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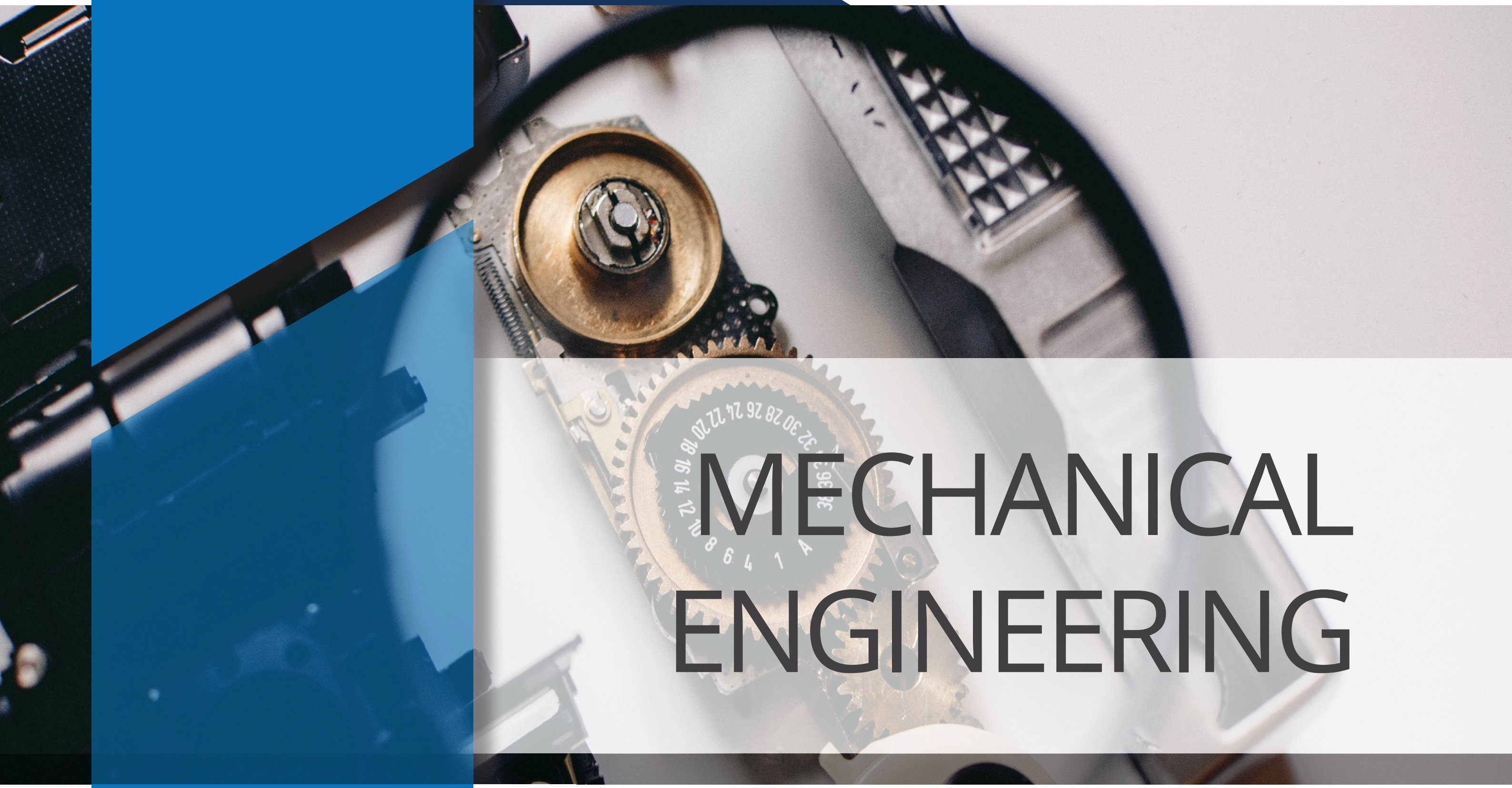

MECHANICAL ENGINEERING

Engineering technologies 2

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Contents

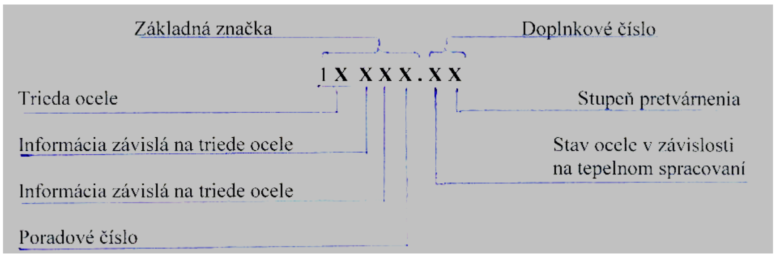
1. MARKING OF TECHNICAL MATERIALS

Metals are marked by numerical marking according to the standard STN 42 0002, which is, however, only temporary. There has already been used marking according to EN. The numerical mark is written in the component drawing, list of details in machine assemblies designs, it is also used in business.

1.1. Marking of technical iron

Formed steel:

The marking consists of a five-digit mark and a two-digit additional mark, separated by a point. Based on the chemical composition, steel is divided into classes. The marking indicating the class is the **first two digits** of the basic marking, separated by a gap from the other numbers. This is referred to as the **steel class marking**. Steel class marking always starts with ***1.*** The marking pattern is as follows:



Legend: základná značka – basic mark, doplňkové číslo – additional number, trieda ocele – steel class, informácia závislá na triede ocele – information depending on the steel class, poradové číslo – series number, stupeň přetváření – degree of forming, stav ocele v závislosti na tepelnom zpracovani – steel condition depending on heat processing

In mechanical engineering chart, the meaning of the individual digits is explained in detail.

Steel classes are as follows:

10 + + + without guaranteed chemical composition
Structural steel of usual quality
11 + + + guaranteed S and P content
–––
12 + + + carbon steel (for case-hardening, refining, spring steel)

13 + + + alloy for case-hardening (Mn, Si, Mn-Si)
––
14 + + + for refining (Cr, Mn-Cr, Si-Cr,
Structural steel Cr-Al, Cr-Mn-Si)
15 + + + steel for quenching (Cr-Mo, Cr-V, Mn-Cr-Mo,
refined Mn-Cr-V, Cr-Mo-V, Cr-Mo-Al)

16 + + + for nitriding (Ni, Cr-Ni, Cr-Ni-Mo,
Ni-Cr-W)
17 + + + alloyed with high content of additives corrosion-resistant and refractory steels
High-temperature steel
18 + + + additional materials, sintered metals
–––
19 + + + tool steel carbon, alloy, alloy steel for tools, alloy high speed steel

The meaning of the ***second two digits*** depends on the steel class. The last number represents the important properties (e.g.: *1*-suitable for forming, *3*- weldable steel).

The first additional digit means the state, the type of heat processing (e.g..: *1*-normalized steel, *4*-hardened steel, *6,7,8*-refined to lower, upper, and middle strength).

The second additional number indicates the degree of forming.
Example: 11 523.11 12 061.4 19 436.4

Steel for casting:

The basic marking is a 6-digit marking. The first two digits are *42*, the metallurgical group. This is followed by a gap. The second two digits are: ***26* – carbon steel, *27,28,29* – alloy steel**, the meaning of the third two digits depend on the kind of steel. The first additional number after the point indicates the state, the second one the required properties.

Example: carbon: 42 2650,   alloy steel: 42 2712, 42 2815, 42 2931

Cast iron:

Marking of cast iron is a 6-digit number starting with *42*. The second two digits indicate the type of cast iron:

Ductile cast iron - ***23***,

grey cast – ***24.*** The third two digit indicates the lowest tensile strength in the case of ferritic ductile cast iron (in tenths of MPa),

malleable cast iron: the second two digits - ***25***, the third two digits indicate the lowest ductility (in %) in the case ferritic cast iron, and the lowest tensile strength in the case of perlitic cast iron (in tenths of MPa).

Example: 42 2438,   42 2530.

1.2. Marking of non-ferrous metals

Aluminium and its alloys

The marking consists of six digits, where the ***first two digits*** are ***42***, ***the third digit is 4***, which is a designation of light metals.

The fourth number: even number denotes formed alloys, ***odd number*** indicates alloys for casting.
The two digits consisting of the fourth and fifth number designates light metals (e.g. pure aluminium, Al Cu Mg, Al Mg alloys, etc.).
The sixth number is the serial number of metal or alloy.
The additional two-digit number indicates the state and quality of the formed material.

In the case of cast materials, the first additional digit indicates the state after the casting heat processing, the second additional digit indicates the casting method.

