VŠB - Technical University of Ostrava

Forming and casting of non-ferrous metals

(E-LEARNING)

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STUDY REGULATIONS

Forming and casting of non-ferrous metals

For the subject "Forming and casting of non-ferrous metals" in the 2nd semester of the follow-up Master studies of the branch "ADVANCED ENGINEERING MATERIALS" you have obtained an educational packet including integrated lecture notes for the combined study comprising also study regulations.

Prerequisites

Knowledge of fundamentals of materials forming and foundry

The objectives of the subject and outputs from the education

The aim of this subject is to describe the basics of forming and casting of non-ferrous metals and their alloys. Students will acquire broad theoretical and practical knowledge of up-to-date forming and casting technologies, as well as of structure-forming, hardening and restoration processes occurring in materials during the manufacture and follow-up processing. Problems of particular technological procedures in the production process of specific products are summarized.

Acquired knowledge:

- *The student will be able to describe particular forming and casting methods*
- *The student will get a comprehensive look at the manufacturing procedures used in a field of non-ferrous metals and their alloys*

Acquired skills:

- *The student will be able to identify and choose appropriate methods of certain non-ferrous metal forming and casting*
- *The student will be able to apply the theoretical knowledge in real operating situations*
- *The student will be able to show knowledge of particular casting as well as forming operations*

After studying the subject, a student should be able to:

- summarize positives and negatives of conventional technological forming and casting procedures, to know their principles and partial influences on affecting materials properties
- identify effects of various influences on forming, to propose applicable processes for the manufacture of final products for selected (industrial) applications

For whom the subject is intended

The subject falls within the Master's study of the study programme MATERIALS ENGINEERING, but it can also be studied by applicants from any other branch, on condition of having met the demanded prerequisites.

The lecture notes are divided to parts – chapters, which correspond to the logical dividing of the studied subject matter, but they are not of the same volume. The assumed time for the study of the chapter may differ significantly, therefore large chapters are further divided to numbered subchapters and these correspond to the structure of the lecture notes described below.

Recommended procedure for studying each chapter:

Each chapter needs to be comprehended thoroughly, including figures and equations. Behind each chapter, there is a summary and questions relevant to the respective text. The time required for the study is suggested, but this is for information only and depends on an individual approach of a particular student.

A way to communicate with lecturers:

For the students of the combined form of study, possibilities to communicate with a lecturer are above all in agreed individual consultancies on the given topic. More detailed instructions will be discussed with students at the beginning of the course in which students will be present.

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1. Formed products of non-ferrous metals, manufacturing technologies

Objective: After studying this chapter a student will know

- Basic classification of manufacturing processes

- Spheres of application of non-ferrous metals and their alloys

- Classification of particular forming methods

- Information on processes accompanying hot and cold forming

Lecture

Development of non-ferrous metals production is nowadays determined mainly by requirements of mechanical engineering, electrotechnics, chemical industry, building industry or by development of aircraft, automotive and ship-building industry. These branches influence above all the quantitative aspect of the development of non-ferrous metals. In connection with the increased demand for non-ferrous metal products, the final economic aspect of these components has been developed, too. An increase in price of basic raw materials, as well as of various pre-alloys used for the manufacture of final alloys, has been noticed for a long time. It is evident that the price increasing trend is caused, among others, by ever increasing requirements of branches such as medicine and electrotechnics in particular. An important field, where non-ferrous metals play an unsubstitutable part, is also metallurgy, where along with the development of new-type steels with modified properties a demand mainly for alloying elements rises. Aside from the demands for quantity, demands for physical – chemical and mechanical properties of non-ferrous metals intensify as well.

The above mentioned automotive industry heads towards gradual replacement of original steel components by components manufactured from lightweight materials in order to reduce weight of vehicles for fuel consumption reduction resulting from less powerful car engines. A concrete example can be application of light Al and Mg based alloys for castings

or formed products. In order to replace steel components by non-ferrous metal components effectively, the latter need to meet quite demanding limits of mechanical and other properties. This can be achieved by their manufacturing process, involving chemical composition modification, heat treatment and plastic deformation, or more precisely the forming technology.

Another branch is electronics, where we can see an increasing trend of production of computers and other systems used generally in all spheres. This brings along a need of materials such as Ag, Au, Pt, Cu, Al, W etc. In medicine, a gradual increase in application of Ti based materials for long-term or permanent implants can be seen, and of Mg based alloys for temporary implants, which are absorbed in organism after some time.

All of these alloys differ in the resulting price according to particular specifications. Nevertheless, it is evident that a price depends also on the manufacturing technology (Fig. 1). As a matter of fact, there are four processes of the manufacture of final components from non-ferrous metal alloys. The first one is the conventional metallurgy – foundry. The second one is powder metallurgy, the third one is the vapour deposition, however, this is limited mainly for components small in dimensions. The last way to obtain the demanded components is a combination of foundry and following forming. We need to mention, that a substantial part of non-ferrous metals and their alloys are processed just by forming. Formed semi-products serve for the manufacture of structural and other components, where replacement by different materials is not possible or cost-effective.
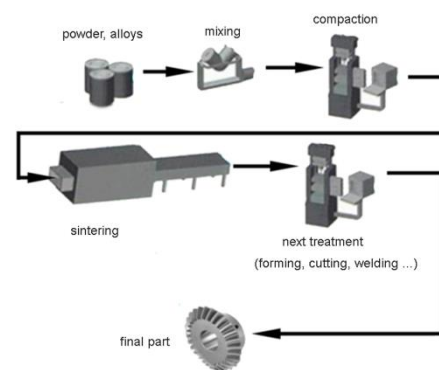
(a)   (b)

Fig. 1 Example of casting technology (a) powder metallurgy technology (b)

Forming is used for processing of ingots, conticast products and powder metallurgy semi-finished products. Generally, forming ensures transformation of the initial work-piece

to the final form and also improvement of mechanical properties of materials as a result of structure changes in materials. Cast semi-products are usually processed through hot forming followed by cold forming.

The following technological forming processes are applied when processing non-ferrous metals: rolling, extrusion pressing, hammer forging and die forging, precision forging, rotational forging, drawing and profiling. Formed products can be further treated or modified. These operations cover the above mentioned heat treatment, straightening, surface finishing and welding.

Non-ferrous metals and their alloys can be divided according to various aspects, however, the melting temperature influence is probably the most widely used one. This general categorization does not cover metals exhibiting another significant property (e.g. low specific weight, high chemical stability or radioactivity).

Non-ferrous metals can be divided to the following groups:

1) Easily meltable metals (low melting temperature):
   - Alkali metals (Cs, Rb, Na, K, Li)
   - Metals of subgroups II b – V b (Hg, Ga, Id, Sn, Bi, Tl, Cd, Pb, Zn, Sb)
2) Light metals (Mg, Al, Be, Ba, Sc, Ca)
3) Metals with medium melting temperature (Cu, Ni, Co, Fe)
4) Noble (precious) metals (Ag, Au, Pa, Pt, Rh, Ir, Ru, Os)
5) High melting temperature metals (Ti, Zr, Hf, V, Nb, Ta, Cr, Mo, W)
6) Trace metals (Y, lanthanides)
7) Radioactive metals (U, Pu)

1.1 Principle of plastic deformation of non-ferrous metals and their alloys

Plastic deformation is a permanent change in a shape and dimensions of a body caused by external or internal forces on condition of preserving the continuity of material. After plastic deformation the material must remain changed even after discontinuing the action of external forces. There are several possible methods of plastic deformation processes. Slip mechanism, which can be combined with other mechanisms, is probably the prevailing mechanism in plastic deformation of non-ferrous metals. A concrete example is the diffusion mechanism, and above all under high temperatures the grain boundary sliding mechanism is usually detected. Under certain conditions, by effect of stress the diffusion motion of atoms, which are not bonded to dislocations, may occur. During the diffusion mechanism, individual atoms move by means of motion of vacancies. However, atoms do not follow crystallographic directions, but their motion direction is determined by the stress field gradient. The diffusion mechanism allows large plastic deformations, but it needs high

temperatures and very long times. This mechanism often occurs on boundaries of grains and blocks. However, the above mentioned alternatives require certain conditions for their development, which include deformation under high temperature or application of lower strain rate etc.

Generally it can be stated that the slip mechanism prevails during plastic deformation at the moment, when in some slip systems the shear stress reaches a critical value. Slip propagates through a crystal gradually and is explained by a motion of dislocations along slip planes. Plastic deformation of polycrystalline matters is caused by deformation of individual grains and their relative motion and rotation.

This occurs through the motion of line defects – dislocations. Deformation progresses by a continuous slip of individual crystal layers; the slip distance is a multiple of the shortest interatomic spacing. The slip of the crystal layers is determined by the so-called slip systems along certain crystallographic planes and directions, these planes and directions depend on the lattice type of the particular metal. The slip direction is identical with the direction with the highest atomic density, the slip plane is the plane with the highest atomic density. Each lattice type has a different number of basic slip systems; 48 systems for the body cubic centered lattice (α-Fe, Cr, W…), 12 systems for the face cubic centered lattice (γ-Fe, Cu, Al…) and 3 basic slip systems in total for the hexagonal close-packed lattice (Mg, Ti…). The more active slip systems in the lattice, the higher formability of the particular metal.

1.1.1 Formability of metals and alloys

This is an ability of objects to change their shapes and dimensions permanently without cohesion failure. It depends on metallurgical and thermomechanical factors. The most important are above all chemical composition, structure state, forming temperature, deformation velocity and degree, geometrical proportions and state of stress.

From the point of view of crystal lattice influence, the highest formability can be expected in metals with FCC (face cubic centered) and BCC (body cubic centered) lattice, which have the highest number of slip systems. However, some metals have higher formability even with a lattice different from the above mentioned ones. Concrete examples can be Sn, Zn, the formability of which is higher than e.g. of Fe, which is caused by their low melting temperature. Just the low melting temperature means that these metals can be formed at room temperature in the region of their recrystallization temperatures.

Formability in alloys depends on the initial material structure. Homogenous metal materials, which are plastic under the forming temperature, can be formed without problems. Alloys comprising two heterogenous components can be only formed, if at least one of the both components is plastic in the range of forming temperatures. If both of the components are plastic within this range, then these alloys can be formed as homogenous materials. If one of the components is brittle at the forming temperature, the forming process depends on the proportions of both the components and the process of their disengagement. On the basis of this viewpoint, we can distinguish structures with a brittle component in a form of plastic primary crystals of pure metal and brittle components disengaged in a form of isolated particles or continuous envelopes on boundaries of primary crystals. The second group of alloys covers primary crystals with a eutecticum comprising a brittle component separating individual primary crystals.

Materials of the second group can be formed under hot condition with certain difficulties. Plastic deformation occurs in the plastic component of the alloy and the influence of brittle crystals depends on their amount. However, if the brittle component started to disengage in a form of continuous envelopes, forming becomes more complicated and the brittle component failure may occur (crack formation). In the case of cohesion failure of envelopes during the primary stages of forming, even these materials can be hot formed under specific conditions.

Formability of non-ferrous metals and their alloys is significantly affected by the mentioned deformation temperature, which determines not only activation of slip planes, but also progression, or on the contrary impossibility, of restoration of a deformed structure. Just the temperature, next to other factors such as a lattice type, the presence of secondary phases, chemical composition and stacking fault energy, determines whether a material will be only hardened or recovered at the same time. More detailed information on material restoration can be found in specialized materials dealing with the theoretical analysis of plastic deformation.

1.1.2 Deformation under hot condition

A material is hot formed, if deformation is performed under a temperature, which is higher than 40% of melting temperature (more precisely, this value ranges between 30% - 80% T_t and this value depends on the material type). Non-ferrous metals and their alloys can be

always hot formed within a certain interval of forming temperatures, whereas with an increasing temperature generally the material strain resistance decreases and formability improves, because dislocation movability and diffusion velocity increase. However, if the temperature is too high (exceeding the upper limit of the interval of applicable forming temperatures), the material formability drops rapidly and overheating occurs, or even burning of the material. During overheating of the material, abnormal coarsening of grain occurs; this can be remedied through suitable heat treatment. On the contrary, burning of the material occurs at very high temperature, which is an irreversible process. This can be remedied only through remelting, because the material, due to considerable weakening of grain boundaries, disintegrates to individual grains during any further forming.

1.1.3   Deformation under cold condition

Cold forming is performed if the temperature during deformation does not exceed 40% of the material melting temperature, so below the recrystallization temperature. Forming is accompanied by intensive hardening of material, so also very high strain resistances. Under cold condition, slip deformation mechanism occurs in material, but also twinning. Gradually, plasticity of the material is exhausted and its strength increases. During forming, grains become noticeably flattened and elongated in the deformation direction, orientation of structure phases in this direction occurs and a texture causing anisotropy of its properties forms in the material step by step. Anisotropy is most frequently planar (differences between the different directions along the plane of the work-piece) or normal (differences between two planes perpendicular to each other).

A texture can be defined as a regular geometrical and crystallographic arrangement of the structure and substructure of a polycrystalline metal. Deformation textures can be divided to a structure texture (formed as a result of inhomogeneity of chemical composition and the presence of inclusions) and a crystallographic texture (formed as a result of grains arranged to a specific preferred orientation, which is different for each type of the material lattice). The so-called recrystallization texture forms after recrystallization.

1.1.4   Restoration processes

During forming a change of a shape of individual grains occurs, however, their volume remains constant. In order to refine the grains, some of structure-forming, restoration

processes need to be initiated in the material. To initiate such a process, a defined value of accumulated inner energy needs to be exceeded. This is imposed into the material through forming processes, due to which a growth in density of imperfections and accumulation of dislocations occurs. When reaching a defined limiting value of energy, restoration (de-hardening) processes begin to activate; the type of the restoration process depends on the type of the forming process, i.e. hot or cold forming.

