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VŠB – Technical University of Ostrava

Faculty of Metallurgy and Materials Engineering

Department of Materials Forming)

ADVANCED FORMING TECHNOLOGIES

Subject number: 633-0807

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Content

1. CLASSIFICATION OF FORMING PROCESSES

Time to study: 45 min.

Aim: After study of this chapter students will be able to:

- Differentiate individual forming technologies according to basic classification to classic and progressive,
- identify structural processes occurring during hot and cold forming, interval of forming temperatures, recrystallization and recovery temperatures.

Lecture

1.1. Introduction

Forming can be distinguished according to several criteria:

a) According to products: forming of semi-products, final products

b) According to temperature: forming under cold, warm or hot conditions

c) According to temperature effect occurring during forming (a larger portion of the total energy changes into heat):

1) Isothermal forming (at constant temperature) – the entire generated heat is transferred to the surrounding environment and thus the temperature remains constant.

2) Adiabatic forming (at constant heat) – the entire generated heat is accumulated in the deformed work-piece and is consumed by temperature increase. It is similar to high energy rate forming.

3) Polytropic – a portion of the generated heat is accumulated, a portion is transferred away. The temperature usually increases, but less than during adiabatic forming; is usually neglected during forming via conventional technologies.

d) According to effect of deformation force: static, dynamic (cyclic, by explosion).

e) According to relation of deformation zone to volume of the work-piece: bulk, sheet.

1. Bulk forming – the workpiece is subjected to a high strain, which results in significant changes in its shape and cross-section. The strain affects the entire work-piece, or its substantial part (the deformation zone is located in the entire work-piece, or in its substantial part). The work-piece surface (S) to volume (V) ratio increases significantly during forming. Plastic strain is critical for the volume of the work-piece, while elastic strain can be neglected. Intermediate products for bulk forming are ingots, slabs, blocks and rods of circular and else-shaped cross-sections.
2. Sheet forming – intermediate products for sheet forming are sheets or components produced from sheets. The deformation zone is located only in a portion of the work-piece volume. The imposed strain changes significantly the shape of the work-piece, but the change of its cross-section is not substantial. The V/S ratio of the work-piece and product change only marginally or do not change during forming. Plastic and elastic strains are equal during the process, a significant spring-back can even happen.

f) According to sources of energy and the method of its transfer to deformation zone, unusuality of technical design or processing parameters, the following categorization of forming methods has been established: conventional (usual, used in a casual production and for processing of casual materials), progressive (new, less usual).

1.2. Technological forming procedures

The technology of forming involves the design of processing procedure and selection of machines and devices (including lubrication) suitable for production of the desired product. From the intermediate product to the final product, the material is processed considering the requirements on the final properties. Individual procedures are organized with the aim to maximize productivity and minimize defects while maintaining favorable economy of the process.

The sequence of the individual hot forming steps serves to achieve changes in shapes of bulky work-pieces (ingots) and to refine and homogenize their original cast structures. Hot forming typically consists of multiple steps (passes, reductions) following closely one after another after initial pre-heating, the temperature of which provides the material with sufficient formability, low flow stress and a sufficiently high supply of heat, so that even rapidly cooling locations (e.g. edges) do not exhibit cracks during final processing steps. Nevertheless, even a too high heating temperature together with adiabatic heating can lead, for a rapidly deformed material in a cast state, to melting of segregations and subsequent material failure. The common characteristic of hot forming processes is gradual unification and refinement of grain size and gradual improvement of material formability. For a variety of products, hot formed material is only a semi-product, possibly a finished product. Its structure imparts final mechanical and usable properties. This applies to most of the forged-products, beam profiles and rails, thick sheets, hot rolled strips etc. In these cases, forming can be viewed as a set of technological procedures imparting shape to the material, but also as a set of procedures, which, via processing parameters (temperature regimes of heating and forming, strain, strain rate, inter-pass intervals, cooling process) essentially predetermines development of inner structure of the formed material.

1.3. Hot forming

Hot forming is defined as forming at such temperature-velocity conditions, at which the recovery and recrystallization, i.e. softening processes, occurring during deformation keep the flow stress at a low value.

During hot forming, strengthening and deformation texture occurring during forming are rapidly eliminated by development of new structure resulting from recrystallization. Significant reductions can be achieved, since softening processes are in equilibrium with the imposed strain. Flow stress decreases with increasing temperature. For pure metals, temperature of recovery and recrystallization can approximately be determined from the relations:

$$T_{rec} \geq 0{,}3\, T_{melt}$$
$$T_{rx} \geq 0{,}4\, T_{melt} \qquad (1.1)$$

where T_{rec}, T_{rx}, and T_{melt} are temperatures of recovery, recrystallizations and melting

The energy necessary to realize a process is generally lower for hot forming than for cold forming.

For the majority of common alloys, the forming temperature has to be higher than given by equation (1) to ensure the required recrystallization rate. Softening processes have almost no effect during cold forming, during which strengthening of the material occurs and deformation texture develops.

Conventional technologies: open die forging, rolling, extrusion, are the most commonly used hot forming technologies. They feature large strains (ε = 2 – 4), strain rates in wide ranges ($\dot{\varepsilon}$ = 0,5 – 500 s^{-1}) and temperatures above 0.6 T_{melt}. They result in decrease in chemical and structural inhomogeneity of cast structures, elimination of inner cavities, refining of cast structure, increase in formability and ductility of metal materials.
The low limit of the forming temperatures interval is generally the lowest temperature, at which recrystallization is rapid enough to eliminate strengthening caused by plastic deformation. For a given metal or alloy, the low forming temperature limit depends also on the overall strain imposed within the given time and at the given temperature. The higher is the strain, the lower is the recrystallization temperature and low forming temperature limit.

It also depends on the strain rate. A metal, which is deformed with a high strain rate and cooled rapidly down from the forming temperature requires, for the same deformation degree, a higher forming temperature than a material deformed and cooled slower.
The upper forming temperature of any material is limited by its melting temperature and temperature of intensive surface scaling. Important is especially the melting temperature of phases segregating at grain boundaries (primarily Fe, Ni and Mo-based sulphides and complex Fe, Mn, Si, Cr-based oxides).
The majority of hot forming technologies consist of a set of operations. Generally, the working temperature between the individual operations is maintained a little above the recrystallization temperature to ensure low flow stress and consequently low energy intensity of the process (directly related costs of energy and equipment). However, the final forming step is favorably performed at a temperature only slightly above the recrystallization temperature and with a relatively high strain to achieve fine grain size in the final product. The interval of forming temperatures is depicted in Fig. 1.

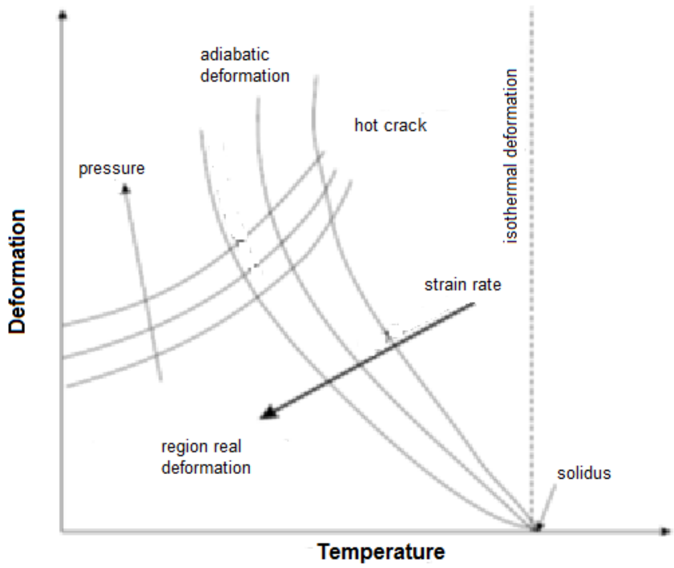

Fig. 1 Hot forming region limited by the mutual influences of temperature, pressure and strain rate

From the curves depicted in Fig. 1 can be seen that, for given forming pressure and temperature, only a certain strain can be imposed into the material. This is controlled by the dependence of flow stress on temperature.

The left set of curves shows that the possible reduction increases with temperature increasing theoretically up to the solidus temperature, but the practical limit is the region of cracks development during hot forming.

The right set of curves depicts the influence of strain rate. Increasing strain rate increases the flow stress and also temperature of the material due to generation of deformation heat.

Increase in temperature of the formed material depends on: the initial temperature of work-piece and dies, deformation heat generated by plastic deformation, heat generated by the influence of friction between the material and dies, heat transfer between the material, dies and surroundings.

Recommended literature:

[1] ASM HANBOOK – Metalworking: Bulk Forming (Vol. 14A). Materials Park, Ohio, 2005.

Summary and conclusion of the section:

- bulk forming - sheet forming
- hot forming - cold formin

2. STRENGTHENING OF METAL MATERIALS

Time to study: 90 min.

Aim: After study of this chapter students will be able to:

- Determine theoretic strength of metals,
- calculate strengthening increments for individual strengthening phenomena.

Lecture

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2.1. Introduction

Mechanical properties, especially strength and other properties derived from tensile tests results, are important for practice. They ensue from crystal structure and possible occurrence of lattice defects, especially dislocations, and their changes. The important parameter, having both the theoretical and practical significance, according to which materials are classified into groups determining their use, is the ultimate strength.

2.2. Strength

Strength is in the technological practice determined as the highest stress achieved during a tensile test. It can also be determined via pressure, bend or torsion loading. Conditions for the tests are given in standards. Among the ultimate strength, another parameter which can be determined using a tensile test is the yield strength (Rp0.2). Furthermore, elongation and contraction can be determined. Loading is uniaxial and homogenous from the beginning of the test till the moment, in which the cross-section of the sample starts to locally narrow and exhibits a local necking. In this location, three-axial stress state occurs, which also changes deformation conditions.

Theoretical strength is determined by inter-atomic forces. For metals, the maximum strength can be expressed as:

$$G/2\pi \qquad (2.1)$$

or approximately

$$E/10. \qquad (2.2)$$

In practice, the measured values are usually by 2 or 3 orders lower due to lattice defects, which facilitate slip and plastic deformation, decrease stress necessary for failure and thus also strength of the material. The highest strength have monocrystals with relatively low dislocation densities (whiskers), for which the strength can be of one order higher than for the same metal or alloy in a polycrystalline form.

2.3. Strengthening

The strength of pure metals is usually lower than desired. By this reason, methods for its increase – strengthening – have been developed. For pure metals, strength can be increased by cold forming or grain size decrease. In cases in which the mentioned means are not sufficient, pure metals are replaced with alloys. Strength can furthermore be increased by alloying for pure metals and by heat treatment for alloys. The methods can also be combined, e.g. alloying, forming and grain size controlling.

2.3.1 Deformation strengthening

Via e.g. extrusion, rolling, drawing, plastic deformation can contribute to fabrication of required shapes, and also to strengthening. During plastic deformation, decrease in the cross-section area, which can be expressed by the following relation, usually occurs:

$$\varepsilon_s = \frac{S_o - S_1}{S_o} \cdot 100 \qquad (2.3)$$

where S_0 and S_1 are cross-section areas before and after deformation, respectively.

Plastic deformation typically proceeds via slip, which preferentially proceeds in planes and directions with the highest atomic densities. Slip is initiated by motion of dislocations in active slip planes at stresses higher than the critical resolved shear stress values. The value of the critical resolved shear stress depends on the type of the metal, its purity and state and on deformation conditions. Higher strains imposed into polycrystalline materials activate multiple slip systems (minimum five for metals and alloys with cubic lattices) according to orientation and magnitude of the acting force and deformation conditions. Under certain conditions, deformation proceeds via generation of twins. Twins generate typically in systems with lower number of slip planes, e.g. in metals with hexagonal lattices, or at higher strain rates and lower temperatures. The rate of twin generation in crystals is close to the rate of sound propagation in the given metal.

Strengthening during slip mechanism is caused by increase in density of dislocations and their accumulation on obstacles, which results in increases in the critical resolved shear stress and consequently in the yield and ultimate strengths. On the other hand, strengthening caused by twins generation is relatively low. Other consequences of plastic deformation can be changes in physical parameters, especially in those depending on the amount and behavior of lattice defects (electrical conductivity, magnetic properties etc.).

The maximum achievable strengthening is an important material parameter and is directly related to the shear modulus for KPC metals. The following relation is usually used:

$$\left(\frac{d\sigma}{d\varepsilon}\right)_{\max} = (200 \div 300) \cdot G \qquad (2.4)$$

Strengthening is significantly influenced by temperature and loading rate, the temperature changes not only the absolute values of stress, strain and strengthening. If we want to compare strengthening curves of various metals, we have to do it at homologous temperatures. An example of strengthening curves for various metals is depicted in Fig. 1.

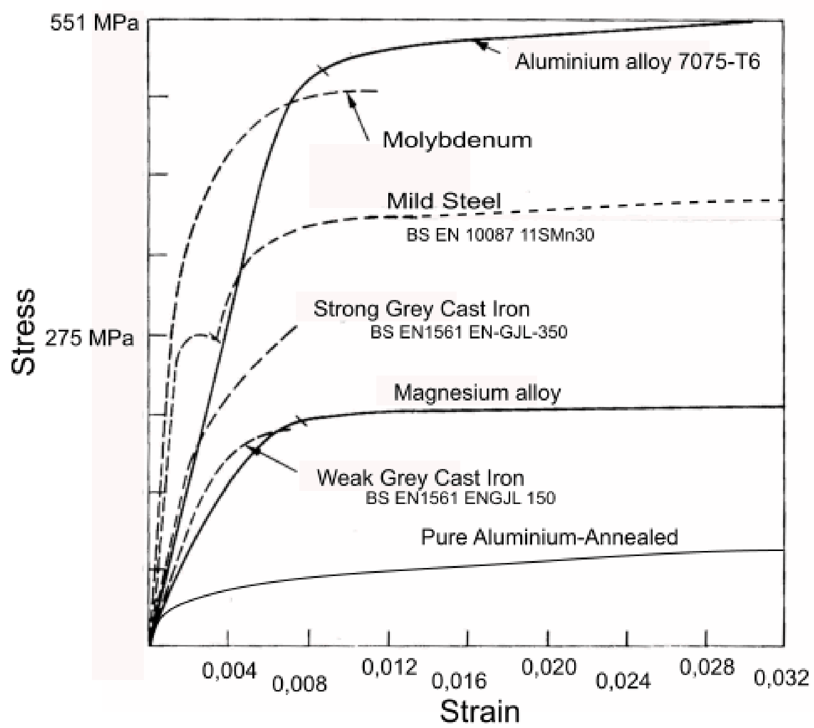


Fig. 1. Strengthening curves for selected metals

Materials formed under cold conditions are in non-equilibrium states. The influence of temperature can initiate softening processes, e.g. recovery or recrystallization, which can cause the metal to lose strengthening imposed via plastic deformation. Generally, materials strengthened by plastic deformation under cold conditions should be used only at temperatures at which they were formed, or lower. Softening processes depend on the temperature, crystal lattice of the metal and the overall strain imposed under cold conditions. Therefore, the temperature for usage of cold formed materials cannot be unambiguously limited. For example, for a very pure copper, softening processes can occur already at the temperature of 100 °C. Therefore, metals with low melting temperatures can only be used at ambient temperatures.

2.3.2. Strengthening by grain boundaries

Grain boundaries are substantial obstacles for dislocations movement. During plastic deformation, dislocations cumulate in the vicinities of grain boundaries and generate on grain boundaries. The following Hall-Petch relation was derived to describe the dependence of the properties of metal materials on the grain size:

$$Rm = \sigma_o + k \cdot d^{-1/2} \quad (2.5)$$

where σ_o and *k* are constants independent on the grain size *d*.

σ_o represents the value of stress necessary for movement of dislocations in the basic material without consideration of grain boundaries, while *k* represents the influence of grain boundaries on the induced slip process in neighboring grains, yet plastically undeformed. σ_o can be determined from the critical resolved shear stress in monocrystals and depends on temperature. The constant k depends less on temperature.

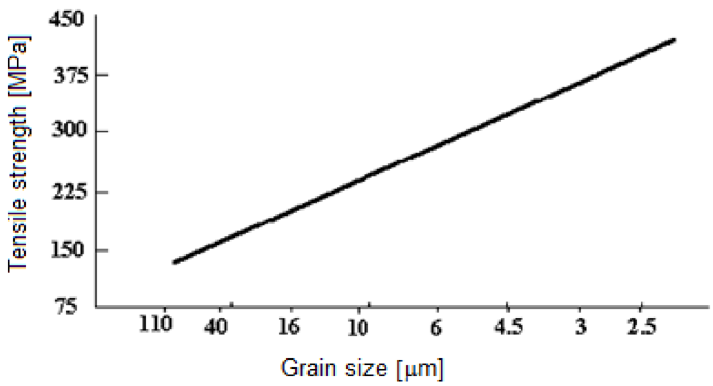


Fig. 2 General dependence of strength properties on grain size

Fig. 3 depicts the dependence of yield strength on grain size for copper and aluminum. The Hall-Petch relation is generally applicable for all metals. More detailed investigations have shown that the exponent is not identical for all materials and that it varies from -1/4 to -1.

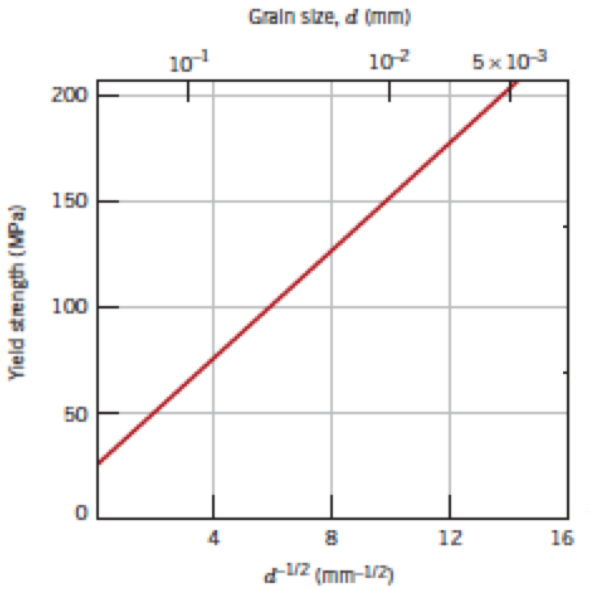


Fig. 3 Dependence of Yield strength on grain size (for coarse-grained materials)

The increase in strength of metals caused by newly generated dislocations can be determined by the equation:

$$\sigma_d = G \cdot b\left(\rho + \frac{3m}{d}\right)^{1/2} \tag{2.6}$$

where G is shear modulus, ρ is dislocation density in the original metal, m is dislocation density, b is burgers vector, d is grain size.