Example: 42 4004,   42 4415.

Copper and its alloys

The marking consists of six digits, where the ***first two digits*** are ***42***, ***the third digit is 3,*** which is a designation of heavy metals.
The fourth number: even number denotes formed alloys, odd number denotes alloys for casting.
The two-digit number consisting of the fourth and fifth number indicates heavy metals.
The sixth number is the serial number of metal or alloy.
Additional two-digit number indicates the state and quality of the formed material.

In the case of cast materials, the first additional number indicates the state after heat processing of casting, the second additional number indicates the method of casting.

Example: 42 3016, 42 3256.

The marking is similar in the case of soft solders for which the melting temperature is the most important information. For example, the solder material for with a melting temperature of 183 °C is marked as 42 3635, for silver solder with a melting temperature between 650 and 810 °C has a marking 42 3809. For more details, see the chapter *Solders.*

1.3. Marking of non-metallic material

Marking of rubber
For rubber, a 6-digit number is used, where the ***first two digits*** are ***62.***

Example: 62 2026 – for hoses, washers, general use,
62 2314 – resistant to chemicals.

Marking of plastics
Plastics are marked with a 6-digit number, where the ***first two digits*** are ***64.***

Example: 64 3211 – machinable hard polyvinyl chloride plates,
64 7003 – plastic leather on fabric or any other textile.

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1.4. Brief overview of technical materials marking

Steel: a five-digit number, always starting with 1, the second two digits indicate the class (from 10 to 19). This is followed by a point and an additional number (the state of steel).

Example: 11500.4 19 436.6

Cast steel: a six-digit number. Starting always with 42, the second two digits 26 – (most often), or 27, 28, 29. The additional number as in the case of steel.

Example: carbon steel - 42 2650, alloy steel - 42 2712, 42 2815, 42 2931.

Cast iron:
Grey cast – a six-digit number, starting always with 42, followed by 24, or 23.
Tempered – a six-digit number always starting with 42 followed by 25.

Example: grey - 42 2438, tempered - 42 2530.

Aluminium and its alloys: a six-digit number starting with 42 followed by 4.

Example: 42 4004, 42 4415.

Copper and its alloys: a 6-digit number starting with 42 followed by 3.

Example: 42 3016, 42 3256.

Rubber: a 6-digit number starting with 62.

Example: 62 2026, 62 2314

Plastics: a 6-digit number starting with 64.

Example: 64 3211, 64 7003

2. PHYSICAL PROPERTIES AND MECHANISM OF PLASTIC DEFORMATION

2.1. Physical properties

Density – the ratio of mass *m* to volume *V* of a homogeneous material at certain temperature:

$$p = \frac{m}{V} \; [\,kg/m^3]$$

The melting and solidification temperature T *[°C, °K]* – the temperature at which the material changes its state. It is important for foundry, plating, welding, etc. Pure crystal materials (1 element only) have constant melting and solidification temperatures. Alloys, glass, ceramics have a certain range (interval) of melting and solidification.

Linear and volumetric thermal expansion – change of length and volume due to temperature. It is an important variable for foundry, welded joints, etc.

Thermal conductivity λ $[Wm^{-1}K^{-1}]$ – it is the amount of heat that at steady state passes over a unit of time between two opposite walls of a cube of a 1-m edge, if the difference between the walls temperature is 1° K. The best heat conductor is silver (Ag). Other materials conductivity is given in % to silver (Cu – 94%, Al – 55%, Fe – 21%).

Electrical conductivity *G [S]* – the ability of the material to conduct electricity. A conductor with a resistance of 1 Ω has conductivity 1 S (siemens). Based on conductivity, we distinguish between conductors, non-conductors (insulators), and semi-conductors (selenium, germanium, silicon, et al.) The best conductors of electricity are silver, copper, and aluminium. Copper is used for comparing the materials conductivity with other metals.

Superconductivity is a property of some metals whose electrical resistance decreases to an undetectable value (almost without resistance) at very low temperatures (close to 0°K). This is mostly in the case of direct current and semi-conductors.

Specific electrical resistance – is the resistance of a conductor of a 1-mm^2 cross-section and 1-m length. The best insulator is vacuum.

Magnetic properties – characterize the behaviour of metals in a magnetic field. Depending on permeability $\boldsymbol{\mu}$ the materials can be divided into:

Diamagnetic materials – $\mu < 1$. They do not enhance the effect of the external magnetic field. These materials include H, Au, Ag, Sn, Pb, etc. and most of organic alloys;

Paramagnetic materials – $\mu > 1$, but closer to *1*. These include oxygen, rare earth elements, alkali metals, aluminium, platinum, etc. They slightly enhance the effect of the external magnetic field;

Ferromagnetic materials – high μ depending on the intensity of magnetic field. These include Fe, Ni, Co, Cr alloys and Mn. Ferromagnetic materials are:

Magnetically hard – hard to magnetize x retain the magnetism even after the magnetic field is removed (permanent magnets),

Magnetically soft – easy to magnetize + easily lose magnetism. They are used for creating magnetic circuits in electrical machines and devices.

2.2. Chemical properties

The surface of metal components is often damaged due to the environment acting. This is called corrosion, which annually damages up to 3 % of metal. Corrosion resistance is determined in particular environment – in the nature or in laboratories.

The corrosion effect is identified by the loss of metal per 1 hour. It is given in *g* on a cm^2 $[g\ cm^{-2}\ h^{-1}]$.

Fire resistance is determined at higher temperatures (over 600 °C). It increases with adding Al, Cr, Si.

2.3. Mechanical properties

Components are subjected to tensile strain, compression, twisting, shearing, and bending. To resist it, the material must have properties such as strength, hardness, flexibility, ductility, etc. These materials are tested in order to find whether they have the desired properties.

2.4. Technological properties

Material is processed in various ways that require corresponding properties. They are called technological properties, since based on them, the processing technology is chosen, or vice versa – the material adapts to the processing technology. For example, duralumin (AlCuMg) – is used for manufacturing solid but light parts. For forming, the material must not be rigid; therefore, it is processed so that it is soft and ductile. Subsequently it is processed and then it is cured. Technological properties include ductility, machinability, weldability, castability.

2.4.1. Alloys

As technically used metals, alloys are considered, since so-called pure metals contain other elements that appeared in them from the initial materials during the production process or were intentionally added into them. ***Alloys*** *are thus multi-component materials, in which metals are predominant elements.*

Component is an individual pure chemical substance forming a part of an alloy.

Components of alloys interact with each other. Depending on the interaction, we distinguish between the following types of alloys:

homogeneous:

- ***Solid solution***: is marked as *α =A (B)*, which means that the metal *B* dissolves in metal *A.* The solution is either limited or unlimited. Solid solution formation can be as follows:
    - By substitution of basic metal by atom of additive. It is substituted in the lattice. This type of solution is a ***substitute*** solution. If the substitution is regular, it is an ***arranged solid solution,***
    - Atom of additive is added between the atoms of base metal (in the spaces in the lattice). This is an ***interstitial solution****;*

- ***chemical compound***: when the number of atom of the elements penetrating into the alloy can be expressed in whole numbers and cannot change. This is described by a chemical formula.

- ***intermetallic – intermediate phase***: base metal with additive create a new spatial lattice in which the atoms of both substances substitute each other. It forms a new material which is neither chemical compound nor solid solution.

heterogeneous:
if the second material has a different crystal form, both co-exist finely spaced but each one has a separate form. It´s a heterogeneous mixture (similarly as e.g. grains and poppy seeds).

Types of alloys structure are shown in Figures 6.10 and 6.11.