From the point of view of time, the restoration processes can be divided to dynamic and postdynamic. Dynamic processes occur during deformation, postdynamic after the end of the material deformation. This can be after the finishing of the whole forming cycle, during cooling or even between the individual passes (e.g. during continuous rolling). Recrystallization in material occurs most frequently after hot deformation. New grain nuclei form and grow-on on energy advantageous locations (on grain boundaries). For initiation of recrystallization it is necessary to achieve a critical deformation.

During cold forming a recovery can occur in material, which is a process of an incomplete restoration of material, when a decrease in the dislocation density, their annihilation and regrouping occurs and subgrains form (polygonization). In order to initiate recrystallization, the complete restoration of the structure, further energy needs to be imposed, for example through recrystallization annealing.

Regarding the stress and deformation aspects, different presuppositions concerning the restoration process need to be considered. There are different conditions for initiation of static (postdynamic) recrystallization and different conditions for initiation of dynamic recrystallization. Initiation of static recrystallization is easier than initiation of dynamic recrystallization. Velocities of the both types of recrystallizations differ as well, whereas dynamic recrystallization is mostly faster. As soon as dynamic recrystallization begins in material, stress in the material decreases and after specified time the steady-state occurs in the material, when hardening and de-hardening processes are in equilibrium. On the contrary, recrystallization does not run during deformation under cold condition, material usually hardens until recovery begins, which only means a partial restoration of plastic properties, though.

☑ **Summary of terms**

Forming is used for processing of non-ferrous metals and their alloys in a form of ingots, conticast products and powder metallurgy semi-finished products.

Slip mechanism is the prevailing mechanism in plastic deformation of non-ferrous metals.

Formability is an ability of materials to be subjected to plastic deformation without cohesion failure.

Hot forming is application of plastic deformation at temperatures higher than the material recrystallization temperature.

Cold forming is application of forming at temperatures lower than the material recrystallization temperature.

Restoration of materials is an ability of materials to restore plastic properties. This is generally divided to dynamic and postdynamic. According to the forming method and the particular material, recovery and recrystallization can be distinguished.

(?) **Questions**

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1. How can non-ferrous metals be divided?
2. What are possible deformation mechanisms in non-ferrous metals and their alloys?
3. Define hot and cold forming, including accompanying processes.
4. What is formability and how can be influenced?
5. Analyze differences between the particular restoration mechanisms.

2 Forming methods

Time needed for the study: 20 hours

Objective: After studying this chapter a student will know

- Basic classification of forming methods
- Specific classification and technological principles of conventional forming

- Assortment produced by particular processes
- Information on particular procedures and their influence on final properties of formed products

📖 **Lecture**

2.1 Forging

Forging is one of the oldest forming procedures in general. Nowadays there are four basic types of forging: hammer forging, die forging, rotational forging and orbital forging. As there is a wide variety of metal materials, a great attention needs to be paid to their proper selection when designing particular components, namely regarding to their formability. Fig. 2 shows forgeability of selected materials. It is evident that manufacturing complexity depends, among others, e.g. on ability of material to fill cavities of a die. Typical representative components manufactured from non-ferrous metals using forging include e.g. components used in automotive industry, such as crankshafts, axle arms, brake drums, brake components, movable components for engines such as connecting rods, pistons, wheel discs, but also geared shafts etc.
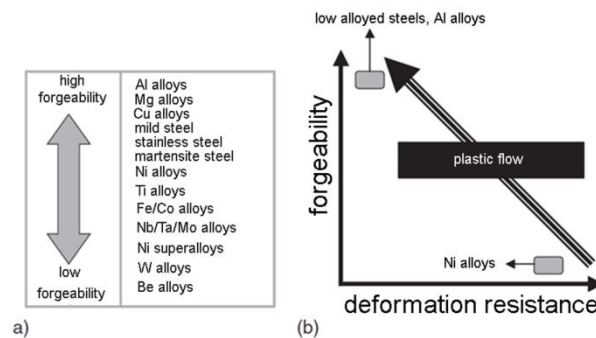

Fig. 2 Formability of selected materials (a) dependence of strain stress on formability (b)

2.1.1 Hammer forging

Hammer forging is defined by free flow of formed metal during plastic deformation (Fig. 3). Hammer forging consists of basic operations, which are used depending on the subsequent

application of the forging. The basic hammer forging operations include fullering, upsetting, recessing, chiseling, punching, bending and twisting.

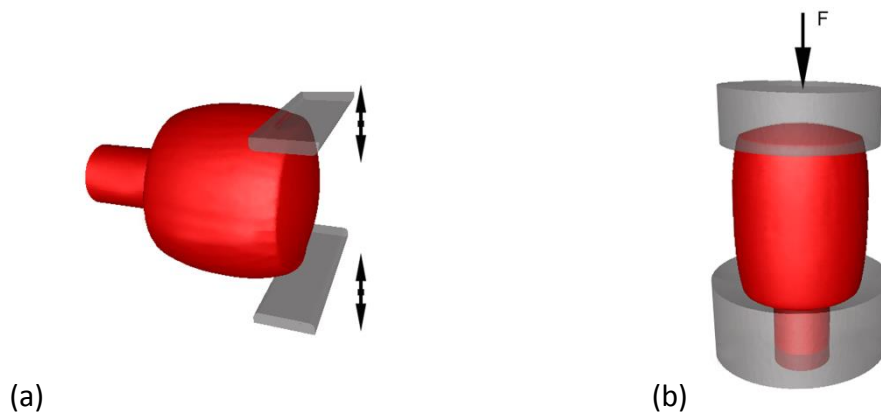(a)   (b)

Fig. 3 Basic operations of hammer forging (a) fullering (b) upsetting

Fullering is probably the most frequently used hammer forging operation, where continuous increase in length occurs at the expense of a decrease in cross-section of the work-piece (Fig. 3a). Fullering is performed using smooth anvils or shaped anvils. The next primary operation is upsetting, where a height reduction occurs, while the forging transversal cross section increases (Fig. 3b). This operation is usually used above all in cases, when it is needed as a preliminary procedure for following fullering (ensures a satisfactory degree of forging through). Using upsetting a decrease in anisotropy of mechanical properties can be ensured or obtaining punched rough forgings. This operation is characterized by inhomogeneous deformation, with occurrence of barelling. During upsetting, certain rules should be observed, for example the length of the upset work-piece should not exceed 2.5 multiple of its diameter. Also, faces of the upset work-piece should be perpendicular to its axis and flat. Other hammer forging operations are described in details in the special literature dealing with forging technology.

2.1.2 Die forging

Die forging features a limited flow of the formed metal (Fig. 10). The initial work-piece fills the die cavity and gains the desired shape. The purpose of forging is to make material fill perfectly the whole cavity in the die. Various shapes with weight from several grams up to 3 tons are forged in dies. Initial material is usually a rolled semi-product of a square or round cross section and a needed length. In this technology the so-called follow-die forging is used,

where a forging is forged gradually in several cavities placed in one die one after another. In the follow-die forging, the first cavity is used to distribute the metal into the rough shape and the final shape is forged in a "final" or "finisher" cavity. The number of the strokes of the hammer should be optimal. Nevertheless, the number of operations depends on other factors, such as a shape complexity of the forging, force demands, temperature field of the forging etc. For example, if die forging is performed by only a single stroke, this does not necessarily ensure a complete filling of the die cavity with metal for forgings with more complicated shapes. On the contrary, with a high number of strokes the die is damaged by blows and thermal stressing as a result of a contact with a heated forging.

According to the design, dies can be divided to open dies and closed dies. These are distinguished according to the factor, whether a die design allows or does not allow a free flow of formed metal during deformation. Forging in preliminary cavities is always accompanied by a certain lack of metal in the die. Final cavities have also open and closed variants. Open cavities have a groove for excess metal squeezed-out, forming what is referred to as "flash". The groove is located on the dividing plane along the periphery. It needs to be stated that a flash represents the largest metal loss (10-30%), but it is needed for several functions. It must ensure enhanced resistance against metal flow before dies getting into a contact; this forces the metal to completely fill the die cavities. It also eliminates the volume differences of the initial material and acts as a shock absorber between the dropping parts of the die. However, the situation is different in the case of closed cavities. These do not have a groove for a flash, by which theoretically high material losses are avoided. However, disadvantages need to be considered, such as application of this method for forging of simple rotational forgings. The precise determination of the initial material is really necessary, because the material has no other way to flow. Typically the forgings made this way feature higher wastage due to incomplete filling of die cavities.

At present, ways to replace conventional materials by lightweight alloys based materials have been searched due to ever increasing requirements imposed on car manufactures. Apart from others, Al alloys have been tested, being even reinforced with fibers for increasing their strength and a possibility of application for heavy duty components. Aside from these procedures, technologically more advanced forming processes followed by heat treatment, the so-called thermo-mechanical processing, have been tested as well.

2.1.3 Rotational forging

Rotational forging is a technology used for reduction of longer components of round or rectangular cross section (Fig. 4). Its principle is forging by many strokes of a die rotating around the formed material. Anvils as well as dies get to move by effect of a centrifugal force and strike the work rolls, which push the anvils back to the forged material, which results in repeated blows. The work-piece rotates slowly and moves along the axis to the forming process. Dies are placed in a rotational forging head, which can be replaced. Rotational forging can be performed under cold and hot condition (components of large diameters and materials with high strain resistance). This forging can be used for production of both full-volume rods and pipes with complicated shapes. Rotational forging under cold condition is a promising process, which involves gradual (incremental) deformations, widely applicable for the manufacture of engineering parts, such as discs, annuli, geared shafts etc. Rotational forging under hot condition differs by a selected working temperature of the process and also by the used lubricant (when forging under cold condition).

The advantage of rotational forging is great material saving and high working speed resulting in high productivity. This forming process is characterized by very high deformation speed (i.e. potential manufacturing possibilities of production are 4-6 pieces per minute). Semi-products of more or less unlimited length can be processed by rotational forging, typically there are lengths up to 1000 mm.
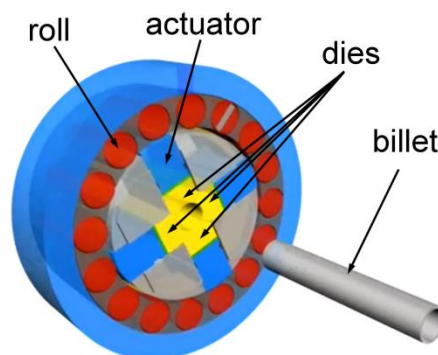

Fig. 4 Rotational forging principle

When compared to conventional forging, there are high cross section reductions at relatively low energy cost, significantly dimensionally more precise forgings, higher surface quality and considerable improvement of mechanical properties of products formed by rotational forging. Enhanced strength properties allow using e.g. products defined by very

thin thickness of a wall (lighter material) or application of material, which featured lower hardness in the initial state (cheaper material). In this context we may say that rotational forging enables to make even products featuring complicated inner geometries (Fig. 5). An important benefit of rotational forging is also achieving an excellent surface quality of forged products, which is comparable to a ground surface.
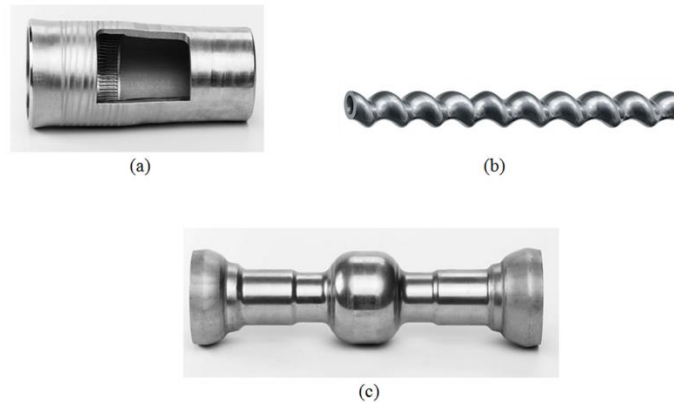
Fig. 5 Examples of forgings made by rotational forging: valve (a) pump rotor (b) shift lever gate (c)

A highly positive aspect is a possibility to form materials with low formability, such as tungsten, molybdenum and their alloys, or other materials with "problematic formability" (SMA, Mg alloys etc.). Among others, this process is used also for a field of Ni-Ti based alloys called shape-memory alloys (SMA). The performed high-temperature rotational forging evidently does not cause necessarily a significant difference in achieved transformation temperatures in comparison with e.g. the initial state of SMA after the performed homogenization. The main reason for more advantageous deformation behavior of rotationally forged materials is, among others, also the stress state, characterizing the entire process. Owing to the simultaneous move of anvils in the direction against the formed material, this can be characterized as an advantageous compressive stress state. Moreover, during rotational forging a filament structure formation can be achieved, which is, in contrast to e.g. machining processes, a considerably more advantageous state for their subsequent applications. In specific cases this method may eliminate a subsequent conventional machining. A product manufactured by this procedure enables to optimize its weight, whereas inner geometry can also be formed.

2.2 Rolling

Rolling is one of the basic forming operations used in a field of non-ferrous metals. The rolling process can be divided to transverse, rotary (slantwise) and longitudinal rolling.

During transverse rolling the rolled product axis is parallel to axes of rolls. Rolls rotate in the same direction. The metal is subjected to rotational motion relative to its axis and is thus worked in the transverse direction. This is used e.g. for the manufacture of shafts or for rolling of milling balls for cement plants.

Rotary (slantwise) rolling is a special case of transverse rolling. The plastic deformation mechanism is similar. Axes of work rolls are not parallel, but slantwise. The translational motion is imparted to the metal body along its axis through slantwise positioning of the rolls (the rolled product moves along the screwline). This rolling method is used for the manufacture of seamless tubes and pipes. This is one of the most widely used processes of the manufacture of hollow semi-products.

