles in the form of cylindrical steel vessels with fireproof lining are used to hold liquid pig iron or raw steel, for transport, for laddle metallurgical treatment and for pouring.

Lapping medium *see "Lapping"*

Paste of water or lapping oil with grains of aluminum oxide, silicon carbide or diamond, which is used as the active ingredient in lapping.

Lapping Fine machining process for smoothing surfaces with tight tolerances using lapping powder (abrasive grain) loose in a paste. In contrast, grinding process, the grinding grains are firmly bound, for example in grinding wheels. Lapping can be performed manually or mechanically.

Laser cutting *see "Laser fusion cutting" or "Laser vaporization cutting"*

Laser drilling Generation of a hole by means of a laser beam, which brings so much energy that the material is melted and partly vaporized.

Laser melting *see "Selective laser melting (SLM)"*

Lathe Turning machine for the production of rotationally symmetrical turned parts, with the tool being guided by hand.

Lattice Defect Imbalances in a real crystal lattice, which influence the diffusion in the crystal as well as chemical and mechanical properties, e.g. the malleability, and which are distinguished according to the spatial extension in zero-, one-, two- and three-dimensional lattice defects as well as in structural disorder.

Lattice transformation Change of the crystal structure with changes in temperature and pressure, e.g. the lattice transformation from the space-centered cubic (α-iron) to the face-centered cubic lattice (γ-iron) when iron is heated above 911 °C.

Lattice *see "Crystal" and "Crystal lattice"*

Atomic structure of crystalline solids in the form of three-dimensional arrangement of points representing the atoms. The smallest unit of a lattice is the "elementary cell".

Law of volume constancy Applies to plastic forming: The volume of the workpiece before (V_0) and after the forming (V_1), for example during rolling or forging, is equal, has not changed: $V_0 = V_1 = V = \text{constant}$.

LD-Process *see "Oxygen-Blowing Process"*

The **L**inz-**D**onawitz process for refining liquid pig iron in a blast furnace using oxygen.

LD-Slag *see "Converter Slag"*

Ledeburite *see "Eutectic"*

An eutectic mixture named after its discoverer, Karl Heinrich Anton Ledebur (1837–1906), consisting of austenite and cementite in steel.

Light metal Lightweight metal, such as aluminium and magnesium, with a density below 5.0 g/cm^3 (steel is between 7.85 and 7.87 g/cm^3 depending on composition).

Limit gauge A gauge with a previously defined measure to check whether the actual measurement of a test item is within the tolerance of the desired measurement, also called "caliber gauge".

Line defects Crystal defects in the form of displacement lines such as steps and screw dislocations.

Linear expansion coefficient *see "Expansion coefficient"*

Linz-Donawitz process (LD) *see "Oxygen blowing process"*

Long forging machine *see "Long forging"*

Forging unit for the mechanical forging of rotationally symmetrical long products.

Long forging Forging process for the automated forging using long forging machines (radial forging machines), in which pairs of hammers striking each other radially act on the forging to produce rotationally symmetrical long products such as tapered shafts, axles and bar stock.

Lubricant carrier Phosphate, lime or borax, usually applied to the wire surface in liquid form to secure the lubricating effect in the drawing tool together with the lubricants used in the drawing process (dry drawing soap or wet drawing agent).

Lump furnace Predecessor of the blast furnace, named after the piece of iron that could be extracted from iron ore with this type of furnace per smelting, while later in the blast furnace the process takes place continuously. From the twelfth century, with the use of water-powered bellows, lump furnaces (or "wolf furnaces") were operated in the form of brick shaft furnaces. Over time, until the seventeenth century, lump furnaces reached heights of up to 10 m.

Machinability *see "Machining"*

Material property that allows it to be machined under given conditions.

Machine hammer Term for a machine device for forging, such as a drop hammer, steam hammer or air hammer.

Machining steel Special steel with defined alloying elements, suitable for machining on CNC turning, drilling and milling machines. Defined phosphorus and sulfur contents cause inclusions that result in short chips. These are important for uninterrupted, automated precision production.

Machining A general term for all manufacturing processes that work on pieces by removing material in the form of chips to achieve a certain geometric shape. The main methods are "turning", "drilling", "milling", "planning" and "grinding".

Macroscopic purity *see "Degree of purity", "Macroscopy"*

Non-metallic inclusions in steel detected by macroscopic methods such as blue fracture testing and ultrasonic testing.

Macroscopy Viewing objects with the naked eye, in practice also with magnifying glasses or reflected-light microscopes at max. 50x magnification, for example to examine fractured planes and surfaces.

Macrosegregation Segregation in a casting ingot that occurs during solidification and affects the entire casting, therefore also called "ingot segregation". Since solidification of the molten metal always proceeds from the outside (contact and cooling effect of the mould) to the inside, elements such as carbon, phosphorus and sulphur collect in the last solidified ingot interior.

Magnetic forming *see "High energy forming"*

The pressure impulse required for forming is generated directly in the conductive workpiece by a magnetic field, which in turn originates from an external coil.

Magnetic powder crack test *see "Magnetic powder testing"*

Magnetic powder testing Procedure for detecting cracks and pores on workpiece surfaces, which uses the testing media aligned in a magnetic field to detect defects by magnetic field disturbances. For this purpose, the workpieces to be tested must be magnetized, so this method only works with ferromagnetic (magnetizable) materials. After magnetization, iron powder is applied with a liquid, whose fine particles accumulate (accumulate) where defects have caused a magnetic stray flux. This is then the display for these defects, whereby the detectability of defects can be improved by using fluorescent test media under ultraviolet light. The various methods of magnetic powder testing differ in the way the workpieces to be tested are magnetized by yoke magnetization, current flow or field flow.

Magnetic valve A valve for shutting off or controlling the flow of liquids or gases, which is operated by an electromagnet.

Mandrel "A thorn in the eye" or "No rose without thorns": These word games refer to thorns in nature. For steelmaking and forming, other thorns are used, for example, fixed or flying mandrels during tube drawing, hole mandrels during extrusion or pilgrim mandrels during the pilgrim step-rolling of tubes.

Manganese hard steel *see "Manganese steel"*

Manganese steel Manganese-alloyed steel with a special property in the quenched state. The originally relatively low tensile strength is increased by cold working with cold hardening, so that for example machining at room temperature is not possible, or only limited with carbide tools. This manganese steel, which becomes hard and wear-resistant, is preferably used for security technology such as grilles, locks, safes, but also for bucket bolts, crusher jaws and gripper teeth.

Mannesmann cross rolling process *see "Cross rolling"*

Process for hot rolling of seamless steel pipes invented by the brothers *Mannesmann* at the end of the 19th century using rolls arranged obliquely to the rolling direction (oblique rolls).

Mannesmann process *see "Mannesmann cross rolling process"*

Maraging steel A special, almost carbon-free high-strength steel that is also tough and has favorable processing and welding properties. The name comes from **mar**tensite + **aging**.

Martensite Characteristic, needle-like hard microstructure in steel, which forms during transformation hardening in a fast cooling process from a temperature range where the austenitic microstructure was present. The cooling took place so quickly that no transformation from this austenitic into the actually stable ferritic structure at room temperature could take place. *A. Martens* (1850–1914) was the first to discover this "forced state" of the quenched microstructure, which from then on is named after him "martensite".

Martensite-hardenable *see "Maraging steel"*

Martensitic steel *see "Martensite"*

High-strength steel with a martensitic microstructure formed by transformation hardening, the strength (hardenability) of which depends decisively on the carbon content and the heat treatment (hardening and tempering).

Mass austenitic steels *see "V2A steel"*

Chrom-Nickel-Steels with austenitic, cubic-surface-centered lattice structure, which is usually produced and used in very large quantities, such as the classic V2A steel 1.4301 – X5CrNi18-10 or the steels 1.4305 – X8CrNiS18-9, 1.4306 – X2CrNi19-11, 1.4307 – X2CrNi18-9, 1.4401 – X5CrNiMo17-12-2 and 1.4404 – X2CrNiMo17-12-2.

Mass steel Unalloyed and alloyed steel, produced and applied in large quantities for purposes that, like the basic steels, only require low requirements in terms of the properties during use.

Material fatigue Slowly progressing damage process in a workpiece under external, usually changing mechanical stress, at changing temperatures, radiation and possibly by influence of corrosive media, whereby a total failure can occur, such as fatigue breakage.

Material testing Generic term for all test methods that provide data on the condition and properties of materials such as chemical composition, purity, microstructure, strength, toughness, hardness, corrosion resistance, surface condition, machinability, etc. Non-destructive and destructive testing are distinguished.

Material Generic term for a usually solid material from which parts are made, i.e. the raw material for the production of a product.