Alloys:

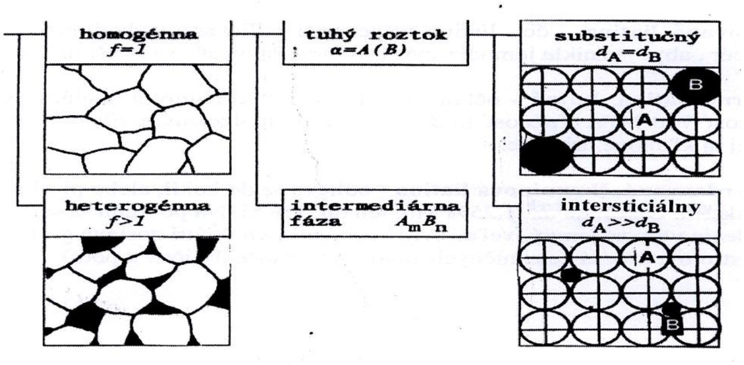


Figure 6.10 Kinds of alloy inner structure (f-number of phases, d_A, d_B –components´ atom diameters)

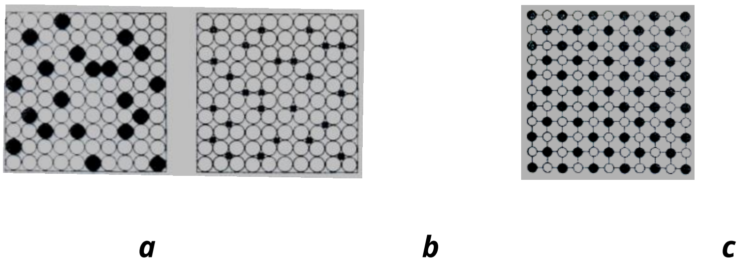


*Figure 6.11 Solid solutions: **a** – substitutional, **b** – interstitial, **c** – arranged solid solution*

<u>Crystallization of alloys</u>

We distinguish between three states of materials – solid, liquid, and gaseous. Here we will deal only with solid and liquid state. In order to gain a liquid state (melt), the metal must be heated: atoms oscillate, the volume increases, specific weight is lower. When the temperature is so high that the atomic oscillation is large, the metal loses its cohesion, it melts.

Here, the ***Dulong – Petit rule*** is applied: multiple of specific heat and atomic weight is approximately equal to 6.2 cal/g °C. This means that the materials with high atomic weight (Au, Pt, Pb) have a low specific heat.

As it has already been stated, heat often changes the crystal lattice even in its solid state – the atoms are rearranged. It is called over-crystallization: a new ***modification*** is created; e.g. in the case of iron, tin (tin pest) and others. This phenomenon is called **allotropy.**

Melt cooling causes its ***solidification****.* Solidification is the process of transformation of liquid state into solid state. If the material solidifies as crystal, this is called ***crystallization.***

Primary crystallization process – it is a transition from the melted state into solid state. The laws of thermodynamics are applied there. The transitions occur on the basis of change of energetically less efficient phase into a more efficient phase. When the solid phase is energetically efficient, the solidification process starts.

In order to fully understand the above-mentioned process of transition, it will be described more in detail in the following chapter. First, a few new terms shall be mentioned:

Pure metals, eutectic alloys, chemical compounds crystallize, that is, solidify ***at constant temperature;*** they also melt at the same temperature. Other alloys solidify in an interval of temperature.

For crystallization, the following factors are important:

- ***spontaneous crystallization capability*** (gives a number of crystallization nuclei),
- ***linear crystallization speed*** (expresses the speed of crystals growth).

Besides these factors, ***supercooling (undercooling)*** – lower atomic mobility which are more likely to collide, and thus the germ is formed, which grows subsequently.

The size of the factors mentioned above and their mutual relation affect the roughness of the structure. It is also influenced by casting moulds, chills, inoculation, metal purity.

If the nuclei originate directly from the base metal, it is called *homogeneous nucleation*. We say that crystallization is spontaneous.

If the nuclei are formed and grow on other material (carbides, oxides, nitrides, graphite, solid metal additives, inoculants, impurities, etc.), it is called *heterogeneous nucleation.*

Nuclei only occur at certain temperature, if the temperature is higher, the nuclei melt.

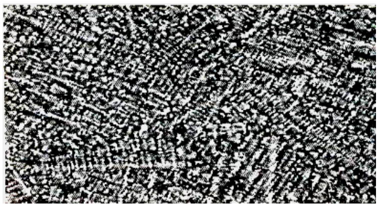
Unlike pure metals, crystallization of alloys involves several processes:
- from homogeneous melt, several phases may crystallize,
- crystallization takes place in a certain temperature range,
- crystallization phase has a different composition than the original homogeneous phase.

Structural changes occur during crystallization, and new phases appear.

Phase – it is a homogeneous part of a system which is separated from other parts by a surface interface and has the same properties, structure, and chemical composition (e.g. the mixture of grains and poppy seeds is a system as a whole, poppy seeds are one phase, grains represent another phase). Phase can be a homogeneous matter or dispersion.

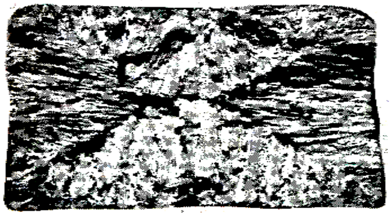
Dispersion – it is a system containing at least two kinds of matter, when one matter is dispersed in the other. It is a heterogeneous system of two or more phases.

During crystallization, ***trans-crystallization takes place*** – formation of ***dendrites*** – tree-like crystals, crystallization axes (Figure *6.12a*), lunkers, microlunkers (between crystals, act like a notch Figure *6.12b*).



a

Figure 6.12 cast steel – in alloy Fe-



b

Dendrites in a, crystallites Ni – b

3. BASIC QUANTITIES OF PLASTIC DEFORMATION

3.1. Limit states of materials

In most branches of mechanical engineering, the technical parameters of machines and devices have increased in the last decades (e.g. work pressure, temperature, revolutions, performance, etc.), while their weight per unit of power has decreased.

Limit state – definition

- Limit state is a state of material when the material loses its functional and utility properties due to the acting of the external or internal factors or by combined acting of external or internal factors, when there is a change of functional and utility properties of certain level.
- Step change in material state.

The second definition describes the limit state as a loss of utility properties and includes also the phenomena that do not have to affect the functional properties of the given structure, such as the transition from ferromagnetic to paramagnetic state (Curie temperature), polymorphic transformations, etc.

- Limit state is a state of system expressed by conditions (parameters) of the system activity, which cause temporary or permanent failure of the system function when exceeded. System limit state is between the normal and failure state.
- The third definition defines limit state as a place of a step interface between two states – applicable and non-applicable.

Reaching limit state depends on the *dynamics of damage accumulation,* which is a function of a sub-structural and structural state of material, technological characteristics of production, and construction conditions of using a body, depending on the size and type of load, reaction of the material to the load and mainly to the time of acting of the factors that can (separately or together) cause the limit state.

- *Degree of material damage* is characterized by the level of internal energy, mainly at the points of its concentration, or by the share of the areas with affected material cohesion due to acting of external of internal limit state factors.
- *Plastic deformation* is the ability of material to change its shape and dimensions due to acting of sufficient load without changing its crystal structure.
- *Local damage of material* is an irreversible loss of cohesion limited in volume and area, which results in a separation of a certain amount of material, formation of a

crack or cracks, or a layer with different utility properties than the other part of the material.

- *Cracking* is an irreversible loss of material particles cohesion in a part or in the whole cross-section.

Factors influencing limit state

- Structure and substructure – morphology of the individual phases, precipitates, segregates
- Technology of production – residual stress after forming, welds, defects
- Operation conditions (environment) – operational atmosphere, lubrication, revolutions, period of operation
- Size and type of stress – size, direction, static stress, impact stress
- Chemical composition
- Speed of stress – plastic instability phenomenon
- Corrosion
- Time – stress history
- Temperature
- Multi-factor superposition

3.2. Classification of limit states

Ultimate limit state:

Deformation – exceeding the stress limit

- Elastic limit,
    - Excessive elastic deformation (micro plastic deformation, macro plastic),
    - Damaged elastic stability,
    - Decrease of elastic deformation (relaxation),

- Plastic deformation limit
    - Excessive plastic deformation (critical)
    - Damaged plastic stability

Limit state of damage (cracking).

- Overload:
  - fragile,
  - malleable,
  - creep,
  - impact,
  - heat shock deformation,
  - corrosion,
  - stalled,
  - early
- Wear,
  - mechanical ε=f(σ),
  - thermal ε=f(T),
  - thermal-mechanical ε=f(T, σ),
  - creep ε=f(T,σ,t).

Local damage:

- Of volume by:
  - hydrogen,
  - Intercrystalline corrosion,
  - Liquid metal,
  - welding,
  - radiation,
  - swelling,
  - energy fields
- Of surface by:
  - adhesion,
  - abrasion,
  - erosion,
  - cavitation,
  - contact,
  - vibration,
  - corrosion,
  - heat,
  - extraction,
  - energy rays.

Serviceability limit states:

- Excessive deflection.
- Size of dynamic response.
- Loss of stability of position.
- Vibration, noise

Stress corrosion cracking

It is one of the forms of corrosion caused by the simultaneous acting of corrosion and stress (Table 7.1). Corrosion acting is more intensive in such a case than it would be under the condition of separate acting of both factors. Corrosion cracking occurs when the following three conditions are fulfilled:

- corrosive environment,
- cracking-prone material,
- presence of certain tensile stress component.