The most frequently used type of rolling of non-ferrous metals and their alloys is longitudinal rolling, therefore these lectures are focused mainly on it. From the economical point of view, this is the most important forming operation. This can be used for forming of large ingots of 500 mm thickness to final thicknesses of several micrometers (Al foil). A total length of rolled products can be up to several hundreds of km. At present, particular reductions in individual passes are characterized by deformations as high as about 50%.

The equipment on which the process is performed is called a rolling mill stand; they can be divided according to various aspects. Rolling mill stands are designed in different types of configurations and number of rolls. The basic types are 2-high, 3-high, 4-high (quarto) or cluster stands (Fig. 6). The particular rolling mill stand incorporates an assembly stand, rolls, bearings of the counterbalance and adjusting equipment, a drive of the mill stand and a gearbox.
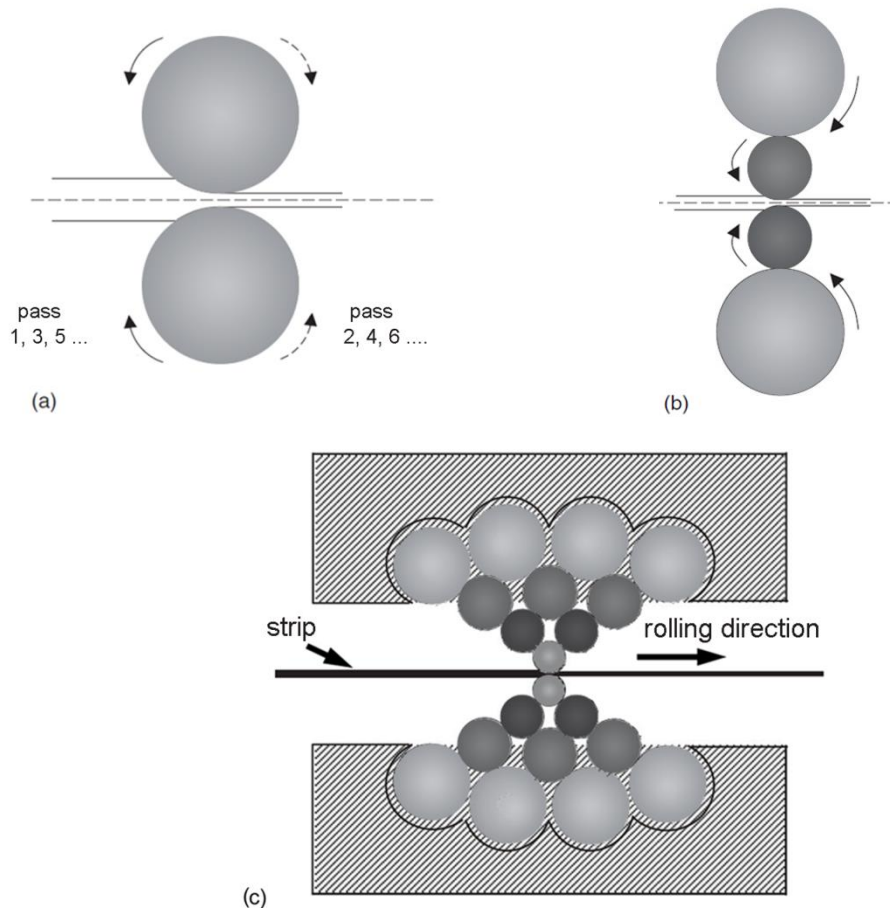
Fig. 6 Examples of rolling mill stands: (a)2-high reversing mill stand (b) quarto (4-high) mill stand (c) cluster mill stand

Longitudinal rolling can be preferably used for production of strips (sheets), shaped rolled products, sections and also wires. Strips, or sheets, take probably the highest proportion of rolled products. The mentioned strips, or sheets, belong to the category of flat products and they are produced using above all two-high and four-high mill stands (Fig. 6a, b). They are rolled from slabs or slab ingots, which are at first hot rolled on 2-high stands followed by 4-high stands. Strips of thin thicknesses are manufactured by cold rolling.

A usual procedure of strip rolling consists in a gradual rolling of slabs from 500 mm thicknesses down to 30 mm through 10-20 passes. Follow-up, even higher deformation per pass can be applied, providing that work rolls with smaller diameter are used. However, due to this smaller diameter there is a risk of flexure of rolls and a need to use rolling mill stands with a higher number of rolls, which have a function of backup rolls. Generally, with a decreasing diameter of work rolls a number of backup rolls increases (an example of a

cluster mill stand is a 20-high Sendzimir mill) – Fig. 6c. However, the number of rolls is not limited in general.

Stands can be used as separate devices or combined in rolling mills. A typical example of one stand rolling mill used for strip production is a quarto stand (Steckel mill). This is a solution for production hall space saving and production equipment cost saving. Aside from this one stand, the whole system is complemented by two strip coilers, or more precisely furnace coilers (Fig. 7). In a case of reverse run of the quarto stand, an exchange of functions of both the coils occurs. However, the use of typical rolling mills is a more common production process. Thus, rolling mills can be divided according to configurations of rolling stands and a number of rolls, according to the type of a rolled product and a diameter of work rolls, a way of roll rotation or according to arrangement of rolling stands. Implementation of universal mill stands, which have also vertical rolls aside from horizontal rolls, was an innovation as to the rolling effectivity enhancement. Upsetting of a rolled product from the sides is performed by this, creating vertical sides, precise angles and sharp edges.
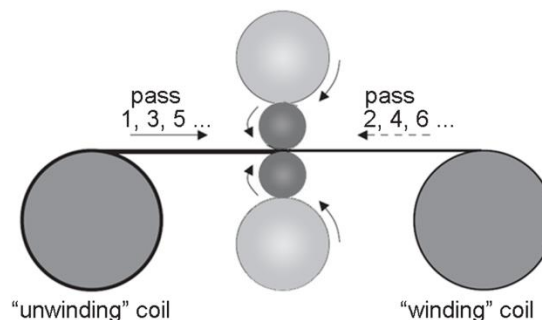
Fig. 7 Reversing quarto mill stand for cold strip rolling

Rolling mills can be also classified by the type of rolled products. There are mills for rolling blooms and mills for rolling final products (sheets, rods, strips, sections). Further, mills are categorized according to roll diameters. There are rough rolling mills, heavy, medium and fine section mills, wire rolling mills, strip rolling mills, universal rolling mills.

Classification according to the direction of roll rotation: reversible rolling mills and non-reversible rolling mills. The last aspect for classification is the arrangement of rolling mill stands. There are single-stand rolling mills, open rolling mills, semi-continuous rolling mills, continuous rolling mills and mini-mills. Nowadays a concept of continuous wire mills is mainly used for non-ferrous metal wire rolling (high production effectivity) (Fig. 8). A typical

continuous mill arrangement with quarto stands is used e.g. for rolling strips of a thickness down to tens of millimeters. The production speed is very high, however, relatively high costs are needed to purchase the production equipment. Another drawback of this arrangement is that a speed of particular stands needs to be controlled with high accuracy, because these are usually mills, where a rolled product is placed in more than one stand at the same time.
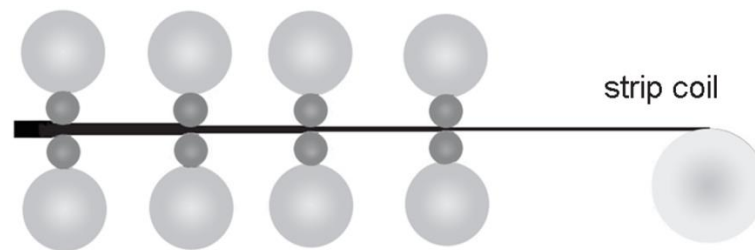
Fig. 8 Continuous mills comprising quarto stands for cold strip rolling

Besides these widely used products (strips or sheets), longitudinal rolling is very often applied also for the manufacture of sections, rods and wires. A usual procedure is based on gradual rolling of a bloom or a billet, which is an initial semi-product. These products are rolled using caliber rolls, whereas rules necessary for such processing depend on a design of caliber passes and also a geometry of the formed product. Wire making also depends on the type of the formed metal (alloy). Generally, wire rolling is performed under hot condition, as long as to the final diameter of 5 mm. If possible for the particular material, the rolling procedure is arranged within a single technological material flow at the beginning of which is casting. It is evident that thinner wires, for example Al or Cu, can be processed by subsequent cold drawing after rolling. On the contrary, for example Mo or W wires (filaments), widely used for production of bulbs, are manufactured in a different way.

2.3　Drawing

As already mentioned, drawing is used for manufacture of wires, but also rods, sections and tubes and pipes of various cross sections with high accuracy, which cannot be achieved by any other conventional forming method. Drawing improves outer surface and dimensional accuracy of products, but also the resulting structure (a specific texture is formed usually). These changes typically bring along also an increase in values of mechanical properties, for example strength can be increased 1.5 − 2 times, while ductility decreases

rapidly. Due to different deformation conditions, residual stresses remain in material after drawing. They are usually of the tensile character in the surface layers and the compression character in the central layers. This is a reason to involve heat treatment to follow the performed drawing, with the aim to relax these stresses.

The principle of drawing is to pull material through a conical hole created in a die (Fig. 9). Prior to drawing the beginning end of the wire is prepared so that it fits the die and is put into the die, then drawing pliers grip it and pull as far as the pulling drum, which continues the pulling process. Drawing is usually performed at room temperature, thus classified as a cold working process, but it may be performed at elevated temperatures depending on the worked material. Due to the high melting temperature of some non-ferrous metals (Mo, W, etc.), the high strain resistance of these materials makes certain difficulties during drawing by a conventional process. Hot drawing is performed within the temperature interval as high as (500-700°C). This working temperature decreases along with a reduced diameter of the drawn wire. It is possible to state that hot drawing is also used, when a work-piece diameter is larger by about 35-40% compared to a diameter of the required final wire. Cold drawing is usually a following processing step.
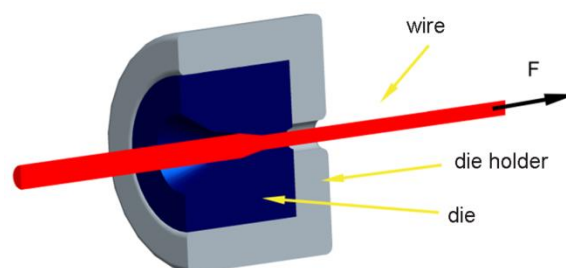
Fig. 9 Drawing technology principle

The final quality of wires is influenced by thickness and stability of a surface oxide layer, material of the die, a used lubricant and drawing velocity. The surface oxide layer thickness becomes a critical indicator at the moment, when the final product reaches a thickness approximately 0.5 mm. A relatively positive property of these layers is their ability to lubricate, by which they contribute to a decrease in stress in the drawn wire and also in the die. A properly chosen combination of the annealing temperature and holding period is a major parameter for minimizing an oxide layer formation. This layer can be removed from

the drawn wire by a mechanical or chemical method. The cleaning process can be included following the performed hot forming prior to cold forming.

Lubrication during drawing is a special problem. This is a necessary condition for successful drawing, not only for reduction of friction between the die and the work-piece. The used grease should also ensure partial cooling of both the tool and the work-piece, which become heated due to friction. Requirements for lubricants are quite high. It is necessary to use lubricants meeting the above mentioned, on condition of elimination of a danger of corrosion formation or human health threatening. During cold drawing, considerably high friction occurs between the drawn wire and the die. Therefore it is necessary to select a proper lubricant, as well as an optimal drawing speed, so that a damage of the die, failure of the wire or an undesirable influence on the wire microstructure does not occur. Soap-based lubricant containing Na-stearate, MoS_2, water and graphite or oil-based lubricants are used very often for this purpose. However, there are also other ways to reduce friction between the wire and the die. A concrete example may be application of a counteraction, when the drawn wire is gripped on both of its ends, whereas a higher pulling force is developed in the drawing direction, while in the opposite direction a lower pulling force is purposely applied. This effect results in the friction force reduction at the expense of the counteraction. However, a certain disadvantage of this procedure is more demanding equipment and also the necessary precision of control of both the forces. Another possibility to perform drawing is a drawing procedure without a die – dieless drawing. This procedure principle lies in clamping the drawn wire on both ends, whereas the wire is axially loaded with a constant force. Local heating is moved along all the wire length and always heats only a particular place to initiate plastic deformation, while surrounding wire sections are cooled. Negatives of this process are evidently above all in the processed wire length and high demands on the process control.

Other important parameters affecting the drawing process is the die angle (2α). This angle determines stress magnitude during drawing and also the resulting wire surface quality including tolerances of final dimensions. Dies made of tungsten carbide (WC) allow using higher drawing velocities, however, wire rupture occurs quite frequently. This is a serious problem for example for SMA wires of diameters lower than 0.5 mm. Another material, from which dies for very fine wires can be made, is diamond (PCD). In this case very favourable

dimension tolerances and very high surface quality of drawn wires can be reached. PCD dies can be used for the manufacture of wires of diameters lower than 0.3 mm.

As previously mentioned, aside from wires, especially thin-walled pipes can be made this way, and also sections and rods of defined cross sections. The final shape, or more precisely a surface relief, is determined by the die cavity shape. Tube drawing process: rod drawing is performed with rods to a diameter about 50 mm, tube drawing for tubes from several tens up to 500 mm and a wall thickness from several hundreds to 40 mm. Tube drawing can be performed by different methods: mandrel drawing (fixed plug/stationary mandrel drawing), rod drawing (moving mandrel drawing), floating mandrel (floating plug) drawing, tube sinking (free tube drawing), expanding of tubes.