Material-joining connection Non-dissolvable, permanent material to material joining connection, which is created by an intimate material bond at the joint by welding, soldering and gluing.

Materialography While classical metallography refers to the complex microstructure of steels and its image, materialography also includes new materials and composite materials.

Measuring An activity to determine an unknown size on a workpiece with the goal of obtaining a specific measurement result in the form of a physical size using suitable measuring technology, such as measuring the diameter of a rod with a caliper.

Melt analysis Sample taken for chemical analysis directly from the liquid steel melt before casting with a ladle or a dipping tube.

Melt charge Batch production is given when different results (batches) are obtained in a production process with the same material usage. The material usage per batch is the "charge". So the theory, in practice it looks like this: In an electric steelworks, several hundred tons of a certain steel quality are to be melted. However, the available electric arc furnace can only melt about 45 t of steel. Therefore, several melts, called "melt charges", have to be produced. All of these melt charges relate to the same steel quality, but differ slightly in terms of chemical composition within the given tolerance range.

Melt electrode An electrode (cathode) in electric slag remelting plants, as a solid steel block that is melted (dropped) during direct current passage, cleaned during passage through the liquid slag, and solidified into a new block in a water-cooled mould.

Melt swamp The area inside of an ingot or of a billet that remains liquid during solidification, while the outer zones have already solidified due to the cooling effect of the mould.

Melt-dip coating A process for coating semi-finished products (wire, strip) or workpieces by completely immersing them in a molten metal bath.

Melting and expansion alloy An alloy with a thermal expansion coefficient which agrees with those of glasses and porcelain in a certain temperature range. In this way, vacuum-tight passages are created when wires made of such alloys are melted into glass or porcelain, e.g. in lighting technology as connecting wires for electrical conductors for halogen and LED lamps.

Melting cutting *see "Laser melting, plasma or electron beam cutting"* A process for thermal cutting, in which the material is locally melted at the separation point and the liquid melt is thrown out of the separation gap in droplet form.

Melting point Temperature at which a substance melts, i.e. changes from the solid to the liquid state, for example iron at 1538 °C.

Melting temperature *see "Melting point"*

Metal powder injection molding A process for producing molded parts similar to the injection molding technology of plastics. A mixture of fine metal powder with an organic binder is given the final form by means of an injection molding machine.

Metal powder Metal in fine powder form (particle size usually smaller than 0.6 mm), produced by grinding solid metal or by pulverization metal melts.

Metallography The study of the microstructure with the task of imaging complex spatial structures of steel and describing the microstructure qualitatively and quantitatively.

Metallurgical iron slag *see "slag"*

Generic term for the non-metallic, crystalline, solidifying by-products that are produced in almost all metallurgical production and processing processes (high-temperature processes).

Micro blow hole *see "Blow hole"*

A very small, pronounced cavity in the casting (casting defect) formed during the solidification of the steel melt.

Micro segregation Concentration difference, i.e. increase or decrease of chemical elements within solid solutions, which arises during solidification of the metal melt and thus during formation of the solid solutions. A very slow solidification leads to diffusion processes, whereby such microsegregation can be avoided. Otherwise, the microsegregation can be eliminated by subsequent diffusion annealing.

Microalloyed steel Steel with a very low content of 0.01 to 0.1 mass-% of aluminum, niobium, vanadium and/or titanium, in order to achieve high strength through carbide and nitride formation as well as grain refinement.

Microscopic purity *see "Purity"*

Number of non-metallic inclusions in steel, determined by metallography on the basis of polished samples under the microscope, classified according to appearance, color and size.

Microscopy Viewing of tiny objects which cannot be seen by the naked eye, such as microstructures, with high magnification of up to 1000 times, using suitable microscopes, mostly with image evaluation systems.

Midrex process *see "Direct reduction"*

Milling *see "Machining"*

Chip-removing manufacturing process, in which the chip removal takes place from a stationary workpiece with a multi-edged, rotating tool (milling cutter), whose cutting edges do not always engage. Depending on the direction of rotation and the feed, "concurrent milling" and "opposed milling" are distinguished.

MIM *see "**M**etal powder **I**njection **M**olding"*

Abbreviation for the name of metal powder injection molding: **M**etal **I**njection **M**oulding.

Mixed crystal *see "Exchange mixed crystal", "Interstitial mixed crystal"*

Crystal or crystallite made of at least two different chemical elements, where the foreign atoms can replace atoms of the host lattice (substitution mixed crystal) or be incorporated in interstitial sites (interstitial mixed crystal).

Mix-up test Method of quality assurance to determine whether material has been confused in production or delivery. It can be carried out fully automatically by means of magnetic induction, for example by means of eddy current bar passage testing machines, or mobile by hand by means of spark spectrometer.

Monel Name for a copper-nickel alloy with high tensile strength, consisting of about 65 mass-% nickel, 33 mass-% copper and about 2 mass-% iron, also called "Monel metal".

Monier iron Former name for reinforcement steel as reinforcement in steel-reinforced parts.

Mould casting Includes all casting methods used to bring liquid metals into a form suitable for future use, such as sand casting.

Mould filling ability The ability of a metal or alloy to be processed by casting, thus influencing the casting process and the quality of the casting; and this property is primarily the flowability, also called "form filling ability". Sometimes you also hear in the practice of forming the term flowability, but this means the "formability", ie the ability of the steel to be deformed plastically by flow. Depending on the material, this "formability" increases with increasing temperature.

Multiple-drawing machine A machine for drawing metals with several, consecutive drawing stages using liquid drawing lubricant, such as oil for drawing stainless steel wire or soap emulsion for drawing galvanized steel wire.

Multi-roll stand *see "Sendzimir stand"*

Rolling stand with several rolls, where a driven roll pair is used as working rolls in direct contact with the rolling stock for forming and all other rolls support these working rolls (back-up rolls) in order to prevent deflection and to roll thin strips and sheets with tightest thickness tolerances.

Necking (Z in %) Measure of the ductility of a material, specifies the value for the largest cross-sectional reduction in the area of the tensile test where the break occurred. Indication in % based on the initial cross-sectional area.

Necking (Z in %) *see "Fracture necking"*

The reduction in cross-sectional area of a specimen that occurs during stretching under tensile loading.

New lining It concerns in the metallurgy the new lining of blast furnaces and converters, of melting vessels of electric and induction furnaces, of treatment vessels, transport and casting laddles, of linings in tapping channels, in distributors and forehearths for example at continuous casting plants, of preheating and heat treatment furnaces and others.

New silver Term for a silver-shiny copper-nickel-zinc alloy with high strength and good corrosion resistance, also known as "Alpaca", "Argentan" or "Hotel silver".

Nickel based alloy Material with exceptional properties, consisting of the main component nickel and other elements. Nickel based alloys include, for example, the nickel-copper, nickel-iron, nickel-iron-chromium, nickel-chromium, nickel-molybdenum-chromium and nickel-chromium-cobalt alloys, all materials that leave the range of steels and exceptional the areas of non-ferrous metals and superalloys.

Nickel plating Process for surface finishing (coating) of metallic workpieces with nickel.

Nitride former *see "Nitriding Steel"*

Chemical element that is added to steel in order to form nitrides. Good nitride formers are chromium, molybdenum and aluminum.

Nitride *see "Hard Material"*

Chemical compound of nitrogen, used mainly for surface hardening like titanium nitride or hard material in the composite of hard metals.

Nitriding steel Steel that is alloyed with nitride formers such as chromium, molybdenum and aluminum and has good wear resistance.

Nitriding *see "Gas Nitriding", "Plasma Nitriding", "Salt Bath Nitriding"*
Process for surface hardening by enrichment with nitrogen. Chemically speaking, it is actually a nitride formation on the surface of the component, comparable to the case-hardening of steels. Gases, plasma-ionized gases and salt baths are used as nitriding media.

Nitrogen embrittlement *see "Aging"*
Increase in brittleness, mainly in unalloyed and low-alloy steels, due to the presence of nitrogen (aging phenomenon).

Non-destructive testing A general term for all material testing methods that have the advantage of being able to examine semi-finished products or components in the finished state and without damage, usually non-contact and also automated.

Non-ferrous metal All metals except iron.

Non-metallic inclusion Inclusion in steel, which has arisen during steel production and consists mostly of oxides, sulfides and nitrides. These do not have metallic properties and have a negative effect on the steel properties. Non-metallic inclusions in steel can come from the refractory lining of the blast furnace, the converter, the melting vessel of an electric furnace or the laddle, be produced by deoxidation processes for binding the oxygen released during pouring, or by sulfur-containing sulfide formation.

Normalizing Heat treatment process for steel to achieve a uniform, fine-grained microstructure with high toughness and good machining properties. All microstructure and property states that the steel had before are reversed.