The overall strength of metals can be predicted using the equation:

$$\sigma = \sigma_F + G \cdot b \cdot \rho^{1/2} \cdot \left(1 + \frac{3m}{\rho \cdot d}\right)^{1/2} \tag{2.7}$$

where σ_F is basic strength of the metal without any dislocation strengthening. If the dislocation density of the original metal is low, the dependence of strength on grain size is a function of $d^{-1/2}$. If the dislocation density is high (e.g. $3m < \rho.d$ after deformation), equation (2.7) can be modified:

$$\sigma = \sigma_F + G \cdot b \cdot \rho^{1/2} + \frac{3G \cdot b \cdot m}{2\rho^{1/2}} \cdot \frac{1}{d} \quad (2.8)$$

It is obvious that the dependence of strength on grain size is a function of d^{-1}. This can be put together with the Hall-Petch relation and modified:

$$\sigma_o = \sigma_F + G \cdot b \cdot \rho^{1/2} \quad (2.9)$$

which includes strength of the original material counting in the influence of dislocations in the original state. From the comparison ensues also the following value:

$$k = \frac{3G \cdot b \cdot m}{2\rho^{1/2}} \quad (2.10)$$

which specifies coefficient (k) of grain size influence.

The value of m in equation (2.10) can be defined using experimentally determined values of strengths at various grain sizes.

Contrary to strengthening by plastic deformation, the influence of grain boundaries is permanent due to equilibrium conditions (if grain growth does not occur). However, the influence of grain size on strength and other properties depends on temperature. The maximum increase in strength is achieved for fine-grained materials at low temperatures.

2.3.3. Strengthening by alloying

Presence of a larger amount of different atoms in the basic metal lattice distorts its arrangement and, when differences in atoms sizes are significant, also causes elastic deformations of the solid solution crystal lattice. Formation of solid solutions is influenced not only by different atom sizes, but also by electrochemical factor and difference in valences. The range of solid solutions is the larger, the more similar are the alloying elements to the basic metals, especially considering atoms sizes and valences. Alloying elements also influence behavior of lattice distortions in the basic lattice. All the above mentioned also influence properties of solid solutions and arrangements of atoms. Instead of ideal substitute arrangement, solid solutions feature areas with short-period arrangements. A short period arrangement develops when the difference of valences is positive, i.e. if the alloying element has a higher valence. When the difference of valences is negative, the alloying atoms form clusters.

Substitutional atoms in the lattice of the basic metal act as obstacles and increase stress necessary for dislocations movement, which increases the yield and ultimate strengths. The influence of alloying elements on shear stress τ_o in dependence on their concentration c is described by the equation:

$$\tau_o = \tau_{ks} + Z_1 \cdot G \cdot \zeta^{3/2} \cdot c^{1/2} \quad (2.11)$$

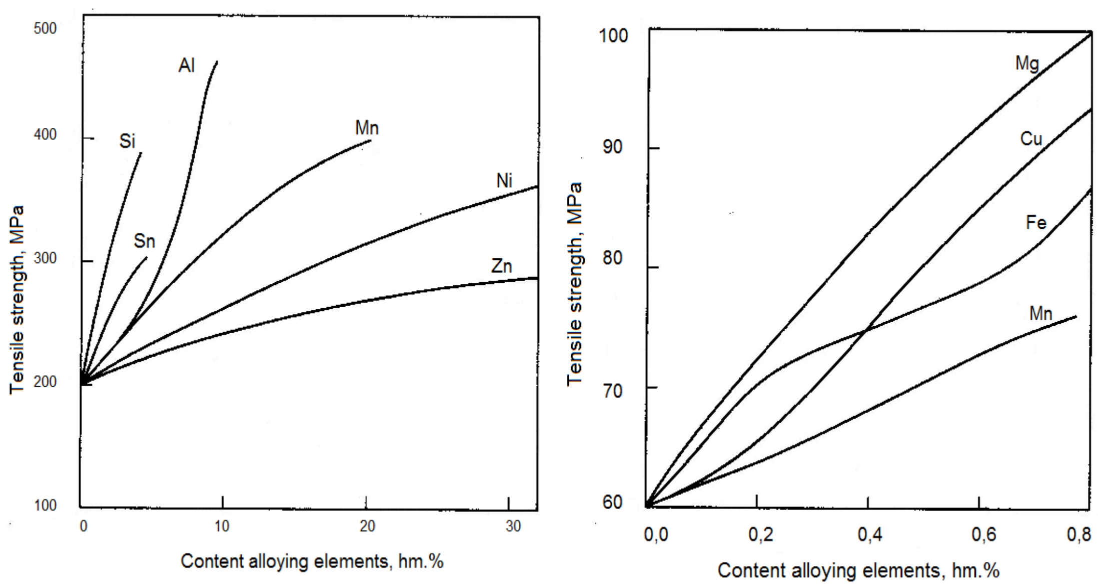
where $\tau_{K\sigma}$,φe is critical shear stress for pure metal, Z_1 is constant, G is shear modulus, ξ is combined alloying parameter, which includes change in lattice parameter and stress.

Equation (2.12) can be modified as:

$$\tau_o = \tau_{ks} + Z_2 \cdot G \cdot \quad (2.12)$$

where Z_2 is a constant different than Z_1.

The influence of concentration of alloying elements on strength of Cu, Al and Ni-based alloys is depicted in Fig. 4.



a) b)

Fig. 4 Influence of concentration of alloying elements on strength of: a) Cu-based alloys, b) Al-based alloys

From the mentioned relations ensues that the maximum effect of strengthening by solid solutions can be expected in systems with maximum differences in atomic diameters of both the elements.

2.3.4. Precipitation strengthening

The strength of solid solutions, the solubility of which decreases with temperature, can be increased by heat treatments – precipitation or hardening. The principle lies in rapid cooling of a solid solution from the temperature of its maximum solubility resulting in acquirement of an oversaturated solid solution, from which then, at ambient or increased temperatures, very fine structural phases precipitate. These increase strength and hardness of the alloy, although at the expense of plastic properties. The first part of the process, i.e. heating to the temperature of homogenous solid solution followed by rapid cooling, is denoted as solution annealing, while the second part is denoted as ageing, which can be either natural (at ambient temperatures), or artificial (at elevated temperatures).

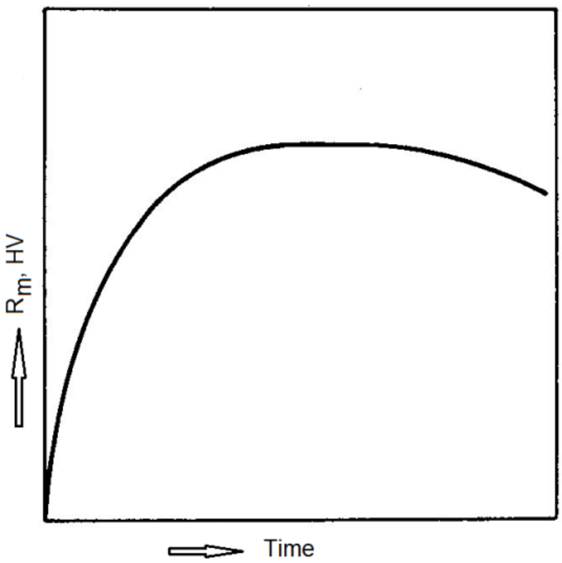


Fig. 5 Change of properties of Al-based alloy in dependence on precipitation time

An oversaturated solid solution is unstable, since precipitation occurs continuously. Changes of selected properties depending on precipitation times are depicted in Fig. 6.

Development and growth of precipitates are influenced significantly by temperature. From this ensue not only conditions for optimization of the entire process, but also limited applicability of properties at elevated temperatures. To achieve maximum strength, it is necessary to ensure conditions, under which temperatures and times resulting in over-ageing are not exceeded. Plastic deformation after solution annealing accelerates development of precipitates. The strengthening rate increases and the entire ageing process shortens. The maximum value of strength or hardness is also higher than for natural ageing.

2.3.5 Dispersion strengthening

Dispersion strengthening refers to the last stage of precipitation strengthening and is characterized by generation of stable non-coherent equilibrium precipitates. Equilibrium phases segregate from an oversaturated solid solution in compositions and volumes corresponding to the appropriate equilibrium diagrams. During plastic deformation, dislocations usually pass by such obstacles and the strengthening rate is indirectly proportional to the distance between obstacles.

An idea occurred, to use this means of strengthening to artificially introduce obstacles by generating or alloying of suitable compounds into the basic metal or alloy, which subsequently act as efficient obstacles for dislocations movement. The requirements are for the individual particles to be the finest possible and uniformly distributed in very short distances. A characteristic feature of such systems is that the strengthening particles are located within the basic phase. Typically, the systems consist of metals or alloys with intermetallic compounds. Dispersion systems are characterized with the volume of the added particles, their dimensions, distance and distribution function. It is necessary to take into account their crystal structure, shape and phase boundary.

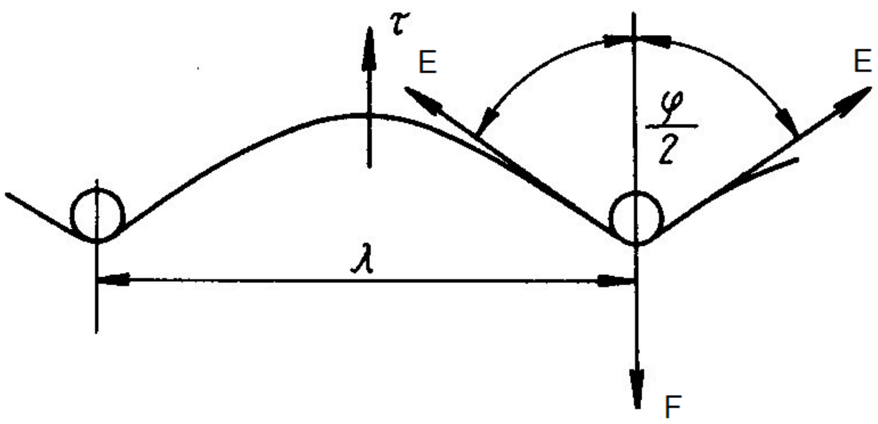


Fig. 6 The effect of obstacles during dislocation movement

Strengthening induced by a presence of dispersion particles can be expressed by an increase in resistance against dislocation movement. Second phase particles can be impermeable and then dislocations have to pass them by (Orowan mechanism), or dislocations can cut them through at stresses lower than the Orowan stress. When a dislocation gets pinned between two obstacles, it bows by the effect of stress τ till the angle φ between the two arms of the dislocation reaches a certain critical value and the dislocations breaks (Fig. 6). The strength of an obstacle F related to dislocation stress is then given by the relation:

$F = 2E.\cos \varphi/2$ (2.13)

and the stress causing breaking of a dislocation can be determined by:

$$\tau\tau = \frac{F}{b \cdot \lambda} = \frac{2E \cdot \cos\varphi / 2}{b \cdot \lambda}$$ (2.14)

where λ is effective distance between particles.

In practice, the goal is to determine the value of λ and validate the correspondence of the model with real values, including validation for concrete systems. Generally, the equation for shear stress increment can be given as:

$$\Delta\tau = \frac{\alpha \cdot \beta \cdot \gamma \ \cdot G \cdot b}{\lambda}$$ (2.15)

where G is shear modulus, b is burgers vector, α determines influence of distribution and orientation of particles, β determines particles size and γ determines dislocation properties.

Dispersion strengthening is important especially for components used under higher temperatures. Among mechanical properties, physical properties, such as electric conductivity, change as well. Alloys featuring optimum properties can be achieved by suitable combinations. To prepare such systems, conventional metallurgical processes, as well as powder metallurgy methods, can be used. Non-metallic compounds (mostly oxides, but also nitrides, borides, silicides etc.) can generate directly in given systems by reactions, e.g. by internal oxidation, or they are directly alloyed into the systems during their preparations.

2.3.6 Spinodal decomposition

Some solid solutions are not stable within the entire range of compositions and temperatures. During cooling, solid solutions decompose to two solid solutions of different compositions and identical crystallographic structures (Fig.7).

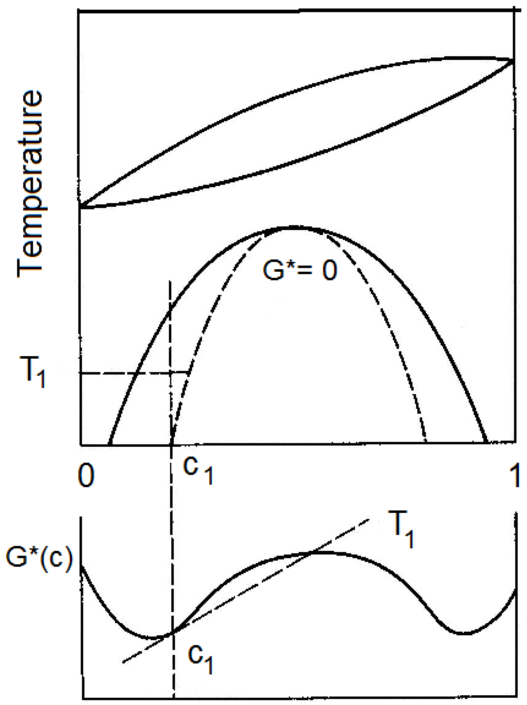


Fig. 7 Principle of spinodal decomposition

This is denoted as spinodal decomposition Contrary to precipitation, decomposition of an oversaturated solid solution process spontaneously without any incubation period. Within an oversaturated solid solution, periodically repeated regions with lower and higher concentrations of alloying elements develop. With increasing time these regions of concentration changes develop larger, as do concentration differences. Curious is that the diffusion process against the concentration gradient and decomposition is finalized by establishment of equilibrium compositions at a given temperature.

From a comparison of spinodal decomposition and hardening is obvious that a consequence of the spontaneous process of structural changes is a faster change in mechanical properties occurring during spinodal decomposition. Decomposition can occur already during cooling and then solution annealing and ageing is not necessary.

2.3.7. Strengthening by fibers

The highest strengths were achieved when whiskers were used (thin monocrystals), although wires of polycrystalline metals and alloys and even fibers from plastics and glass can also be used. Such materials are denoted as composites. A basic matrix with lower strength transfers deformation to fibers featuring higher strength. Cohesion of the fibers and basic materials has to be perfect and must not be deteriorated by reactions on contact surfaces. Fibers have to exhibit higher tensile elasticity moduli and suitable shapes to ensure the largest possible

contact areas with the basic material. A suitable volume to surface ratio has to be achieved. Therefore, thin fibers or laminas are the most convenient. Force is transferred via shear stress. The final strength depends not only on the volume of introduced fibers, but also on their diameter to length ratio, since shear stress increases with increasing fiber length and the maximum strengthening can be achieved only at a certain length. Fig. 8 shows the dependence of increase in strength for precipitation and dispersion strengthening (in dependence on particles sizes and volumes) and for materials strengthened by fibers (in dependence on the ratio of fibers length *L* to their diameter d_f at various relative volumes V_f). Strengthening is expressed by the ratio of $R_{P0.1}$ of the strengthened and basic materials.
Metallic whiskers feature strengths around 15 000 MPa and whiskers of non-metallic compounds (nitrides, borides, but also oxides) feature similar or even higher strengths (up to 25 000 MPa).

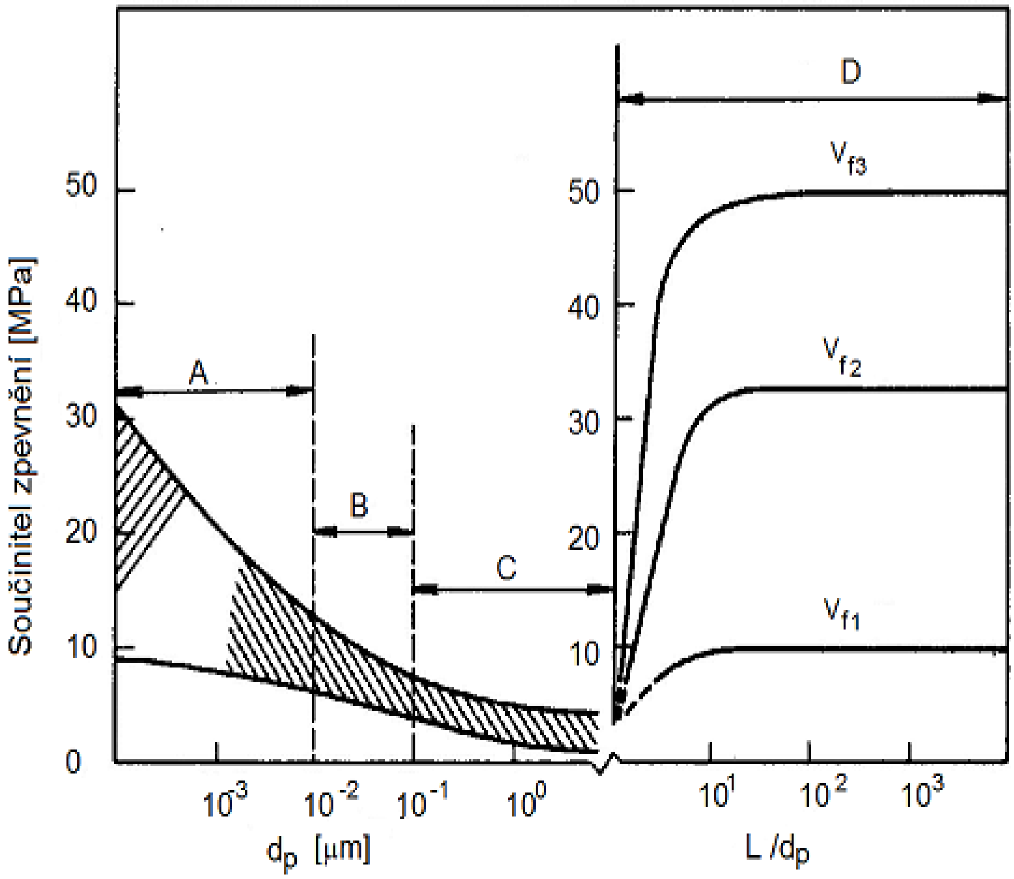


Fig. 8. Comparison of various strengthening methods: *A* – solid solutions and precipitation strengthened alloys; *B* – dispersion strengthened alloys; *C* – cements; *D* – composite materials strengthened by fibers; d_p – particles size; d_f – fiber diameter; L – fiber length.

Fibers of metals and alloys have strengths from 2 000 to 4 000 MPa. The mostly used fibers are: steel, fibers from titanium, molybdenum, tungsten alloys etc. Typical is application of wires with diameters around 0.1 mm. An example of the increase in strength of copper reinforced with tungsten fibers is depicted in Fig. 9

Examples of strengths of selected systems are depicted in Tab. 1. Due to their high price, composite materials are at present only used for special cases. However, their wider application is presupposed in future.

Table 1. Strengths of alloys reinforced with fibers.