2.4 Extrusion

Extrusion is one of the most frequently used processes for production of tubes, rods and sections of non-ferrous metals and their alloys. This is a process, where a material is placed into a container and subsequently extruded out. When being pushed through an opening in the container, the material adopts a desired shape; owing to this, very complex cross section rods can be produced. The process is usually performed at high temperatures (0.5-0.75 Tt), mainly in order to decrease a necessary compression and wear of a die. Nevertheless, for soft materials the process may be performed even at room temperature.

Next to the direct extrusion, there is also an indirect extrusion (or backwards) and transverse extrusion. In the direct extrusion of rods and full-volume sections, the material flow direction is congruent with the longitudinal axis of a semi-product and also with a direction of the acting force. On the contrary, the indirect extrusion is characterized by the material flow direction opposite from the direction of acting of a ram. One of advantages of this type is no relative movement between the container wall and material because the billet moves with the container, so the frictional forces are eliminated and the demanded stress level is lower. But the complicated construction of the whole system seems to be a disadvantage. Therefore this process is used above all for production of large diameter tubes. A hollow extrusion punch (broach) can be also used in this process. On the other side, a hollow punch limits the loading, which can be used. In transverse extrusion (extrusion pressing), the material movement direction is perpendicular to the direction of the piston movement. There is a single-channel and double-channel transverse extrusion. The metal

flow character in this method reduces a difference in mechanical values along the longitudinal and transversal direction. Another variant of this process is impact extrusion. It is used e.g. for production of short hollow products (toothpaste tubes etc.). The slug is pressed at a high velocity with extreme force into a die/mold by a punch. The punch is attached to a high-speed mechanical press. A cold slug is placed below the punch and over the die. The punch makes contact with the slug forcing it around the circumference of the punch and into the die. The metal slug deforms to fit the punch on the inside and the die on the outside. Extrusion tools are cheap, a time of the process relatively short and it is possible to produce complex shapes.

However, as the extrusion is a discontinuous process, there are problems with finishing the operation and beginning a new cycle. After the extrusion a rest of the extruded material remains in the die (the so-called light tread). This is return waste and reduces utilization of metal. Therefore extrusion procedures leading to elimination of this drawback were developed. Pressing without a light tread is solved in a way that e.g. for Al alloys the light tread is not separated from the pressed product, but after inserting a new work-piece into the die, this is pressure welded with a new work-piece. A disadvantage of this procedure is a difference in mechanical properties in the area of the weld and surrounding areas. For a case of higher requirements in this aspect, the whole of this process needs to be performed in vacuum.

Presses along with dies, punches, recipients, pressing rings are used as working tools. Main advantages of pressing include a positive state of stress (i.e. three-axis compression) increasing technological formability. Another positive is a faster transition to a different product line or a possibility to manufacture hollow and full-volume sections of highly complicated shapes (profiles with periodical cross sections). This method is preferable also for the cost-effective production even for small series and a transverse cross section tolerance lower than in rolling. The main disadvantages are higher waste rates mainly in a form of light treads and higher differences in mechanical properties along the length and across the extrudate. Lower outlet speed and lower production effectivity needs to be mentioned, too.

Due to relatively complex shapes obtained during extrusion, plastic deformation in a work-piece is distributed with a high variability. In the central layers the state is similar to the uniaxial tension, while on the edges (for flat areas) gets near to the plain strain compression.

On the other side, near the surface, where the material flows along the die wall, there are places defined by large shear components. Especially Cu and Mg alloys can be extruded easily, because their oxides are softer than the metal itself and act as a natural lubricant. The die geometry is also an important factor for facilitation of the material flow without excessive friction and heterogenous deformation. Well lubricated work-pieces are extruded through dies with conical inlets (a typical angle is 45-60°) for reduction of the extrusion pressure. Nevertheless, some metals (Al) form a dead zone during extrusion, around which an inner slip occurs, thus creating an "own" angle. In these cases the inlet into the die is usually straight. A typical temperature range for Al alloys extrusion is 450-500°C, however, it can be even below 400°C, or 350°C, for some softer alloys. The extrusion speed depends on the die geometry complexity. Particular examples are extrusion speeds from 0.5-2 m/min for 7xxx alloys, 10-80 m/min for 6xxx alloys and 20-100 m/min for commercially pure Al. By this, the strain rate range is determined as well (0.1-50/s, i.e. the same as for hot rolling). Deformation magnitude is typically 1-4, sometimes even higher (very soft metals). No lubricant is used for Al extrusion, so the direct adhesion of Al to the die walls increases shear strain. Similarly as in rolling, a temperature increase (20-50°C) in highly deformed regions occurs in extrusion as well.

Because metals such as high alloyed Al or Cu are susceptible to high-temperature brittleness, the extrusion speed needs to be limited to low values (to 1 m/s). Higher speeds would result in a temperature increase due to excessive friction. The high-temperature brittleness exhibits formation of periodically located small cracks (tree shape). On the contrary, for materials with low formability (W, Mo), extrusion should run as fast as possible due to a rapid heat transfer through the die (speeds as high as 30 m/min). During extrusion shear forces in the material develop, nevertheless, tensile stresses usually do not occur, so high deformations can be performed by a single operation. High-melting temperature non-ferrous metals are extruded under hot condition at typical temperatures (900-1200°C), i.e. under hot condition, therefore they are subject to the same strain transformation reactions as in hot rolling. There are general efforts to develop the cold extrusion technology, because the products have higher strength thanks to deformation hardening, higher surface quality and better tolerances. Cold extrusion is only possible with phosphate lubrication. Steel surface is covered with a porous phosphate layer absorbing a lubricant (often based on soap), thus reducing friction and wear during extrusion considerably.

Rolling is the most frequently used forming technology for non-ferrous metals and their alloys. At present, transverse, rotary (slantwise) and longitudinal rolling processes are used.

Forging is a frequently used forming technology, which is generally divided to hammer forging and die forging. In addition, there are other types of forging, such as rotational forging.

Drawing is a forming technology, in which a material is drawn through a conical opening in a tool (die). This way, mainly wires, rods and profile sections are produced.

Extrusion is a unique forming technology, which can be used for production of profiles of very complicated shapes and cross sections.

? **Questions**

1. Characterize the forging technology.
2. Describe the rolling process including equipment used for this technology.
3. Explain differences between the particular types of rolling.
4. Explain fundamentals of the drawing technology.
5. Characterize the extrusion technology.

3 Forming of non-ferrous metals and their final processing

Time needed for the study: 15 hours

Objective: After studying this chapter a student will know

- Basic classification of forming procedures for particular non-ferrous metals
- Methods of final processing of products of non-ferrous metals and their alloys

- Classification of particular methods of heat treatment

Lecture

In spite of the fact that forming is applied both for steel and non-ferrous metals, in contrast to steel, direct casting immediately followed by forming is more frequently applied here. One of the known processes is e.g. production of strips by continuous casting and rolling or other alternative procedures with a following forming phase. Due to different thermal and physical properties, these technologies are applied above all for light metals (aluminum, magnesium etc.) and their alloys.

3.1 Aluminum and its alloys

Aluminum is often used for the manufacture of transport means, such as aircrafts, cars and bicycles. The most widely used alloys cover AlZnMgCu-based ones, which are, thanks to their favourable mechanical properties, used above all for manufacture of forgings and pressed parts of bearing components. AlMgSi-based alloys are usually used for pressed parts and sheets for vehicle bodies.

Forming of aluminum parts is commonly performed by die forging on presses. Sheets, which are further used for pressing, are rolled, exactly like food aluminum foil, for the manufacture of which special 20-high rolling stands are used. Aluminum profiles are manufactured by extrusion, special components, such as space shuttle tanks, can be manufactured by roll bending.

3.2 Magnesium and its alloys

Magnesium alloys are also used in the transportation industry, their popularity increases, because magnesium is even lighter than titanium. It is used above all for race cars constructions, its alloy with aluminum – dural (AlCuMg) – is often used in aircraft industry. Magnesium alloys feature low specific weight, high ductility and strength, high resistance to corrosion and creep. However, pure magnesium has lower formability under cold condition and low mechanical properties because of its internal structure.

Magnesium alloys are applicable both for die forging and for extrusion or rolling. Magnesium strips can be manufactured by the method of direct casting between mill rolls. Foundry magnesium alloys are more common, however, these alloys usually contain also aluminum and zinc. They are processed by casting under pressure.

3.3 Copper and its alloys

They are well formable under hot and also cold condition, the presence of impurities have a deteriorating effect (Pb a Bi). Main alloys are Cu-Zn (brasses) and Cu-Sn (bronzes). Single-phase alloys exhibit good formability and ability to surface finishing (properties derived from Cu). Deep-drawability is usually reached at a content of Zn 4-20 % (Ms 96-85), the so-called tombac (e.g. brasses CuZn30). Admixtures of Pb, S, Bi, As, Sb (even at low contents) have an undesirable effect, above all on hot formability. They are used in imitation jewellery, cartridge cases, musical instruments, sieves etc. In two-phase alloys various situations can occur according to a rate of exceeding of solubility (ß – formable under hot condition, ß´ - hard and brittle) – CuZn 37-42 (Ms 65-58). On the other side, these two-phase alloys have lower sensitivity to a content of impurities during hot forming.

Bronzes are alloys of Cu and other elements (except Zn). Cu-Sn (tin bronzes) to 9 % Sn belong among the most widely used formable alloys. During forming, higher affecting of mechanical properties occurs. For example CuSn8 (Rm= 400 MPa in the soft state) can be hardened up to 1000 MPa by deformation under cold condition. A harmful effect of admixtures, such as P, exhibits here (above 0.05 % decreases hot formability). Bronzes find an application e.g. for bearings, springs, sieves etc. (low friction coefficient).

3.4 Titanium and its alloys

Titanium is a frequently used material above all in aircraft and space industry. It is much-favoured in particular for its high values of mechanical properties, corrosion resistance and high specific weight. Titanium is typically used particularly at higher temperatures, for example in high-speed airplanes, the casing of which is heated by effect of the speed; aluminum alloys decrease strength in these situations.

Titanium alloys offer broad possibilities for forming. Longitudinal rolling can be applied for production of both flat and long rolled products (strips, thick and thin sheets, rods, wires...), extrusion can be used for production of profile sections, rods and tubes and pipes. However,

titanium forming needs to be performed under hot condition, because it has low formability under cold condition.

Final processing of formed products involve surface finishing, possibly an inner structure processing, for which heat treatment is used above all. However, there are also other procedures, the so-called thermo-mechanical processing, which is a proper control of forming and thermal conditions, so that as good as possible resulting properties of treated products are achieved.

3.5 Nickel and its alloys

It is well processable under cold as well as hot condition, can be easily surface treated and welded. Other important property is its high corrosion resistance. Nickel finds its use in mechanical engineering, food and chemical industry, namely as an alloying element, for surface finishing and in alloys with special physical properties. Ni structural alloys are generally harder than most of non-ferrous metals and many steels. Ni alloy with additive of 1.7-2 % Be, or 4.5 % Al, exhibits faster hardening during plastic deformation (precipitation hardening Rm up to 1800 MPa, A = 5 % - without corrosion resistance decrease). A similar situation is for an alloy of 66 %Ni + 30 %Cu (monel) with an additive of 2-4 % Al (monel K), which can be hardened.

3.4 Structural processing - heat treatment

Heat treatment can be carried out as an intermediate operation or as a final operation in all basic types of forming. In these procedures a material is heated to a demanded temperature, which depends on a type of required structural changes, holding time on this temperature follows and then cooling (free or controlled).

The most frequent heat treatment is annealing. This is performed either with or without structural transformation (phase transformation) and can be divided to several basic types, some of which are presented in details below. Annealing can be complemented by quenching or tempering. To understand the whole complex system of heat treatment, one should know binary, possibly quasi-ternary, diagrams, or also IRA and ARA diagrams of the particular materials.

3.4.1 Annealing without structural transformation

Recrystallization annealing

The purpose is to restore plastic properties after cold forming, so removal of hardening caused by cold forming. New grains form at the same time. The procedure involves heating to the recrystallization temperature, a short dwell and then cooling. The heating temperature depends on the deformation degree. The beginning of recrystallization and thus also the recrystallization temperature are influenced by various factors, but especially by the previous degree of forming.

Spheroidizing

The aim is usually to transform lamellar pearlite to globular, spheroidization of carbides, possibly achievement of higher homogenization of a structure applicable for subsequent quenching. A principle is in heating to temperature just below the range of transformation or within this range (depending on composition), holding at the temperature, or fluctuating around the temperature, and following controlled cooling usually in a furnace or in a protective case.

Annealing for stress relieving

Due to inhomogeneous cooling, local heating e.g. during welding, or similar procedures, internal stress in a material may occur. This can be relieved through this type of annealing. A principle is in slow heating (100 – 200°C / hour), holding time on the temperature until the entire object is heated evenly (usually 1 – 2 hours) and slow cooling (30 – 50°C / hour).

3.4.2 Annealing with structural transformation

Homogenization annealing

A purpose of homogenization annealing is homogenization of chemical composition of an alloy by diffusional processes. This type of annealing is used particularly for ingots, where there are many casting defects and inhomogeneities. Strip heterogeneity (liquation) depends on a shape of the cast or formed semi-product and concerns above all impurities and gases. Interdendritic heterogeneity (segregation) depends on the dendrite morphology, which affects distribution of alloying and accompanying elements. Homogenization annealing involves heating to a temperature considerably higher than in the annealing

processes mentioned above, an adequately long dwell on this temperature (6 – 15 hours) and slow cooling from this temperature according to shapes of castings.

Normalizing

Normalizing is carried out to achieve a fine-grained and homogenous structure comprising typically a mixture of ferrite and pearlite. The normalizing procedure involves heating to a specified temperature as fast as possible, short temperature equalization across the entire cross section and further cooling usually in free air (100 – 200°C / hour). Normalizing is most frequently used for castings, forgings and cold pressed parts. The resulting steel structure upon normalizing depends on chemical composition as well as on the normalized product size.