Notch impact toughness (J/cm^2) *see "Charpy impact test"*
A measure of the resistance of steel to sudden, ie dynamic, stress, expressed as the notch impact work divided by the size of the fracture surface in joules per unit area.

Open die forging Shaping by forging, where the blacksmith has free design options and is not bound by a tool shape (die), usually forge on a flat anvil. There is a distinction between manual and industrial forge.

Open semi-finish rolling mill Rolling mill with several rolling stands arranged next to each other, mostly three-roll (trio) and reversing duo rolling stands with profiled rolls, which are connected to each other in terms of drive technology, that is, they only require one single drive.

Opposed milling *see "Milling"*
Milling process with a milling cutter rotating against the feed direction of the workpiece.

Optical emission spectroscopy (OES) *see "Atomic emission spectrometry (AES)"*

Ore reduction Reduction is a chemical reaction between the oxide to be reduced and the reducing agent required for this purpose. In ores, the metals are always present as chemical compounds, e.g. in iron ore mainly as iron oxide magnetite (Fe_3O_4 with up to 72 mass-% iron) or as hematite (Fe_2O_3 with up to 70 mass-% iron). In order to obtain iron as a metal for steel production, this iron ore must be reduced, i.e. the oxygen must be removed from the iron oxide by means of reducing agents such as carbon, carbon monoxide or hydrogen. The reducing agent oxidizes in this process.

Oxygen blowing process *see "Linz-Donawitz-**Process**(LD)"*
A process for refining the raw iron produced in a blast furnace in a converter by means of injecting oxygen into and onto the liquid raw iron.

Partial degassing *see "RH process", "DH process"*

Pasty lump iron Product of early pig iron production in the blast furnace, porous and interspersed with slag, also called "sponge iron".

Pearlite *see "Eutectic"*
Lamellar-shaped eutectic microconstituent of steel (phase mixture of ferrite and cementite), whereby 100% pearlite occurs at 0.83 mass-% carbon and has the eutectic point of 723 °C.

Pearlitic *see "BG annealing"*

Peeling Remove the outer shell from the object with a tool.

Pendelum impact testing machine *see "Notch bar impact test"*

A device for carrying out notch bar impact tests.

Penetration testing Destructive testing method for making surface defects (pores, cracks) visible. For this purpose, the cleaned test piece surface is provided with a penetrant which, due to capillary action, penetrates into the smallest, surface-open defects. This penetrant can be colored or fluorescent. In this way, defects can be contrasted under daylight or UV light and made visible.

Permanent magnet alloy Alloy, e.g. made of iron, cobalt and nickel, which constantly retains a strong magnetic field and is therefore permanently magnetic. Therefore, such alloys are also referred to as hard magnetic materials and the magnets made from them are "permanent magnets".

Permanent magnet steel *see "Permanent magnet alloy"*

Perthometer *see "Surface scanning device"*
A device for determining the surface roughness by means of the touch step method.

Phase boundary *see "Phase"*
Boundary between two phases in the microstructure.

Phase transformation *see "Lattice transformation"*

Phase A spatial region in the microstructure with the same properties, such as density and chemical composition. For example, steel can form different phases at different temperatures despite the same chemical composition, such as the body-centred cubic ferritic or the face-centred cubic austenitic phase.

Phased-Array-Method Non-destructive ultrasonic testing of metal products for internal defects, as used in medical diagnostics. Phased array means phase-controlled (pulsed). Here, many US probes are electronically excited individually in groups as group emitters (multi-element probes) so that, by this group-wise further switching on (virtual rotation), a radial ultrasonic scan, for example, of a round bar is possible.

Phosphatizing A process for coating semi-finished products or workpieces, in which a firmly adhering phosphate layer is formed by means of chemical reactions between the metal surfaces to be coated and aqueous phosphate solutions. This protects against chemical influences, is porous and forms a good "anchor" for subsequent coatings. In addition, phosphate layers have a good sliding effect, which is advantageous for cold forming.

Pickling It is known that wood surfaces are pickled for protection and coloring. The treatment is carried out with a liquid pickling agent. A similar pickling also takes place as a chemical surface treatment of steel products. The aim is to clean the steel surface by means of liquid media (lyes, mineral acids, fluorine and additives) from oxide compounds.

Piece galvanizing with zinc Surface coating of metallic workpieces individually by dipping in a liquid zinc bath.

Pilger rolling process As with a Pilgrim's step, in this rolling process the rolled material is constantly rolled back and forward between two profiled rolls that rotate in opposite directions. For example, a seamless pipe can be gradually produced from a pipe blank with a wall thickness reduction of up to 80%.

Pilgrim's step *see "Pilger Rolling process"*

"Two steps forward, one step back"—this is sometimes used today to describe progress that is constantly hindered by setbacks. This expression comes from the so-called "Pilgrim's step", a possible sequence of steps when dancing.

Pilgrimage *see "Pilger Rolling Process"*

Pipe blank *see "Pilger rolling process", "Mannesmann cross rolling"*

Hollow block, resulting from pipe rolling according to the Mannesmann cross rolling process or used as a preform in the Pilger rolling process, in German "Luppe".

Planetary skew rolling mill A device for oblique rolling of long products, in which the forming is carried out with three cone-shaped rolling discs that orbit the incoming round material like the planets around the sun and cause a reduction in diameter.

Planing "Where planing is done, chips fall"—in this sense, a planing tool is used to remove chips from the workpiece, always resulting in flat surfaces.

Plasma nitriding A process for surface hardening by enrichment with nitrogen, which uses a nitrogen-hydrogen gas mixture as a nitriding medium, which is ionized in a vacuum furnace by means of plasma. Under these conditions, nitrogen can diffuse into the edge zone of the workpieces.

Plasma polishing Fine machining process for polishing, cleaning and deburring of metallic surfaces, wherein the workpiece is treated in an electrolyte by a high electric potential with point-like short circuits, which lead to plasma formation.

Plasma spraying Thermal coating process, in which, as in flame spraying, metal powder is sprayed onto a component only using a plasma burner. There it melts with the surface of the workpiece in order to protect against wear and corrosion.

Plastic forming *see "Forming"*

Forming, that is, the change from a raw to another finished form, without removing or adding material and without destroying the material connection. This shaping takes place necessarily "plastically" by means of plastic forming, for example by rolling, pressing, forging, extrusion, drawing or deep drawing.

Plasticity Ability of solid materials to deform plastically, i.e. permanently, under the action of force after exceeding the elastic limit. One also speaks of "plastic formability" or "moldability".

Plating Process for the production of composite metals, wherein a base material is provided with one- or two-sided metal coatings. A bonded connection is created by a combination of high pressure (e.g. by means of plating rolls) and temperature action (special heat treatment).

PM steel **P**owder **m**etallurgically produced steel.

Point defects *see "Lattice defects"*

Point-like lattice defect in the dimensions of an atom, e.g. vacancy, interstitial atom, substitution atom.

Poldi hammer Hardness tester, very handy and mobile for use on site and dynamically plastic. A typical feature is the necessary rectangular comparison rod with known hardness, which is inserted between the test ball and the punch. With a blow of the hammer on the punch, the test ball creates imprints on both the comparison rod and the test surface. The diameter difference between them can be used to determine the hardness of the material to be tested.

Polishing Fine machining process for smoothing surfaces while maintaining tight tolerances using polishing grains loose in a paste.

Pore Small cavity formed during melting and casting of metals, caused by gases dissolved in the melt that remain trapped in the solidified metal, typical of "unsettled" cast steels. Depending on the manufacturing step (cold pressing of pre-compacted green bodies or hot pressing of highly compacted finished parts), the product contains different sized and many pores, which result in the material property "porosity" or "residual porosity".

Pot annealing furnace Resembles a large, round pot with a lid, used for heat-treating ring-shaped charge, e.g. steel wire coils, under normal atmosphere, also under protective gas or vacuum.

Powder flame spraying *see "Flame spraying"*

Powder forging Combination of powder metallurgy (powder production and compaction into a preform) and subsequent precision hot forging (die forging) to produce almost perfectly dense parts with high accuracy and surface quality.

Powder metallurgy Branch of metallurgy that includes the production and further processing of metal powders.

Precipitation hardening Heat treatment process with the aim of increasing the strength of the steel by many, as small as possible, precipitations. Therefore also referred to as "hardening". For this purpose, the steel is first subjected to a "solution annealing", in which all alloying elements go into solution. This annealing is called "diffusion annealing" or "homogenization". This is followed by quenching and finally by precipitation (aging) to form the desired deposits.

