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NATIONAL METALLURGY ACADEMY of UKRAINE

V. N. DANCHENKO

METAL FORMING

Dnepropetrovsk NMetAU 2007

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The present book is recommended by the Ministry
of education and science of Ukraine as a text-book
for students of higher educational institutions
studying along direction "Metallurgy"

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The fundamental of metal forming theory, the theories of processes of rolling, forging and stamping as well as drawing and pressing (extrusion) have been given.

The characteristics of the shop equipment for metal forming and technology of the main metal forming methods have been given in separate sections.

The text-book is intended for students of higher educational institutions, specialty "Metallurgy".

Fig. 80. Table 3. Reference list: 3.

Приведены основы теории обработки металлов давлением, а также процессов: прокатки, ковки и штамповки, волочения, прессования.

В отдельных разделах приведены характеристика оборудования цехов обработки металлов давлением и технология основных видов обработки металлов давлением.

Предназначено для студентов по направлению "Металлургия".

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INTRODUCTION

Metal forming is the final stage of metallurgical manufacturing permitting to produce metal ware used in national economy as the finished products or as the billet for further processing. Metal forming is the main method of making metal products and semi-finished products. More than 90% of smelted metal is processed by different methods of metal forming.

Plastic properties of metals are used during the process of metal forming. That is the ability to change without damage the shape and dimensions in hot and cold condition under the pressure of machining tools. The knowledge of metal forming rules permits to realize the forming at optimum deformation regimes and to use the appropriate main and auxiliary equipment. The variety of methods and kinds of metal forming permits producing the wide range of metal products with high productivity, exact dimensions, required mechanical properties.

The development of metallurgical manufacture has resulted in appearance of new kinds of metal forming where the processes of casting and hardening metal reduction are being combined.

New technological processes of metal forming give the possibility to shape the product at high strain rate, to obtain the products with especially high mechanical properties, to reduce the number of process stages and equipment used for it.

1. THE FUNDAMENTALS OF PLASTIC DEFORMATION OF FERROUS METALS, NON-FERROUS METALS AND ALLOYS

1.1. The types of metal forming

Rolling is the most commonly used and the most efficient type of metal forming, which consists in deformation of metal by means of rotating rolls (Fig. 1.1, *a*, *b*, *c*); 75-80% of the total quantity of smelted metal is being processed by rolling.

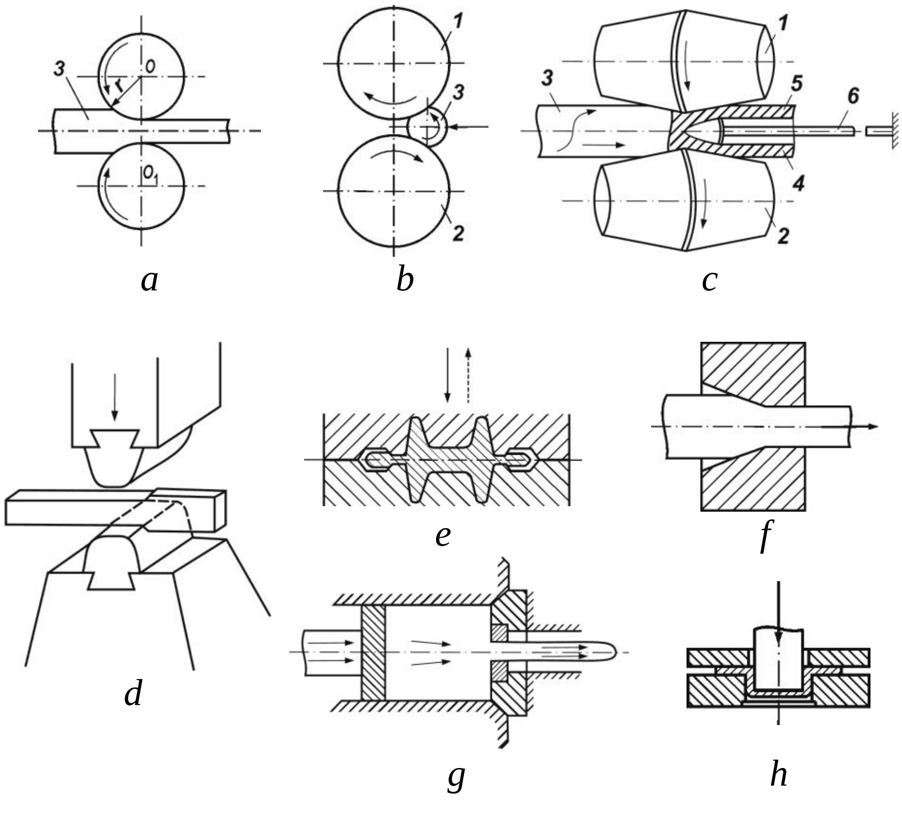


Fig. 1.1. The schemes of the metal forming processes: *a* – lengthwise rolling; *b* – cross rolling; *c* – helical rolling (*1*, *2* – rolls; *3* – billet; *4* – shell; *5* – mandrel); *d* – smith forging; *e* – closed die forging; *f* – drawing; *g* – pressing (extrusion); *h* – sheet stamping