3.4.3 Quenching

A principle of quenching is accelerated cooling of a product from the high temperature after forming or after annealing. Hard martensitic or bainitic structures are formed by this process. Quenching is performed in media with higher cooling ability than air, often water of various temperatures, oil or salt melts.

3.4.4 Tempering

Tempering is heat treatment following quenching. It is used above all for steels. The aim is to achieve a state closer to the equilibrium state of steel. It comprises heating to a temperature, dwelling on the temperature and subsequent cooling at an appropriate speed. As internal stress can be a cause of crack occurrence even after taking off the quenching bath, tempering should follow quenching immediately. Tempering can be divided to high-temperature and low-temperature. When increasing tempering temperatures, generally strength properties and hardness decrease, while plasticity and toughness increase.

Temper brittleness

Sometimes low-temperature embrittlement occurs upon tempering. This is a result of processes occurring during tempering on boundaries of initial grains and leading to their embrittlement. This embrittlement is irreversible. However, aside from this, there are types of embrittlement that can be removed.

3.5 Surface finishing

Surface finishing is performed in order to improve a surface quality or for a protection against the base material corrosion. A protective coating – organic or inorganic – can be deposited on the product surface or the surface can be metal-coated. Metal coating is carried out using zinc, aluminum, tin or copper, through the hot dipping process or electrodeposition.

Copper coating is carried out above all for wires, as an intermediate operation in drawing, as the copper coating reduces friction between a wire and a die. When copper coating is performed as a final operation, a thicker copper layer is used. This is applied e.g. for mattress springs or welding wires. Copper coating is carried out through electrodeposition.

Aluminum coating is carried out through galvanizing. The aluminum coating has higher corrosion resistance in more aggressive atmospheres than zinc coating (2-3x). In operational conditions, aluminum alloys with zinc are often used for coating.

Tin has very good protective properties, because it is passivated by a layer of its oxides. It is not toxic, therefore tin coating is often used above all in food-processing industry and, thanks to tin high solderability, also in electrotechnics. Tin coating can be carried out either by hot dipping process at temperatures to 310°C, or by electrodeposition.

Chromium coating is a very favourite and decorative final processing, coatings are highly resistant to corrosion even at elevated temperatures and to mechanical wear.

There are also other possibilities of surface finishing of non-ferrous metals and their alloys. There are anodic oxidation of aluminum (eloxation), chemical electroless nickel plating and bright nickel plating, bright nickel and zinc galvanizing, titanium oxidation, blasting by sand, cast iron, corundum, ballottini, shot peening, painting and also removing the nickel plating coat.

☑ **Summary of terms**

Heat treatment is a process based on heating of material to a particular temperature and an appropriate holding on this temperature for a specified time. Usually after this a specified cooling process follows.

Quenching is a specific type of heat treatment defined by very fast cooling. In order to decrease brittleness, the tempering process is applied following quenching.

Surface finishing is performed in order to modify the formed semi-product surface quality. Protective coatings are usually used for this purpose.

(?) **Questions**

1. Define the main forming technologies used for particular types of non-ferrous metals.
2. Describe essentials of heat treatment of non-ferrous metals and their alloys.
3. Characterize differences between the particular types of heat treatment.
4. Define basic information concerning surface finishing.

📖 **Recommended literature for further study**

[1] HUMPHREYS, F.J., HARTLEY, M. Recrystallization and related annealing phenomena. 2nd ed. Oxford: Pergamon; 1996, 617 p. ISBN 978-0080441641.
[2] VERLINDEN, B., DRIVER, J., SAMAJDAR, I., DOHERTY, D.R. *Thermo-Mechanical Processing of Metallic Materials*, Pergamon Materials Series- series ed. R.W. Cahn, Elsevier, Amsterdam, 2007, 332 p. ISBN 978-0-08-044497-0.
[3] JONAS, J.J., SELLARS, C.M. *Thermomechanical Processing. In* Future developments of Metals and ceramics. (Edited by J.A.Charles, G.W. Greenwood and G.C. Smith), London Institute of Materials, 1992, 150 p., ISBN 09017-16030.
[4] PŘEPIORA, Z. *Tváření neželezných kovů,* VŠB Ostrava, 1991, 200 s.

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3 Casting – technological procedure of production of castings

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⏰ **Time needed for the study:** 2 hours

⊕ **Objective:** After studying this chapter a student will know

- Fundamentals of casting production
- Advantages and disadvantages of castings
- Comparison of foundry technology with other types of manufacture of

final products or semi-products

📖	**Lecture**

Foundry is an industry field that allows a transformation from raw materials to products using the shortest way – casting. Casting is a way to produce products of such shapes, which could not be produced by any other process. Casting is a method of manufacture of a component or object through casting of molten metal or other material into a mould a cavity of which has a shape and size of the demanded product. The product created by solidification of the molten metal in a mould is called a casting.

3.1 Technological manufacturing flow in a foundry
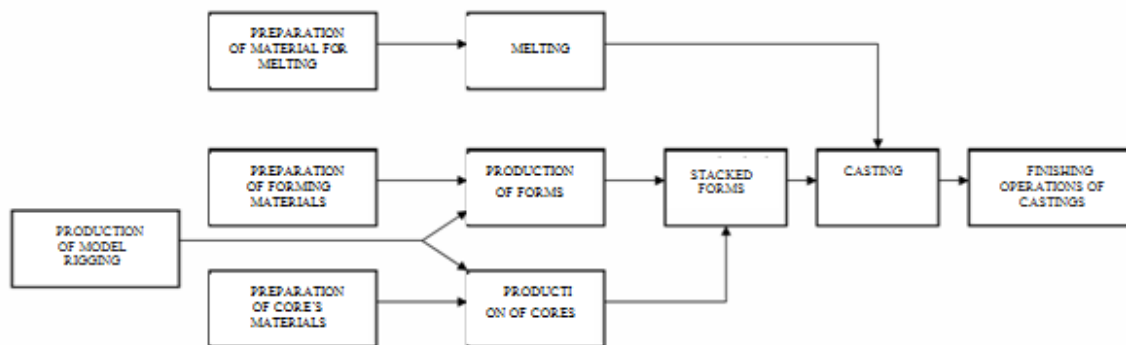
3.2 Advantages of castings

- A direct route from raw materials to products
- A possibility to make parts within a wide range of weights from several grams to tens of tons
- A possibility to achieve highly complicated spatial shapes
- A possibility to form castings according to loading or a need to limit a space/area
- A possibility to reach high rigidity
- A possibility to cast most of metals and alloys

- A possibility to control a structure and properties of castings through a selection of composition, modification and inoculation of molten metal, controlled solidification and heat treatment

- A high rate of material utilization and recycling

- A relatively low consumption of electricity

- A possibility to achieve quite high precision and low roughness through special procedures

- A possibility of casting parts of different metals

3.3 Disadvantages of castings

- Large shrinkage of some alloys during solidification requires the use of large risers, which reduce utilization of molten metal and increase labour input during processing of castings

- A risk of occurrence of inner defects (porosity, blow holes, shrink holes…) - can be eliminated by a properly selected foundry technology (modification of a design allowing a suitable solidification procedure, positioning of risers, a possibility of removal of gases from a mould and cores)

- Differences in wall thicknesses of a casting lead to uneven solidification and cooling, resulting in differences in a structure and properties in particular parts of a casting, occurrence of stresses and strains, in some case even failure of cohesion (can be eliminated by a properly selected foundry technology)

☑ **Summary of terms**

Foundry is an industry field that allows a transformation from raw materials to products using the shortest way – casting.

Casting is a method of manufacture of a component or object through casting of molten metal or other material into a mould a cavity of which has a shape and size of the demanded product. The product created by solidification of the molten metal in a mould is called a casting.

1. Define the main terms – foundry, a casting.

2. Describe the process through which a casting is made.

3. Characterize advantages and disadvantages of castings.

Recommended literature for further study

[1] MICHNA, Š.; NOVÁ, I. Technologie a zpracování kovových materiálů. Adin, Prešov 2008, 326 s. ISBN 978-80-89244-38-6.

[2] JELÍNEK.P. Slévárenství, ES VŠB Ostrava, 2007,255s.

[3] SCHIEG,F.P. Technology of Metalcasting. American Foundry Society,Des Plaines,IL 2003.

4 Classification and application of foundry alloys of non-ferrous metals

Time needed for the study: 25 hours

Objective: After studying this chapter a student will know

- Basic classification of foundry alloys of non-ferrous metals

- Methods of final processing of products of non-ferrous metals and their alloys

- Basic use of alloys of non-ferrous metals for castings

Lecture

Foundry is an industry field that allows a transformation from raw materials to products using the shortest way – casting. Casting is a way to produce products of such shapes, which could not be produced by any other process. Casting is a method of manufacture of a component or object through casting of molten metal or other material into a mould a cavity of which has a shape and size of the demanded product. The product created by solidification of the molten metal in a mould is called a casting.

4.1 Classification of non-ferrous metal alloys

− according to the basic element – usually more than 50 %
− according to the processing method – according to the technology (foundry and forming)
− according to the density
  - light (Al, Mg, Ti)
  - heavy (Cu, Zn, Ni, Pb, Sn) – 4500 kg.m^{-3}
− according to the melting temperature
  - up to 600°C – with low melting temperature (Sn, Pb, Zn)
  - up to 1500°C – with medium melting temperature (Mg, Al, Cu)
  - with high melting temperature (Ti, Cr, V, Mo, Nb)
− according to the chemical reactivity
− or according to other criteria

4.2 Aluminum and its alloys
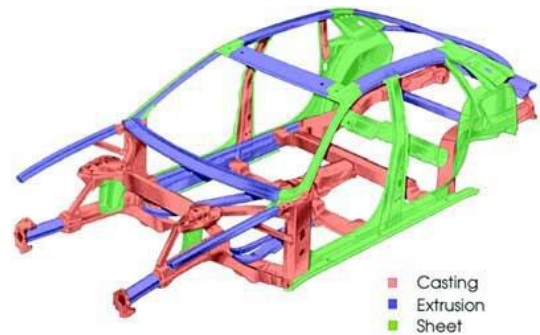
- **4.2.1 Labeling of aluminum alloys for castings according to the ČSN EN 1706**

− This norm applies for casting and it specifies the labeling by letters EN AC and five numbers.
− Numerical label may be amended by the chemical one, for example EN AC-21000 [AlCu4MgTi].
− The prefix EN is followed by a space,
− The letter A stands for aluminum,
− The letter C stands for castings,
− hyphen,
− four numbers specifying the chemical composition.

Numerical labeling of alloys
EN AC-XXXXX
X 1 – specifies the main ingredient
(2 - Al-Cu, 3 – Al-Si, 4 –Al-Mg, 5 – Al-Zn)
X 2 – specifies the alloy group and is practically used only in Al-Si alloys

X 3 – is the order number in the group
X 4 and X 5 – are zeros

- **4.2.2 Classification of aluminum casting alloys according to the ASM**

• Al-Cu
• Al-Cu-Si
• Al-Si
• Al-Mg
• Al-Zn-Mg
• Al-Sn
• Al-Li

Table 1.4.1.1. Properties of the chosen die casting alloys.

ASM	ČSN	Rm [MPa]	Rm [MPa]	A [%]
AA 380.0	42 4339	320	160	2.5
AA 360.0	42 4331	300	170	2.5
AA 390.0	42 4386	280	240	1.0
AA 443.0	EN AC – AlSi5Cu1Mg	230	100	9.0
AA 518.0	EN AC / AlMg5	310	190	5.0

Physical properties of the same alloys as in Table 1.4.1.1. are given in Table 1.4.1.2.

Table 1.4.1.2. Physical properties of the chosen die casting alloys.

ASM	Density [kg.m^{-3}]	Melting range [°C]	El. conductivity [% IACS]	Thermal conductivity at 25 °C [W.m^{-1}.K^{-1}]	Coefficient of thermal expansion [K x 10^{-6}] at °C	
					20-100	20-300
AA 380.0	2740	520-590	27	0.26	21.2	22.5
AA 360	2685	570-590	37	0.35	20.9	22.9
AA 390.0	2740	510-650	25	0.32	18.5	-
AA 443.0	2685	575-630	37	0.34	-	-
AA 518.0	2519	540-620	24	0.24	24.1	26.1

Nowadays many research works are being made in the field of optimisation existing alloys or

- **4.2.3 Advantages of Aluminum casting alloys**

− good castability, which becomes considerably better with increasing share of the given eutectic according to the chemical composition,
− low melting temperature,
− low crystallization range,
− the content of hydrogen in the cast, which is the only soluble gas in aluminum, can be minimized by suitable technological conditions,
− good chemical stability (corrosion resistance),
− good surface properties of the casts,
− for most of alloys, there is a low susceptibility to the formation of cracks at high temperature.

- **4.2.4 Factors for selecting suitable alloys for making the required casting**

1. Casting properties:

- castability,
- resistance to cracking at high temperatures,
- small range of crystallization,
- good properties for die casting.
- Castability is mostly influence by the temperature range of crystallization, the viscosity and the surface tension of the melt.
- Resistance to the formation of cracks at high temperatures is in general decreasing with the widening range of crystallization and decreasing strength properties at higher temperatures.

2. Required mechanical properties:
- toughness and plastic properties,
- hardness,
- the possibility of increasing the strength properties by heat treatment.

3. Chemical properties:
- corrosion resistance (considerably decreased by the presence of Cu),
- finishing option – anodizing.

4. Properties of final products:
- impermeability of liquids in the casting due to the pressure
- dimensional and thermal stability.