Precipitation It is not meant in the biological sense of the excretion of substances into the external environment, but the precipitation of many homogeneous particles inside, that is, in the microstructure of steel, and they remain there. Precipitations are formed when the solubility of alloying elements in the iron lattice decreases with decreasing temperature.

Precision forging Burr free stamping to produce precision parts such as gearwheels and waves for automotive

Press hardening Process for hot forming and hardening sheet metal, whereby a cut-to-size and preheated sheet metal panel is simultaneously cooled and hardened directly in the water-cooled press tool during hot forming, also known as "mould hardening".

Press welding *see "Friction welding"*

Process for producing a material-jointing connection, which is created by applying high pressure forces to the joining zone and thus by local heating up to plasticisation of the materials on the contacting surfaces. "Friction welding", for example, is widely used.

Pressed blank Semi-finished part formed by pressing.

Pressing Pressing is a pressure forming process with forging tools (hammer and anvil or press die), i.e. forging with lower forming speed compared to hammering. Pressing is the generic term for the forming machines of various designs used for press forming, such as hydraulic presses, eccentric presses, crank presses, toggle presses and screw presses.

Pressrolling Similar to pottery, rolling also works with steel or all malleable metals and metal alloys. Using a rotating roll, the blank, such as a sheet metal round, is "stretched" over a rotating conical or cylindrical mandrel, i.e. brought to flow. This creates a rotationally symmetrical profiled part.

Pressure drawing die Special design of a drawing tool to press drawing lubricant onto the wire surface with higher pressures and thus reduce friction, thus achieving higher service life and also higher drawing speeds.

Primary cementite *see "Cementite"*

Cementite Fe_3C primary formed during the crystallization of a steel melt.

Primary forming *see "Casting"*

Primary grain Component of the microstructure of polycrystalline metals with a certain crystal orientation, also called "crystallite", which forms primarily, that is, directly during the solidification of a melt on crystallization nuclei and grows until it comes into contact with other grains with different orientations, but with the same crystal structure.

Profiling process *see "Roll profiling"*

Bending forming by means of profiling machines to produce defined profile cross-sections on sheets and strips. The most important process is "roll profiling", also called "roll forming", "roll shaping" or "roll bending".

Puddle iron *see "Puddling process"*

Puddle iron produced in a basic oxygen furnace and still containing slag particles, with a low carbon content.

Puddling furnace *see "Puddling process"*

Furnace plant for “puddling” pig iron, i.e. for refining pig iron according to the puddling process, also called “flame refining hearth”.

Puddling process Process for converting pig iron from a blast furnace into wrought iron, invented in 1784 by *H. Cort* (1740–1800) and used industrially in the 19th century. In this process, the liquid pig iron was refined in a furnace. Workers, also called “puddlers”, constantly moved the quite viscous pig iron around in it with iron rods. Gas from the combustion of coal flowed over the pig iron and reduced the carbon. This produced a low-carbon puddle iron, but still containing slag particles.

Pulse-echo method Method of ultrasonic testing for core defects, using a probe that simultaneously serves as a transmitter and receiver.

Pure water beams *see “Water jet cutting”*

Procedure of water jet cutting using pure water without additives of abrasives.

Purity grade The content of inclusions in the interior of a material, for steel the content of non-metallic inclusions, which affect its use properties. The evaluation is based on standardized methods as a macroscopic and microscopic purity grade. In a second meaning, the purity of the surface of a component with respect to the amount of adhering particles or the degree of wetting with liquids is meant, formerly “standard purity grade” and today “surface preparation grade” named. This purity grade is important in connection with a subsequent coating.

Purity The quality of a material such as raw, pure, purified and ultrapure, which refers to the proportion of impurities in the material.

Pushing Process for removing metal with a single-edged tool, the punch, whereby the cutting movement is not carried out by the workpiece as in milling, but by the punch.

Quality steel Unalloyed or alloyed steel with a carbon content in the range of 0.2 to 0.65 mass-% and a limited content of phosphorus and sulfur of 0.045 mass-%, which has a certain quality in terms of formability, weldability, deep drawability and grain size.

Quality “The quality is right!” – already heard or even said yourself. There the lifetime, the appearance, the properties, the material appearance and much more correspond to one’s own expectations of the purchased product. Quality includes the very complex, controlled, continuous process in production always with the goal of producing a final product with quality. Quality characterizes the agreement with the requirements (customer specification), is thus also a measurable term.

Quenching and tempering *see “Hardening” and “Tempering”*

Combination of the heat treatment processes of hardening and tempering.

Quenching medium Medium used to quench the workpiece, e.g. water-, oil-, salt-, lead- or polymer-baths.

Quenching phases The blacksmith dips a still red-hot workpiece into a water-bath for hardening. It hisses and water spurts out. During this temperature drop, the workpiece passes through three phases in the quenching medium, the steam skin, the boiling and finally the convection phase. These quenching phases can also occur simultaneously and under certain circumstances cause distortion, hardening and areas with different microstructures in the workpiece.

Quenching test Method for testing the hardness of steel, in which the highest achievable hardness is determined during quenching (hardening) and the course of hardness is determined in the interior of a certain cross section (hardening), also called *"Jominy test"*.

Quenching Faster cooling of workpieces than is possible in stationary air.

Radial forging machine *see "Long forging"*

Forging unit for the mechanical free-form forging of rotationally symmetrical long products.

Rare Earths Oxides, formerly known as "earths" because they were very rare to find. Metals derived from these oxides include cerium, yttrium and neodymium.

Raw iron refining *see "Refining"*

Raw steel The raw steel, also called crude steel, coming from the converter of the blast furnace-converter route or from the electric arc furnace, which still has to be secondary metallurgically treated in order to obtain the desired steel alloy.

Recipient Hollow chamber for holding the round bloom for extrusion, also called "bloom receiver" or "extrusion cylinder".

Recrystallization temperature *see "Recrystallization"*

Temperature at which a metal completely recrystallizes in a certain time, i.e. a lattice defects in the crystals by new formation of the structure occurs. In practice, the rule of thumb for the recrystallization temperature is 40 to 50% of the melting temperature. Forming above this temperature is a "hot forming".

Recrystallization Breakdown of lattice defects in the crystals and new formation of the structure by nucleation and grain growth, with a decrease in strength. This can take place during forming as "dynamic recrystallization" or after completion of forming in the structure as "static recrystallization".

Recyclable and valuable material Material that can be reused, converted into another product or recycled after use.

Recycling Reuse or reprocessing, refers to all recycling processes to prepare waste into products, materials or substances for the original or for new purposes, therefore one speaks of "recycling" or "waste disposal". And only if the material to be processed was previously considered as waste, the term "recycling" is legally exact, otherwise it is a reuse. In practice, however, this is not distinguished so clearly.

Red fracture Fracture (tearing) of the red-hot steel during forming at 800 to 1000 °C, today hardly present in steels with low sulfur and oxygen content.

Reducing agent Substance that can reduce other substances chemically by giving them electrons, while being oxidized itself. A classic example from steel metallurgy is carbon. This reduces iron oxide from the ore to iron and is itself oxidized to carbon monoxide.

Reduction process *see "Reduction", "Direct reduction", "Smelting reduction"*

Process of primary steel production to reduce iron oxide from the ore to iron. This also includes the blast furnace process. However, this term is used colloquially mainly for the "direct reduction processes".

Reduction Chemical reaction, always coupled with an oxidation. A substance is reduced if another substance withdraws oxygen from it. In doing so, this other substance is oxidized, i.e. it chemically reacts with the oxygen.

Refining *see "Converter"*

A process for reducing carbon from pig iron or steel using oxygen in a converter or refining hearth.

Refractory material Ceramic products for use at temperatures above 600 °C such as fireclay, silica and magnesia, used inter alia for lining blast furnaces, converters, melting vessels, transport and casting ladles, heat treatment furnaces.

Reinforcing steel *see "Concrete steel"*

Non-prestressed concrete steel.

Reinforcing steel Steel for the reinforcement of steel-reinforced parts in the form of lattice mats and bars. One also speaks of "concrete steel", "armouring iron" and formerly of "monier iron".

Remelting Cleaning process by re-melting of already melted, secondary metallurgically treated and cast steel under vacuum, protective gases or slags.

Residual stress Are internal stresses in a workpiece, even though no external forces are acting. Causes of residual stresses are, for example, deformations, inhomogeneous structures or thermal influences. A distortion of components is often the result of residual stresses, e.g. distortion during welding.

Resistance alloy *see "Heating conductor"*

Alloy that, due to its high specific electrical resistance, impedes an electric current, and can thereby effectively convert electrical energy into heat energy, e.g. a "heating conductor".

Resistance to deformation (k_w in MPa or N/mm^2) A measure of a material's resistance to plastic deformation, given as stress (force required per unit area of deformation), also known as "forming resistance". In practice, the force required for a given deformation can be derived from the known yield strength.