Cracking susceptibility is influenced by metallurgical (chemical composition of metal, internal stress, level of deformation, presence of inhomogeneity) and electrochemical factors (electrochemical potential, metals ability of passivation, character of corrosive environment).

Corrosion cracking (see Figures 7.3 and 7.4) can be intercrystalline or transcrystalline. In corrosion cracking, the cracks are often initiated by existing surface defects as grooves or chases after machining, or sharp edges.

Table 7.1 Combination of metals and environment in which corrosion cracking occurs

Al-Mg, Al-Cu-Mg,Al-Mg-Zn	seawater
Cu-Al, Cu-Zn-Ni, Cu-Sn	ammonia
Carbon steel	Hot solutions of nitrates, carbonates, and hydroxides
austenitic stainless steel	Concentrated hot chloride solutions, chlorine contaminated vapours
Titanium and its alloys	10% HCl
Nickel and its alloys	Solutions of NaOH and KOH at 130°C

Figure 7.3 Corrosion cracking scheme

Legend: korózne trhliny – corrosion cracking, korodujúci material – corroding material

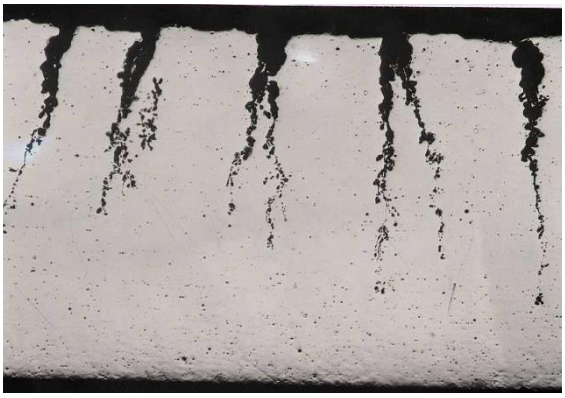


Figure 7.4 Microphotograph of corrosion cracking

Due to changing of chemical and mechanical degradation, there is a jump growth of cracking. Chemical reaction at the front of the crack accelerates its spreading and the accumulation of stress at the front of the crack increases the reactivity of this place. This results in the synergy of both active processes.

Prevention

- Study of material and its reactions to different structure elements and technological processes – the influence of welds, notches, oscillation, stress, energetic processing etc.
- Choosing the right material – right combination of material properties for the given stress and environment.
- Improving design solutions and stress determination processes at individual places on the structure.
- Follow the technological production processes.
- Correct installation.
- Correct operation – lubrication, temperature, not overloading.
- Maintenance and regular inspection of equipment, constructions, or system – crack control (airplanes, bridges)
- Products tested by producers
- Non-destructive testing – inspection of manufactured components before they are used in the operation and during operation, e.g. inspection of pipes, blades of aircraft engine, cavities in welds, etc.
- Learning from past mistakes – finding the causes of industrial accidents and taking steps to avoid similar problems in the future.

4. INFLUENCE OF TEMPERATURE ON PLASTIC PROPERTIES OF MATERIAL

4.1. Technological properties of materials

- **formability** – ability of material to change its shape by acting external forces without damaging the integrity
- **weldability** – it is the material ability to create a welded joint of desired quality
- **castability** – set of properties characterizing material suitable for casting
- **machinability** – set of properties referring to the ease and results of machining the giving material

4.2. Stress

Definition: the ratio of force and cross-section
Stress is created at the cross-section due to acting of external force on the body (Figure 8.1)

$$\delta = \frac{F}{S_0} = \left[\frac{N}{mm^2}\right][Mpa] \qquad (8.1)$$

$$F_N = F.\cos\alpha \qquad F_S = F.\sin\alpha$$

$$\delta = \frac{F_N}{S_1} \qquad \tau = \frac{F_S}{S_1}$$

Where: F_N – normal component

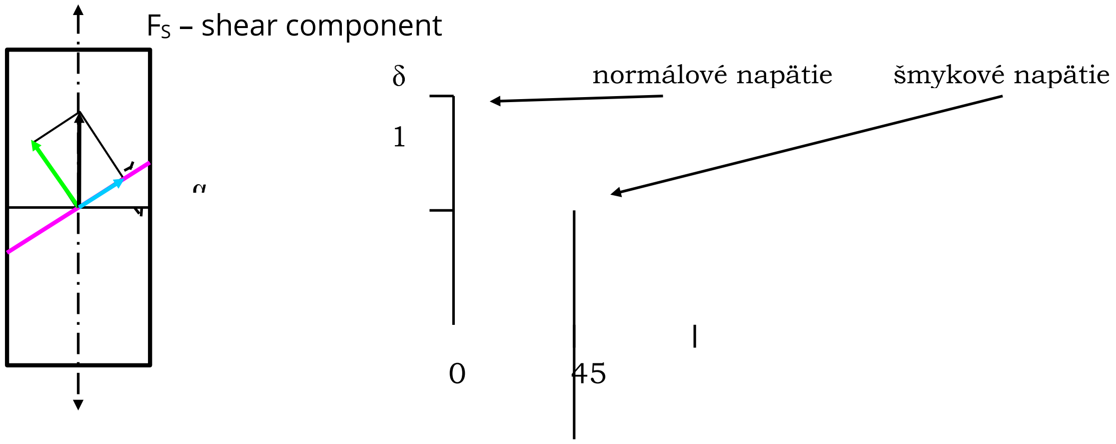


Figure 8.1 Creation and course of stress
Legend: normálové napätie - normal stress, šmykové napätie - shear stress

4.3. Acting of external forces – definition of strength

Strength – the ability of material to bear the load. Ultimate strength is the stress under which the material is damaged – separated into two parts.

$$R_m = \frac{F_{max}}{S_0} \left[\mathrm{Mpa}\right] \quad (8.2)$$

4.4. Elastic and plastic (permanent) deformation of metals

Deformation – change of shape and dimensions due to external force acting force (Figure 8.2)

Elastic deformation

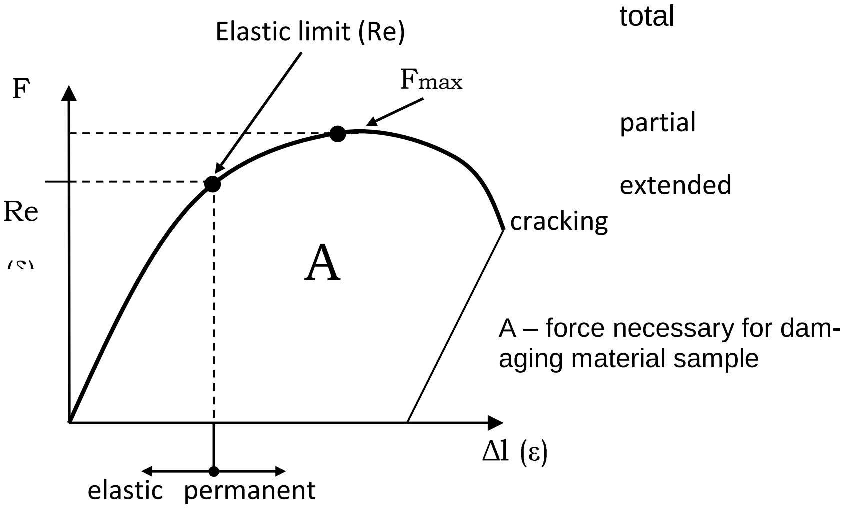
The material returns to its original shape after the external load stops acting

- It occurs when the atoms, due to the acting of external force in crystal lattice, deviate from their equilibrium points by a distance lower than a half of the lattice parameter. After the removal of the load, the atoms return to their original position.

Plastic (permanent) deformation

When the external load stops acting, there is still certain deformation depending on the size of the loading force

- It occurs if the atoms deflected from their equilibrium position by a distance higher than the lattice parameter, due to which they are not able to return back to their original position after the load is removed.



$$\Delta l = l - l_0$$

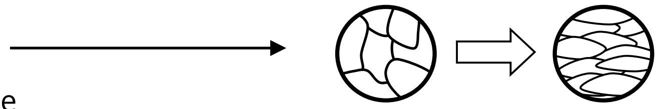
$$\varepsilon = \frac{\Delta l}{l_0} = \frac{l - l_0}{l_0}$$

Figure 8.2 Elastic and plastic deformation

Mechanism of plastic deformation:

- By slipping (slipping plane, slip direction)
- By twinning

Effects of plastic deformations



- reinforcement of material
- Formation of deformation texture
- Anisotropy of mechanical properties
- Increase in the number of defects

Removing effects of plastic deformations

- **By heating the material:** based on the material temperature, we speak about lattice recovery. Result: Partial recovery of properties, reduction of tension.
  Heating to the temperature $T < T_{recr.}$ $T_{rekr} = 0,35 – 0,4\ T_{tav}$ (8.3)
- **By recrystallization**
  Heating to the temperature $T > T_{recr.}$

These effects are removed by recrystallization anneal. Recrystallization deformation of grains to non-deformed completely removes the effects of plastic deformation.