The long length products of constant or variable cross-section along the product length are produced by method of lengthwise rolling. The direction of rolls rotation promotes pulling the billet by means of friction forces to the gap between the rolls where the billet is reduced in thickness. It results in increase of the length and the width of the billet. The rolls with smooth surface are used for rolling plates and roll grooves forming the required shape of strip cross section – passes – are used for production of section bars – beams, channels, rails etc.

During the process of cross rolling the rolls are rotating in the same direction. The billet is fed in axial direction and it receives the rotational movement contacting the rolls. The billet is retained in rolls by special device during the process of rolling and reducing by rolls. The sections being the bodies of revolution such as balls, gears etc. are produced by cross rolling.

The helical (skew) rolling is realized in barrel-shaped rolls rotating in the same direction and installed with some skewness of axes. The billet feed in axial direction receives the rotational movement and simultaneously, due to the rolls skewness of axes, the translational movement ahead. During the process of billet rolling its diameter is reduced, the core of the billet becomes. The mandrel installed towards the billet movement direction allows to obtain the hollow product – the shell from which the tube is produced by means of the further processing.

Forging is a widely used method of metal forming. There is a free forging (Fig. 1.1, *d*) and closed die forging (Fig. 1.1, *e*). During the process of free forging the reduction of the forging piece height is realized between two parallel surfaces of hammer heads, and the flow of metal in the transverse direction is not limited by the shape of the heads. The variety of the manufactured products shapes is achieved by the reduction of the billet in different directions, using of auxiliary operations of bending, twisting, drawing, piercing etc. The billet is placed to the cavity of one die part and under the action of another part of the die the billet is filling the cavity taking its shape during the process of die forging. It makes the process of the product shaping simpler and permits to increase the efficiency of forging.

The drawing of the metals is used in manufacturing of small sections and relatively long length products such as wire, rods, tubes (Fig. 1.1, *f*). The pointed end of the rod is pushed through the conical hole of the tool (drawing die), is clamped at the die exit by clips or spooled and under the action of applied force is drawn through the die with reduction of cross section area and corresponding elongation. The drawing permits to obtain the products with exact dimensions and good quality of surface.

Pressing is the method of product manufacturing by means of metal extrusion through the die hole (Fig. 1.1, *g*). It is mainly used in non-ferrous metallurgy and aviation industry where the shaped sections are produced from such materials as Al- and Ti-based hard-to-deform and low-plasticity alloys.

Sheet stamping is the method of metal plastic processing in which the sheet and strip bars are used for product manufacturing (Fig. 1.1, *h*). The complex shape products with high strength and rigidity and small mass are produced in the process of separating, shaping and assembly operations; they are widely used in many sectors of national economy. Sheet stamping is the highly efficient method of metal forming and has the wide spreading.

1.2. Mechanical properties of metals

Forces and deformations during the hot and cold metal forming depend upon mechanical properties of processed materials, which in their turn depend upon the nature (chemical composition, structure) of metal as well as upon the deformation conditions (temperature, degree and rate of deformation).

Strength, elasticity, plasticity, impact strength and hardness are concerned to be the mechanical properties.

The strength of the metal is interpreted as its ability to stand without damages applied loads at which the internal in stresses metal do not exceed some limit value for the given metal. This value is called ultimate strength or ultimate resistance (σ_{ult}).

The actual data about the mechanical properties of the metals may be obtained by means of testing the standard specimens according to the regulated by standards methods at room and high temperatures. Linear stretching is one of the most widespread methods of testing. The diagram of the stresses $\sigma_{conv}=P/F_0$ changing during the process of deformation $\varepsilon=\Delta l/l_0\cdot 100\%$ (where σ_{conv} is conventional value of stresses at load P correlated to the initial specimen cross-section area F_0; Δl is the absolute elongation of specimen; l_0 the initial length of specimen) is given on Fig. 1.2.