Return transported scrap Scrap resulting from production and quality-related processes in steel mills with attached forge shops and rolling mills that is used internally in the steel mill again.

Reverse strand extrusion A variant of flow pressing in which the strand exits the die and the hollow punch in the opposite direction to the press stamp movement, also known as "indirect strand extrusion".

Ring rolling machine *see "Ring rolling mill"*

Ring rolling mill Special rolling mill for rolling forged and punched blanks to final dimensions and shapes such as wheel rims, large bearing housings or preforms for gears and cones. It consists of a main roll driven by an external force acting on the outer ring wall and a smaller mandrel roll acting against the inner wall. This roll pair reduces the wall thickness of the ring, which increases in circumference. The height of the ring to be rolled is influenced by two cone-shaped axial rolls on the other side of the machine.

Rockwell hardness test HRB or HRC Hardness test according to Rockwell, whereby the size of the indentation caused by a ball (HRB) or a cone (HRC) is not measured, but its depth of penetration.

Roll designing Determination of the geometries (calibers) of the rolls to achieve defined individual forming degrees per rolling pass as a function of the steel quality (formability) and the end geometry to be achieved after several rolling steps on the rolled product.

Roll drawing Tensile-compressive forming process, comparable to drawing, but without using a fixed tool (drawing die), instead using mobile, non-driven forming rolls (drag rolls).

Roll gap The gap between the rotating rolls, formed from the entry to the exit of the workpiece, for the forming process.

Roll pass shape Smooth or profiled, calibrated outer surface of rolls.

Roll shaping *see "Profiling process"*

Roll bending process using cold rolling to create defined profile cross-sections on sheets and strips, also known as "roll forming".

Roll bending Bending process using rotating, smooth or profiled rollers, e.g. for corrugated sheet metal.

Roll forming *see "Profile rolling"*

Rolling straightening *see "Straightening"*

A process for straigthening bars and pipes using several profiled rolls arranged parallel to the axis, as well as sheets or strips with smooth rolls in roll straightening machines.

Rotary friction welding *see "Welding"*

Rotary peeling Continuous machining with a special tool (peeling tool) that rotates around the workpiece (bar or wire). In this way, the outer layer is removed from the rotationally symmetrical workpiece.

Rotation straightening *see "Wing straightening"*

Roughing Mill Informal term for a rolling mill for rolling semi-finished products, e.g. round steel bars, consisting of several rolling stands (trio and duo stands), which are usually "open", that is, arranged side by side.

Roughness Unevenness of a surface, which can be influenced by fine machining of metals, such as polishing, rolling, grinding, lapping, honing, also by radiation, pickling, etching, coating, as well as by corrosion.

Round Cross rolling *see "Cross rolling"*

Ruhrstahl-Heraeus process A process for vacuum treating liquid steel in the furnace, developed by Ruhrstahl and Heraeus at the end of the 1950s. In this process, partial quantities of the steel are constantly sucked into a vessel that dips into the melt surface from above, where they are decarburised and degassed under vacuum and oxygen. Because of this circulation of partial quantities of the steel melt, the process is also known as the “vacuum circulation process”.

Rupture strain (A in %) *see “Tensile test”*

Characteristic value for the permanent elongation A in % after the break, i.e. the permanent elongation of the tensile test, based on the initial length. Depending on the steel quality and heat treatment condition, engineering steels, tool steels and alloyed steels can have elongation values of 11 to 26%. Quenched and tempered steels, i.e. hardened and annealed, have lower toughness and thus elongation values of 9 to a maximum of 20%. Austenitic steels are well malleable and show elongations of 40 to 45%. Superplastic steels behave interestingly. Like gum, these steels reach elongations of up to 1000% at temperatures between 700 and 800 °C and at very slow tensile stress.

Rust *see “Corrosion”*

Corrosion product of iron or steel with oxygen in the presence of water, that is, water-containing iron oxide, porous and brownish.

Salt bath nitriding *see “Nitriding”*

A process for thermally surface-hardening steel parts, whereby these are treated in a salt melt at approx. 580 °C. In doing so, nitrogen diffuses out of the salt melt into the surface layer of the parts. Subsequently, post-oxidation in a quenching bath can improve the surface properties.

Sandblasting A colloquial term for compressed air blasting with solid blasting media for surface treatment of a workpiece.

Sawing A machining process for slotting and cutting workpieces using circular or straight tools, carried out by hand or machine.

Scale scrubber A device on hot rolling mills to remove the scale on the preheated blocks by high-pressure water jets (descaling) and thus prevent hot rolling into the surface of the workpiece. Scale scrubbers are also used in forging lines.

Scale Oxide layers on steel surfaces that are formed at very high temperatures (melting temperatures, annealing or preheating temperatures for hot forming) under the influence of oxygen.

Scaling resistance Resistance of the steel against scaling, the formation of oxide layers at high temperatures. Scaling resistance can be increased by alloying, for example with chromium.

Scanning electron microscope (SEM) *see “Electron microscope”*

Electron microscope that uses an electron beam to scan the surfaces of objects to be imaged and produces images with high depth of field.

Scrap type Scrap classified according to intended subsequent use, e.g. for melting in an electric furnace, composition, size and degree of contamination.

Scrap Important secondary raw material, generated by the scrapping of metallic products at the end of their useful life (scrap metal) or as a production residue during manufacture, e.g. in the form of chips.

Secondary cementite Cementite Fe_3C is formed by precipitation from austenite.

Secondary metallurgical slag A type of slag that is produced during a secondary metallurgical treatment of raw steel.

Secondary metallurgy A process for the further processing of raw steel to produce the desired steel alloy, also called “ladle metallurgy”, “ladle matallurgical treatment or “fine treatment”.

Secondary steel production Production of steel from secondary raw material scrap (electrical steel production).

Segregation Segregation as an increase or decrease of certain elements, which arises during the transition of the metal melt into the solid state and leads to local differences of the chemical composition and thus to different properties within a casting.

Selective laser melting (SLM) Additive manufacturing process in which the material in powder form is applied in thin layers, locally melted with computer-controlled laser radiation and solidified layer by layer to form a solid body. Metals such as aluminum, stainless steel (e.g. 1.4542 – X5CrNiCuNb16-4), tool steel (e.g. 1.2709 – X3NiCoMoTi), titanium, nickel or silver can be printed into components with complex geometry.

Semiconductor A material with an electrical conductivity that lies between that of electrical conductors and non-conductors.

Semi-finished casting Casting process for the production of semi-finished products made of metal, which can be carried out in portions in permanent moulds to blocks or continuously, almost endlessly to a strand or strip. The preforms thus cast are further processed by forming.

Semi-finished product Pre-manufactured or semi-finished raw material in an even simpler form, such as pipes, bars, profiles, wire, plates.

Semi-hot forging *see “Semi-hot forming”*

Forging not at the usual forging temperatures, but at lower temperatures in the range of 750 to 950 °C.

Semi-hot forming *see “Semi-hot forging”*

A forming process in the temperature range between cold forming and hot forming, usually at up to 950 °C, in order to produce more demanding components with better tolerances and less scaling, for example by means of flow forming or forging.

Semi-precious metal A metal that is not as corrosion-resistant as a classic precious metal, that is, it is to be classified between the non-precious metals (e.g. iron) and the precious metals (e.g. gold, silver, platinum) in terms of corrosion resistance, such as copper, nickel, tin.

Sendzimir mill Multi-roll mill stand construction with a working roll pair supported by many supporting rolls against deflection and used for cold rolling of very thin high quality flat products.

Sendzimir process Process for hot-dip galvanizing of steel cold strip, named after inventor *T. Sendzimir* (1894–1989).

Shaft furnace An oven in the form of a hollow cylinder, hollow cone or hollow cube with a height that is much greater than its dimensions of the base area, used to create a chimney effect, used for heating, burning e.g. limestone or bricks, and in metallurgy for smelting ores, such as the “Blast furnace”.

Shape hardening *see “Presshardening”*

Shear cutting Dividing a material by two cutting edges moving past each other.

Shear forming Process for the plastic forming of metals using shear forces, such as used in “twisting” or “shifting”.

Shear strength The resistance of a solid material to applied shear forces, specified as the maximum allowable shear stress before the material shears, based on the resulting fracture surface area.

Sheet iron A flat rolled product, the width and length of which are much greater than the thickness (up to 0.1 mm thickness possible), usually made of unalloyed or low-alloy steel.

Shift *see “Shear forming”*

Short name *see “Steel short name”*

Siemens-Martin Process *see “Hearth refining process”*

Hearth refining process for the cleaning and decarbonization of pig iron, used industrially from 1864 to the first half of the twentieth century, whereby heat was supplied by a special regenerative firing in chambers under the furnace and temperatures were reached for pig iron treatment of up to 1800 °C.