Základní materiál	Vlákna	Obsah vlákna (obj. %)	Rm (MPa)	Poznámka
Cu	W	65 - 75	1 560 - 1740	
CuNiS	W	76 - 79	1 530 - 1720	
CuAlS	W	63 – 76*	692 – 1082*	*křehký lom
CuAlO	W	76	970	křehký lom
CuTilO	W	78	1565	
Al-Mg-Si	Fe	39	1350	
Al-Mg	Fe	35	1200	E = 115 GPa

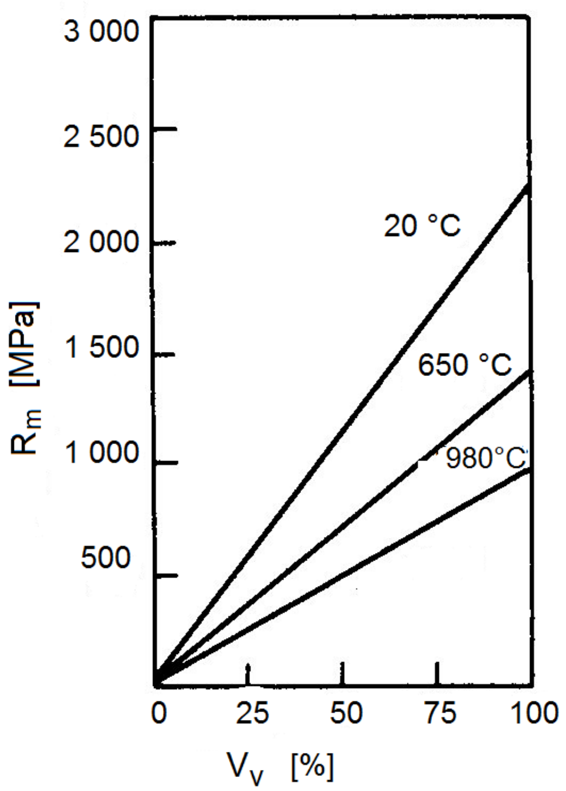


Fig. 9 Increase in strength of copper with various contents of tungsten fibers

Summary and conclusion of the section:

At present, the attention is paid to strengthening processes. By calculations, the courses of strengthening curves have been determined. These are closely similar to experimentally obtained curves.

Questions

1. Which strengthening methods are used in metal systems?
2. Describe the process of strengthening during plastic deformation and precipitation.

Recommended literature:

[1] ASKELAND, D.R. et al. The Science and Engineering of Materials (Sixth Edition). Global Engineering,2010, pp. 923.

[2] ASM HANBOOK – Metalworking: Bulk Forming (Vol. 14A). Materials Park, Ohio, 2005, pp. 888.

[3] MONNET, G. et al. Orowan strengthening at low temperatures in bcc materials studied by dislocation dynamics simulations. Acta Materialia, 2011, Vol. 59, pp. 451–461.

3. HYDRO-MECHANICAL DEEP DRAWING

Time to study: 90 min.

Aim: **After study of this chapter students will be able to:**

- describe selected technologies of forming by liquid, determine their pros and cons, application in industrial practice and will be acquired with formed products assortment.

Lecture

3.1. Introduction

Sheet or bulk forming can generally be categorized in two large groups, conventional and non-conventional forming methods. Conventional methods are known methods widely used in production. Machines for these methods are often economically more available than machines for non-conventional methods. Non-conventional methods are new methods developed via modifications of conventional methods, or by applications of new technologies. These methods bring about many advantages comparing to conventional methods.

Forming by liquids belong to non-conventional forming methods, for which liquid is used as non-solid forming devices serving as forming surroundings. The liquid replaces punch or plunger, possibly another tool, the production of which is often costly. Equipment for forming by liquid can either be individual machines, or it can be additional equipment of hydraulic presses. Purchase cost of such equipment is high, thus these methods are used for forming in serial productions. These methods are used to produce complicated and precise components. Liquids have their application also during forming and bending of tubes, during which they are advantageously used to stabilize the bent.

3.2. Technology of Hydro-mechanical deep drawing (HMDD)

Hydro-mechanical deep drawing can be categorized as a progressive sheet forming technology. Contrary to the conventional deep drawing technology, HMDD uses, instead of a conventional blank holder, a die (draw ring), which is usually filled with a water-based emulsion. A groove with sealing is located in the vicinity of the drawing edge. The pressure liquid represents the blank holder including the drawing edge. A cut-piece of sheet (hold-down cylinder) is placed on the pressure plate, while its lower side is in contact with the level of the liquid in the die cavity. After the blank holder fixed on the outer ram of the press touches down, closing and sealing of the cylinder-die cavity system happens. By pushing of the punch on the sheet and by its entering into the liquid, a steep increase in pressure occurs in the die cavity, which results in shaping of the sheet by collaring around the entire punch surface till the final shape of a hollow cylinder component is achieved. Overflowing liquid is drained out from the die cavity through control and regulation systems of the machine. The value of pressure changes during drawing. The pressure is required to be regulated especially during drawing of thin sheets with wall thicknesses around 1 mm.

Hydro-mechanical deep drawing (HMDD) represents a technically and economically progressive technology of deep drawing by a working liquid and belongs to non-conventional technologies of sheet forming. The mentioned technology can be applied to produce deeper hollow vessels, of rotary and non-rotary shapes, as well as drawings with flanges.

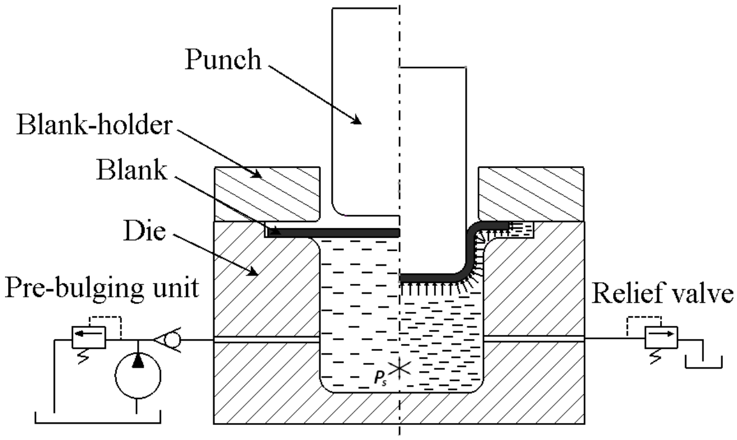


Fig. 1 HMDD technology

At present, there are various technologies derived from the basic HMDD method. From the constructional point of view, these are especially the following: double acting drawing, drawing with rotary punch, drawing with movable chamber bottom/walls, drawing with pushing ring, reverse drawing, drawing with a second draw, drawing into a chamber with transducer, and finally drawing with the first and second draws. For example, during double acting drawing, a single cylinder punch is replaced by a cylinder punch with a shoulder. This enables production of more complex product shapes.

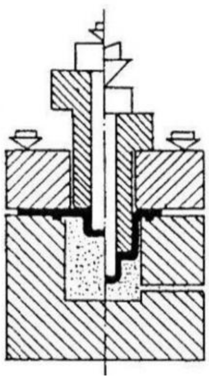


Fig. 2 Double acting drawing

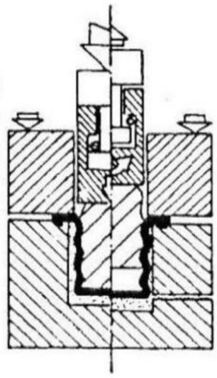


Fig. 3 Drawing with rotary punch

3.2.1 Advantages of HMDD

Decrease in number of processing steps, lower number of inter-pass annealings, high-quality surfaces and shape accuracy of drawn products, minimum thinning of the products in the bottom bends (only 2-3%), possibility to drawn surface-treated sheets (with no damage).

3.2.2 Disadvantages of HMDD

The necessity to use specialized devices and presses, only drawn products with flanges can be produced when the basic method is applied, high holding pressure.

3.2.3 Materials applicable for HDMM forming

- carbon steels grade 11 (Rm 280 to 500 MPa): ČSN 11 300, 11301, 11 302, 11 304, 11 305, 11 320, 11 321, 11 342 and 11 402.
- stainless steels grade 17 (Rm 500 to 700 MPa): 17 240, 17 241, 17 242 and 17 246.
- copper and its alloys (Rm 206 to 390 MPa): ČSN 42 3003.11, 42 3004.11, 42 3005.11, 42 3016.11, 42 3201.11, 42 3202.11, 42 3210.12 and 42 3215.13.
- aluminum (Rm 70 to 100 MPa) and its alloys: ČSN 42 4003.11, 42 4004.11, 42 4005.11.

Σ

Summary of the section:

During forming of complex components by the HMDD method, the mass of the products can be decreased while maintaining their stiffness. Formed components are often used in automotive industry

Tasks: Describe applied technologies of hydro mechanical deep drawing.

4. EXPLOSIVE FORMING

Time to study: 90 min.

Aim: After study of this chapter students will be able to:

- describe selected technologies of forming by liquid, determine their pros and cons, application in industrial practice and will be acquired with formed products assortment.

Lecture

4.1. Introduction

Metallic materials are formed by a shock wave invoked by: combustion of gaseous mixtures, explosion of a propellant, explosion of an explosive. Contact of the formed material with energy source can be direct (approximating), or transmitted by a carrying medium, water, sand, possibly air, or by a solid instrument. Graphical depiction of the individual possibilities is shown in Fig. 1.

4.2. Explosive forming by a gaseous mixture

Energy sources are usually flammable gasses: hydrogen, methane, propane, butane. Subsequently, they are mixed with oxygen and inert gases. The combustion speed of an explosive mixture can be regulated by added volume of inert gases (He_2, Ar_2, N_2, CO_2). This method is used to form thin-walled products of smaller dimensions. It requires a massive die of a relatively complex construction.

4.3. Explosive forming by propellants and explosives

Propellants and explosives are characterized by the following parameters: heat of explosion (expresses the amount of energy chemically bound in 1kg of an explosive), detonation velocity (velocity of the chemical reaction), relative working capacity, i.e. relative effective energy – REE (coefficient of energetic efficiency of an explosive compared to the standard

Nitroglykol efficiency). Propellants feature relatively low combustion velocity (~ 2000 ms^{-1}) and explosion pressure (2 GPa). A slower development of heat from propellants can be transferred to formed components. Propellants are used to form components of smaller dimensions.

The carrying medium is most often water or sand. Calculation of the charge is based on determination of the relation between the deformation energy necessary to invoke forming of a product and the energy released by an explosive. For the energy contained within an explosive it is necessary to calculate with its loss during transformation from chemical to pressure energy and loses in transferring environment.

Loses describe efficiency of the process:

$$\eta c = \eta ch \cdot \eta p \cdot \eta d \qquad (4.1)$$

where ηc, ηch, ηp, η_d are overall, chemical, transfer and deformation efficiency of the process.

The overall efficiency ηc of explosive forming is around 10%.

Explosive forming is a technology suitable for single-part productions of large components, for which forming devices cannot be applied due to large dimensions of the components or insufficient outputs of presses. It is also suitable for forming of materials with low formabilities and for production of prototypes. It features low costs of equipment, usually only die. A schematic depiction of individual methods of explosive forming is in Fig. 1.

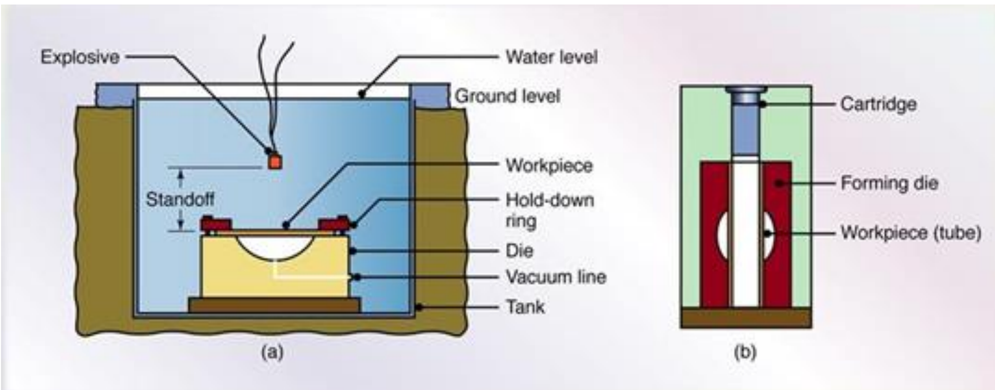


Fig. 1. Schematic illustration of the explosive forming process (a), Illustration of the confined method of the explosive bulging of tubes

Tasks: Describe advantages and disadvantages of explosive forming technologies.

5. ELECTROHYDRAULIC AND ELECTROMAGNETIC FORMING

Time to study: 45 min.

Aim: After study of this chapter students will be able to:

- describe the principle of influence of individual parameters on plastic deformation,
- predict application of the mentioned technologies in industry.

Lecture

5.1. Introduction

The principle of electrohydraulic forming is creation of a blast wave within a liquid via discharge, by releasing of electric energy by condenser discharging. The discharge can be released: a) between two electrodes, b) via exploding wire.

The principle of electromagnetic forming is based on discharging of electric energy accumulated in a condenser battery. The energy is discharged within 10 to 100 milliseconds through an induction coil, a strong pulse magnetic field generates, which induces plastic deformation in the material.

5.2. Electrohydraulic forming

5.2.1 Discharge via spark gap

Amplitude of the pressure in a ball shock wave reaches the value of 105 MPa within the time interval of 10^{-6} s. Energy W_E accumulated in condenser has to be higher than the deformation energy by losses of the process:

$$W_E = \frac{1}{2} C U^2 = \eta_c \cdot W_{def} \qquad (5.1)$$

where C is capacity, U is voltage, η_c is overall efficiency.

The pressure on the shock front is a function p=f (discharged energy W_E, inductivity, working spark gap length, geometry of electrodes, their number and locations).

The arrangement of electrodes (spark gap) in the technological entity in shown in Fig. 1.

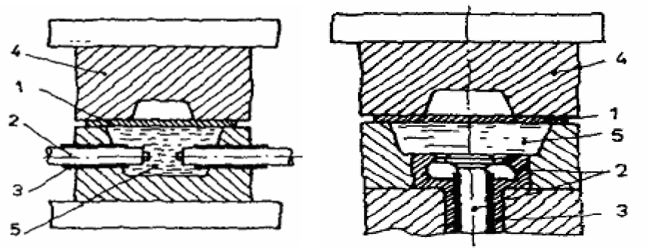


Fig. 1 Arrangement of electrodes in technological entity

1 – workpiece, 2 – electrodes, 3 – insulation, 4 – instrument, 5 – water area

For components of large dimensions and complex geometries, the shock wave can be directed and concentrated by reflectors (Fig. 2).

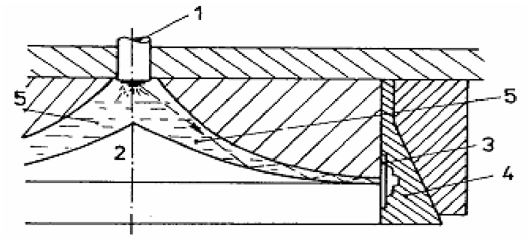


Fig. 2 Technological entity with reflectors

1 – electrode, 2 – reflector, 3 – workpiece, 4 – instrument, 5 – liquid

5.2.2 Discharge via exploding wire

Bridging of the spark gap using a wire can bring about the following advantages: vapors of evaporated wire increase expansion pressure, wire can direct shock wave movement, efficiency of discharge increases and magnitude of applied voltage decreases. Disadvantage is the necessity to input new wires for repetitive discharges. Arrangement of the device is shown in Fig. 3.

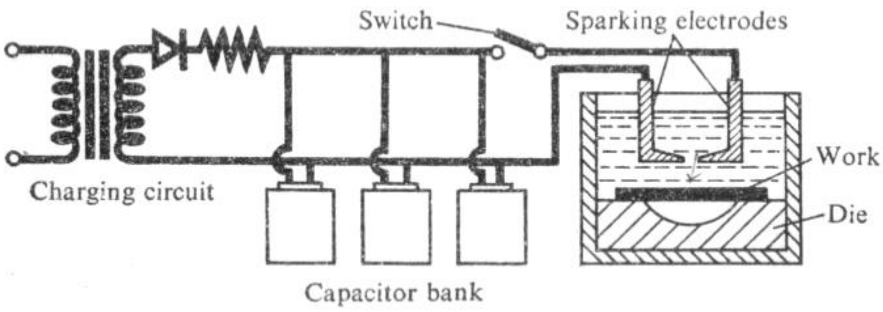


Fig. 3 Schematic depiction of device for electrohydraulic forming via exploding wire

5.3 Electromagnetic forming

The principle of the method is discharging of electric energy accumulated in a condenser battery within 10 to 100 milliseconds through an induction coil, which invokes generation of a strong pulse magnetic field. Current is induced in a formed material (magnetic conductor) inserted into the magnetic field, which generates its own magnetic field. Forming is performed by repulsive forces of both the fields. In the commonly used devices, the pressures usually reach up to the orders of 1000 MPa. A basic scheme of the device is shown in Fig. 4.

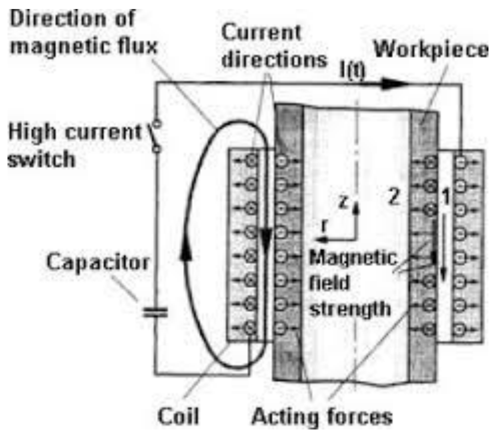


Fig. 4 Schematic depiction of electromagnetic pulse device

Section summary:

According to the mutual positioning of the coil and workpiece, forming can be categorized as: expansive (coil is within workpiece cavity), compressive (workpiece is within coil cavity).

Magnetic field can be rectified by so called concentrators. Concentrators enable to increase technological elasticity (by replacement of concentrators), simplicity (without movable components) and consequently ensuing reliability, low noisiness, high and uniform pressures, low weight of the device.

Recommended literature:

[1] ASM HANBOOK – Metalworking: Bulk Forming (Vol. 14A). Materials Park, Ohio, 2005.
[2] BAČA, J. BILÍK, J. Non-conventional forming methods – explosive forming (Nekonvenčné metody tvárnenia - tvárenie výbuchom), Trnava, 1991, 25 p.

6. HYDROSTATIC EXTRUSION

Time to study: 45 min.

Aim: After study of this chapter students will be able to:

- describe the principle of influence of hydrostatic pressure on plastic deformation,
- predict application of the mentioned technologies in industry.

Lecture

6.1 Introduction

Hydrostatic extrusion is defined as an extrusion under cold or hot conditions, during which direct contact of the punch with material is replaced by application of a high-pressure medium surrounding the workpiece from all sides. The principle of the method is shown in Fig. 1.