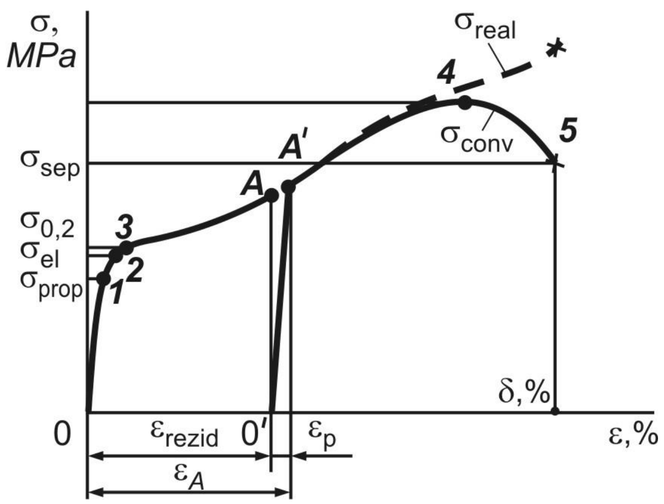


Fig. 1.2. The diagram σ–ε
at tensile test

The proportional connection between stresses and deformation according to Hook's law $\sigma=\varepsilon E$ (where E is the modulus of elasticity) is taking place at the 0-*1* area. The stress at the point 1 is called the proportional limit and designated as σ_{prop}. At the area *1-2* the deformations are elastic (that is, they disappear after removing the load), but the connection between the stresses and deformations becomes nonlinear. The stress in the point *2* is called elastic limit and designated σ_{el}. After point *2* the plastic (residual) deformation is beginning and in point *3* runs up to 0.2%. The stress corresponding to the position of point *3* is called conventional yield strength and designated as $\sigma_{0.2}$. The further deformation at the area *3-4* is accompanied by increasing of conventional stress (the effect of metal hardening during the process of deformation). If to relieve the load at any point *A* in the area *3-4,* the total deformation ε_A will be decreased for value ε_{el} and the beginning of the diagram will move to point O'. During the next loading the limit of material plasticity is increasing and the plastic deformation begins only in the point *A*'. The variable value of stresses in the area *3-4* is called yield stresses σ_{yield}.

On reaching the maximum of conventional stresses in the point *4* the specimen deformation becomes irregular: the local reduction of cross section (the neck) is forming, conventional stresses are reduced and the destruction is taking place in the point *5*. The value of conventional stresses corresponding to the point *5* on the diagram is called the stress of breaking σ_{sep}.

If to take into account the change of cross section area of specimen during the process of stretching, which becomes considerable by the moment of neck formation, then the view of diagram will be changed (is shown by dotted line), the hardening of metal (the increase of stresses $\sigma_{real}=P/F_{real}$) is going on up to the moment of destruction.

In addition to the specimen strength indexes metal plasticity indexes are also determined during tensile test. Plasticity is the property of metal to be deformed without damage. Plasticity index is the maximum obtainable value of relative deformation before destruction. During the tensile test the relative elongation is considered to be the index of plasticity:

$$\delta = \frac{\Delta l}{l_0} \cdot 100\%,$$

where Δl is the maximum value of absolute residual elongation.

The shape of tested specimen influences the value of this index, ratio of the specimen length l_0-to-diameter d_0. The specimens with the ratio $l_0/d_0=5$ or $l_0/d_0=10$ are used. The indexes of relative elongation for this tests are indicated as δ_5 or δ_{10}.

The plasticity properties of metals are evaluated by the index of relative reduction:

$$\psi = \frac{F_0 - F_1}{F_0} \cdot 100\%,$$

where F_1 is the area of cross section of the specimen at the place of fracture.

Besides tensile tests mechanical properties of metals may be determined also by means of test for setting, twisting, impact buckling as well as by different technological probes.

The index of impact elasticity KCU is determined by the value of work A expended for fracture of the standard specimen correlated to the area F of the specimen cross section at the place of the cut: KCU=A/F, J·cm^{-2}.