5. Economic factors:
- costs of mechanical processing,
- casting and melting,
- thermal processing,
- castability.

- **4.2.5 Chemical composition of aluminum alloys**

The alloys contain:
- basic element – determines the kind of alloys (aluminum)
- main additive element – crucial for determining the properties of the alloy (in Al alloys Al – Si, Cu,Mg … Zn, Mn)
- minor additive elements – elements that positively influence some of the properties of the given type of alloy
- accompanying elements – elements that were not added to the alloy on purpose

based on the number of additive elements, they are divided into: Binary (basic element and main additive element) ternary and multicomponent.

- **4.2.6 The influence of alloying elements or impurities**

– B – the structure refines, – electrical conductivity is increased in technically pure Al due to the precipitation of V, Ti, Cr, Mo from the solid solution – it increases the ability of Al to capture neutrons.
– Bi – is alloyed for the purpose of improving the mechanical machinability.
– Sb – increases the corrosion resistance in sea water, – decreases the susceptibility of Al – Mg alloys to form cracks at high temperatures, – in bearing alloys it is alloyed by the amount of 4 – 6 %.
– Cr – lowering the susceptibility to grain growth in Al – Mg alloys, – hindering the process of recrystallization in Al – Mg – Si and Al – Mg – Zn alloys, in hardenable alloys it increases the hardenability.
– Cu – increasing the strength properties – by hardening, - decreases the corrosion resistance – most commonly alloyed together with Mg.
– Co – in some Al – Si alloys with the presence of Fe the transformation of needle like phase rich in Fe to a spherical morphology increasing the strength and plastic properties.
– Fe – a common impurity in Al, – the solubility in solid state is low (~ 0.04 %), it is present as an intermetallic compound with Al in the structure – in Al – Cu type alloys, by creating and intermetallic I7FeCu2 phase, there is depletion of solid solution α of copper – decreasing the strength properties – it blocks the grain growth in case of dispersive exclusion of Fe–rich particles in the structure – in Al – Cu – Ni type alloys it increases the strength properties at higher temperatures; and creep.

- **4.2.7 The properties of Al alloys**

Technological properties
– The set of mechanical and physical properties of material, which allows the production of a casting in a defined method
– Among the most important technological properties there are castability, formability, weldability and machinability.
– Machinability – given by a combination of machining forces, the character of particles, the quality of finished surface and the durability of the cutting edge of the machining tools (in Al alloys, the machinability is increased by Cu) – machinability is decrease by hard phases (intermetallic compounds of additive elements and impurities) – influence of Fe
– Corrosion resistance – the ability to resist chemical action of gaseous or liquid environments - in Al-Si alloys the relatively good corrosion resistance is decreased by Cu
– Weldability - the ability of connecting using various welding technologies and the reachability of the strength and quality of connections
– Polishability and the possibility of finishing – the ability of surface processing of the castings - in Al alloys, the anodic oxidation is common

− Impermeability – the ability to prevent the pressurized media (gas, liquid) from coming through the walls of the casting → stress tests – the tightness is mainly related to the occurrence of cracks and or microshrinkages

Casting properties

− fluidity – the ability of the liquid metal to fill the mold cavities – it depends on the size of the solidification range of the given alloys – e.g. eutectic alloys (narrow solidification interval) → good fluidity – the influence of surface tension, wettability of the form, modification
− tendency to shrinkages – the volume decrease of the metal during the solidifying and the tendency of creation of concentrated (inner and outer) shrinkages and shrinkage porosities
− tendency to gassing – characterized by the solubility of gases in liquid state, the level of gassing determines the formation of gas bubbles
− resistance to the formation of cracks – the ability to withstand the stresses at the solidifying temperatures range and during the cooling

Mechanical properties

− Depends mainly on the type and properties of the main metallic matter, on the dispersity of the structural components, on the presence and shape of intermetallic phases and on the heat processing,
− Fine-grained structure clearly improves all the mechanical and a number of technological properties of alloys,
− The following are monitored especially: tensile strength at normal temperature, yield strength (limit $Rp_{0.2}$), elongation and hardness, properties at high temperatures.
− Limit strength – Rm – in Al alloys – 150 to 250 MPa – after hardening (alloys with the addition of Cu, Mg) – increase by 30 to 50% → 330 MPa
− Elongation - 1 – 4 %, an increase can be reached by the modification of the eutectic
− hardness – at the cast state in Al-Si : 60 – 80 HB, after hardening – 100 HB
− quality index – determined by tensile strength and elongation: Q = Rm + k.log A5 (MPa)

▪ **4.2.1 Selected aluminum alloys**

❑ **4.2.1.1 Al – Cu type alloys**
The content of Cu is usually in the range of 4 – 5 %. Their strength properties can be increased compared with cast state by heat treatment.
Alloys with Cu content of 9 – 11% are also produced, and they have good strength properties at higher temperature and also good abrasion resistance.
Adding Ni and Mg helps in achieving very good strength properties at higher temperatures.
The disadvantage of these alloys is the worse castability and low corrosion resistance.

The examples in Czech norms are these alloys:
- AC – AlCu4MgTi (4.2 – 5.0 % Cu, 0.15 – 0.35 % Mg, 0.15 – 0.35 % Ti)
- AlCu4Ni2Mg2 (3.75 – 4.5 %Cu, 1.75 – 2.25 % Ni, 1.25 – 1.75 % Mg)

❑   **4.2.1.2 Al – Mg type alloys**

They have a very good corrosion resistance especially in sea water. Alloys made of highly pure materials exhibit the best corrosion resistance. They are weldable and also have a good mechanical machinability. When applied in architecture, there is possibility of anodizing the casting.

The disadvantage of these alloys is their bad castability and susceptibility of magnesium to oxidation during the process of melting.

The following are the examples of these alloys:
- ČSN 42 4515 - AlMg5Si1Mn alloy (4.40 – 5.50 % Mg, 0.60 – 1.50 % Si, 0.25 – 0.6 % Mn)
- ČSN 42 4519 - AlMg10SiCa alloy (7.00 – 10.00 % Mg, 0.01 – 2.00 % Si, 0.01 – 0.15 % Ca)

❑   **4.2.1.3 Al – Si alloys**

They are applied when good castability and corrosion resistance are required.

The amount of Si in these alloys usually varies between 5 and 13 %. According to the amount of silicon they are divided into under-eutectic (less than 12 % Si), eutectic (around 12 % Si) and over-eutectic (more than 12 % Si).

In cases where Mg is not alloyed, there is a possibility of heat treatment of these alloys and they are not alloy by copper.

According to ČSN, SN 42 4330 is available - AlSi12Mn alloy (11.00 – 13.00 % Si, 0.1 – 0.4 % Mn).

The industrial importance of Al – Si is given by their high fluidity, low susceptibility to the formation of shrinkages during casting and the possibility of welding and soldering.

Solid particles of silicon increase the resistance to abrasion.

„Modified" alloys (with small additions of 0.01 wght.% Na, Sr or P) considerable improve the microstructure (refinement of Si particles in under-eutectic alloys) and the mechanical properties of binary alloys.

Cu or Mg may also be added to Al – Si alloys with the intention of hardening by aging.

▪   **4.2.2 Aluminum – silicon diagram**

Silicon has a very limited solubility in aluminum at the eutectic temperature the solubility is only 1.65 % Si and it continues to decrease with decreasing temperature.

In foundry alloys, the amount of silicon is always higher than the maximum solubility in solid solution α(Al), that is why they always contain α(Al)-Si eutectic.

Eutectic concentration of silicon is 12.5 % Si (according to some sources only 11.7 % Si), eutectic temperature is 577°C. Eutectic is a mixture of α-phase and eutectic silicon created by an eutectic transformation. It is formed by eutectic cells.

Eutectic cell is a crystalline unit formed during the eutectic transformation. Eutectic phases are continuously excluded in the eutectic cells.

A characteristic feature of these eutectics is the invisible interface between cells.

hm. % Si

8 at. % Si   12 at. % Si   20 at. % Si   50 at. % Si
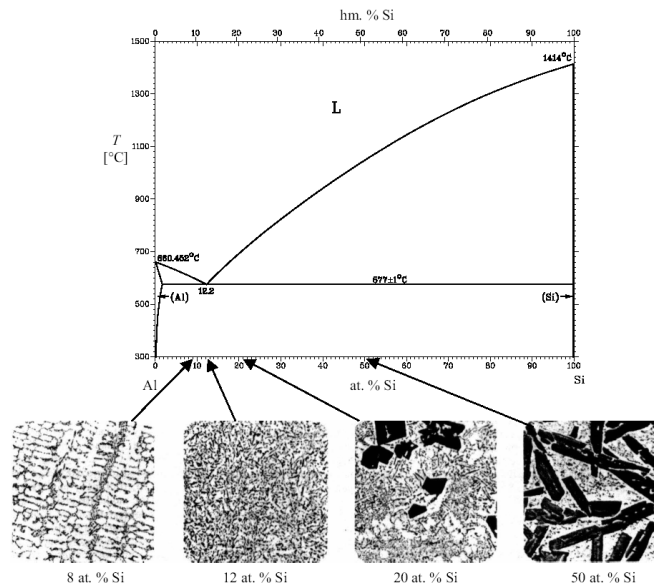
❑   **4.2.2.1 The Classification of silumins according to the content of silicon**

– Under-eutectic – the structure is created by a network of primary dendrites of the α(Al) phase and the eutectic that is excreted in the interdendritic spaces. With the increasing amount of Si, the amount of eutectic also increases. Under-eutectic alloys contain more than 5% Si, most commonly between 7 and 11 % Si.

– Eutectic alloys – contain approximately 11.5 – 13 % Si. Their structure is formed only by the eutectic, sometimes (especially in modified alloys), the single α(Al) phases also occur.

– Over-eutectic silumins – contain particles of primary silicon and the eutectic. The usual content of Si in over-eutectic silumins is around 14 – 17 % Si, in some cases even up to 25 % Si.

❑   **4.2.2.2 Morphology of the eutectic in Al-Si alloys**

The type of eutectic is linked to the mechanism of crystallization of eutectic silicon.

The particles of aluminum phosphide AlP serve as the crystallization nuclei. Phosphorus gets into the melt as an impurity especially from the raw materials, but also from the used metallurgical products and salts, or from lining materials.

To create a sufficient quantity of the nuclei, its amount in the melt has to be only several ppm units of phosphorus (1 ppm = 0.0001%).

Silicon is excreted in the Al-Si alloys as a pure element with minimal content of other additives. The size of particles of eutectic silicon can be in the range from less than 1 μm up to more than 2 nm. It may occur in three distinct forms in the eutectic.

The type of eutectic is named after the shape of silicon particles:

- granular
- lamellar
- modified

Eutectic present in the unmodified Al-Si alloys is a two-phase structure consisting of α-phase dendrites and plates of eutectic silicon with different orientation, which in metallographic section appears as gray needles stored in bright α-phase matrix.
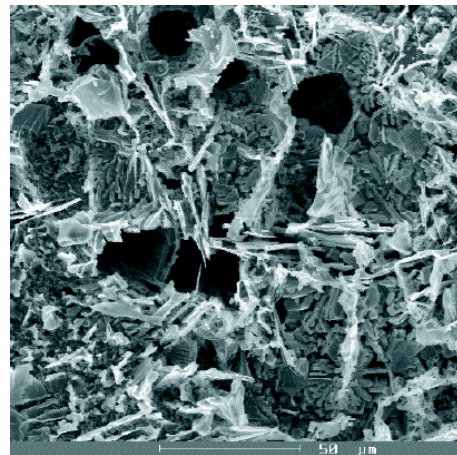
The distribution of plates of eutectic silicon in the unmodified eutectic can be of two types.
− The first type of distribution represents a non-oriented distribution of plates of eutectic silicon, which is labeled by foreign authors as granular eutectic.
− The second type of distribution represents a fan-shaped (straight or angled) distribution of plates of eutectic silicon, labeled by foreign authors as lamellar eutectic.

Granular eutectic – is formed when the content of phosphorus is above approx. 5 – 10 ppm – eutectic silicon is excreted in the shape polyhedral grains or thick lamellae.
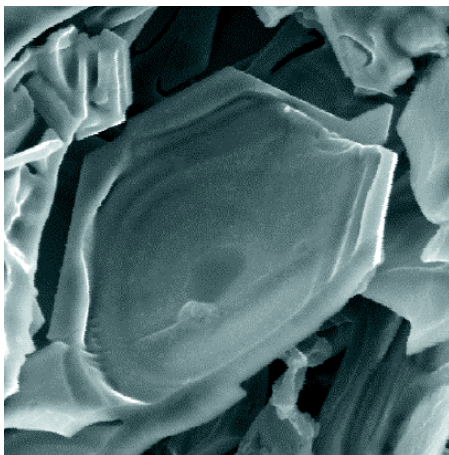
The spatial shape of hexagonal plate of non-modified eutectic silicon in the AlSi10MgMn alloy, deeply etched by the etchant, Aachen REM.

Non-oriented distribution of silicon plates in the AlSi10MgMn alloy– non-modified eutectic Si

Lamellar eutectic – formed in pure alloys with very low content of sodium and a content of phosphorus approximately 1-2 ppm. The conditions for nucleation of lamellar silicon are less suitable (smaller content of phosphorus gives smaller number of nuclei), it crystallizes the lamellar eutectic at higher supercooling under the equilibrium eutectic temperature – approximately 2 – 5 K.

Silicon creates fine lamellae, arranged next to each other in more or less parallel manner. The eutectic grains are considerably smaller than in granular eutectic. This type of eutectic also occurs in alloys modified by the following elements – arsenic, antimony, selenium or cadmium.

The structure and properties of casting alloys can generally be influenced by changes in the liquid metal. These changes consist of adding a small amount of appropriately selected substance, which influences the process of crystallization. One of these changes of liquid metal is modification, which is used to influence the method of growth of crystalline nuclei resulting in morphological changes in excreted phases.