Siemens-Martin Steel *see “Siemens-Martin Process”*

Steel produced in a Siemens-Martin furnace.

Single draw One forming step in the drawing process using a drawing die, i.e. a single cross-sectional reduction.

Single-pass drawing machine A drawing machine for drawing wire, designed for only one pass, whereby the drawing drum can be arranged vertically or horizontally to apply the drawing force, also known as a “single-block drawing machine”.

Sink eroding *see “Spark eroding”*

Producing contours into an electrically conductive workpiece using a tool that has the corresponding negative contour. In a non-conducting liquid, sparks are generated specifically between the workpiece and the tool, which lead to removal, melting and vaporization of material from the workpiece.

Sinking Machining process for post- or further machining of holes, such as deburring or funnel-shaped sinking.

Sintering *see “Green preform”*

Process of powder metallurgy, used since the invention of ceramics, to join and compact powdery substances by heating them together.

Skew rolling A method of rolling with rolls that are not arranged parallel to the axis of the rotating workpiece, but obliquely thereto. This results in a longitudinal feed and, at the same time, a reduction in diameter at the workpiece due to the narrowing roll gap. If in addition a fixed mandrel is used, a pipe can be produced from a full round block as in the “Mannesmann skew rolling process”.

Slab Cast block whose width and length are several times its thickness.

Slag sand *see "Metallurgical sand"*

Slag Glassy or crystalline solidified mixture of basic and acidic oxides, which forms as a residue in high-temperature processes with liquid pig iron, raw steel or steel.

Slagging *see "Slag"*

Slag floats on the surface of the melting bath due to its low density, can be easily separated or pulled from the melt of pig iron, raw steel or steel in the laddles before tapping. This process of removing the slag into separate slag buckets is called "slagging".

Slaty fracture Brittle fracture of steel with a slate-like appearance, caused by oxygen, among other things.

Sliding mould Water-cooled crystallizer of an **E**lectro-**S**lag-**R**emelting furnace, which moves upwards slidingly with increasing solidifying block volume, also called "sliding crucible" in practice.

Smelting reduction *see "Corex process"*

A process for the direct reduction of iron ore without a blast furnace and without coke. The ores are reduced to sponge iron and this is converted into pig iron in a further process using coal and oxygen.

Smelting General term for metallurgical processes that take place in a metallurgical plant (e.g. ironworks, copperworks, smelter, remelter, recycling plants) and concern more than the extraction of metals from ores.

Soft annealing Heat treatment process to achieve a soft, malleable structure, that is, to anneal a hardened or cold-worked steel by recrystallization with the formation and growth of new crystals.

Solidification Transition from liquid to solid state, usually achieved by cooling.

Solution annealing *see "Homogenization annealing"*

Heat treatment process to dissolve precipitates present in the microstructure from upstream production steps, therefore also called "homogenization".

Spark eroding Thermal, abrasive manufacturing process for electrically conductive materials, which is based on electrical discharges (sparks) between the workpiece and the tool (wire, sink) switched as an electrode, also called "electrical discharge machining EDM".

Spark spectrometer *see "Optical Emission Spectroscopy", "Flame Spectroscopy"*

Device for determining the chemical elements in steel, based on the spectroscopic examination of the light, which, excited by an arc (spark), emits the elements of a steel sample. This light is examined according to wavelength and intensity and assigned to the individual elements in comparison with calibration curves.

Special austenite Austenitic chromium-nickel steel with a special chemical composition for special applications, such as 1.4435 – X2CrNiMo18-14-3, 1.4441 – X2CrNiMo18-15-2, 1.4529 – X1NiCrMoCuN25-20-7 or 1.4539 – X1NiCrMoCu25-20-5.

Spheroidal graphite Spherical form of carbon in the iron matrix of cast iron.

Spindle press *see "Presses"*

Machine for forming by pressing with a threaded spindle, which is constructed like a historical wine press. The spindle converts a rotary motion into a vertical displacement. As a result of the transmission ratio resulting from the inclined plane of the spindle thread, high compressive forces can be generated.

Sponge iron *see "Midrex process", "Corex process"*

Spongy, porous product with an iron content of 92 to 95 mass%, also called "iron sponge". It was the result of the early smelting of iron ore with wood charcoal in the blast furnace, had to be compacted by hammering and freed from the slag. Today, sponge iron is the result of direct reduction and smelting reduction processes. This sponge iron also has to be melted down to get pig iron.

Spreading "Going into the width", e.g. in rolling the rolled material flows transverse to the rolling direction.

Spring steel Steel with special elasticity properties, used to manufacture springs for a variety of applications.

Sputtering The term means "atomization", a physical process in which atoms are released from a solid (coating material, called target) by bombardment with ions. They go into the gas phase and are then deposited on the steel surface of the component to be coated (substrate).

Stacking fault *see "Lattice defects"*

Two-dimensional lattice defect, leads to the formation of grain boundaries.

Stainless steel soap An "odor killer" made of stainless steel in the form of a soap bar that acts as a catalyst and destroys unpleasant odor molecules.

Stainless steel In practice, a commonly used name for a group of about 120 different, non-corrosive high-quality steels.

Stalk-like crystal Long, stalk-like crystal, which forms during the solidification of a liquid metal melt by growth in a preferred crystal orientation.

Static recrystallization *see "Recrystallization"*

Removal of lattice defects in the crystals and reformation of the structure by nucleation and grain growth immediately after completion of forming.

Steel short name Short name for steels, consisting of main and additional symbols, which can be letters (e.g. chemical symbols) or numbers (for content of alloying elements). These differ for unalloyed, alloyed and highly alloyed steels as well as for high-speed steels such as e.g. C15, 28Mn6, X5CrNi18-10 and HS 6-5-2.

Steel A malleable iron-carbon compound, alloyed with other metallic and non-metallic alloying elements, with a carbon content less than 2.06 mass-%.

Steelworks slag *see "Slag"*

Type of slag, which is produced in steelworks during the production of raw steel and steel and is distinguished according to the place of production in: *"Converter slag"*, *"Electric arc furnace slag"*, *"Stainless steel slag"* and *"Secondary metallurgical slag"*.

Stellite *see "Hard Alloy"*

Commercial name for cobalt-chromium based hard alloys (non-ferrous alloy).

Step Turning Test *see "Macroscopic Purity"*
Standardized method for testing steels for macroscopic, non-metallic inclusions ("macroscopic purity"). For this purpose, a sample is produced from the billets and bars to be examined by turning three cylindrical steps with decreasing diameters. On the bright outer surfaces of these steps, thus increasingly deeper, the non-metallic inclusions stand out darkly, which are detected by naked eye on each step with a size of 0.5 mm and grouped.

Straightening by bending Procedure for straightening workpieces, whereby these are pressed by a stamp against two supports, thus slightly bent. This bending stroke (location, number and strength) is determined by the material (steel quality), the initial deviation and the straightness to be achieved.

Straightening by Stretching *see "Stretching"*
Procedure for straightening bends in round bars, profiles or pipes by means of tensile force. Plastic deformations (stretches) of 1 to 2% are applied. As an alternative to rolling, straightening by stretching is also used for strip material.

Straightening press *see "Straightening"*
Facility for bending straigthening of long products, manually or hydraulically operated.

Straightening with straightening nozzles *see "Rotational straightening"*
Special process of straightening in the bright steel production, where instead of a straightening rotor with adjustable jaws the direction with several vertically to the axis of the direction good is carried out by means of shiftable but rotatably arranged nozzles.

Straigthening Often one has to "straighten something out" in life, that is, "bring it into shape", as is the case in industrial production: Unwanted unevenness, bends, wave-like deformations, and thus also dimensional tolerances must be straigthened between the manufacturing steps and at the end of a production process. This is done similarly to bending by a slight plastic deformation by means of "bending straightening", "stretching straightening" or "rolling straightening".

Strain *see "Fracture elongation"*
Relative change in length of a speciment under load.

Strand Extrusion Flow pressing process, in which by means of a press stamp a flowable material is extruded from a pressure chamber (recipient) through a die to form a strand. Depending on the direction of exit of the strand and the direction of movement of the press stamp, the "direct extrusion" and the "indirect extrusion" are distinguished.

Strength The ability of a material to withstand mechanical stress before failure occurs. Strength is described by the stress (force per unit area) that the material can withstand before it permanently deforms or tears. The strength of steel depends on the type of stress (tension, compression, bending, shearing), the course (constant, changing) and the speed of the stress.