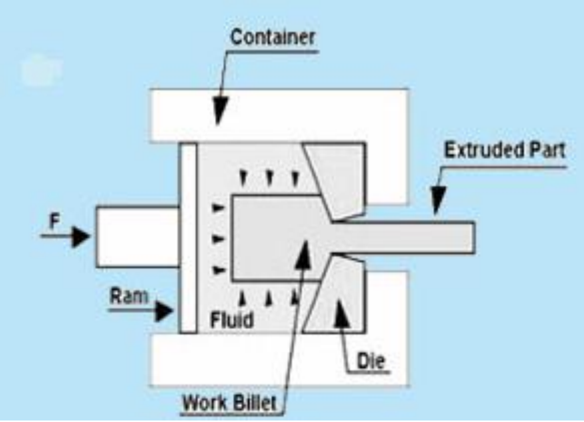


Fig. 1 Principle of hydrostatic extrusion

For hydrostatic extrusion, single-purpose hydrostatic extrusion presses or hydraulic presses with specialized equipment are used. The mostly extruded materials are carbon and alloyed steels, multilayered materials combining ferrous and non-ferrous metals, Al, Mg, Cu alloys, composites, materials with low plasticities (Mg, Mo, Be, W) and high-speed steels.

6.2 Pros and cons

1) During conventional extrusion, the extrusion force is increased by friction forces occurring at container walls. Likewise is the length of the extruded workpiece, which limits the workpiece length. During hydrostatic extrusion (HE), contact of the

workpiece with container wall does not occur and workpiece length is practically unlimited.

2) During conventional extrusion, short shots (waste) containing up to 15% weight of the workpieces occur.
3) During HE, hydrodynamic lubrication regime can be induced, brittle materials can be formed, extruding pressures can be decreased and thus loading of the instruments can be decreased and their lifetimes increased.
4) deformation degree can be increased, as well as extrusion speed and formability of the extruded material.

The main disadvantage ensues from compressibility of the working medium (some liquids compress by up to 30% at the pressure of 2500 MPa).

The consequence is decreased stability of the process accompanied by crumpling of the extruded material surface. The effect of force is transferred on the formed material via a pressure medium (with a certain compressibility), which results in an unsteady linking of the pressure source with workpiece.

The hydrostatic pressure reaches its maximum value at the beginning. As soon as the material begins to move, friction coefficient decreases from the quiescent value to movement value, workpiece accelerates and pressure decreases to the value necessary to continue the movement. Then the process is repeated. This results in an unstable extrusion velocity, which is related to pressure oscillation.

The pressure media have to meet the following requirements: uniformly transfer pressure load and feature low compressibility. Physical and chemical reactions with material, instruments and lubrication should be minimal. They should enable application of a wide interval of working temperatures, feature low thermal conductivity and thermal capacity. Viscosity and lubricating properties have to be stable within the range of working temperatures. At present, cold extrusion is almost always performed with liquid media.

Section summary:

Hydrostatic extrusion was developed especially to form materials with low formabilities. Theoretic principles for formability increase at hydrostatic pressure are mathematically described using the Kolmogorov equation.

Recommended literature:

[1] ASM HANBOOK – Metalworking: Bulk Forming (Vol. 14A). Materials Park, Ohio, 2005

7. INFLUENCE OF ULTRASOUND ON PLASTIC DEFORMATION

Time to study: 45 min.

Aim: After study of this chapter students will be able to:

- analyze physical principles of the influence of ultrasound on plastic deformation,
- predict application of ultrasound in industry for selected forming technologies.

Lecture

7.1. Introduction

The influence of ultrasound on plastic deformation was investigated for various metals and alloys. During a tensile test, ultrasound was turned on after the yield strength had been exceeded and the deformation stress decreased by 40%. After turning off the ultrasound, the stress increased again to its original value. For a sample loaded by a constant static stress, its decrease by the influence of ultrasound is constant even when strain increases. When ultrasound is cyclically turned on and off, the static stress decreases by approximately 10%. When ultrasound affects the sample from the beginning of a tensile test, the stress curve has a significantly flatter character.

The flow stress of metal materials changes by the influence of ultrasound. The value of the change depends primarily on the intensity of the acting ultrasound energy. Up to a certain (limiting) value, decrease in flow stress always occurs. The course of change of the flow stress depends on the intensity of the ultrasound energy, type of the material and its physical and mechanical properties, type of the ultrasound system and sound distribution scheme, temperature, stress-strain conditions of the test, moment of turning the ultrasound on and effecting time.

The higher is the energy density, the lower is the flow stress, and after exceeding the limiting value also the better is the strengthening. Materials with higher initial strengths, strengthening more intensively, with higher elasticity moduli, higher acoustic impedances and lower melting temperatures decrease the flow stress with ultrasound less intensively.

7.2. Physical principle of the effect of ultrasound on plastic deformation

The mechanism of the effect of ultrasound on the process of plastic deformation can be evaluated from the point of view of metals physics, or from the point of view of mechanics, Fig. 1 – 2. According to the first point of view, the outer signs of the effect of ultrasound can be explained by its contribution to the forming process – activation of blocked dislocations and initiation of new ones.

Fig. 1. Double-slotted block horn and ultrasonic transducer with attached mounting structure for ultrasonic compression tests.

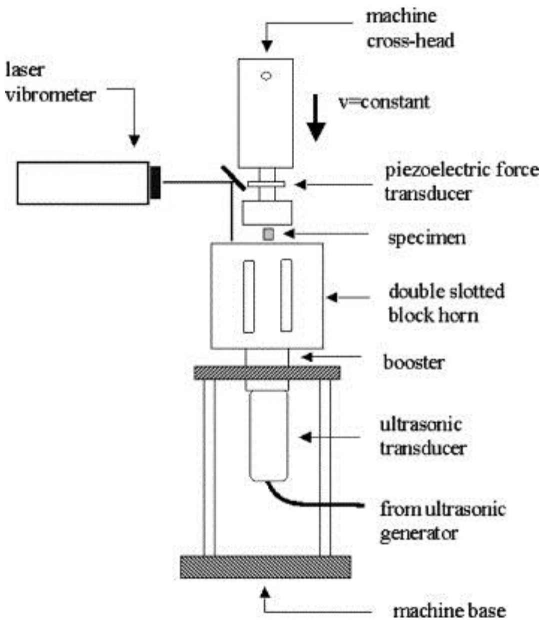


Fig. 2. Schematic of an ultrasonic compression test.

Ultrasound can be a form of energy, by which plastic flow can be continued or renewed in the material. The mechanism of plastic deformation with ultrasound differs from the mechanism of deformation at a static stress by the fact that activation of dislocations occurs in the entire material volume, in grains with different orientations, basically uniformly. Cross-slip occurs at significantly lower strains. By development of cross-slip, generation of other dislocation sources is supported. The consequence of this is a progressive growth of plastic flow.

Ultrasound activates generation of vacancies as well. During plastic deformation, a complex interaction of dislocations, point, planar and volume defects occurs. Dislocation slip leads to generation of point defects and, on the other hand, dislocations are advantageous locations for pinning of vacancies. A presence of a large number of jumps and concentration of vacancies together with the effect of outer and inner stresses can lead to climb of dislocations at normal temperatures. A high concentration of vacancies can not only be a cause for edge dislocations to climb, but can also stimulate cross-slip of screw dislocations. A simultaneous effect of the cross-slip and climb of dislocations enables both the dislocation components to overcome obstacles in movement.

Section summary:

Ultrasound is primarily absorbed by lattice defects. This increases their energy and thus the ability to release from pinning and overcome obstacles in movement. Migration of dislocations under the effect of ultrasound has been proved by numerous studies. However, no unambiguous answer to the question, by which mechanism are dislocations activated via ultrasound, has been given so far.

Recommended literature:

[1] DUTTA, R.K., PETROV, R.H. et al. Accommodation of plastic deformation by ultrasound-induced grain rotation. Metallurgical and materials transactions A, 2015, Vol. 46A, pp. 3414-3422

[2] ASM HANBOOK – Metalworking: Bulk Forming (Vol. 14A). Materials Park, Ohio, 2005.

[3] SALINAS, V., LUND, F., MUJICA. N. In situ monitoring of plastic deformation using ultrasound. Acta Materialia, 2000, Vol. 48, pp. 517–524.

[4] REED-HILL, R. E., ABBASCHIAN, R. Physical Metallurgy Principles, WS Publishing Company, Boston, 1991.

8. RADIAL FORGING

Time to study: 90 min.

Aim: After study of this chapter students will be able to:

- describe technologies of forming on radial forging machines, determine their pros and cons,
- analyze courses of stress and strain in forged rod.

Lecture

8.1 Introduction

By forging of longitudinal products on radial forging machines, materials with low formabilities can be processed (Ni, Ti alloys, tool steels). Driving of working tools (strikers) is mechanic, or hydraulic. When mechanic driving is applied, the housing contains four independent symmetrically positioned strikers (Fig. 1).

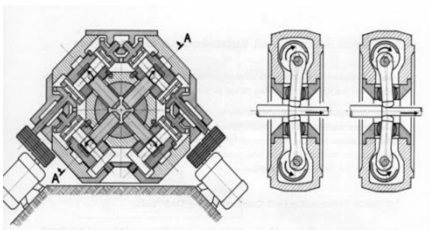


Fig. 1 Schematic depiction of strikers of radial forging machine

Reductions in individual passes can be adjusted using eccentrics for each of the opposite pair of strikers individually, or simultaneously. The described system enables the modern types of radial forging machines (e.g. SX 90, SX 16) to forge rods of circular, rectangular or hexagonal cross-sections. Manipulators controlling infeed speed, reductions and stroke areas of the working parts of the strikers are located at both sides of a forging machine. Manipulator jaws rotate the forged rod during forging of circular workpieces. During forging of flat, rectangular or hexagonal rods, manipulator jaws are fixed in stationary positions.

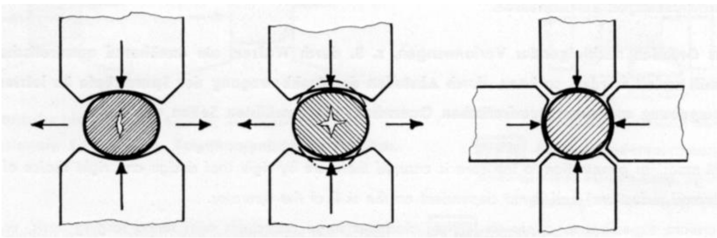
Strikers of various shapes can be used. Universal strikers are used to forge circular and rectangular cross-sections (Fig. 2).

Fig. 2 Shapes of strikers for forging of rods of circular and rectangular cross-sections

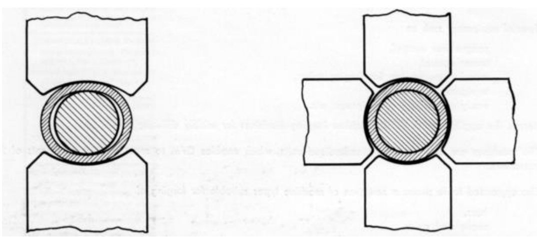
8. 2. Radial forging machines

The strain rate is comparable to strain rates achievable during forging on hydraulic forging presses. This advantage is used for forging of highly-alloyed materials, for which the flow stress increases significantly and formability decreases with increasing strain rate.

By forging on radial forging machines, quality of forged rods can be increased. This applies to their surfaces, as well as to their internal structures and their homogeneities. Occurrence of surface defects during forging is practically impossible. This is given primarily by elimination of tensile stresses on the forged surfaces. The difference between conventional forging on presses using two punches and radial forging using four strikers is depicted in Fig. 3.



a) c)



b) d)

Fig. 3 Forging of solid and hollow rods on a press (a, b) and on a radial forging machine (c, d)

The depth to which the plastic strain affects the material, depending on relative stroke area, influences the quality of forged rods as well. A schematic depiction of the depth to which the plastic strain affects the material during forging on radial forging machines is shown in Fig. 4.

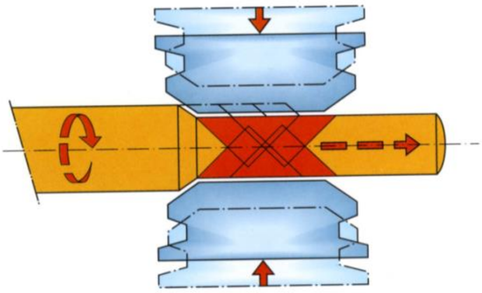
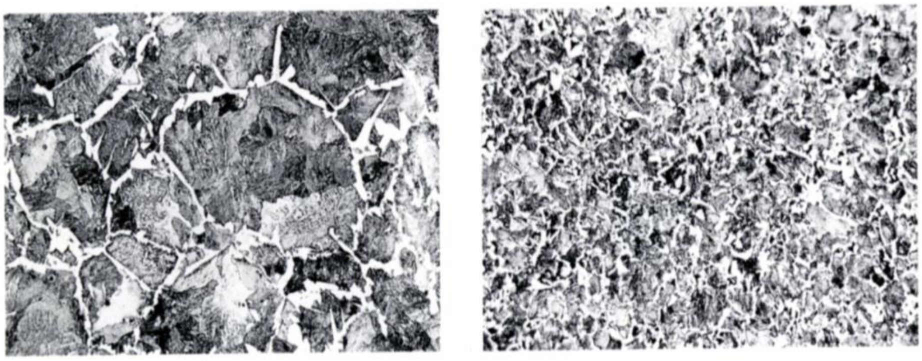


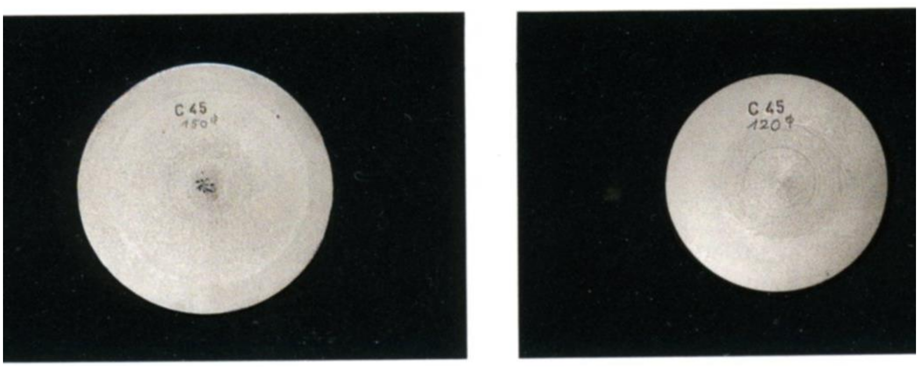
Fig. 4 Depth to which the plastic strain affects the material during forging on radial forging machines

Requirements of customers for microstructures are already quite common. Usually, fine-grained structure is required. The development of structure for C45 steel after deformation is demonstrated in Figs. 5 and 6.



a) b)

Fig. 5 Development of C45 steel microstructure: a) initial structure, b) after forging on radial forging machine



a) b)

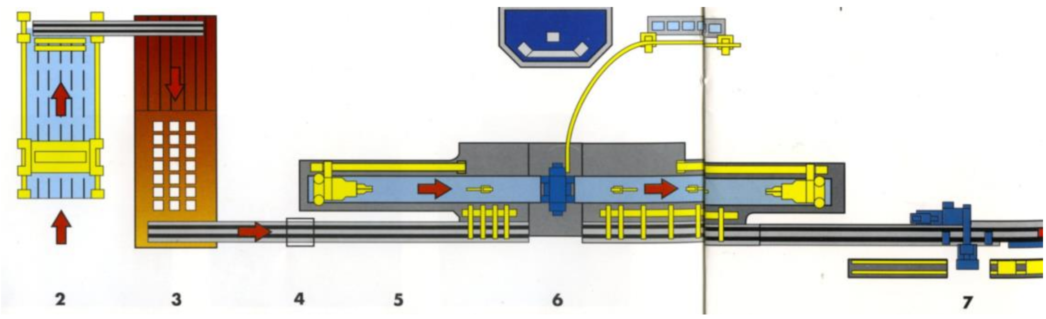
Fig. 6 C45 steel macrostructure: a) initial structure, b) after forging on radial forging machine

By forging of rods on radial forging machines in combination with controlled cooling after the final forging and consequent heat treatment, the required properties can be achieved within the entire lengths of the forged products. A photo of forging of a rod with a circular diameter on an EUMOCO radial forging machine is shown in Fig. 7, while a schematic depiction of a forge equipped with a radial forging machine is shown in Fig. 8.

The process of production of forged pieces is the following: Heated material is fed by a grip-type auto-manipulator on a roller conveyor of a forging machine, from which it is further rolled over to a feeding device and inserted into manipulator jaws and forged to the required diameter and dimensions. The forged rod is then taken out by a similar technology on the roller conveyor, on which it is transported to a circular saw, by which it is cut (being still warm) to required lengths.

a) b)

Fig. 7 Forging of rods on radial forging machines: a) EUMOCO, b) SXL



8.3 Forging tools

The tools (strikers) are manufactured from creep-resistant steels. A scheme of the shapes of used strikers is in Fig. 9.

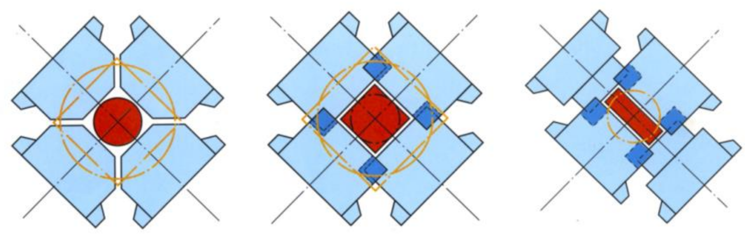


Fig. 9 Basic shapes of rotary forging machines strikers

Section summary

Alloys of metals with low formabilities can advantageously be forged using radial forging machines. A larger relative stroke area during forging has a positive influence on the quality of longitudinal products due to a greater depth to which the plastic strain affects the material.

Tasks: Calculate forging degree for rods forged on radial forging machines.

Recommended literature:

[1] DOMBLESKY, J. P. et al. A review of radial forging technology including preform design for process optimization. The Ohio State University. COLUMBUS, OHIO, 1994, pp. 97.
[2] Radial forging machines SMX. Leaders in plant construction and machine engineering. SMS GROUP, 2014, pp. 22.
[3] LAHOTI, G. T., ALTAN, T . Analysis of the radial forging process for manufacturing rods and tubes. Journal of Engineering for Industry, 1976, | Vol. 98, Issue 1, pp. 265-271.
[4] YANG S. Research into GFM forging machine. Journal of Material Processing Technology, 1991, Vol. 28, pp. 307–319.

9. FORMING TECHNOLOGIES IN THE STAGE OF DEVELOPMENT

Time to study: 90 min.

Aim: After study of this chapter students will be able to:

- describe forming technologies being prepared,
- evaluate advantages and disadvantages of their industrial application.