Hot forming is in solid solution γ (austenite), since it has a lattice K12 characterized by a good formability. If the initial temperature of forming is high, it reduces the austenite strength upon intensive recrystallization of deformed austenitic grains. In order to achieve a certain deformation, a smaller amount of energy than in the case of lower temperatures is required. However, the temperature of forming is limited to 100 – 200°C below the solidus temperature in order to avoid grain thickening or “burning” of the steel. Forming must be completed to the temperature of Ar_3 in the case of sub-eutectoid steels and Ar_1 in the case of super-eutectoid steels. At the temperatures of Ar_3, or Ar_1 the deformation process predominates over recrystallization process; after cooling, the forming temperatures create a fine-grained structure. In the case of super-eutectoid steels, forming (at the temperatures between Ar_{cm} and $Ar_{1)}$ causes grinding of secondary cementite lattice, thus increasing the deformation properties (ductility, contraction) of this alloy. For forming temperatures, see Figure 8.3.

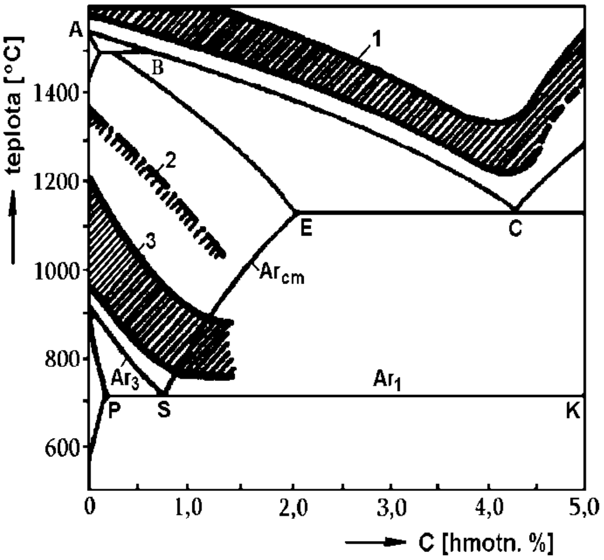


Figure 8.3 Characteristic temperatures in diagram Fe – C

1 – casting temperatures, 2 – upper limit of forging temperatures, 3 – forming temperatures

***Heat processing*.** The Fe-C diagram is most important for the processes of heat processing, which enable to change material properties in a wider range. According to the critical temperatures of A_1, A_3, A_m, annealing, quenching, and temperatures of phase changes are determined. The diagram also enables to determine the resulting structures after heat processing.

The above-mentioned examples, as well as other applications such as choosing temperatures for individual types of chemical and heat treatment, thermal-mechanic treatment etc., show, that the Fe-C equilibrium diagrams provide very valuable information for achieving optimal properties of Fe-C alloys.

5.CLASSIFICATION OF TECHNOLOGICAL FORMING PROCESSES

Forming is a technological process during which the shape of the starting material is changed by a forming tool without chip removal. Forming is a progressively production technologies. The progressivity of forming consists mainly in reduced consumption of starting material for manufacturing the components or structure, in improving mechanical properties of the starting material in a short period of time, in high productivity, in the possibility of producing parts for the finished product and in full automation of the additional operations and actions.

Blank is a product manufactured by forming regardless the type of forming operation used.

Depending on the type, shape of the initial material and change of cross-section (thickness), forming is divided into **sheet metal forming and bulk forming.**

- Sheet metal forming is a process in which the required change is achieved without a significant change of thickness of the starting material (tin sheet mostly).
- Bulk forming is a process in which the required change of shape is achieved by changing the cross-section (thickness) of the starting material.

Technological forming processes can be classified by:

- Temperature used
- Thermal effect
- Level of deformation achieved

Classification of forming by temperature used:
In terms of forming, plastic properties of pure metals and alloys change due to acting of temperature, i.e. their resistance against the permanent change of shape changes. At high temperatures, the plastic properties of most metals and their alloys are improved.

Plastic deformation that occurs at technological cold forming processes causes change of mechanical, physical, and chemical properties of metal. The phenomena related to these changes are commonly referred to as reinforcement. Depending on whether forming takes place at temperature above or below recrystallization temperature, technological forming processes can be divided into:

- Cold forming
- Hot forming

Cold forming refers to a technological material processing during which the material temperature is below the recrystallization temperature. This means that the reinforcement of the material caused by forming is mostly retained. Cold forming takes place at temperatures lower than T ≤ 0.3.Ttav, where the temperatures are given in K.

Cold forming is mostly used for:

- Achieving a shiny and smooth surface of the product, such as in the case of rolling sheets, strips, wire and bars drawing, etc.
- Achieving the exact dimensions of the product (extruding, wire drawing, deep drawing, etc.).
- Increasing the strength and hardness of the formed material
- For non-recrystallizable alloys
- For the materials where hot forming is not possible because the surface of the material is so large that it cools down quickly due to its small cross-section
- For cheap and fast production of components at a satisfactory quality

Cold forming increases the material strength and hardness while reducing its ductility, which is an evidence of the material plasticity. This results in structure deformation and anisotropy of mechanical properties.

Hot forming refers to forming at temperatures at which recrystallization takes place so quickly that the solidification caused by forming process disappears during or immediately after forming. Hot forming takes place at temperatures higher than the recrystallization temperature. Hot forming processes include the processes that occur at the temperatures higher than 0.7 Ttav.

During hot forming, two processes take place simultaneously: destruction (deformation) and recrystallization.

Classification of forming by thermal effect

Depending on the amount of heat used for increasing the temperature of the formed metal, forming processes can be divided into:

- **isothermal** – the generated heat is in the environment, the temperature of the blank does not change.
- **adiabatic** – all generated heat remains in the metal formed, its temperature rises.
- **polytropic** – the generated heat is partly in the environment and partly remains in the metal formed. This type of processes in the most frequent one in practice.

Classification of forming by the deformation:

By the ration between the free surface of the formed material and the material in touch with the tool, the technological forming processes can be divided into three groups:

- the free surface is larger than the surface which is in touch with the tool (free forging)
- the free surface of the material formed is approximately of the same size as the material in touch with the tool (forging in open dies)
- the free surface of the formed material is smaller than the surface in touch with the tool (forging in closed die forging, extrusion).

5.1. Shearing – classification and principle

Shearing is one of the most frequently used operations in mechanical engineering production, used for manufacturing semi-finished products for making finished blanks or as an auxiliary operation for manufacturing mechanical engineering products. Shearing is an operation during which a part of the material is gradually or immediately separated by a shearing tool.

The basic shearing operations include:

- punching (making holes)
- trimming (separating unnecessary material)
- blanking (cutting out a part of material)
- parting
- lancing (partial cutting of material)
- shaving (achieving more precise shapes)
- fine blanking (precision blanking)
- plunging

Shearing in shearing tools:

It is the most widely used method of making blanks. Basic operations include punching and blanking.

Shearing die is a cutting tool – tool for making blanks of a specific shape and dimensions (Figure 9.1).

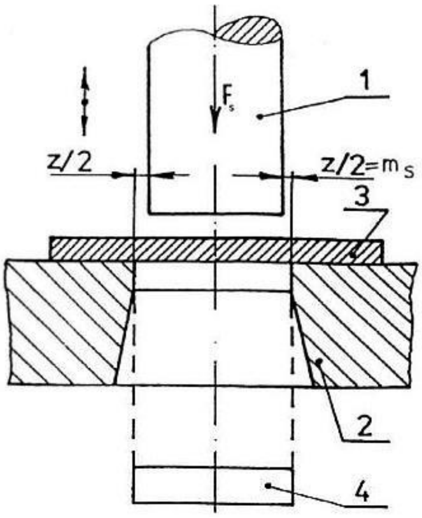


Figure 1 Shearing tool, z – die clearance, m_s *-blade gap, 1. Shearing punch, 2. Shearing die, 3. sheared material (sheet strip), 4. Sheared material (blank)*

Shearing process can be divided into three basic stages:

- **elastic deformation** – at the beginning of acting of the blanking tool on the material, elastic deformation occurs in the material until the stress at the point of shearing reaches the yield strength Re. This stage is 5 – 10 % of the material thickness.