Stretch rolling process *see "Pilger rolling process"*

A discontinuous longitudinal rolling process in which the two reversing rolls have an increasing diameter over half the circumference, in the manner of the pilger rolling process. At the moment when the roll gap is at its greatest, i.e. the reversing rolls are opposite each other with their smallest diameters, the workpiece is quickly introduced. Then the workpiece is rolled back with a corresponding reduction in diameter.

Stretching *see "Strain"*

Measure of the relative change in length of a speciment under tensile load, usually referred to as "strain". With stretching, the forming process for lengthening (e.g. by stretching) or straightening a material can also be meant.

Strip apparatus of horizontal continuos casting machine On a horizontal continuous casting machine, the strip apparatus is used to strip the just solidifying strand in short individual steps from the mold.

Stripping Not the stripping of clothing, but the stripping of the mold from the cast and cooled ingots, that is, the removal (separation) of the slightly conical mould from the solidified ingots.

Structure The structure and arrangement of the components of a material in the visible and microscopic range (microstructure), consisting, for example, of crystallites, grains, and foreign phases. The "primary structure" and the "secondary structure" are distinguished. When a steel melt cools, it begins to solidify, crystallization begins, and the primary structure is formed. Often, due to the residual heat still present in the casting, there are transformation, precipitation, and recrystallization processes that then form the secondary structure. In practice, the term "structure" is always used to mean the secondary structure when referring to metals.

Sublimation Cutting *see "Melting Cutting"*

Method of melting cutting by means of process gas and laser beam, which vaporizes the material at the cutting point.

Substitution mixed crystal The name expresses it: It is a crystal mixed with atoms of at least two or more alloying elements. The atoms of one element sit on the lattice sites of the other element, i.e. atoms have been exchanged by the other atoms, that is, substituted. Therefore, in practice, the name "substitution mixed crystal".

Substrate Material to be treated, e.g. when coating the workpiece to be coated.

Super Duplex Steel Steel with a two-phase microstructure of ferrite and austenite, with higher alloy content of chromium, nickel and molybdenum as well as improved corrosion resistance compared to a standard duplex steel.

Superalloy It was not the very high price, but the super property of being able to withstand much higher operating temperatures than any steel is known for, that gave the name. It is a metallic material with a very complex composition of iron, nickel, platinum, chromium and cobalt with additions of molybdenum, tungsten, tantalum, niobium, titanium, zirconium and other elements, adapted for high temperature applications such as in engines, turbines, engines, in aviation and space.

Surface quality class The surface quality is influenced by the manufacturing process and any subsequent surface finishing and is an expression of the roughness. In the practice of bright steel production, surface defects such as cracks, scales, overlaps are also used as quality features and classified into surface quality classes according to special standards. These standards specifie the permissible depth of defects and the maximum percentage of the delivery quantity of defects depending on the dimensions.

Tandem rolling mill Tandem bicycles are known to us as a means of transport with at least two seats arranged one behind the other. And similarly, tandem rolling mills are constructed, that is, with two and more rolling stands arranged one behind the other. This design is mainly used for the rolling of steel strip, in order to continuously reduce the strip thickness in several individual rolling steps in one pass.

Tapping During blast furnace operation, the taphole of the blast furnace, also called "tapping hole", is opened at regular intervals. The tapping is carried out and the liquid pig iron now flows via a tapping channels into a ladle or into a ladle wagon (torpedo wagon).

Temper embrittleness The behavior of some steels to embrittle during annealing. There is the 300 °C embrittlement, also called "blue brittleness"; a phenomenon in steels with higher carbon content (precipitations of carbon and nitrogen at the grain boundaries). In addition, the 500 °C embrittlement, the classical annealing embrittlement, is to be mentioned, which occurs in manganese, manganese-chromium and chromium-nickel steels at annealing temperatures around 500 °C in the form of carbide enrichment at the austenite grain boundaries.

Tempering Heat treatment (reheating) of a hardened workpiece immediately after hardening. The aim is to make the steel less brittle in a targeted manner. The combination of hardening and annealing is called "temper hardening".

Teniferation *see "S alt bath nitriding"*

Tensile Forming Plastic forming process of materials under the influence of tensile forces only, such as during elongation (tensile drawing), width and depth.

Tensile strength R_m in MPA or N/mm^2 The highest tensile strength that can just be withstood by the material based on the cross section of the sample. After exceeding the tensile strength, the necking begins and it leads to breakage.

Tensile Test Standardized, destructive test that is carried out on standardized samples under the influence of tensile forces in order to determine material properties such as yield strength, tensile strength, elongation at break and necking.

Testing Generic term for all methods of determining whether a test object is within or outside of specified limits. It is tested subjectively without aids, only with the human senses, or objectively with technical testing equipment. The result is not a numerical value, but a statement such as i. O., n. i. O., good, bad, scrap, rework.

Thermal conductivity Property of a material, indicating how well it conducts heat or how suitable it is for thermal insulation.

Thermal cutting Process for separating workpieces at such a high temperature that locally at or in the separation point melting or vaporization of material is caused, as in the *"melt cutting"* and *"flame cutting"*.

Thermal spraying Thermal process for surface coating with metals, in which melted or vaporized additive materials are hurled in the form of spray particles onto the surface of the workpiece to be coated, such as *"flame spraying", "plasma spraying",* or *"arc spraying"*.

Thermomechanical treatment Process combination of plastic forming and simultaneous thermal treatment, i.e. a hot forming with targeted temperature control, in order to form certain structures and properties of steels.

Thin slab casting *see "Thin slab"*

Continuous casting of thin slabs, which are then immediately hot rolled after a heat treatment.

Thin slab Rectangular thin slab casting with thicknesses of 40 to 100 mm and widths up to 2600 mm as raw material for hot strip rolling.

Thixoforging Forging at temperatures above the usual hot forming in a range where materials have a state that can be classified between solid and liquid, that is, doughy, and can be formed very well, similar to casting.

Thomas process *see "Thomas-Gilchrist process"*

Thomas steel Steel produced by the Thomas-Gilchrist process with high hydrogen and nitrogen content, therefore less tough, susceptible to nitrogen embrittlement and difficult to weld.

Thomas-Gilchrist process A process for desulphurising pig iron in a converter with a basic refractory lining, also known as the *"Thomas process"*.

Thread rolling A rolling process used to form a thread on a blank, between two profiled rollers, e.g. for the production of screws.

Thread rolling Variant of rolling for the production of threads, for example for the production of screws. The processes "flat die rolling", "punching rolling" and "segment rolling" are distinguished.

Through hardening A comprehensive hardening that occurs during heat treatment with austenitizing and quenching (hardening), i.e. the formation of a uniform martensitic structure throughout the workpiece down to the core.

Time-temperature-transformation diagram (TTT) Representation of the microstructure development for a steel at different time-temperature profiles, stored for many steels in steel databases.

Tinning Process for surface finishing of metallic workpieces with tin.

Toggle press Type of press that uses the so called toggle lever effect: The further the knee lever resembling a human knee is extended, the slower but more powerful the press stroke. *D. Uhlhorn* (1746–1837) developed the first press suitable for minting coins with a toggle lever. Today, such toggle presses are used, inter alia, for stamping, deep drawing, powder pressing and die casting.

Tool steel Type of steel used to manufacture tools and dies to machine other materials or parts. "Cold work steels", "hot work steels" and "high-speed steels" are distinguished.

Top pouring Casting process in the mould ingot casting, in which the liquid steel melt is poured directly from above into the mould.

Torch cutting Thermal cutting process, also known as “oxygen cutting” or “oxy-acetylene cutting”. The cutting edge is heated and burned by oxygen.

Torpedo wagon A ladle wagon in the form of an elongated container similar to a torpedo for receiving liquid pig iron from the blast furnace and for rail transport of the pig iron to the converter steelworks. The container is mounted so that it can rotate, can hold up to 320 t of pig iron, and can keep it liquid for up to 30 h.

Total degree of forming *see “Forming ratio”*

Sum of all individual forming degrees in a multi-stage forming process, such as in the multiple wire drawing in line one after the other with several individual drawing steps.

Touch scan method Method for measuring the surface roughness by means of a pointed touch probe, which is moved horizontally over the test material surface at constant speed and records the vertical deflections as a measurement profile. The devices used for this purpose are called “Perthometers”. The roughness parameters such as roughness depth, center roughness and maximum roughness depth can be determined from the measurement profiles obtained.

Transmission electron microscope *see “Electron microscope”*

Operating mode of the electron microscope for direct imaging of thin objects that are irradiated.

Transmission *see “Ultrasonic testing”*

In core defect testing with ultrasound, the test piece is sonicated, i.e. ultrasound is sent from a transmitter through the workpiece to the opposite receiver.