Lecture

9.1. Introduction

Hot production of steel strips with thicknesses t ≤ 1.0 mm using devices of conventional rolling plants is difficult. The rolling speeds required to achieve necessary temperatures for finishing rolling increase with decreasing thickness of the rolled strip and decreasing velocity enabling transport to rolling plant runout. The technology solving the mentioned issues is "endless rolling", during which workpieces are welded together before entering the finishing stands. This creates an endless strip, which is then, after rolling has been finished, divided into coils of required weights.

The described process has been introduced by a rolling plant in Japan. It is the basis for growth of productivity of the entire rolling plant. By realization of the mentioned process, loses of profits have been decreased and steel quality has been increased, as well as necessary energy was decreased. A scheme of the hot endless rolling process of the Kawasaki Steel Works company is shown in Fig. 1.

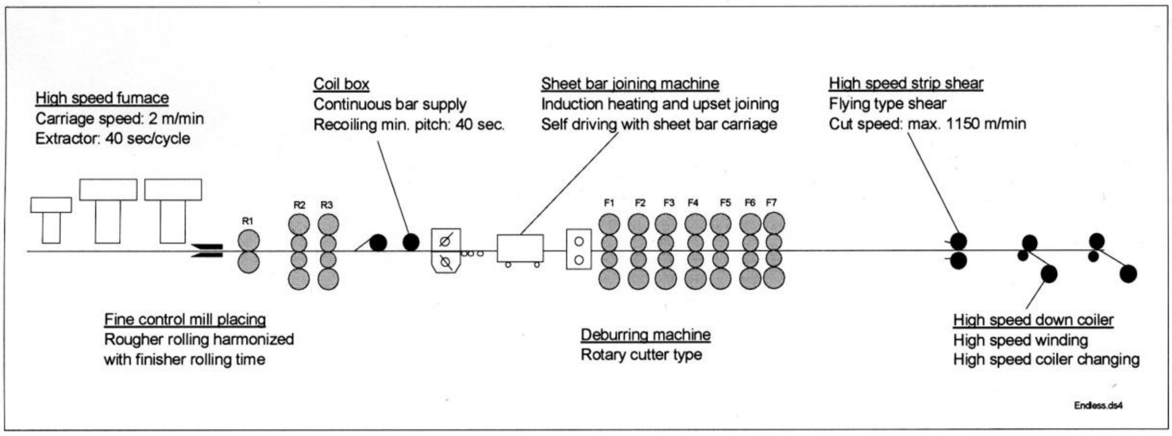


Fig. 1 Schematic depiction of hot endless strip rolling process

9.2. Continuous strip casting

During the past years, several companies have been working on the development of strip casting technologies. Whereas casting of thin slabs with directly connected rolling technologies are, in principle, improvements of the conventional rolling technology, direct strip casting is a new technology. Via direct casting of strips, which can subsequently be cold rolled, the process time from melted steel to final products can be significantly shortened. Table 1 depicts a comparison of characteristic parameters for slab, thin slab and strip casting processes.

Table 1 Comparison of selected parameters for various casting technologies

Technology	Continuous casting	This slab casting	Strip casting
Product thickness	150 – 300mm	20 – 60 mm	2 – 4 mm
Solidification time	More than 600 s.	Approx. 60 s.	Less than 1 s.
Casting speed	1 – 2.5 m/min.	4 – 6 m/min.	30 – 90 m/min.
Average heat flow in crystallizer	1 – 3MW/m^2	2 3 MW/m^2	8 – 10MW/m^2
Metallurgical length	More than 10 m	More than 5 m	Less than 0.5 m
Melting mass in casting machine	More than 5 000 kg	Approx. 800 kg	Less than 400 kg

Direct strand reduction processes, which link a thin slab caster and a following hot rolling mill, are commercially available from different plant manufacturers. Several concepts have been developed, e.g. CSP (Compact Strip Production) by SMS, ISP (In-line Strip Production) by MDH or CONROLL (CONtinuous thin slab casting and ROLLing) by VAL These concepts, combining continuous casting and hot rolling, take advantage of the heat contained in the cast steel. Thin slabs are cast with a thickness of about 50 mm (CSP), 60 mm (ISP, directly soft reduced to about 45mm) and 75-130 mm (CONROLL) and are then further reduced in rolling stands. The basic technologies of casting and rolling of strips are shown in Figs. 2 and 3.

9.2.1 CSP – Compact Strip Production

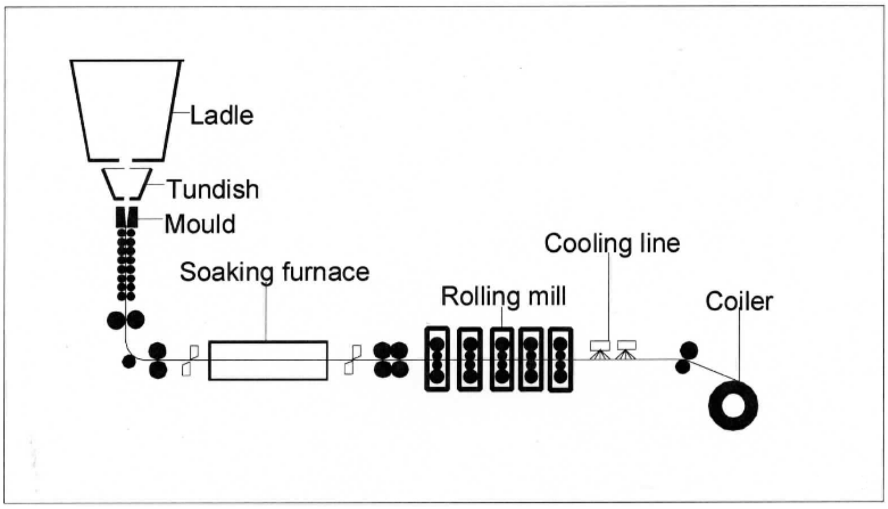


Fig. 2 Diagrammatic view of an CSP plant

Products that have already been produced with the CSP technology show a thickness range from 25 mm down to l mm for many steel grades (e.g. next to carbon steel also micro-alloyed steel and Si-alloyed steel for electro-plate). CSP plants allow a production of hot strip of about 1-1.5 million tons per strand per year.

9.2. 2 ISP - In-line Strip Production

ISP plants have production capacities of about 1.5 million tons hot strip per strand per year

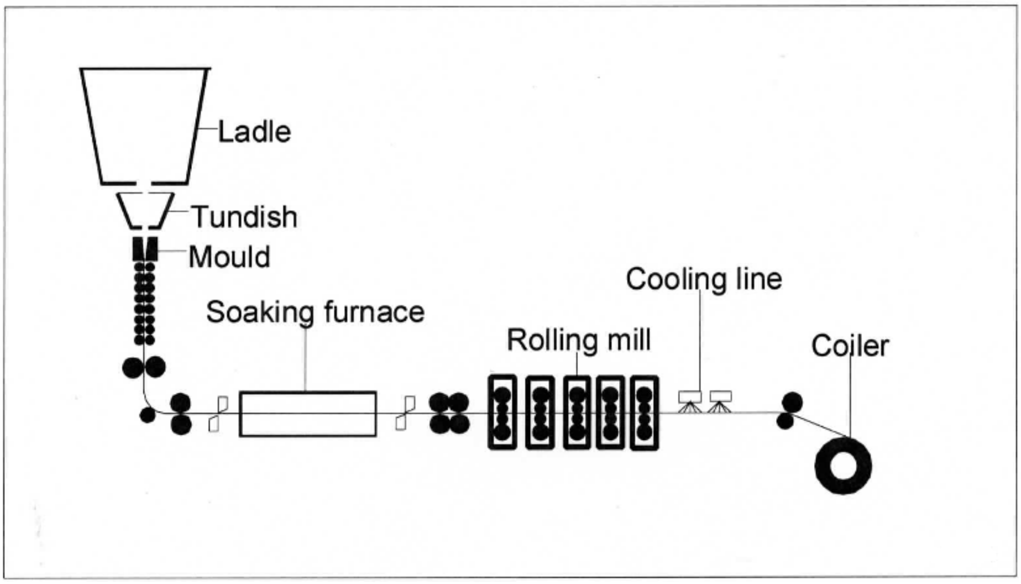


Fig. 3 Diagrammatic view of an ISP plant

The main steps of the ISP process are cast-rolling with liquid core (liquid core reduction), cast-rolling with solid core, intermediate heating, transfer bar coiling and finish rolling. It is possible to roli the hot strip down to a thickness of about l.0 mm with this process, also satisfying deep-drawing requirements. For intermediate heating in the ISP process, often induction furnaces are used.

Depending on the strip thickness to be achieved and the rolling technology (austenitic or ferritic rolling), Fig. 4 and Fig.5, the required temperature elevation differs considerably.

An induction furnace allows a flexible control of the temperature elevation and may save energy up to 56kWh/t.

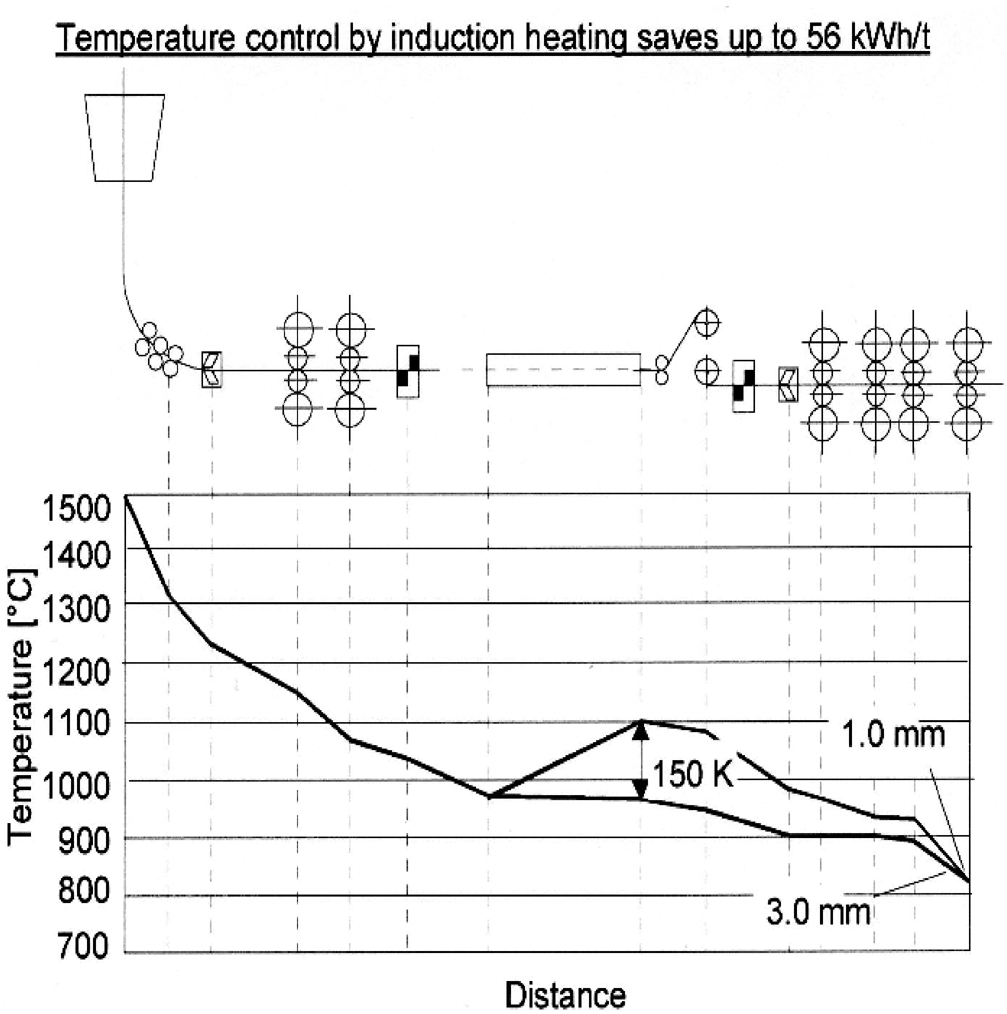


Fig. 4 Flexible temperature control by induction heating

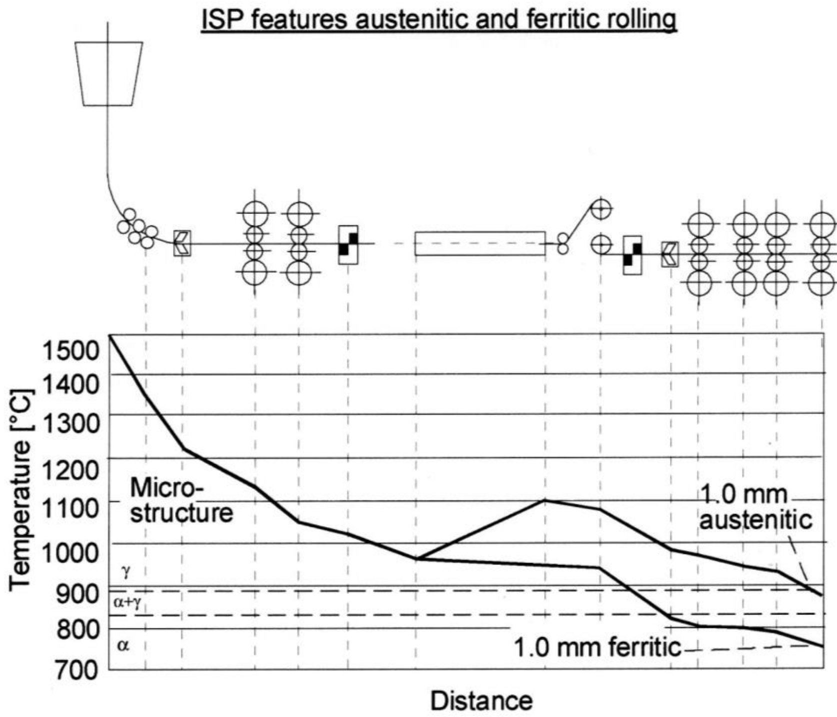


Fig. 5 Flexible temperature control yields new rolling technologies

Figure 6 shows three different plant concepts employing the ISP technology.

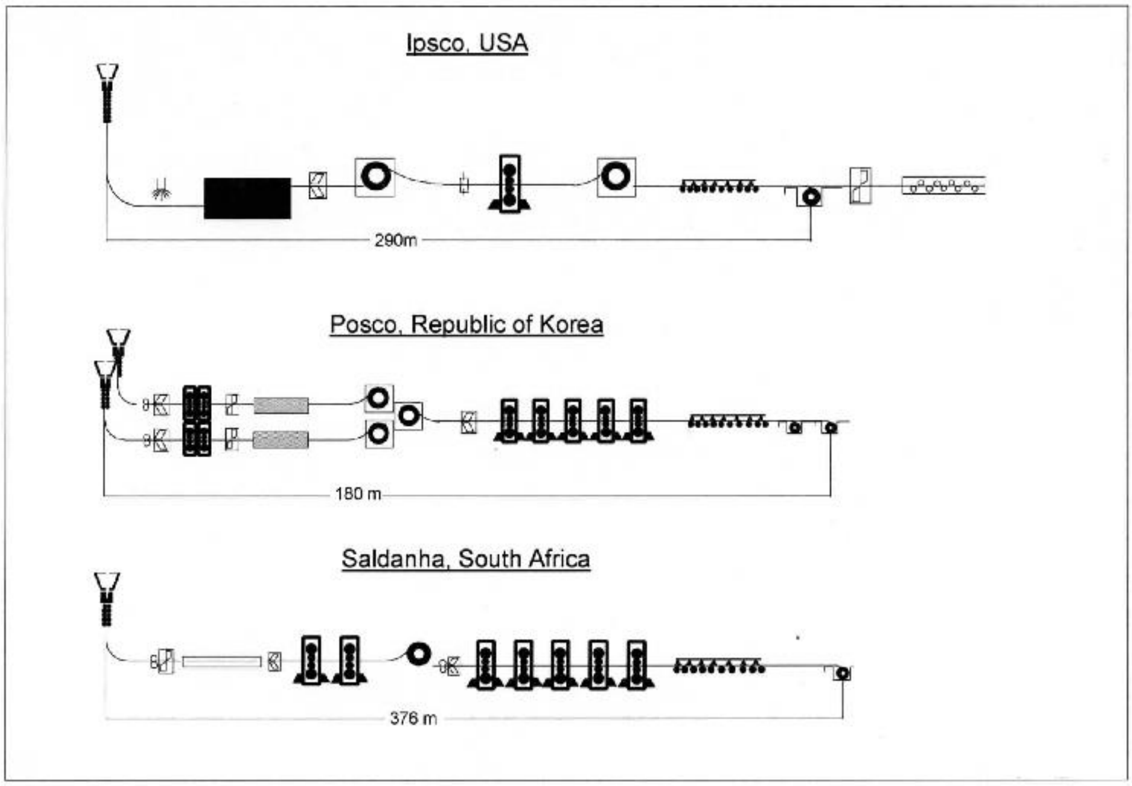


Fig. 6 Different plant concepts using the ISP technology

9. 2.3 Efficient energy use by strip casting (hot forming)

While thin slab casting and directly connected rolling technologies can still be seen as an (significant though) improvement of the conventional rolling technology, the realisation of direct strip casting technologies on an industrial scale represents a change in technology. By direct casting of strip, which can be subsequently cold rolled, the process chain from liquid steel to the final product is shortened substantially.

lot of research has been and is still being done in order to develop strip casting plants on an industrial scale. Figure 7 and Figure 8 show diagrammatic views of pilot plants, which have been developed by a co-operation of several firms.

In particular the research project "Myosotis", carried out jointly by Thyssen-Krupp Stahl AG and Usinor-Sacilor, seems to be very promising. This plant employs the doubleroller technique (Figure 7), while the plant depicted in Figure 8 employs a CPR (Casting Pressing Rolling) process.