Modified eutectic – is formed in the presence of modification elements (especially Na and Sr), sodium has the strongest modifying effect, rare earth metals, for example, and have a weaker modifying effect.

The effectivity of the modifier depends on the density of twins in the particles of silicon. Sodium has the smallest distance of twinning layers, and that is why its effect is the strongest.
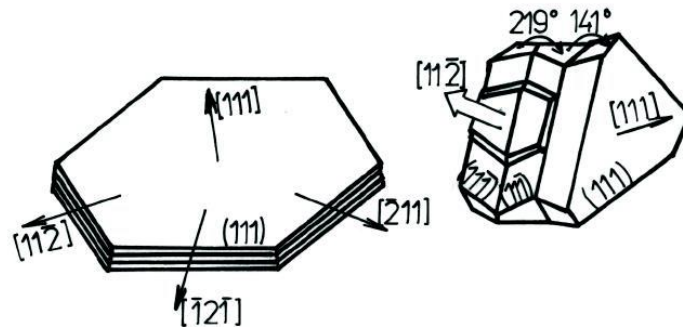
a) multiple twinning in hexagonal crystal of silicon
b) preferential crystal growth of silicon in the direction of <211>

The silicon crystals surface in the modified alloy is rough due to the multiple layers of twinning. The particles of Si are crystallicaly imperfect and each crystalline error is a potential location of another branching.
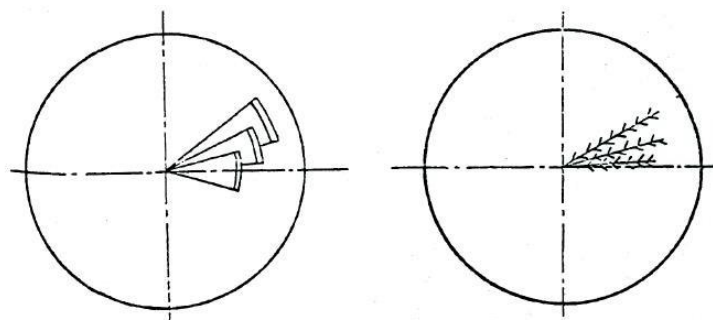
Schematic representation of eutectic silicon growth model
a) unmodified eutectic silicon
b) modified eutectic silicon

The degree of modification depends also on the cooling rate.

At high cooling rates of casts, it is easier to obtain a fine, well modified structure even when using weaker modifying elements (Sr).

At low cooling rates, for example, in the case of thick-walled casts that are cast into sand molds, only strong modifiers are effective, especially sodium.

Casting silumins contain a high content of eutectic, or their structure may be purely eutectic. Therefore, the properties having influence over the mechanical properties of the casts are the properties of the α-phase and the amount, morphology, size and distribution of the eutectic silicon. In Al-Si alloys, modification is used for obtaining the optimal shape of eutectic silicon.

The shape of eutectic silicon (hexagonal plate, in the plane of the needle cut with a sharp ending) in a non-modified eutectic of the Al-Si alloys considerably decreases the mechanical properties of the silumin. This is the reason for performing the modifying of these alloys that results in considerable change of structure and excretion of eutectic silicon in the form of

small bar, or even almost fibers, which appear to be rounded grains in the metallographic cut plane.

The excretion of eutectic silicon in the shape of bars or even fibers causes an increase in mechanical properties of modified Al-Si alloys compared to unmodified Al-Si alloys.

The change of shape of the eutectic silicon by modifying from a plate to a bar or even a fiber increases the tensile strength Rm, plastic mechanical properties (A5, Z) and toughness. The change of yield strength Re depending on the process of modification has not been found.

❑ **4.2.2.3 Al-Si alloys modifiers**

Sodium
− Is among the most commonly used modifiers.
− Sodium is included in pure state in the form of NAVAC – patron (FOSECO company, duration of the effect 30 min.), or in the form of salts, e.g. T3 (duration of the effect 10 to 15 min.), COVERAL Ep 3275 (duration of the effect 120 to 160 min.) and others. The duration of the sodium effect ranges from 10 to 30 minutes, in some exceptions (only in excellent kinds of modified products based on sodium) 1 - 2 hours.
− Sodium same as other surface active elements (e.g. Sr), causes the delay of crystallization of eutectic silicon resulting in a decrease of eutectic transformation temperature to 569°C and the eutectic transformation move from 1.3 % Si to 14 % Si.
− The following disadvantages have been found in the practical use of sodium and its salts: - sodium increases the degree of gasseation of silumins – the alloy modified by sodium cannot be degasses, filtered, etc. because the effect of modification vanishes – sodium increases the coefficient of volume shrinkage in the interval of alloy hardening, resulting in an increased occurrence of diffused porosity - the quick blast of sodium complicates its dosage in the conditions of serial production.
− The mentioned disadvantages made it necessary to find other modifiers and testing their influence on the structure and properties of the silumins.

Strontium
− Is a more and more used modifier in under-eutectic and eutectic silumins
− Its modifying effect is longer (1 to 2 hours.), and the time of effect can be prolonged to up to 10 hours by the addition of 0.05 % to 0.2 % beryllium, which decreases the oxidation rate of the melt and thus stabilizes the effect of strontium
− Another advantage is a smaller decrease of the eutectic transformation temperature
− strontium is inserted in the form of pre-alloy, e.g. AlSi13Sr10, AlSi16Sr10, AlSr5, AlSr10, or in the form of SrCO3. Pre-alloys of the AlSr type contain Sr in the form of particles of the $SrAl_4$ type.
− The amount of pre-alloy has to be calculated for the optimal amount of pure strontium that reaches 0.03 to 0.06 % and depends on the cooling rate of the casting and on the content of silicon in the alloys.
− When exceeding the optimal amount, brittle phases of Al_2Si_2Sr type are formed and excreted in the segregation areas
− The mechanism of modification by strontium consists of the following reactions – decay of $SrAl_4$ particles in the melt – formation of new particles of the Al_2Si_2Sr phase – repeated decay of particles of the Al_2Si_2Sr phase while forming free Sr – the influence of free Sr on

the method of silicon crystal growth in consistence with the theory of influence of the surface active elements – partial reaction of Sr with phosphorus (contained in the alloy in form of impurity from raw materials) while forming strontium phosphides leading to suppressing the modifying effects of strontium.

− The kinetics of these reactions is considerably influenced by the rate of decay of the SrAl4 particles and the reaction between strontium and phosphorus. The rate of decay of the $SrAl_4$ particles depends on the size

− For the pre-alloys contain small particles of $SrAl_4$ with dimensions of 1 - 10 µm the speed of their decay is quite high and the optimal modification effect is reach after 2-5 minutes from the insertion of pre-alloy in the melt

− For the pre-alloys containing bigger particles of $SrAl_4$ with dimensions of 10 - 130 µm or 100 - 400 µm the speed of their decay is slower and the optimal modification effect is reach in 10-30 minutes

− The reaction between strontium and phosphorus causes the suppression of the modifying effect of strontium and it begins to take place after 10 minutes from insertion of the pre-alloy containing strontium

− This reaction causes the bonding of part of the strontium from the pre-alloy on the strontium phosphides. That is why the modifying effect is not of the same size that would be reached if this reaction did not happen

− After finishing the reaction between strontium and phosphorus, the modification reaction may continue with the remaining amount of strontium that was not consumed to form strontium phosphides

− When modifying by the pre-alloys containing strontium, it is necessary to select the period of modification reaction up to 10 minutes, when the reaction between strontium and phosphorus has not yet begun

Morphological scale of eutectic silicon, modification of under-eutectic silumin AlSi10MgMn by strontium - REM

| 0% Sr | 0.04% Sr |
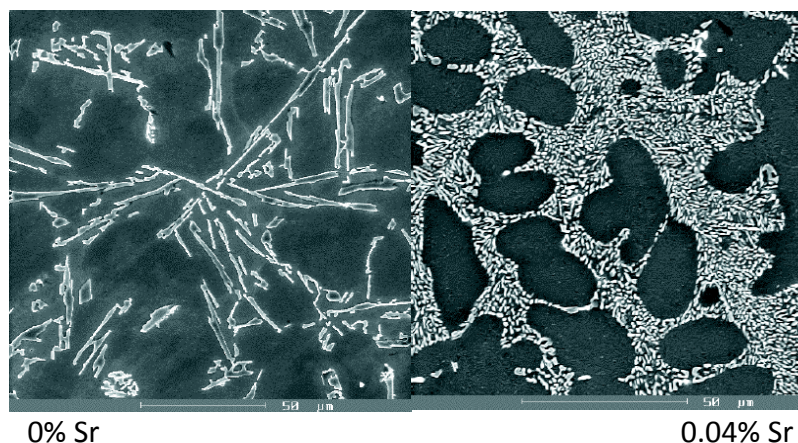
❑ **4.2.2.4 Al-Si alloys inoculation**

− Adding a small amount of suitably chosen substance which affects the process of crystallization (vaccination), which primarily influences the number of crystallization nuclei and it results in softening the structure.

− One of the most important parameters, which determine the properties of aluminum alloys is the size of primary phase.

- Every grain is formed by several dendrites, which grow out of a single crystallization nucleus. The size of grains is usually between 1-10 mm in aluminum alloys.
- They are primarily Al-Cu alloys (which contain only the primary phase) and Al-Si alloys with lower content of an eutectic. With the rising content of silicon, the content of an eutectic is increased, therefore the influence of eutectic silicon is more prevalent and the influence of primary phase dispersity is lower.
- Vaccination is especially effective in sub-eutectic siluminates with high fraction of solid solution α in their structure, i.e. in Al-Si alloys with silicon content of 5-7%.
- During intense cooling (thin-walled casts and casts poured into metal forms), a high overcooling of melt occurs under the equilibrium temperature of crystallization, at which less suitable nucleation appears. This results in obtaining soft-grain structure without any metallurgical intervention.
- Durin the casting with thicker walls of the casts and especially in casting into sand forms, the intensity of cooling is substantially lower and therefore the alloy has a coarse-grain structure.

There are several theories to explain the softening of the phase:
- a theory based on peritectic transition in the system of aluminum-transition metal
- a theory based on the formation of intermetallic compounds of aluminum and transition metal, or the transition metal carbide.
- a theory stemming from the electron structure of transition metals where the softening effect of the metal is stronger if there are less electrons on the d-orbital of its atoms

❑ **4.2.2.5 The principle of inoculation of Al-Si alloys**
- The softening of a solid solution is performed by adding Ti and B, which are introduced into the melt individually or combined. These elements are introduced into the melt in form of intermetallic compounds, which are contained in the corresponding pre-alloys.
- Titanium is introduced into the melt by adding the pre-alloy type AlTi (such as AlTi6), which include the intermetallic compound $TiAl_3$.
- Boron is introduced into the meld by adding the pre-alloy type AlB (such as AlB4), which include the intermetallic compound AlB_2.

Titanium and boron in combination are introduced into the melt by adding a pre-alloy type AlTiB (such as AlTi5B1, AlTi5B0.2), which contain effective elements Ti and B in form of intermetallic compounds TiB_2 and $TiAl_3$.

The intermetallic compound TiB_2 is insoluble in solid solution whereas AlB_2 and $TiAl_3$ are soluble in solid solution. This fact leads to some characteristic properties of softening the solid solution with one of the Ti or B elements individually.

❑ **4.2.2.6 Influence of inoculation on alloy properties**
- increasing the strength and ductility,
- decreasing the tendency of the alloy to form fractures,
- lower porosity of casts,
- increase of cast tightness,
- better malleability,
- increase of properties after thermal processing.

4.3 Copper and its alloys - Classification of copper alloys

based on the main additive element, the Cu alloys can be divided into:
− brasses – alloys of copper and zinc (based on additive elements - manganese brass, nickel brass,...)
− bronzes – most alloys with other elements

Classification of alloys based on the width of solidification range
− alloys with narrow interval of solidification up to approximately 50K: (yellow brasses, Mn,Al,Ni-bronze, CuZnNiSnPb, Cr copper)
− alloys with solidification interval of 50-110 K: (silicon brass, silicon bronze, Cu-Ni alloys)
− alloys with solidification interval of over 110 K (up to 170 K): (tin, leaded tin, red and lead bronze)

Influence of solidification interval on casting properties
− metal substitution
− macro- and micro- segregation

- ### 4.3.1 Bronzes

based on the main additive element or a group of additive elements, they are divided into these types of bronzes:
− tin
− leaded tin
− aluminum
− lead
− less – Cu-Ni, Cu-Cr, Cu-Mn, Cu-Si, Cu-Be

Tin bronzes
− alloying element– tin (9 – 13% Sn)
− nickel is released as an intermetallic alloy Ni_3Sn
− increases strength properties
− nickel improves casting properties and resistance to corrosion
− concentrates on the grain boundaries and in the areas of thermal axis
− improves malleability
− supports self-lubrication ability of bearings
− lowers strength and plasticity properties
− phosphorus
− bronze with 5-10% of Sn and up to 1% P – phosphorus bronze (as a bearing metal)
  nickel is released as an intermetallic alloy Ni3Sn
− increases strength properties
− nickel improves casting properties and corrosion resistance
  lead is insoluble in its α phase
− it concentrates on the grain boundaries and in the thermal axis area
− improves malleability

- supports self-lubrication ability of bearings
- lowers strength and plasticity properties
  use:
- casts in which good strength and high wear resistance is required
- casts worn by sliding friction, plain bearings, gears, pins, fittings, synchronizing rings

mechanical properties:
Rm 250-300 MPa
Rp0.5 140-170 MPa
A 10-30 %
HB 80-100

Special tin bronzes
- bell metal
    - 15 – 20 % of Sn
    - it is hard, has clear, metallic sound
- gunmetal (originally for cannon barrels)
    - 10 – 12 % of Sn
- spiegeleisen
    - 30 – 33 % of Sn
    - originally for production of optical mirrors or very accurate optical devices (it can be polished into high gloss)
- bronze for artistic casting
    - as a binary alloys with 7 - 12 % of Sn
    - also red bronze containing zinc