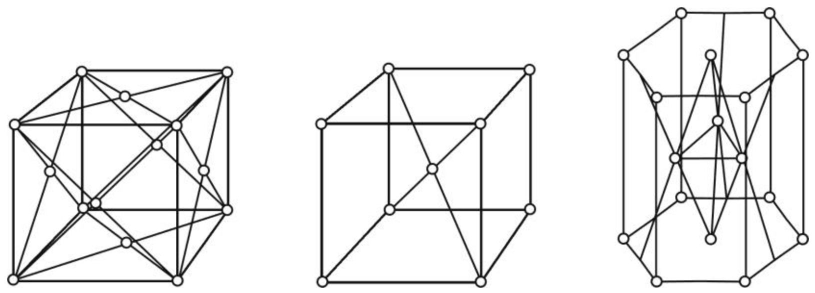
The test for determination of impact elasticity is conducted on pendulum ram engines. The specimen is laid easily on two supports. The expended work for destruction of a specimen is determined according with the change of potential energy of the ram engine mass at the initial position and in the fixed position after deformation.

Resistance to indentation into surface of different kinds of instruments is understood as metal hardness. There are different methods for hardness test in accordance to the used instruments. At the hardness test after Brinell HB, Rockwell HR and Vickers HV the hardness is determined by the depth of intrusion of tempered steel or tungsten ball, diamond cone or pyramid into the tested material. The hardness according to Shore HSD is determined at falling of steel head with diamond on the end in standard conditions and is measured in conventional units according to the height of the head rebound. This method is convenient for application in production conditions.

1.3. Cold metal forming

Plasticity deformation mechanism

The metals have the crystalline structure. As usual metals consist of a great number of crystals of different shape and sizes, which are called grains. Grains are combined between themselves as a single whole by the forces of inter atomic bond. Metal have the arrangement ordered and form lattice (Fig. 1.3).



a *b* *c*

Fig. 1.3. Types of some metals' lattices:
a – face-centered cubic lattice;
b – body-centered cubic lattice;
c – hexagonal cubic lattice

The definite orientation of crystallographic axes causes anisotropy (distinction at different directions) of physical properties of crystals. But in case of disordered arrangement of grains in the metal volume, the physical properties at different directions are averaged and the body becomes as it was isotropic (quasi-isotropic).

Under the action of tangential stresses the shear deformation in the cells of lattice is taking place. In case if the value of atoms displacement of one layer relatively the other one exceeds the half of the inter atomic distance, the transition of atoms to the new position of stable equilibrium is taking place, that is the transition of atoms becomes irreversible, the metal deformation will be residual – plastic. This mechanism of plastic deformation is called slipping (Fig. 1.4, *a*).

Sliding represents the shear of one part of crystal relatively to another in some planes. As usual the slipping is going on simultaneously in many parallel planes, in which connection the number of these planes is increasing as soon as the deforming force is increasing. As the result, the numerous slip bands are formed (as the superfine layers). The sliding planes have definite crystallographic directions. The sliding planes are those

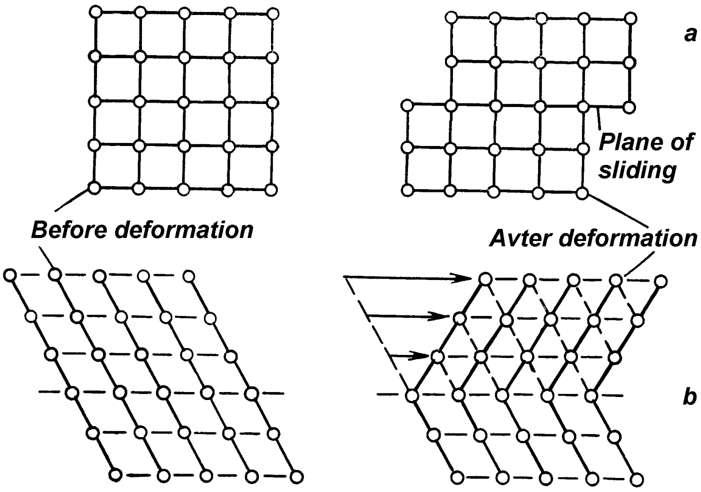


Fig. 1.4. Mechanisms of plastic deformation:
a – slipping; *b* – twinning

with the greatest density of atoms distribution and the sliding is going on along the directions where the distance between atoms has the minimum value. The number of planes and directions of sliding depends upon the type of lattice and in body-centered lattice amounts to 14, in face-centered lattice – 4, in hexagonal lattice – 2.

The process of sliding is greatly facilitated due to the successive shear of atoms in the sliding plane in case of presence of crystal lattice imperfection in real metals. Considerably lesser stresses are required for dislocation displacement in the plane of sliding in comparison the simultaneous shear of atoms along the whole plane. The distortion of planes of sliding is taking place during the process of plastic deformation which makes the deformation along these directions more difficult, the new shears are originating at the new directions. The deformation is stopped when all free directions for shears are used.