TTT diagram *see “Time-Temperature-**Transformation** diagram”*

Turning steel *see “Turning tool”*

The turning steel is not to be confused with the steel workpiece that is to be machined by turning, but rather it refers to the turning tool.

Turning tool Machining tool (“turning steel”) for the turning process, consisting of the tool body with shank and cutting edge.

Turning *see “Machining”*

A machining process in which the workpiece is rotated and the tool, the turning tool, cuts the desired contour into the workpiece by machining with a geometrically determined cutting edge.

Twin boundary *see “Crystal twin”*

The boundary between the two parts of a crystal twin.

Twisting *see “Shear forming”*

Two-roll strip casting *see “Roll casting”*

A process for continuous casting by means of two oppositely rotating, cooled casting rolls.

Ultrasonic testing A non-destructive, contactless testing method for semi-finished products and components for internal defects (core defects) using ultrasound (US), whereby the reflection of ultrasound waves at the interfaces of the defects and their attenuation (“shadowing by a defect”) are used for defect detection.

Undesirable element Chemical element in steel, which has a harmful effect on the steel properties, such as oxygen, hydrogen or arsenic.

Unkilled steel Steel that was cast as it is, without addition of silicon or aluminum, thus not cast, so that the released, unbound oxygen can form gas bubbles during solidification, which can form cavities in the casting and favor aging.

Uphill casting Casting process, so called "bottom casting", in which the liquid steel melt is poured into a funnel, enters the channel system of the bottom plate (clamping plate) and, from below, fills the moulds located on the bottom plate evenly according to the principle of communicating tubes.

V2A steel Stainless steel, named after the "V2A" melting furnace of *E. Maurer* (1886–1969) and *B. Strauss* (1873-1944), which refers to the alloy type 1.4300 – X12CrNi18-8 and, from 1912, initiated the era of non-rusting, corrosion-resistant steels. Today, the group of V2A steels includes the successors 1.4301 – X5CrNi18-10 and 1.4305 – X8CrNiS18-9.

V4A steel A steel comparable to V2A steel with an additional 2 mass-% molybdenum, making it more resistant to corrosion under the influence of chlorinated media such as salt water or chlorinated water in swimming pools, for example 1.4401 – X5CrNiMo17-12-2 and 1.4404 – X2CrNiMo17-12-2.

Vacancies An unoccupied, free space in a crystal lattice, thus a point-like crystal defect (lattice defect).

Vacuum arc remelting *see "VAR-process"*

Vacuum Circulation Process *see "**R**uhrstahl-**H**eraeus-process (RH)"*

Vacuum Induction Multi-chamber Furnace (VIM) Furnace for the production of special steels and special alloys from scrap under vacuum by means of eddy currents induced directly in the metal, which cause the scrap to melt.

Vacuum-lifting process *see "Dortmund-Hörde-process"*

Valve steel Ferritic-martensitic or austenitic steel used for intake or exhaust valves in combustion engines.

VAR-process *see "Remelting"*

Process for the remelting of steel under vacuum in an electric arc furnace (**V**acuum **A**rc **R**emelting).

VD plant Equipment of ladle metallurgy for treating crude steel under vacuum, named after the term "**V**acuum **D**egasing".

Vertical Continuous Casting Continuous casting process in which the solidifying strand exits vertically downward from a mold.

Vickers hardness test HV Vickers hardness test, in which an impression is made using an equilateral diamond pyramid and the hardness HV is determined from the diagonals of this square impression.

Visual Inspection Non-destructive testing method used to detect defects in the workpiece being tested by means of visual inspection. This visual inspection can be carried out directly with the naked eye or indirectly with aids such as magnifying glass, microscope, endoscope, mirror, etc.

VOD plant Facility for secondary metallurgical treatment of liquid steel by means of **V**acuum **O**xygen **D**ecarburization, i.e. decarburization under vacuum with oxygen.

Warm strength Strength of a material at elevated temperatures.

Waste Solid, liquid or gaseous substances that remain after the production of a product, i.e. as residues. In colloquial usage, terms such as “garbage”, “trash” or “rubbish” are also used.

Water blasting *see “Waterjet cutting”*

A high-pressure waterjet is used to clean a surface, such as a house, garden, or car. In industry, waterjets are used to remove burrs, clean, and separate different materials.

Waterjet cutting Manufacturing process for removing burrs and separating different materials using a waterjet with high pressure of up to approximately 6200 bar through a nozzle. “Pure water jetting” uses pure water, while “abrasive water jetting” uses water with powdered hard particles (abrasive).

Welding Thermal joining process for the generation of durable, metallurgical bonds by melting the materials in the joint zone and feeding in filler materials, also under pressure depending on the process.

Wet drawing Forming process for drawing long products such as bars and wire using liquid drawing lubricants, such as oil for wet drawing of stainless steel wire or soap emulsion for drawing of high-strength galvanized steel wire.

White sheet Thin, cold-rolled and galvanized steel sheet with thicknesses of 0.1 to 0.5 mm.

Wide-flat product The name refers to the cross-section, usually with thicknesses over 5 mm and widths over 150 mm, also called “wide flat steel” or also “wide flat iron”.

Winding machine A device for winding and unwinding long products such as wire, strip and ropes.

Wing straightening Straightening process for round bars, whereby the straightening tool consists of several adjustable straightening jaws arranged offset to each other. These rotate in the straightening machine as a straightening rotor parallel to the axis around the material to be straightened and are also called “wings”.

Wire drawing A forming process used since the Middle Ages, in which an output wire is drawn through a conical opening in a drawing tool (die), tapered and lengthened.

Wire pull-trough type furnace Furnace for heat-treating (annealing) of wire, with the wire being continuously drawn through the furnace. Such pull-trough type furnaces mostly consist of a wire discharge station, a pre-cleaning unit, a heating, holding and cooling zone, as well as a winding unit. The length of the furnace and the drawing speed determine the time-temperature course during the annealing process.

Wire Product form made of flexible metal, thin and very long, for example round, flat, square or profile wire, usually wound on spools, bobbins, spindles or held in bundles (coils). A classic example is the copper wire used for telegraph lines. And the one who was telephoning back then and also had to make a decision quickly was “on the wire”, i.e. available, active and decisive, which is still true today in this form.

Wire-cut EDM *see “Spark eroding”*

Cutting process with high precision for electrically conductive materials, which works according to the principle of spark eroding with a thin wire as an electrode. Also common are the terms "wire cutting", "spark eroding" or "eroding cutting".

Wöhler test *see "Continuous oscillation test"*

Wood fiber fracture Fracture pattern in steel with a fibrous fracture surface similar to a wood fracture, caused, for example, by oxygen compounds in the steel.

Working rolls Rolls which directly in contact with the workpiece cause the forming process, i.e. working rolls for quarto and multi-roll stands for strip rolling. In this case, these working rolls are supported to avoid deflection of larger rolls ("supporting rolls").

X-ray fluorescence analysis (XRF) A method of qualitative ("What is included?") and quantitative ("How much is included?") determination of the chemical composition of a material. This uses the effect of X-ray fluorescence, whereby the sample to be analyzed is excited by X-rays. As a result, the sample emits secondary X-rays, which are characteristic of the chemical composition of the sample in individual components.

Yield strength (R_e or $R_{p0.2}$ in N/mm^2) *see "Hooke's Law"*

Important parameter used by construction designers: Up to this stress limit, the material behaves elastically, i.e. after unloading it takes on its original form (length) again. Hooke's law applies. If the load (stress) is increased beyond this point, the material begins to behave plastically, it flows. This technical end of the elastic state is also referred to as the yield point R_e (N/mm^2 = MPa). In practice, steel alloys do not always have a clearly visible yield point. For these cases, the "0.2% yield point" or the "elastic limit $R_{p0.2}$" is given as a replacement yield point, as this can always be determined from the stress-strain diagram, even if there is no clearly defined yield point. This 0.2% yield point is thus the stress (in MPa) for an assumed 0.2% elongation.

Yield strength *see "Tensile strength"*

Up to this stress, the material behaves elastically, above it irreversibly plastically. In tensile loading, as in the tensile test, it is also called "yield strength", in compressive loading or in compression "compressive strength".

Yield strength *see "Tensile strength"*

Yoke Magnetization *see "Magnetic Powder Testing"*

Type of magnetization of the workpiece to be examined necessary for a magnetic powder test, whereby an evaluable magnetic field is generated between two poles, so that surface defects (cracks, pores) become visible transversely to the magnetic field.

Zinc flame spraying *see "Flame spraying"*

Variant of thermal spraying for coating metal surfaces with zinc for protection against corrosion, whereby zinc wire is melted by means of an arc, atomized with compressed air and sprayed onto the workpiece.

α-iron *see "Ferrite"*

γ-iron *see "Austenite"*

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