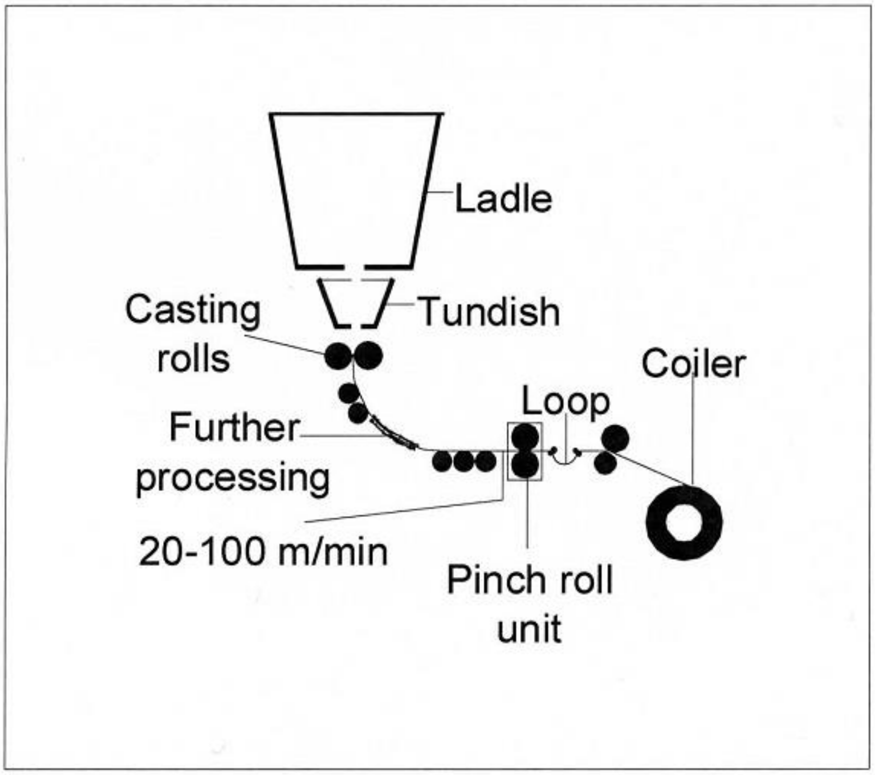


Fig. 7 Continuous casting and rolling of strips

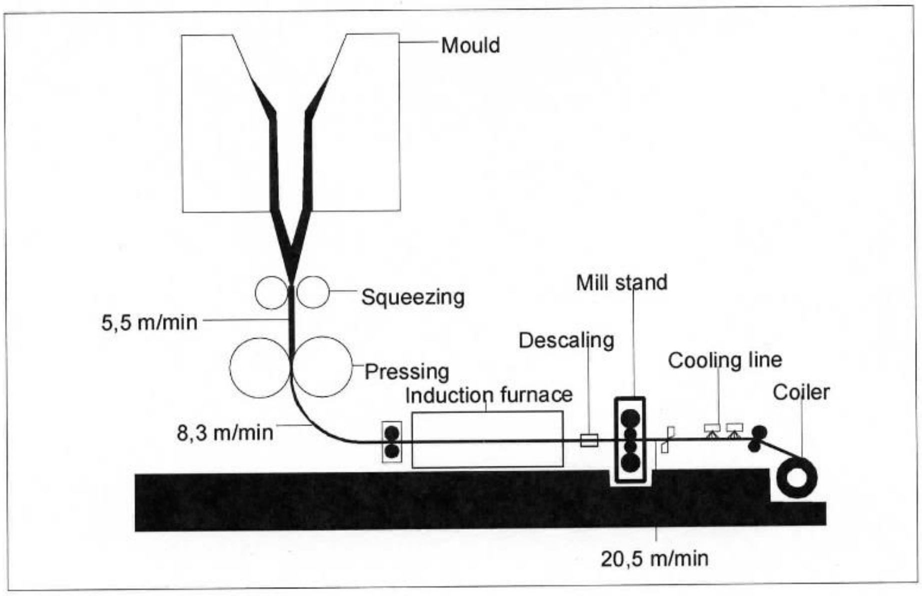
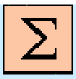
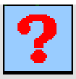


Fig. 8 Continuous casting of strips, additional heating and rolling on a quarto rolling stand



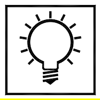
Aim of the lecture and summary

The lecture describes possibilities of thin strips production by hot rolling. Hot production of steel strips with thicknesses t ≤ 1.0 mm cannot be realized using devices of conventional rolling plants. Published reports regarding the mentioned topic contain description of production technologies, information about certain precautions regarding environment protection including data about emissions and consumptions of materials and energies.



Questions to the discussed subject

1. Which methods of so called endless rolling do you know?



Tasks

1. Draw a scheme of continuous thin strip casting.
2. Describe advantages of usage of thin slabs in strip rolling plants.

Recommended literature:

[1]Guindani, A. et al. Properties of hot rolled steel strips produced by endless casting-rolling plant. La Metallurgia Italiana, 2014 No. 1, pp. 25-30.
[2]AVERDI, G. et al. Arvedi ESP first thin slab endless casting and rolling results. Ironmaking and Steelmaking , 2010 , Vol. 37, No. 4, p. 271-275.

10.ROLLING OF RINGS

Time to study: 90 min.

Aim: After study of this chapter students will be able to:

- define requirements on properties and describe progressive rings production technologies,
- design technological process of production of rings by combinations of rolling and forging technologies.
- Calculate deformation forces and strains during rolling of rings.

Lecture

10.1. Introduction

Rolling of rings can be described using the theory of rolling. Unequal size of rolls leads to non-symmetrical deformation zone, which leads to several curiosities within the process. A rolling mill enables to roll flat, as well as shaped rings (Fig. 1). For rolling of shaped rings, it is necessary to pre-form workpieces using open-die or die forging. Rolling mills are components of entire production lines, which consist minimally of a pre-forging machine and a rolling machine with appropriate heating and manipulating equipment. Rolling is most often performed on radial-axial rolling mills, which are more universal but also technologically more demanding.

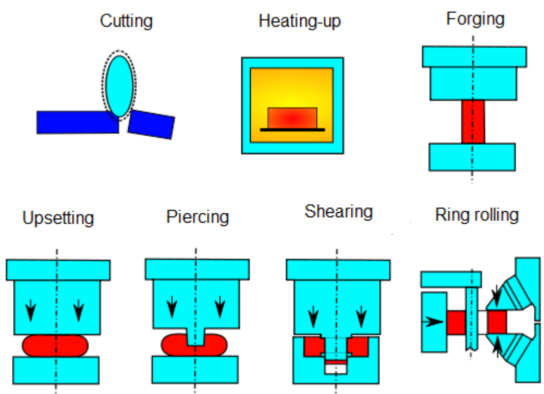


Fig. 1 Forging and rolling of rings

Rings of various diameters and profiles belong to often desired products. Attention is especially given to their accuracy and productivity of manufacturing. The best results are achieved by application of flat ring rolling performed on machines denoted as ring rolling mills. The ring is deformed by one or two pairs of rolls (Fig. 2). The internal roll, often denoted as mandrel, has always a smaller diameter than the external roll, denoted also as main roll. The internal roll has to always have a diameter smaller than the diameter of the opening in the smallest pre-forged piece. This process is denoted as rotary rolling or flat ring rolling, contrary to a conventional longitudinal rolling, which is applied to process most of the produced steel.

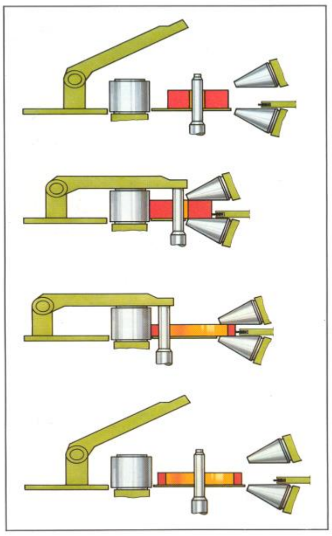


Fig. 2 Rings rolling principle

The rolled rings have diameters from 50 to 6 000 mm, with larger exceptions, and the range of weights from 1 to 15 000 kg. In our country, flat rings and sleeves prevail, while a large amount of various shaped rings is produced in the world.

10.2 Main parameters of rings rolling

The rolls for radial reduction do not have identical diameters (the internal roll is always smaller), which requires certain modifications of relations known from the flat rolling theory. The consequence of unequal diameters is that reductions from the external side Δs_e and the internal side Δs_i are different, as is evident from Fig. 3. The overall reduction Δs can be expressed as:

$$\Delta s = \Delta s_e + \Delta s_i \qquad (10.1)$$

Input ring thickness is denoted as s_o, input ring height h_o, dimensions after rolling are denoted as s_1 and h_1. (For flat rolling, thickness is denoted as h and width as b). The deformation zone length l_d is also different for both the internal and external rolls.

$$l_{de} = \sqrt{2R_e\Delta_e} \qquad l_{di} = \sqrt{2R_i\Delta i} \tag{10.2}$$

where R_e and R_i are radii of the external and internal rolls.

This asymmetry of deformation zone influences the final geometry of rolled rings, negatively, from a significant part. The rolling force F is given by the general equation:

$$F_v = \sigma_p Q_f S \tag{10.3}$$

where σ_p is mean flow stress, Q_f is forming factor, S is contact area (different for internal and external rolls).

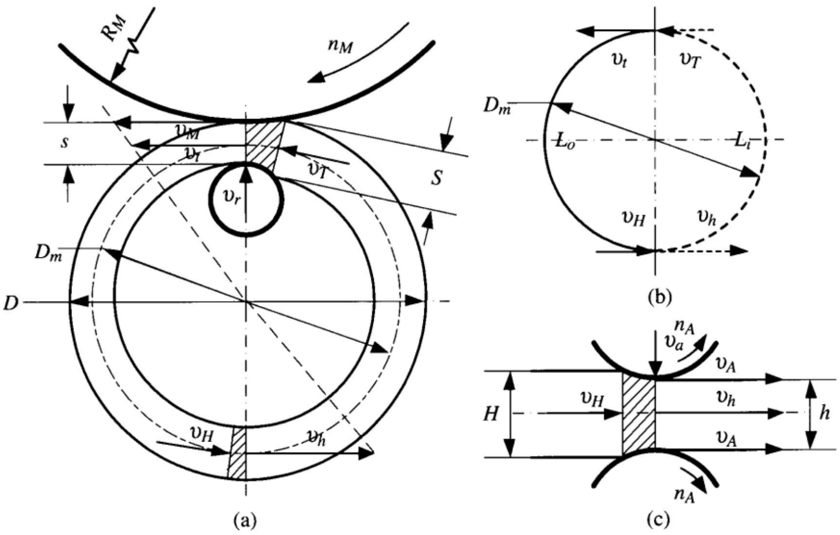


Fig. 3 Assumed geometry and kinematics of radial-axial ring rolling: (a) top view, (b) segmentation of mean circumference of ring and (c) radial view at axial roll gap

The value of the forming factor Q_f is approximately 1 for relatively small deformation zone lengths. Areas adjacent to rolls surfaces are areas of aggravated deformation. Adjacent to these are areas of significant shear strains, in which the most intensive deformation occurs. For relatively small reductions, area of mixed stresses is located in the center of the thickness of the workpiece, in which compression stresses act in the radial direction and tensile stresses act in the two others. If the contact length of tools with respect to the workpiece thickness is small, the area of aggravated deformation consumes the entire contact arch length. If the contact length of tools with respect to the workpiece thickness is large, the area of aggravated deformation consumes only a certain part of the contact arch length. The backward slip zone, in which the velocity of rolled material is lower than the circumferential velocity of rolls, is located at the entering side. The forward slip zone, in which the velocity of the rolled material is higher than the circumferential velocity of rolls, is located at the exiting side. In this case, tensile stresses do not act in the workpiece axis in horizontal direction, the area of mixed stresses is located only in peripheral areas. The forces acting on the internal and external rolls have to be equal, i.e. the equation of forces is applicable:

$$\sigma_{pe} Q_f \, l_{de} \, h = \sigma_{pi} Q_f \, l_{di} \, h \qquad (10.4)$$

where h is height of ring.

The following relation can be used to calculate flow stress:

$$\sigma_{po} e^{-m_1 T} \left(\frac{2\Delta s_e}{s} \right)^{m_2} \dot{\varepsilon}^{m_3} h \sqrt{2\Delta s_e R_e} = \sigma_{po} e^{-m_1 T} \left(\frac{2\Delta s_i}{s} \right)^{m_2} \dot{\varepsilon}^{m_3} h \sqrt{2\Delta s_i R_i} \qquad (10.5)$$

where σ_o, m_1, m_2, m_3 are material constants, T is temperature, ε' is strain rate.
After adjustment of equation (10.5) we get:

$$\frac{D_i}{D_e} = \left(\frac{\Delta s_e}{\Delta s_i} \right)^{1+2n} \qquad (10.6)$$

where hardening exponent n was used instead of m_2 constant; D_i and D_e are diameters of internal and external rolls.

Example: a ring from 14 209 steel is rolled on a mill in which the internal and external rolls have the diameters of 200 mm and 500 mm, respectively. The hardening exponent of the steel is n = 0.205. If the total reduction during one revolution is Δs = 2 mm, then, according to equation (10.6), the internal reduction is Δs_i =1.3 mm and external reduction is Δs_e = 0.7 mm. Considering the deformation zone length, i.e. length of the deformation zone contact arch, then, according to equation (10.2), l_{di} = 18.7 mm and l_{de} =16.1 mm applies for this example. Therefore, reduction on the internal side is significantly larger than on the external side. As a consequence, fibers on the internal surface of the ring elongate more, which results in straightening of the ring in the deformation zone, as is evident from Fig. 4.

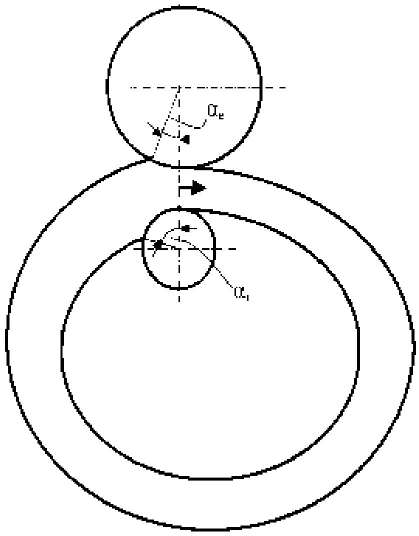


Fig. 4 Geometry during rings rolling

The tendency to create ovality is more significant for greater reductions, straightening in the deformation zone is less significant for smaller reductions. The geometry is in practice controlled using pushing rolls and suitably designed reductions regimes.

Bite angle is another very important parameter during rolling. For rotary rings rolling, there are two of them again: external α_e and internal α_ι, as is depicted in Fig. 4. A condition for bite to happen is, likewise for flat rolling, meeting of one of the following relations:

$$tg\alpha_e \cdot f \; ; \quad tg\alpha_i \cdot f \qquad (10.7)$$

where f is friction coefficient between rolled material and roll.

If only the external roll is driven, which applies to most of the ring rolling mills, the first of these conditions is needed to be met. For rolling of rings, reductions during one revolution (one pass) are relatively small, which results in small bite angles. On the other hand, the rolled ring can move, which can result in a change of geometric conditions and slippage can happen. Radial-axial rolling mills also have rolls for height reductions of rings, as is shown in Fig. 5. Rolls for axial reductions have to be of conical shapes and their axes have to cross the axes of rolled rings workpieces in the planes of appropriate end faces to avoid undesirable slippage. By this reason, conical rolls have to move outwards the center of a rolled ring as its diameter increases. However, meeting of this condition cannot be generally ensured within the entire range of rolled diameters.

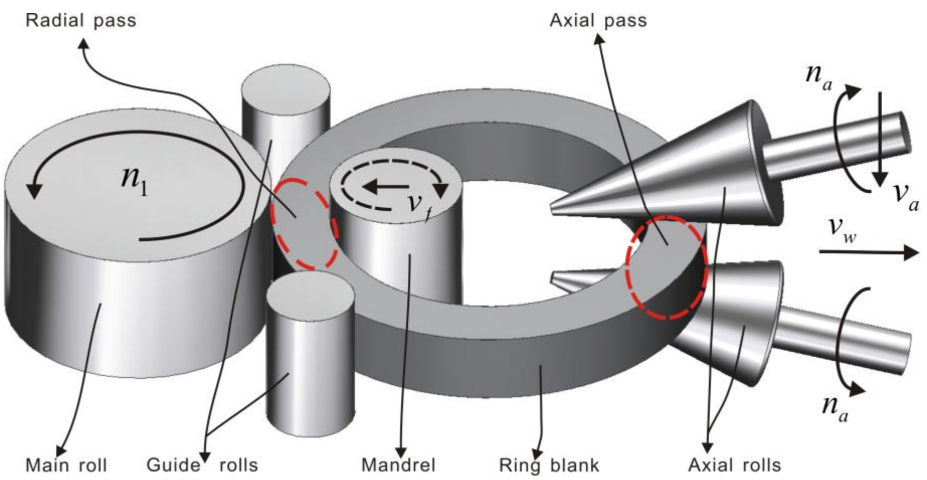


Fig. 5 Scheme of rolling on radial-axial rolling mills

The contact area of the conical roll with a rolled ring has approximately the shape of trapezoid, the length of deformation zone is therefore variable. Another phenomena occurring during rolling is widening. If rolling is performed on flat rolls, the widening is denoted as free widening. During rolling using shaped rolls, limited or constrained widening can occur, depending on the shape of gauges. Free widening Δb is calculated using the equation:

$$\Delta b = \frac{\Delta s}{6}\sqrt{\frac{R}{s_o}} \qquad (10.8)$$

where R is mean value.

$$R = \frac{R_i + R_e}{2} \qquad (10.8a)$$

Typical for rolling of rings on flat rolls are small reductions during a single rotation (on radial and axial rolls). Then, double barreling along the height of a ring occurs.

Rings of more complex shapes are usually rolled in gauges. In these cases, both limited and constrained widening can occur. Using radial rolling mills, even rings with simple cross-sections are rolled in gauges. Double barreling occurring for smaller reductions is there combined with limited widening, which leads to development of surface depressions (grooves).

On radial-axial rolling mills, simple shapes are rolled using flat rolls and double barreling caused by one pair of rolls can be eliminated by a second pair of rolls. This mill type thus provides better conditions for achievement of precise shapes. However, double barreling can occur even in these cases if reductions are not sufficient.

For rolling of complex profiles, the same basics as for longitudinal rolling in gauges are applicable. Unfilling or overfilling of gauges can happen, laps can occur.

10.2.1 Rolled shapes

Very wide range of components and rings, flat as well as shaped, is produced by flat rolling. Rings can be shaped on their internal or external surfaces. Rings with shaped front edges are typically rolled only on axial or orbital rolling mills.

For flat rings, for which no special calibration of rolls is required, even small series productions are economical. Especially a radial-axial rolling mill can be, from this point of view, considered as a universal machine, since no shaped rolls are necessary for rolling of flat rings.

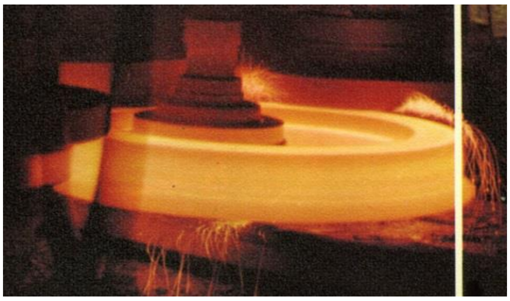


Fig. 6 Rolling of railway rims

Among various kinds of steels, many alloys are typically rolled, including alloys of aluminum and titanium, copper alloys and nickel or cobalt based alloys with low formabilities. The largest diameters of rolled rings are between 3 to 10 meters. The height of rolled rings depends on the method of bearing of rolls for radial reduction. It is relatively low for free bearing, while when the necks of both the rolls for radial reduction are supported, the height of a rolled ring can be greater than 1 000 mm.