- **plastic deformation** – after exceeding the maximum yield strength at the point of shearing the stress is increased until the maximum shear strength. This stage is the 10 – 25 % of the material thickness
- **fracture** – when shear strength is exceeded microscopic and macroscopic cracks are formed in the material, which causes separation of material parts.

Shearing can be hot or cold. Cold shearing is used for soft materials and tin sheets. Hot shearing is used for stronger materials of higher thickness. Shearing can be carried out using: parallel blades, inclined blades, circular blades or in shearing dies.

Shearing tools:

- simple shearing die (Figure 3)

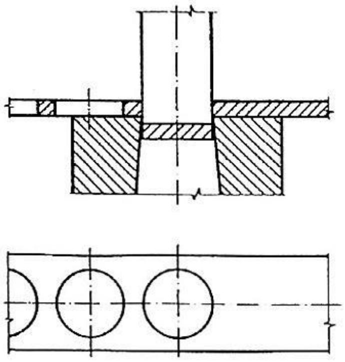


Figure 3 Simple shearing die

- combined shearing die (Figure 4)

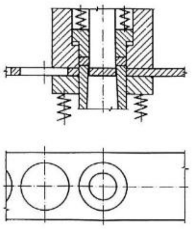


Figure 4 Combined shearing die

- progressive die (Figure 5)

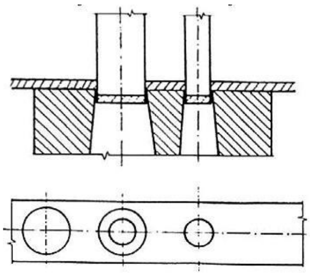


Figure 5 Progressive die

- compound die (Figure 6)

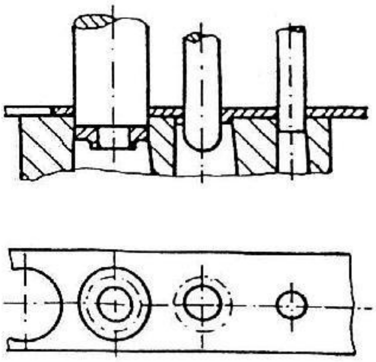


Figure 6 Compound shearing die

5.2. Bending – classification and principle

Bending is a technological process in which the shape of a semi-finished product is permanently changed due to acting of bending moment caused by a pair of forces. Bending is a process by which the desired shape is without a significant change in the material cross-section; therefore, it is included in sheet forming.

The starting material is sheets, bars, profiles.

The movement is accompanied by reinforcement of the material, which changes its **strength properties** and subsequently also the **properties of the bent component**. This results in reduction in the weight of the **machinery units**.

Depending on the movement of the tool to the material, bending can be divided into two basic groups:

- Bending on bending press - material is bent in a bending die, a bender, whose movable part performs linear movements.
- Bending on bending rolls – as a tool, the rolls are used that perform a rotating movement

Bending on bending presses
Bending – the direction of the movable part movement is the same as the direction of the axis of the angle formed by the bent object shoulder, the bending line is usually shorter than the bending shoulder - Figure 7.

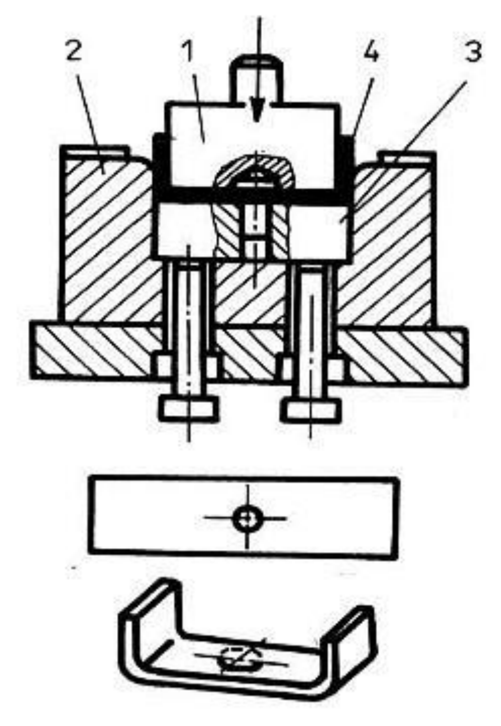


Figure 7 U-shape bending

1. *punch, 2. die, 3. ejector, 4. Bent pressing*

Brake bending – the process of making various profiles by progressive bending. The bending line is usually longer than the bending shoulders – Figure 8.

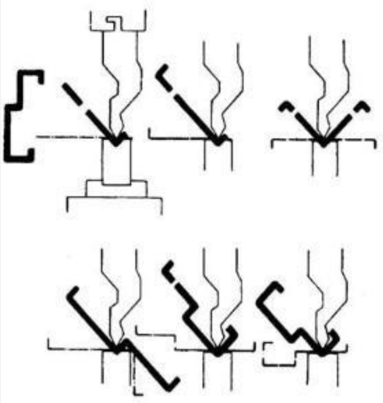


Figure 8 Brake bending

Roll bending – pressure is exerted on the material, causing movement of the sheet on the curved surface of the rigid jaw. The resulting shape can thus be achieved using different tools with a different acting on material – Figure 9.

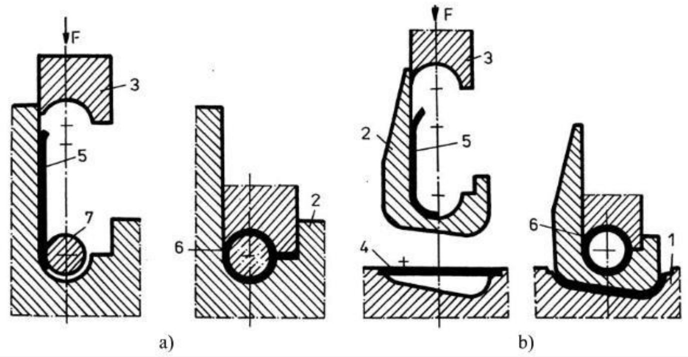


Figure 9 Roll bending
1,2 – die, 3 – punch, 4,5,6, - bent pressing, 7 – mandrel

Flashing – it is used to reinforce the edges of the pressing or to prepare for a joint

Tacking – acting on pre-formed bent flanges creates a rigid joint.

Bending on rolls
In this type of bending, the point of plastic deformation changes gradually. Based on the position of the bending plane to the rolls axes, we distinguish between the following methods (see Figures 10 and 11):

- **cross-rolling** – bending plane is perpendicular to the roll axis
- **longitudinal rolling** – bending plane passes through the axes of two rolls with a specific profile

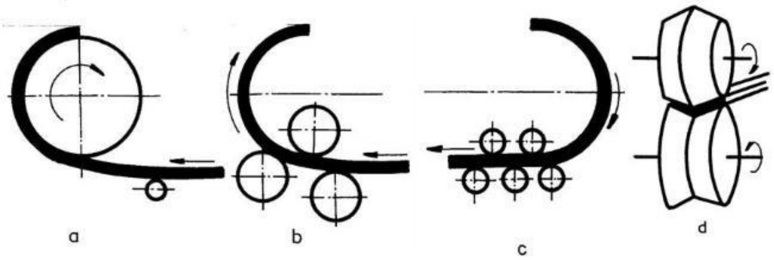


Figure 10 Roll bending
a – winding, b – roll bending, c –straightening, d – longitudinal rolling

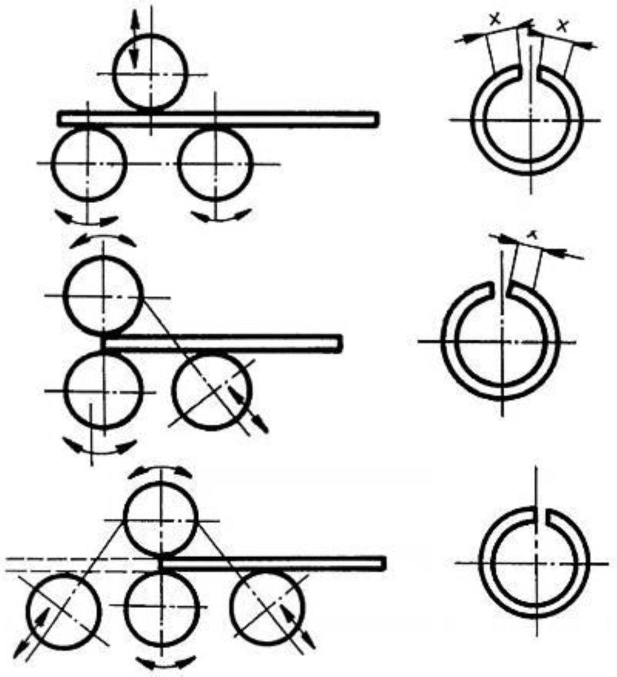


Figure 11 roll bending machines

three-roll symmetrical, 2. Three-roll asymmetrical, 3. Four-roll symmetrical

5.3. Drawing – classification and principle

Drawing is a technological process in which a spatial (hollow) body of a simple or complex shape is created from a sheet. The product manufactured by drawing is called a drawn product. Drawn product can be made for one or more operations (depending on its size and shape). Deformation of a planar object into a hollow body is realized in drawing machines / drawing tool, consisting of drawing punch, drawing die, blankholder (Figure 12).