Leaded tin bronze
alloys of copper with tin, zinc and lead (red bronzes)
- 4 – 8 % Sn, 2 – 9 % Zn, 3 – 8 % Pb
- for example 5 % Sn, 5 % Zn, 5 % Pb

alloys of copper with tin and lead
- 8 - 11 % Sn, 8 - 23 % Pb, max. 2 % Zn

use:
red bronze is used as the cheapest variant of Sn-bronze (it has somewhat lower mechanical properties and especially strength - fittings casts, hydraulic components

mechanical properties:
- Rm 220-260 MPa
- Rp0,2 110-13 MPa
- A 15-20 %
- HB 60-70

use:

leaded tin bronze is used primarily for plain bearings for high loads, tight casts at high pressures, casts for steamy environments, corrosion resistant products,...

mechanical properties:
- Rm 180-220 MPa
- Rp0,2 90-110 MPa
- HB 50-70

Aluminum bronze
- depending on chemical composition– aluminum bronzes are binary or poly-component
- main alloying elements: Fe, Mn, Ni
- outstanding mechanical properties, high fatigue, wear, corrosion and cavitation resistance
- very narrow range between the liquid and solid temperatures (narrow two-phase range) ⬚ dense structure and good tightness of the casts

structure:
- in cast state, it is composed by a mixture of α-phase and an eutectoid ($\alpha + \gamma_2$), which was formed by the disintegration of high-temperature phase β
- in alloys with a content of nickel, phase γ_2 is substituted by poly-component phase κ, which contains Fe, Ni and Al

chemical composition of aluminum bronzes:
- 5 types of Al-bronzes – EN ČSN 1982
- 8 – 11 % of Al (max. 12 %)
- with increasing content of Al, the values of Rp0,2 and HB increase as well
- Fe (up to 3 %, uncommonly up to 6-7 %) softens the structure of the alloy and hardens the matrix through precipitations
- Mn (usually up to 2 %, max. 3 %) narrows the range of the α-phase and also increases strength
- Ni (1 – 6 %) increases mechanical properties (precipitation strengthening by the intermetallic phase CuFeNi, lowers the density

mechanical properties:
- outstandingly high mechanical properties
    - Rm 500 – 650 (750) MPa
    - Rp0,2 180 – 300 (380) MPa
    - A 15 – 30 (6)
    - HB 100 - 150 (180)
    - E 100 – 110 GPa
- thermal processing (alloys with over 10 % of Al content)
    - solution annealing (900°C-2 hours, $\alpha \rightarrow \beta$)
    - fast cooling → formation of unarranged β´- martensite
    - tempering at 560-620°C – 1 hour → precipitation of phase α and formation of tempered β martensite

fields of use:
- parts for pumps
- friction bearings for the highest loads
- gears, worm gears
- parts in non-sparking environment
- parts resistant to sea waters, saline solutions, brackish water and organic acids

Leaded bronze
- in liquid state, Pb and Cu are partially soluble, in solud state almost insoluble - the structure is made from crystals of almost pure copper and crystals of lead
- a big difference in density and solidification temperature - especially prone to segregation - frequent mixing of metal, special metallurgical interventions
- very good sliding properties - bearing metal
- contains up to 25 % of lead, 0 – 10 % of tin
- small amount of Ni, Sn, Zn or Mn softens the structure and limits lead segregation

Manganese bronze
- EN ČSN 1982 – 1 alloy
    - 8-15% Mn, 7-9%Al, 2-4% Fe, 1,5-4,5% Ni
    - material with high strength Rm over 630 MPa
    - ductility A > 18 %, high density
    - for production of weapons, turbines, bearings etc.
- alloys are homogenous with a content of up to 20 % of Mn, with fast cooling even alloys with higher content of Mn remain homogenous
- good mechanical properties (up to 300°C), good resistance to corrosion and specific electro-technical properties
- is not usually cast in foundries

Silicon bronze
- max. dissolvability of silicon in copper is 5,3 % Si
- > 5,3 % Si - formation of brittle phases limiting its technical use
- usually up to 3,5 % of Si
- alloyed by small amounts of Mn, Zn, Ni, Sn
- have good strength and high ductility up to 250°C
- suitable for use at low temperatures of – 180°C
- good chemical resistance in various chemical environments
- very good friction properties

Nickel bronze (cupronickel)
- nickel has total solubility with copper in solid state ⮕ any combination
- ↑ Ni ⇒ ↑ hardness and strength of alloys ↓ ductility
- good density, creep resistance and great corrosion resistance
- Cu-Ni-Zn (white cooper) with content of up to 20-25% of Ni, up to 10% of Zn, or containing Pb and Sn.
- ALPAKA – alloy with 55-65% of Cu, 18-27 % of Zn and approx. 18% Ni

Chrome copper

- used for casts that are required to have good resistance to abrasion and high electrical conductivity
- for example contacts for pantographs, electrodes for resistance welding, water-cooled lances of blast furnaces and cupola furnaces
- chrome forms alloy with copper with limited solubility and forms an eutectic
- eutectic concentration is 1,5% Cr, max. solubility of Cr in Cu at eutectic temperature is 0.65% Cr
- technical alloys contain 0.4-1.2% of Cr
- chemical composition is chosen with regards to achieving the required electrical conductivity

- **4.3.2 Brasses**

- zinc forms substitution solid solution with copper (Cu) with maximum solubility of 32,5% of Zn (at 903°C)
- with decreasing temperature, the solubility of zinc increases up to 39% (at temperature of 456°C)
- α phase has an FCC lattice and therefore good plasticity properties
- β phase has BCC (body centered cubic) lattice, appears in alloys with content of over 38% of Zinc
- β phase forms an unarranged solid solution based on electron compound CuZn and in thermal interval 468-456°C it transforms into a regularly arranged phase β′
- high-temperature phase β is dense and allows for hot forming
- phase β′ is brittle and causes decrease in density
- alloys formed only by phase β′ are practically technically useless (that's why the content of copper in brass is usually higher than approx. 55%)
- TOMBAK – alloys containing more than 80% of Cu
- casting brasses – contain a range of additives and impurities apart from Zn
  - „yellow brass" – alloys based on elements CuZn(SnPb)
  - „white brass" – contain high amounts of Mn (10 – 20%)
- brass solders
  - contain 42-54% of Zn and have melting temperatures of 840-880°C
  - silver solders for electro-technical purposes contain 30-50% of Cu, 25-52% of Zn, 4-45% of Ag

Brass structure:
  influence of individual elements on the area of solid solution α is evaluated based on the so-called equivalent content of zinc.
  equivalent coefficients of selected elements:
  Si – 10, Al – 6, Mn – 0,5, Fe – 0,9, Ni – (-1,3), Pb – 1, Sn – 2, Mg – 2
  for labeling in technical practice, the content of the basic element is used - i.e. copper (such as Ms 58 means that the alloy contains 58 % of Cu)

Properties of brasses:
- mechanical properties
- Rm– 200-300 MPa (manganese brass – Rm – 500-750)

- A – 10-20%
- HB – 70-100 (alloyed brasses up to 200)
    - depends on the value of zinc equivalent (34 – 45% Zn_{eqv})
    - the fraction of α phase decreases from 100 % to 0 %
    - strength in tension increases to approx. double the value, then it decreases rapidly
    - strength increases to double its value
    - ductility decreases to less then a half

  casting properties:
- very narrow area of solidification - outstanding casting properties
- good fluidity and low tendency to formation of shrinkage porosity
- disadvantage – relatively significant linear shrinkage– approx. 1,5 %

  usage
- production of plumbing fittings
- component of pumps, cases, machine parts
- components working in environment of saline solution

4.4 Magnesium and its alloys - Casting alloys of magnesium

- main additive element– Al (Mg-Al)
- Mg-Li – super light alloys (1380 to 1480 kg . m-3)

labeling the Mg alloys:
- labeling system based on American ASTM norm
- (A – aluminum, C – copper, E – rare earth metals, M – manganese, S – silicon, Z – zinc)

- contain 3 to 9% of Al
- for gravitational casting, content of Al does not exceed 5 %
- with increasing content of Aluminum, fluidity is improved
- alloy for pressure casting– AZ 91
    - high strength, medium ductility and impact strength
- alloy with lower content of aluminum and zinc is replaced by manganese – AM20, AM50, AM60
    - higher ductility and strength (steering wheels in cars, seats)

- alloys containing 0,5-1 % of silicon - AS21, AS41
    - increase of mechanical properties
    - higher creep resistance
    - release of intermetallic phase Mg_2Si (good stability at increased temperatures)
- alloys alloyed by rare earth metals
    - for applications at temperatures over 200°C
    - alloying elements – Ce, Nd, Th...
    - increased creep resistance
    - bad casting properties, gravitation casting into sand or metal molds

- AM 60 alloy for casting under high pressure with outstanding plasticity, used for rotors and car wheels
- AS 41 alloy for casting under pressure with good creep properties at up to 150°C; used for car parts
- AZ 81 alloys for casting into sand or ingots for general use in production
- AZ 91 airplane parts, engineering parts, gearbox housing
- AZ 91 alloy for casting under pressure for general use, for car and computer parts, chainsaws, sports equipment, cameras, projection devices, ...
- EZ 33 alloy for casting into sand and into ingots for use in high temperatures; outstanding casting properties; resistant to creep in temperatures up to 250°C and pressure-tight; used in aviation industry
- AZ 63 alloy for casting into ingots for so-called sacrificial anodes (anti-corrosion protection of boilers, tanks and pipelines)

- **4.4.1 Melting of Mg alloys**

- high affinity of magnesium to oxygen
    - melting under a layer of protective slag or in an intert atmosphere
    - oxidation – formation of oxide inclusions, which are not expelled from the melt
- pre-heated batch is added into the liquid metal
- melting in electric resistance or induction furnaces (resistance furnaces are more suitable)
- crucibles – carbon or low-alloyed steel
- furnace lining - based on magnesium oxides

- protection of metallic layer using
    - refinement salts (mixture of chlorides, event. fluorides, calcium, magnesium, sodium and potassium - refinement of the melt (bonding of inclusions))
    - sulfurs
    - inert gasses SO_2, SF_6, CO_2, Ar...
      0,2-0,3 % of SF_6
        Mg + SF_6 + air → MgO (protective coating)

4.5 Zinc and its alloys

ρ = 7130 kg/m^3
t_{melt} = 419°C
t_{boil} = 906°C
crystallization within a hexagonal system

Casting alloys of zinc
- main alloying element – aluminum
- in a Zn-Al system, the primary phase has limited solubility
- an eutectic is formed by the Zn-ZnAl phase
- eutectic temperature is 381°C at the concentration of 5,5% of Al
- amount of aluminum in normed alloys (4-27%)

Secondary additive elements
- copper
    - decreases grain size (such as Al)
    - increases mechanical properties – strength, ductility, impact strength
    - improves fluidity of alloys
        > 0,7 % Cu improves resistance to corrosion
    - usually approx. (0,5-3 % of Cu) in alloys

- magnesium
    - increases strength even in small amounts
    - compensates for damaging influence of tin, lead and cadmium
    - usually approx. 0,01 – 0,03 % Mg
    - ZAMAK

Impurities in Zn alloys
- primarily iron, lead, cadmium and tin
- support the formation of inter-crystalline corrosion
- content cannot exceed a thousandth of one percent - production must start from a very pure base metal containing 99,995 % of Zn

Chemical composition of alloys
- content of aluminum– 8, 12 and 27 % Al
- for pressure casting– 4% Al (Z400, Z410, Z430)

Casting properties
- very good casting properties (ZnAl8 and ZnAl11 – narrow area of solidification) - outstanding tightness
- casting temperatures: 455-610°C - high service life of metallic forms
- outstanding fluidity - thin-walled casts of complex shapes
- pressure casting
    - wall thickness up to 0,3 mm
    - pre-casting of openings with diameter up to 1 mm
- high precision of casts (from 0,03 mm)

Examples of casts
- gas meter case
- bodies of heat exchangers
- for automotive industry (carburetor, headlight frames)
- smaller gears
- decorative objects

4.6 Titanium and its alloys

- **Titanium alloys**

- The highest ratio between strength and specific mass
- Outstanding anti-corrosion properties

- Very good abrasion resistance
- Biocompatibility

- **Use of Ti alloys**

- Use in aviation and aerospace industry
- In chemical industry, titanium is used in production or padding of chemical reactors.
- Material for production of wristwatches, glasses or jewelry parts.
- Apart from these applications, titanium can be found in art, such as coating on Mother Motherland, Kiev.

- **Classification of titanium alloys**

Ti alloys are divided based on their structure:
- α alloys
- pseudo α-alloys
- dual-phase alloys α + β
- pseudo β-alloys
- β-alloys
- intermetallic alloys

☑ Summary of terms

A basic classification of alloys of non-ferrous metals is according to specific weight, melting temperature and chemical reactivity.

Al-Si type alloys are also called silumines. They are the most widely used alloys based on non-ferrous metals. They feature excellent foundry properties.

Copper alloys are divided on the basis of a type of main and secondary alloying elements to bronzes and brasses.

⑦ Questions

1. Define the main groups of non-ferrous metals alloys.

2. Describe fundamentals of casting of particular groups of non-ferrous metals and their alloys.

3. Characterize differences between particular groups of non-ferrous metals and alloys.

4. Define basic information for the use of particular groups of non-ferrous metals and their alloys.

	Recommended literature for further study

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