10.2.2 Types of ring rolling mills

There is a variety of types and variants of ring rolling mills. They can be categorized according to several characteristics. According to the method of forming they can be: radial, radial-axial, orbital (axial closed-die rolling machine).

Radial ring rolling machines require rolling in closed gauges. Radial-axial ring rolling machines can be used to roll ranges of various dimensions with a single set of rolls. Axial closed-die rolling machines are suitable for rolling of rings with shaped front edges, they are used to roll rings with complex shapes. However, they are considered as specialized types of forming machines and are usually not considered as ring rolling mills. According to the driving of the pushing roll, the ring rolling mills are: mechanic or hydraulic. This relates to the driving ensuring the mutual approximation of rolls, rotary drive of rolls is always

mechanic. According to the position of the axis of the formed material, the ring rolling mills are vertical, horizontal, diagonal.
When rolls are fixed at both ends, one of the frames connecting the rolls has to be removable to enable inserting of a workpiece into the working area and removing of the final product. Combined ring rolling mills have the internal roll, which has a smaller diameter, fixed at both ends. Examples of radial ring rolling mills assemblies are shown in Fig. 7.

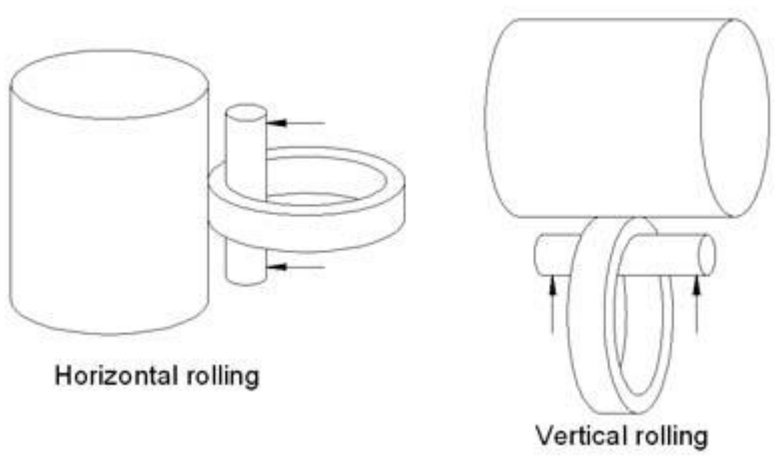


Fig. 7 Radial ring rolling mills

These are ring rolling mills with vertical axis and horizontal axis, respectively. The rolls have both the necks supported and are used to roll relatively high rings.

10.3. Technology of flat rings rolling

For rolling on a radial ring rolling mill, it is necessary to manufacture a pre-forged piece with the height corresponding to the height of the final ring. For rolling on radial-axial ring rolling mill, the pre-forged piece has the thickness and height larger than the required height of the final ring. The initial intermediate product is selected to enable the cross-section area to be reduced by 1.5 to 3 times. Smaller values are selected for harder materials and larger rings. Usually, the cross-section reduces by 2 to 2.5 times.
Pre-forged pieces can be manufactured in several ways. For larger series of rings of small diameters, pre-forging in dies is applied. The initial block is rammed, then pre-pierced in an extrusion cavity and finally the flash is cut. This procedure is widespread. Although pre-forging in an extrusion cavity requires using of an ejector, it enables manufacturing of pre-forged pieces with no chamfers.

Semi-finished products for rings with larger diameters are pre-forged using hydraulic presses. During rolling, reduction within one revolution is important. For radial ring rolling mills, the reduction and also consequent increase in ring diameter is controlled (Fig. 8).

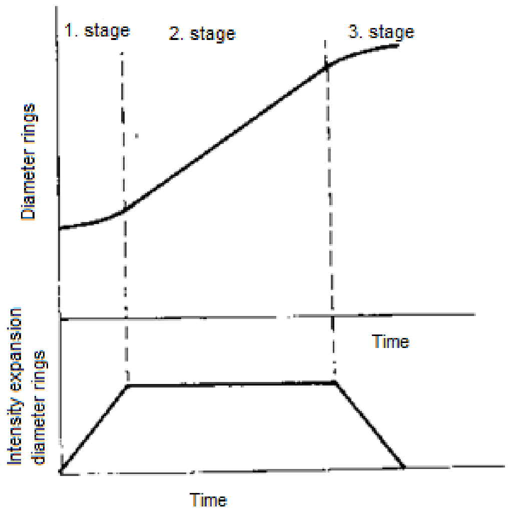


Fig. 8 Optimal course of increase in ring diameter during rolling

In the first stage, inequalities within the pre-forged piece homogenize, the ring diameter slowly increases. In the second stage, diameter increases with a constant velocity. In the third stage, dimensions preciseness are improved. For radial-axial ring rolling mills, it is moreover necessary to be particular in synchronizing the velocities of axial and radial rolls. Incongruity in their circumferential velocities can cause ovality of the final ring. For modern ring rolling mills, the pressure on pressure pulleys is measured and axial rolls velocities are regulated to be identical.

Furthermore, the velocity of diameter increase is measured and according to this, the pressure force is regulated. The regimes of reductions in axial and radial directions are selected according to the ring height to thickness ratio, as can be seen in Fig. 9. The scheme in the figure depicts the cross-sections of pre-forged pieces and final rings and the optimal curves for transition from one cross-section to another.

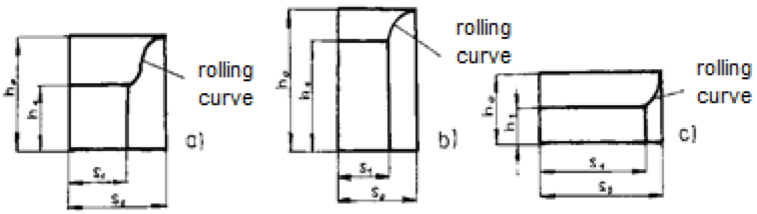


Fig. 9 Scheme of optimal rings rolling technologies

a) rectangular cross-section, b) high ring, c) flat ring

During rolling of a ring with rectangular cross-section (a), it is suitable to intensively reduce height at first and to intensively reduce thickness in the final rolling stage.

During rolling of a high ring (b), it is suitable to intensively reduce thickness at first and to reduce height in the final stage. This is given by the fact that a slender (high) ring wall has low stability and therefore height is reduced minimally at the beginning. A significant height reduction at the end of rolling is performed with the aim to eliminate occurrence of grooves.

On the contrary, height is reduced more at the beginning of rolling of flat rings and the radial direction is reduced more in the final rolling stage. The reason for this is again the danger of losing of stability of a slender cross-section, which would negatively influence geometric accuracy.

For rolling on radial-axial ring rolling mills, it is also necessary to, among selecting a suitable regime of rolls approximation, appropriately select rotational speeds of rolls. If the rotational speed is too high, a too small reduction is performed during one revolution and a significant barreling, which cannot be subsequently eliminated, occurs.

On a radial ring rolling mill, rings of various thicknesses, however of uniform heights, can be rolled in a single gauge.

Rolled rings are machined on their working surfaces. For example, all surfaces are machined for bearing rings, while for railway rims internal and external surfaces are machined and the front edges are maintained in rolled conditions. Machining allowances are selected according to the ring size and hardness of formed material with respect to the ring rolling mill stiffness. The allowances should involve scaling, decarburization, and other surface defects and, above all, geometric inaccuracies, such as grooves and ovality

Despite the fact that machining allowances for small rings are smaller than 5 mm, material loss for them is around 50%. For rings of the largest diameters the machining allowances are larger than 10 mm, however material loss is only 15%.

10.3.1 Technology of shaped rings rolling

Rolling of shaped rings is typically performed using shaped pre-forged pieces. For rings of small diameters, shaped pre-forged pieces are manufactured in dies. Shaped pre-forged pieces for rings of medium and large diameters are manufactured by open-die forging (Fig. 10).

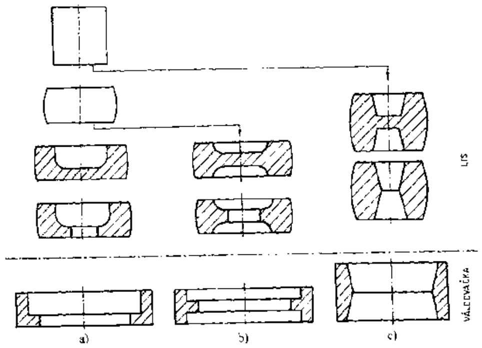


Fig. 10 Manufacture of shaped pre-forged pieces via open-die forging: a) pre-forged piece for a ring of L profile, b) pre-forged piece for a ring of T profile, c) pre-forged piece for a ring with internal conus

10.3.2 Progressive procedures of ring rolling

Rings shaped on front edges can be rolled only on axial ring rolling mills. Scientific workplaces have been solving the issue of rolling of rings with shaped front edges on radial-axial ring rolling mills. The appropriate conical roll has to be shaped. Problematic is however precise synchronizing of movement of conical rolls with increasing diameters of rolled rings. The simplest possibility is when practically no shaping is performed in the radial direction. An example is shown in Fig. 11. A plane shaped ring is shaped only between shaped conical rolls and, at the end of the process, its circumference is shaped by a roll, which is not driven and is located between the conical rolls.

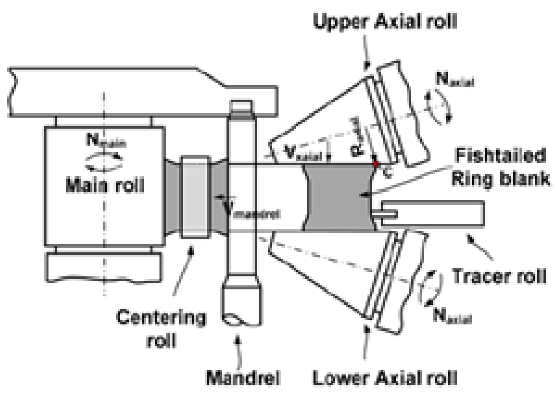


Fig. 11 Rolling of a ring shaped at both front edges

Several workplaces all over the world work on development of new technologies, which could be applied on conventional radial or radial-axial ring rolling mills, which are in the world wide-spread forming machines.

10.4. Defects of rings

Defects of rings can be, similarly to defects of other forged pieces, characterized into several groups. Generally, a higher danger of occurrence of defects is for larger products. Frequent are defects of inaccurate geometry. Some defects are depicted in Fig. 12.

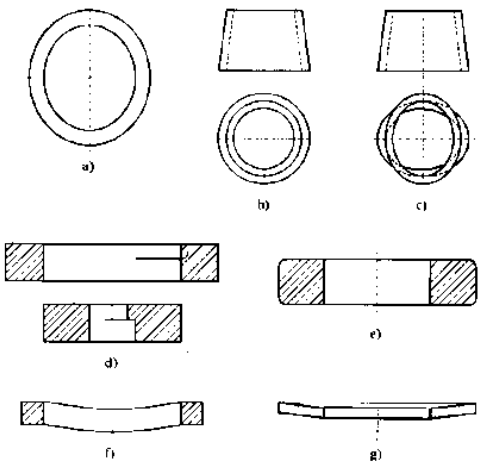


Fig. 12 Geometric defects of rolled rings:
a) ovality, b) conicalness, c) crossed ovality, d) lap from the external roll,
e) unfilled corners, f) bending, g) diameter beveling

For a suitable technological process, during which reduction is gradually increased to the required value and then decreases again during final rolling, ovality should be decreased to minimum. However, materials with higher strengths cannot be rolled with sufficient reductions and thus ovality is not eliminated. High strengths have bearing steels, which are materials from which rings are often rolled and for which calibration is usually necessary.

If the guide-roll is not used, the center of the external roll, center of the internal roll and center of the rolled ring are located along one straight line. For rolling of larger rings, ring rolling mills with two guide-rolls are used. The greatest danger of occurrence of geometric defects is for thin-walled rings. Pierced pre-forged pieces have larger diameters on the bottoms than on the tops. Conicalness can also be caused by a low stiffness of the ring rolling mill. Larger pressures, which can invoke deformation of the frame of the mill or bending of rolls axes, are necessary for rolling of smaller thicknesses. Finally, conicalness can be induced by large reductions on axial (conical) rolls. This mechanism is described in Fig. 13.

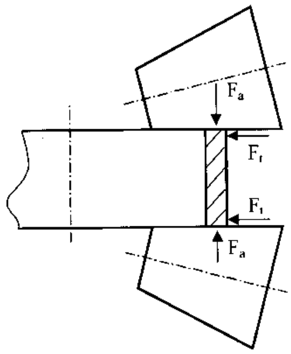


Fig. 13 Forces acting on conical rolls

The forging force **F** develops on rolls for axial reductions. However, since increasing in the ring diameter occurs simultaneously, friction force F_t develops as well. If the wall of the ring has a very slender cross-section, the influence of force F causes tendencies to sloping, which, in this case, results in conicalness. Since friction conditions on the bottom and upper surfaces are not identical (scales loosening is easier on the bottom surface), friction forces F_t are not identical, which again causes development of conicalness.

To reduce this phenomenon, it is necessary to meet the above mentioned principle – during rolling of thin and high rings, it is necessary to apply minimal axial reductions from the beginning and increase the reductions towards finishing of rolling.

An unfavorable defect of thin and high rings is crossed ovality, which results in both the bases being oval and longer axes of the ovals being approximately perpendicular to each other. This defect usually occurs during heat treatment, when a ring is insufficiently supported or unevenly heated. Crossed ovality can very hardly be eliminated by calibration.

Σ

Section summary

Rolling of rings is a technology with a variety of advantages. It is productive, ensures high utilization of metals, works with minimal allowances, enables production of complex profiles and ensures homogenous properties and high quality of final products. Moreover, modern radial-axial ring rolling machines enable economic production of very large rings also in small series or even as single-part productions. By these reasons, the amount of produced rolled rings increases constantly. It is necessary to count with the fact that this trend will continue in the future. The theory of rolling is at present described in sufficient detail and can also be modelled using computers. These methods should be used especially for design of processes for rolling of complex shapes.

11. SEVERE PLASTIC DEFORMATION

Time needed for studying: 90 min.

Aim: After studying this chapter you will:

Define the basic methods of preparation of ultra-fine grained and nanostructured materials

Describe the preparation of nanostructured and ultra-fine grained materials by the SPD processes

Select an applicable method of preparation of an ultra-fine grained structure through application of ECAP

Lecture

11.1 Introduction

In order to achieve an ultra-fine grained or nanocrystalline structure, the real deformation c. 6 ÷ 8 is needed and forming must be performed at low homologous temperatures. This chapter is focused only on the preparation of ultra-fine grained materials by Severe Plastic Deformation – SPD. The advantage of application of the severe plastic deformation is, in comparison e.g. with compaction of powders, a possibility to obtain almost homogenous porousless material, nowadays even of larger dimensions. Over the years, a number of technologies using severe plastic deformation were developed to form structures with a grain size between 10 to 1000 nm. Fig. 1 shows some methods used for the preparation of nanostructured and ultra-fine grained materials.

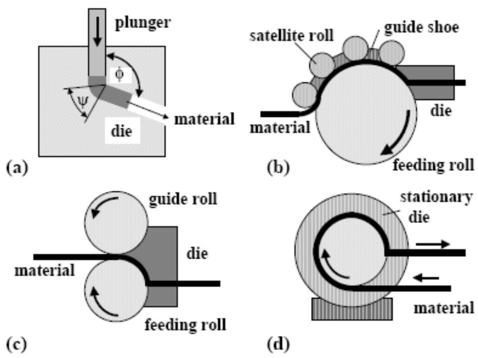


Fig. 1 Schematic depiction of the selected SPD methods: (a) ECAP, (b) Conshearing Process, (c) C2S2, (d) Conform

The above mentioned methods serve above all for preparation of materials for research purposes. They are useful i.a. because they allow various strain rates. They were used experimentally for the research of nanostructures of 4 types of steels. The High Pressure Torsion – HPT method, which is described below, is used the most frequently of the methods shown in Fig. 7 for the research of various aspects of SPD effect on properties of materials.

At present many SPD methods are used and developed for research and pilot plant experiments. These are both methods and technologies through which individual semi-products are made (Batch Processing) and Continuous SPD technologies.

Following is a summary of these methods, which is not complete, however, it presents an adequate overview of the present state of the development.

11.2 Batch processing

These technologies include: ECAP, HPT, MCF, RCS and TE.

11.2.1 Equal Channel Angular Pressing - ECAP

A typical flowchart of this technology is shown in Fig. 2.

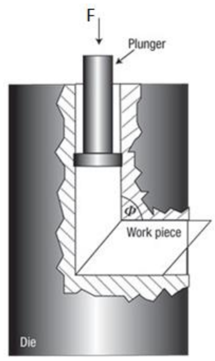


Fig. 2 Equal Channel Angular Pressing (ECAP)

ECAP allows deformation of a metal sample by shear without changing its dimensions. A die comprises two channels with the same cross section, which intersect each other and create a bend. When extruding a sample through the die, the shear strain occurs in this place. The process can be repeated to achieve intensive plastic strain and a finer grain. The real deformation in one pass depends on the angle between axes of both the channels and to a less degree also on the bending radius. A sample can be rotated along its longitudinal axis between the particular passes, thus creating various technological routes of ECAP. The technological route influences the process of refinement of grains and their shapes significantly. To find the most effective technological route for grain refinement of individual materials is a subject of research.

Four technological routes for the development of the formed material microstructure are studied systematically – Fig. 3.

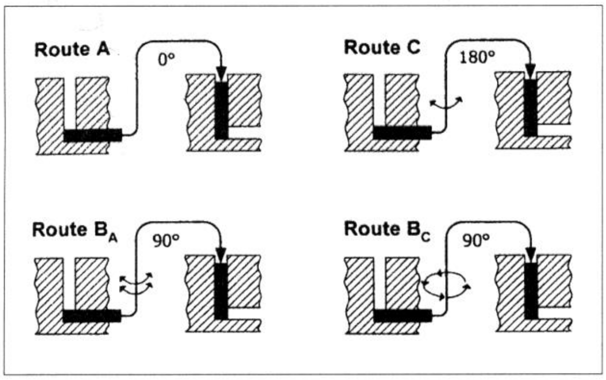


Fig. 3 Technological routes of the microstructure development during the ECAP method application: *Route A - material orientation between the individual passes does not change; route* $\boldsymbol{B_C}$ *- material is rotated clockwise by 90° after each pass; route* $\boldsymbol{B_A}$ *– material is rotated by 90° alternatively clockwise and counterclockwise after each pass; route* ***C*** *– material is rotated by 180° after each pass.*

Another factor affecting significantly the development of the microstructure is the channel bending radius angle Φ. This angle determines the shear strain magnitude during the particular passes. The shear strain can be expressed by a relation:

$$\gamma = 2\ \text{cotg}(\Phi/2) \qquad (11.1)$$

A less angle Φ results in higher shear strain in each pass and then this arrangement is more effective for the grain refinement. Nakashima, et al. studied the influence of Φ angle value between 90^o - 157.5^o for aluminum using the technological route $\mathbf{B_C}$. He found out that at the same number of passes the grain refinement is the most effective at 90^o angle. This is a result of 60^o angle, which is contained by two shear planes in the deformed sample in this case. For materials with low formability an angle of 120^o and a higher extrusion temperature are usually used. The amount of the real accumulated shear strain can be calculated from the relation:

$$\varepsilon = \frac{2N}{\sqrt{3}} cotg\left(\frac{\phi}{2}\right) \qquad (11.2)$$

where N stands for the number of cycles (passes in a die).