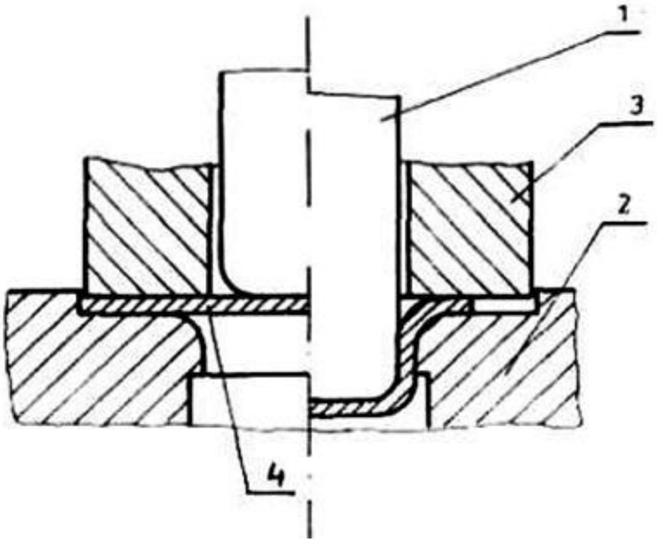


Figure 12 Drawing machine

1. drawing punch, 2. Drawing die, 3. blankholder, 4. Drawn sheet

Drawing is a frequently used technological process for manufacturing components of a complex shape, rigid, with a minimal weight. It is a very productive process.

Drawing is used for manufacturing components used in all spheres of human life, e.g. **metal kitchen containers, packaging for refrigerators, washing machines, ovens**. In automotive, it is used for manufacturing all passengers and truck body parts. Drawing as a technological operation is used for manufacturing parts of aircrafts, ships, toys, food industry, electrical engineering, etc.

Drawing machines have a specific design. Drawn sheet has to be held; therefore, the machine must have two guide blocks – drawing and holding.

Classification of drawing

- ordinary drawing
- thin-wall drawing
- reverse drawing
- beading (increasing the rigidity of the object by drawing shallow depressions)
- stretching (forming hubs or cylindrical walls for threads)
- expanding (increasing the perimeter)
- necking (reducing the perimeter)
- stretching using a drawing tool (forming simple products of larger dimensions of sheet metal clamped at opposite ends. The sheet is stretched by movement of a punch).

5.4. Spinning and extrusion – classification and principle

Spinning, sometimes called **metal spinning or rotating** is a forming process in which a metal sheet spins around the axis of rotation and by acting of spinning tool is moved from the centre to the edge of rotating semi-finished product. The product is called die casting. Metal spinning is a combined bend with deformation under rotation. Bending under rotation with additional pressure to a small volume creates a local plastic deformation and increase in malleability.

Although deep drawing is a sophisticated process, spinning, due to its advantages and flexibility, is a suitable technological production process. Due to its possibility of being used in serial production, spinning is more economical in the case of small and medium-sized enterprises - Figure 13.

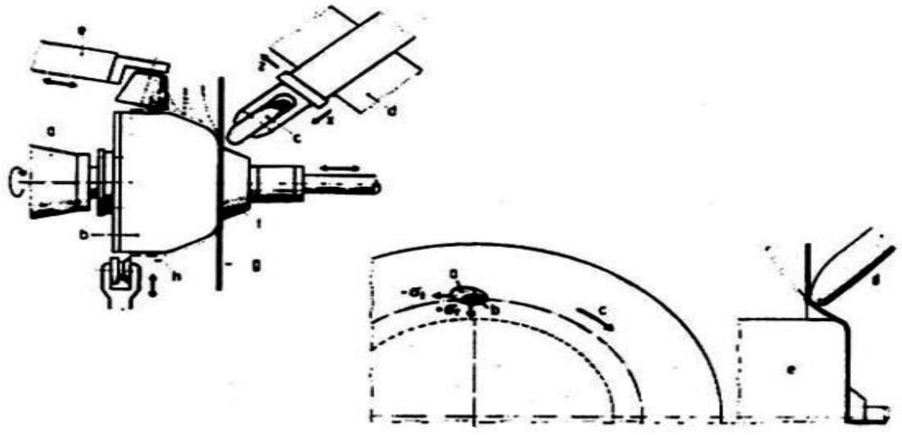


Figure 13 Spinning with more spinning operations

The material deformation at spinning is given by the ratio of clipping D_0 to inner diameter of the pressing d and it is calculated as $K=D_0/d$

The following operations are used for containers manufacturing:

- **Spinning that transforms a planar disc into a hollow container.** A part of it is only tapered or widened.
- **Thickness reduction spinning:** the starting semi-finished product is a drawn product or product manufactured by metal spinning.
- **Roller polishing** manufacturing products by multi-operation drawing.
- **Trimming**
- **Flashing** (to increase stiffness) and to reinforce the edges of pressing.

Extrusion is a basic operation of bulk forming and it is used for manufacturing the most complex shapes. In mechanical engineering, usually cold extrusion is used. The resulting shape of the component is made using a tool consisting of a die and a punch.

The forming force necessary for extruder acting on metal is through extrusion presses. The formed product is processed at a normal temperature of the environment. This is called cold extrusion. However, during the extrusion process, due to high pressure at high speed heat is generated in the component (up to 200°C). Despite this temperature, which is below the recrystallization temperature, this is referred to as cold forming. It increases the hardness and stiffness of the formed metal, while the ductility decreases.

Extrusion can cause high plastic deformation without disrupting the integrity of the material, although extrusion takes place under stress with prevailing pressure stress.

Basic extrusion methods:

Backward extrusion

At backward extrusion, the material flows against the direction of the punch movement. The semi-finished product first fills the lower cavity of the die. The bottom is either closed or with an ejector in it. Punch penetrates into the product, creating a cavity with a desired bottom thickness. The excess material flows through the gap between a punch and a die. Backward extrusion is used for manufacturing containers and cases (shells).

Forward extrusion

During forward extrusion semi-finished product is inserted into a die and pushed in the direction of the punch movement. The punch closes the opening in its movement into the die and the material flows in the direction of the punch movement. The resulting shape of the product is determined by the shape of the die and the depth into which the punch penetrates into the die. This method is used for manufacturing the products with a not fixed cross-section Figure 14.

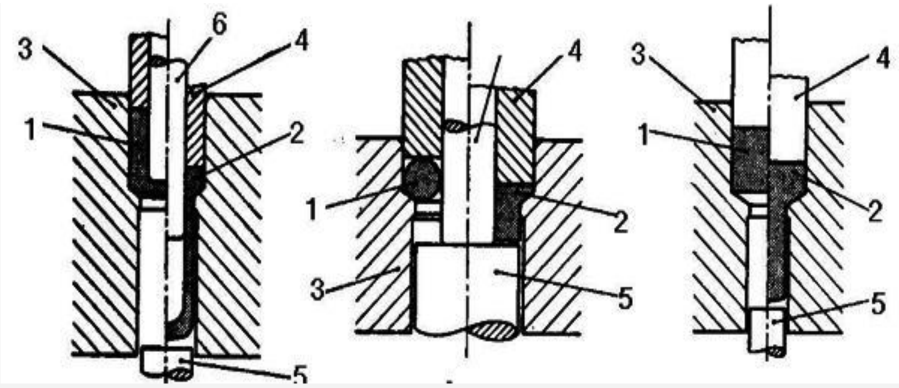


Figure 14 Forward extrusion

1. *Starting product, 2. Resulting shape of product, 3. die, 4. punch, 5. ejector, 6. mandrel*

Combined extrusion

Combined extrusion is a combination of forward and backward extrusion. The material moves both in and against the direction of the movement of the punch. The deformation at the bottom of the die must be smaller than in the upper part extruded by the punch, otherwise the bottom would not be filled with the material.