The microstructure development during the ECAP method was to the great extent studied only for materials with a face centered cubic lattice (Al, Cu) and with a hexagonal close packed lattice (Ti, Mg, Zn). A lattice of these metals contains few slip systems and the strain is influenced by a value of stacking fault energy. Metals with a medium to high value of the stacking fault energy (Al, Cu) are deformed above all by slip mechanisms, while metals with low values of the stacking fault energy (Ag) are deformed mainly by twinning.

Metals with a body centered cubic lattice (Ni, Fe_{α}) have more slip systems, such as {110}<111>, {112}<111> and {123}<111>, therefore they are deformed by slip mechanisms. In the meanwhile, the research of the ECAP method for forming metals with the body centered cubic lattice is of a limited extent, above all due to low formability of these metals at low and medium temperatures.

The ECAP method has been still developed. Improved conditions of friction between the deformed sample and inner surface of the die resulted in obtaining an ultra-fine grained structure in materials with low formability, such as W and Ti.

For example, ultra-fine grained bars with a diameter of 30 mm and length of 150 mm were manufactured from Ti. During the rod forming, the back-pressure on the formed material was also used, which increased formability of the used material significantly. Also, a rotational die was developed, the use of which eliminates a need to perform the extrusion of the entire sample and to re-insert it into the die between the particular passes. A device which is a modification of the ECAP method has been installed in the RMSTC laboratory. The equipment is used for forming of long rods (the Conform technology).

11.2.2 High Pressure Torsion - HPT

A flowchart of this technology and the photo of the real equipment are shown in Fig. 4.

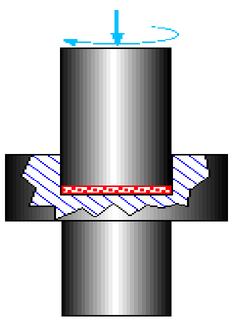


Fig. 4 Metal forming by the High Pressure Torsion (HPT) method

The HPT method belongs among favourite severe plastic deformation processes. The effect of high pressure (several GPa) on a sample can be unlimited (Fig. 4) or limited by a die. Grains with sizes to 10 nm, or also smaller, can be obtained by this method. High-angle grain boundaries form during the deformation. Samples are of a disc shape, typically with a diameter of 10 ÷ 20 mm and thickness from 2 to 5 mm. They are placed between two tools, the one of which is rotating and the second one is fixed. Friction during rotation between the tool and a sample surface enables to increase shear strain gradually. Imposed compression stress during shear strain effectively eliminates a possibility of a sample failure, in spite of very large deformation. Significant refinement of the structure was observed just after half of a turn or a whole turn of the tool. However, more turns are usually needed in order to achieve a homogenous structure. The amount of the real shear strain can be calculated according to the relation:

$$\varepsilon = 2\pi\, N\, r/d, \qquad (11.3)$$

where *N* stands for a number of turns, *r* stands for a sample radius and *t* stands for its thickness.

The HPT method was used successfully for refinement of a microstructure of non-ferrous metals and alloys, steels, composites and semiconductors. At present, HPT is only used for processing of small samples, it is limited to a laboratory research.

11.2.3 High-Pressure Tube Twisting - HPTT

This technology is used for processing of tubes without dimension changes. The deformation process is achieved by high hydrostatic pressure in the axial direction, initiated by a cylindrical mandrel. A tube is inserted into a mould and compressed by a mandrel. The extreme plastic deformation is achieved by friction force, external torque and hydrostatic pressure. HPTT appears to be very promising for future industrial applications. The flowchart of this method is shown in Fig. 5.

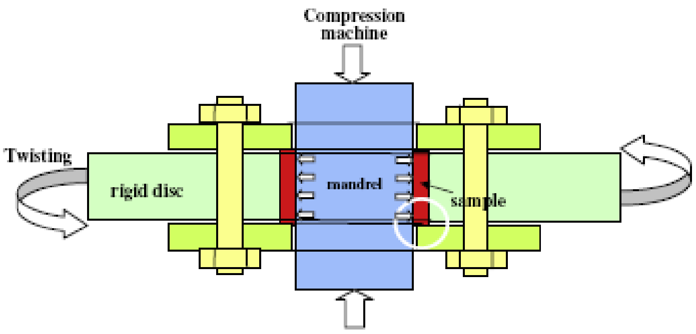


Fig. 5 Method High Pressure Tube Twisting (HPTT)

11.2.4 Repetitive Corrugation Straghtening - RCS

The flowchart of this method is shown in Fig. 6. Two more used names and links are given here. This method principle was used for continuous process of high plastic strain on flat materials.

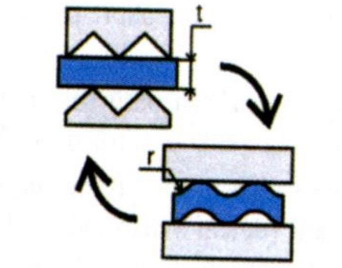


Fig. 6 Repetitive Corrugation and Straightening (RCS)

11.2.5 Twist Extrusion - TE

This technology flowchart and an image of a work-piece are shown in Fig. 7.

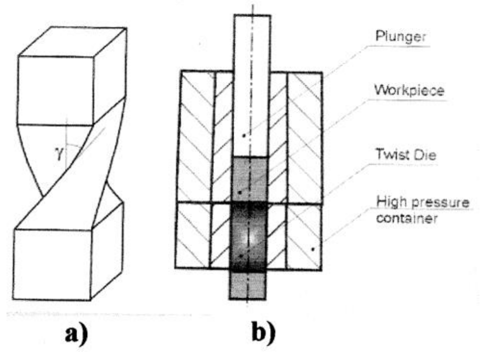


Fig. 7 Method Twist Extrusion

The twist extrusion principle consists in initiating intensive shear deformation by extruding a billet with rectangular cross section through a die with a twist channel. The channel shape and cross section does not change along the axis of extrusion, while the channel is twisted along this axis (Fig. 7a). The work-piece shape and cross section does not change as well, which allows repeated extrusion and thus an accumulation of plastic deformation. There are several possibilities of application of the pressure onto the extruded billet. One example is depicted in Fig. 7b. The billet is extruded through the die using a plunger. Twist extrusion can be used for processing of metal materials (Ti). This technology is at the beginning of its development.

11.3 Continuous SPD processes

These technologies include above all: ARB, Conshearing, C2S2, ECAP-Conform.

11.3.1 Accumulative Roll Bonding - ARB

A flowchart of this technology is shown in Fig.8. The principle of this method is that two sheets with the same thickness stacked on top of each other are rolled simultaneously. In one pass, the thickness of the two sheets is reduced down to the thickness of one initial sheet. Then the sheet is cut into two, stacked together and this operation is repeated several times. This process is accompanied by microstructure refinement. For instance, when processing IF steel with 0.003 % carbon content, the initial grain was reduced from 27 μm to 420 nm after five cycles at the rolling temperature of 600 ^{o}C. The grain in the aluminum sheet (1100 grade) with a size of 37 μm was reduced down to the size of 670 nm in 7 cycles at temperature of 200 ^{o}C. In spite of a significant increase in strength of the sheets, plastic instability at a decrease of the medium size of the grain below 1 μm was found. The causes of this phenomenon have not been known yet.

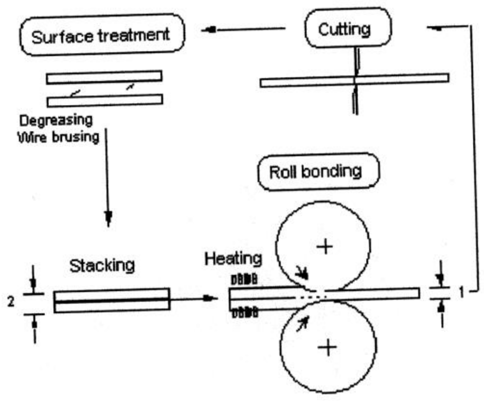


Fig. 8 Flowchart of the process

11.3.2 Conshearing Process

A flowchart of this technology is shown in Fig. 9. In principle, this is the ECAP method adapted for continuous forming. This method is intended above all for thin strip forming. The method was recently used for forming of Al1100 alloy and low-carbon steel. The continuous extrusion occurs, when friction force acting in gaps between four rolls is higher than the extrusion force. In order to initiate this phenomenon, the central roll surface is rough. It is important to find an optimal angle θ for forming various materials or samples of various thicknesses (see Fig. 9). For example, for 2 mm thick sample of Al alloy the optimal angle is c. 65^{o} and for a steel sample with the same thickness 55^{o}.

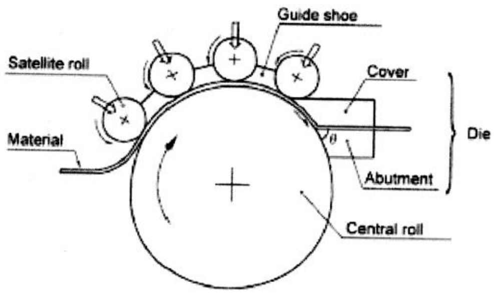


Fig. 9 Conshearing Process

11.3. 3 Continuous Confined Strip Shearing - C2S2

A flowchart of this technology is depicted in Fig. 10. In principle, this method is similar to the preceding one. It is applicable for forming of sheets (strips) with long lengths and large widths.

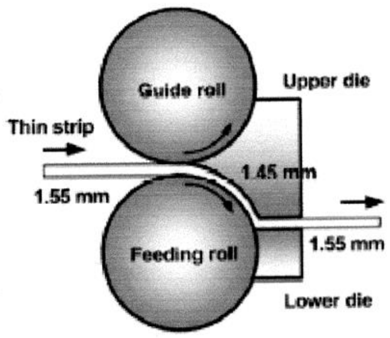


Fig. 10 Continuous Confined Strip Shearing (C2S2)

11.3.4 Conform - ECAP

A flowchart of this technology is shown in Fig. 11, including the photography of a prototype. This process is intended for continuous forming of rod-shaped ultra-fine grained materials.

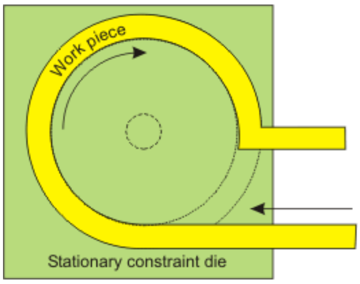


Fig. 11 Method ECAP – Conform

11.3.5 Continuous RCS (Repetitive Corrugation and Straightening)

A flowchart of this technology is depicted in Fig. 12. The principle of this method is repeated rolling and straightening of a work-piece in a system of rolls with a cross section similar to a toothed wheel. This technology, applicable for sheet forming, is nowadays developed in the Los Alamos National Laboratory for industrial usage. The method involves a combination of shear and bending stress developed by compression on a special treated surface of rolls. The advantage of this method is its easy application on existing rolling mills. Its drawback lies in a structure inhomogeneity along the rolled piece, however, this can be eliminated by a higher number of passes.

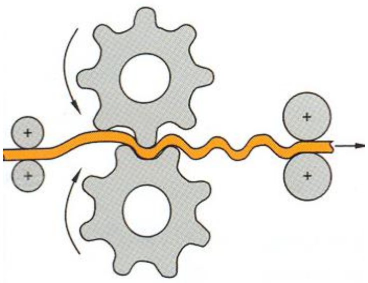


Fig. 12 Method Continuous RCS

11.4 Comparison of the severe plastic deformation methods

Severe plastic deformation can be achieved through many methods, which can be divided according to processes of deformation:

Continuous deformation without changing a deformation route (compression, extrusion, HPT)

Accumulated deformation without changing a deformation route (rolling, drawing, ECAP – route A)

Accumulated deformation with changing a deformation route (CEC – cyclic extrusion and compression, ECAP – route C)

Accumulated deformation with a variable deformation route (die forging, ECAP – routes different than A and C, ARB)

During all of these methods, material is formed at high hydrostatic pressure.

ECAP remains the most favourite process used for formation of ultra-fine grained structures. It has a great potential for commercialization considering that the formed billets are expected to be of larger dimensions and regarding the development of continuous forming technologies (Conshearing, C2S2, ECAP-Conform). The research of optimization of dies and optimal modes and deformation routes for forming of specific materials is in progress.

Another progressive technology (for strip forming) appears to be ARB (Accumulative Roll Bonding), which is a semi-continuous process. Practical application of ARB in commercial production is highly presumable. The essential advantage of this method is its potential to be used in conventional rolling mills. A temporary drawback is a structure inhomogeneity along the rolled product cross section and occurrence of cracks on edges in forming by large deformations. Possibilities to enhance ductility of formed materials need to be found, too. A microstructure formed during ARB is different from that formed during ECAP, since grains are elongated along the rolling direction. As in other methods, during ARB a mixture of low- and high-angle grain boundaries occurs.

All the above mentioned methods need further development in deformation routes and reproducibility of properties of formed materials. It is also necessary for the methods to allow further grain refinement. Nowadays, the grains of sizes below 100 nm can be only achieved by the HPT method, which is not applicable for commercialization. In ECAP, an average grain size between 300 ÷ 400 nm and higher can be achieved so far. On principle, the grain refinement through ECAP is possible by increasing the total accumulated deformation. Technically this can be performed through forming by higher imposed pressures[i].

The main technical problems of the development of the equipment for imposing high plastic deformations are similar to those that we face up when developing conventional forming technologies. The first of them is to maintain the integrity of the formed material. Lightweight ductile materials can be relatively easily formed at 20 °C without fracture. More brittle materials require higher temperature at forming. This is limited by processes of recovering and structure recrystallization, which may negate a favourable influence of the fine-grained structure. A certain solution is application of high strain compression, such as in the HPT or back-pressure ECAP methods.

However, the higher pressure demands a need to solve another problem – a service life of forming tools. Prestrained dies were developed and tool materials were improved. The maximum compression strength of sintered carbides is approximately 3.5 GPa, which is not satisfactory e.g. for the present-day version of the HPT method. High stresses in tools along with high working temperature create difficult conditions for a solution.

Friction also relates to the high pressure imposed on forming tools. This increases along with a forming force, hampers filling the die with material, causes wear of the inner surface of the die and in the worst case results in jamming of the material. Good lubrication is a good solution. This depends on the used material, technology parameters (above all on temperature), a way of application of a lubricant etc. Along with good lubrication, a tool surface finishing using hard coating with a low friction coefficient may help the situation.

Laboratory devices for severe plastic deformations are no problem today. The use of standard tension testing machines is enough many times. The development of equipment for industrial use changes the situation dramatically. Basically, one of two possibilities may be chosen: either the use of existing presses and rolling stands or the development of brand new forming equipment. The first approach is cheaper, but more limited in term of results. It needs to be considered that operational equipment for severe plastic deformation is a system involving the preparation of billets, transportation and handling, lubrication, the forming equipment itself and other necessary equipment for following operations (heat treatment, final operations etc.). The technology needs to be monitored and controlled, too. In the meanwhile, no equipment for severe plastic deformation runs in regular operational conditions. Some methods are relatively near to this target, above all for forming of aluminum alloys.

11.5 Research of steels with ultra-fine grained and nanocrystalline structure

The main motivation for the research of the given steels is their potential application in automotive industry, because they may provide an excellent combination of properties (strength and toughness). Compared to works performed with aluminum alloys (applications in aircraft and space industry and also in cars) and with titanium alloys (applications in medicine), the research of production processes for ultra-fine grained steels and study of their properties is performed in a substantially less extent.

11.5.1 Technology SPD applied on VŠB - TU Ostrava

At the VŠB - Technical University Ostrava, the development of nanotechnologies using the severe plastic deformation is performed in the workplace at the Department of Materials Forming within the framework of the solved project MPO Impuls, FI-IM/033 “Research and utilisation of nanotechnologies and the manufacture of nanostructured materials of high strength for modern constructions" (2004-2007) and GAČR project no. 106/09/1598 „Structure and properties of titanium for dental implants" (2009-2011).

The subject of the research within the project "Impuls" was the research and development of metal materials with a structure in submicron and nanometric region. The research activities were focused on studying processes and mechanisms leading to creating ultra-fine grained microstructures using extreme deformations ($\varepsilon = 2 \div 16$). This way, bulk materials were prepared in order to investigate the physical-metallurgical principle of the development of ultra-fine grained structures (nanostructures) and possibilities for preserving the nanostructure stability and accompanying mechanical properties of metal materials (Cu; Ti, Al, Mg alloys; plain and high-quality steels) at elevated temperatures with application of alloying methods and thermo-mechanical processing of the obtained nanostructures. For preparation of bulk metal materials with a submicroscopic structure (or nanostructure), the following technologies were used:

ECAP - (Equal Channel Angular Pressing) – extrusion through a channel's two parts with a bending containing an angle of 90°, 105°

ARB - Accumulative Roll Bonding

CEC - Cyclic Extrusion Compression

C2S2 – Continuous Confined Strip Shearing

A combination of powder metallurgy methods and CEC, ECAP

In order to keep stability of ultra-fine grained structures at elevated temperatures, thermo-mechanical processing in a combination with alloying and solution annealing was performed (additional hardening by effect of alloying elements and precipitation during plastic deformation under hot condition, or under cold condition). To avoid thermal degradation of the microstructure of hardened materials, a repeated thermo-mechanical processing was applied subsequently.

Investigation and analysis of the severe plastic deformation and an influence of parameters of this method (total deformation, strain rate, temperature) on the formation and thermal stability of ultra-fine grained structures were applied for various metals and alloys (Al, Cu, Mg and various steels).

The following methods were used for the evaluation of assets of the severe plastic deformation (SPD) for creating fine-grained structures: optical microscopy, electron microscopy and X-ray and neutron diffraction (evaluation of the crystallographic texture and development of microdeformations). Further, microhardness, physical and mechanical properties and superplasticity were evaluated and documented.

Conclusion

Severe Plastic deformation: Batch processing and Continuous methods:

- ECAP, HPT, MCF, RCS and TE.
- ARB – Accumulative Roll Bonding
- Conshearing Process
- C2S2 - Continuous Confined Strip Shearing
- ECAP – Conform
- Continuous RCS (Repetitive Corrugation and Straightening)

References

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[2] TSUJI, N. et al: Nanomaterials by Severe Plastic Deformation, ed. M.J. 2004.