Side extrusion

Side extrusion is carried out in a split die so that it is possible to remove the product from the die. By press developed by upper and lower punch the material penetrates into the gap perpendicular to the direction of the punch acting. This method is used for manufacturing the components with protrusions around the product perimeter.

Sinking

Sinking is used for making functional tool cavities in order to make the cavity and increasing its life time. It is used most for production of coining die.

5.5. Free forging, die forging, hammer forging, press forging

Free forging is a technological operation trying to change a semi-finished product in order to achieve the required dimensions and shape.

Free forging operations are divided into **hand** and **machine forging**. Manual forging is done on anvil using hand forging tools. The material is heated in a forge or in smaller furnaces. Hand forging is very scarcely used nowadays (only for small repairs and artistic forging). Machine forging is done using hammers or presses.

For free forging, hammers are used. For forgings products of higher ram weight, hydraulic presses are used. Semi-finished product used is a rolled material or ingot.

Technological process of making forgings by free forging is very variable and often very complex. It includes a range of combined forging operations. The basic free forging operations include: ramming, tapering, stepping, offset forging, punching, cutting and bending.

Ramming – it refers to compression of the formed material while simultaneously decreasing its height and increasing the cross-section perpendicular to the direction of the compression (Figure 15).

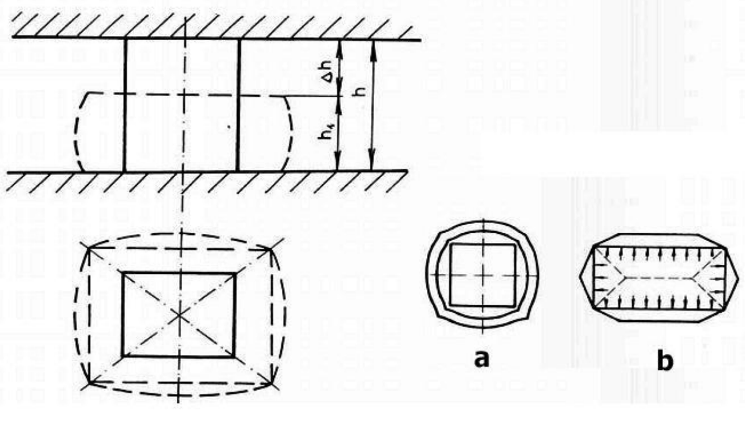


Figure 15 Free forging – ramming and change of cross-section in ramming
a – square cross-section, b – rectangular cross-section

Tapering – it is a forging operation increasing the length of the semi-finished product while decreasing its cross-section.

Stepping - is a forging operation in which a sudden passing of one part of forging into another part is created, with a simultaneous change of cross-section. For necking, flat or shaped punches are used.

Offset forging – it is an operation at which one part of forging is offset against the other either in one or two planes.

Punching – is a forging operation at which a hole is created by pressing a mandrel in a semi-finished product. The punch (mandrel) cross-section corresponds with the required shape of the hole. The punch can be full or hollow.

Cutting – is a forging operation which separates the semi-finished product into two parts or separates the excess material from the forging. Cutting tool (cutter) is pressed into the material, thus causing separation of the material. Cutter can be straight or shaped.

Bending – in free forging, bending is carried out in punches or by clamping the product between the punches and the free end is bent by crane, lever or chain.

Free forging machines
In industrial plants, machines most frequently used for free forging are pneumatic hammer, steam hammer and hydraulic forging presses.

Die forging is characterized by a directed metal flow in a two-part die cavity. The starting product is inserted into the bottom part of the die. Due to the energy of the forming machine, one die part moves against the other and the material fills the die cavity. When the cavity is filled, the die is closed and the material is formed in the required shape.

Dies used in forging:

- Open with a gap between the upper and the bottom part in the parting plane (with a flashing groove along the perimeter of the cavity).
- Closed without the flashing groove, the volume of the initial material equals to the volume of the forging.

Filling the cavity is affected by the speed of the deformation depending on the type of the tool used. The impact effect of hammers causes high speed of the material flow in the direction of the impact and static force of the press causes better filling of the cavities in the direction perpendicular to the force. These differences influence the choice of the forming machine and forging operation for a given component (Figure 16).

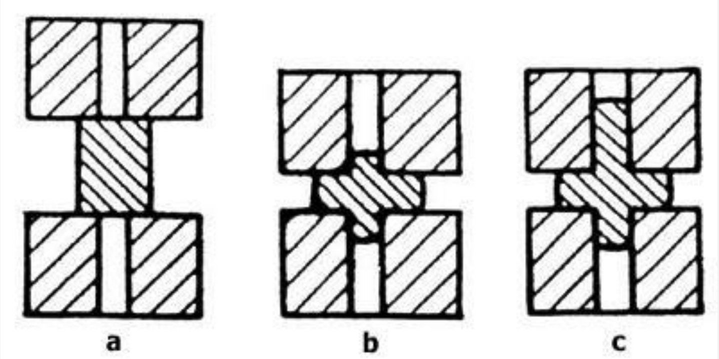


Figure 16 Filling the die cavity

a- Before deformation, b- press forging, c- hammer forging

Flashing groove is used to catch the excess material and for the regulation of the press in the cavity. When the cavity is filled, the excess material is pushed to the flashing groove. The amount of the metal (flashing) depends on the amount of the metal in the cavity and on the relation between the longitudinal section of the cavity and the blank. This determines the character of cavity filling. In filling the cavity by means of hammering, the flashing is smaller than in the case of sinking (Figure 17).

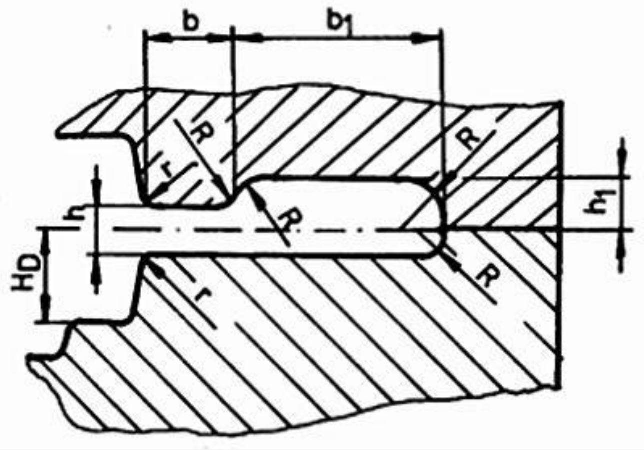


Figure 17 Flashing groove

5.6. Rolling – classification and principle

Rolling in mechanical engineering is used for manufacturing of flat blanks and finished forgings with repeated cross-section (e.g. black tools, rings of various diameters, etc.).

Rolling of rings
Rings of large diameters are manufactured by forming loosely on mandrel or by rolling. Rolling technology for rings is used in hot and cold forming. This technology is suitable for mass production and serial production, since the costs of single-purpose rolling equipment are high (Figure 9.18).

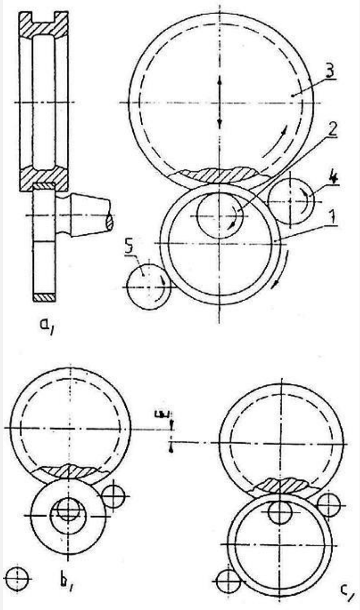


Figure 9.18 Rolling of rings

The starting material is a tube or billet that is hammered, die-forged, punched and then rolled. The ring is then placed on the support cylinder (2) and using advancing cylinder (3) the material is pushed and reduced at simultaneous rotation. The ring guide is secured by the cylinders (2, 4 and 5). When the required parameters are achieved, the control cylinder (5) stops the cylinder stroke (3). Rolling is used for manufacturing rings of a 2500-mm diameter.

Advantages of this technology:

- Machining allowances are smaller and thus the material consumption is reduced, the machining time is shorter, and the consumption of energy and tools is lower.
- Increases the bearing capacity of bearings and other (by nearly 40 %)

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