The second mechanism of plastic deformation is twinning, which presents the shear of the crystal part with formation of mirroring of one part of crystal regarding the other (Fig. 1.4, *b*).

The twinning can be observed more often at lower temperatures as well as at load impacts.

The mechanism of plastic deformation of real metal (poly-crystal) is much more complicated than of separate crystal. The grains of poly-crystal differ between themselves as to the shape and sizes, may be differently oriented as to the deforming load, may have different mechanical properties. During the process of crystallization the intercrystalline layers are formed, which differ from the main metal as to composition, structure and are enriched by admixtures. Two types of poly-crystal deformation are distinguished: transcrystalline (by grain) and inter-crystalline (by grain boundaries). The first is passing by means of sliding and twinning, the second by means of turning and displacement of some grains relatively to another one. The both types of deformation are passing simultaneously.

Since the grains have different orientation of the planes of slipping, the plastic deformation is starting not in all grains at the same time. At first the grains are forming, which planes of sliding coincide with the directions of maximum shear stress action (Fig. 1.5, *a*, grains *1*, *2*, *3*, *4*). The rest of the grains are turning during the process of deformation, their planes of sliding are orienting more favorably to the direction of maximum shear stress action, and they are also subjected to deformation (Fig. 1.5, *b*). As the result the changing of the grains form is going on: they are stretching out at the direction of the most intensive flow of metal (Fig. 1.5, *c*). Simultaneously with grains form change, the turning of sliding planes with formation of similar crystallographic orientation of grains of deformed structure is taking place. This structure of cold deformed metal is called *texture* and causes anisotropy of properties in poly-crystal.

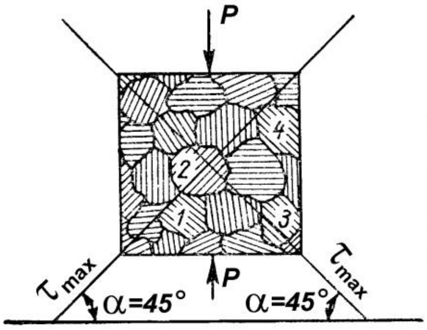


Fig. 1.5. Scheme of successive development
of polycrystal plastic deformation

Metal hardening

Plastic deformation of metal causes not only the change of shape and sizes of billet during the process of cold plastic working (stamping, drawing, thin sheet rolling), but also the change of physical-mechanical as well as chemical properties of the metal. The strength characteristics are increasing with increasing of deformation degree and plastic characteristics are decreasing (Fig. 1.6). Simultaneously the electric resistance is increasing and corrosion resistance and thermal conductivity are decreasing; magnetic conductivity is decreasing and coercive force is increasing. As can be seen from Fig. 1.6, the difference between the yield strength and ultimate strength is decreasing with the increasing of deformation degree, and at 70-90% deformation the yield strength almost coincides with ultimate strength.

The aggregate of phenomena connected with change of mechanical and physical-chemical properties during the process of plastic deformation is called hardening or work-hardening of metal.

The physical nature of hardening is interpreted by the dislocation theory. The dislocation movement is not going freely in

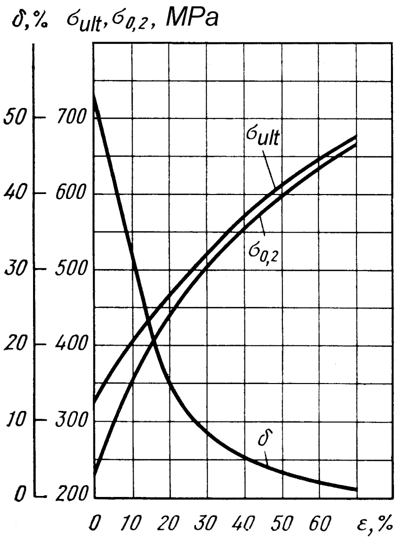


Fig. 1.6. Influence of degree of deformation on mechanical properties of the steel 08кп

real metals .There are obstacles on the way of dislocations such as interstitial atoms, precipitates of other phases, grain boundaries, intersection of sliding planes etc. The field of stresses around the dislocations is resiliently interacting with the field around the obstacles, and sliding in the given plane is short-stopping. To continue the deformation it is necessary to increase the deforming stress and the sliding will go along the less favorably oriented crystal planes. The interaction of lattice defects brings to formation of micro cracks, which are decreasing the plasticity of the metal.

The hardening during the deformation permits to regulate the final properties of metal products within the broad limits. It is possible to increase the strength of the metal 2-3 times by means of cold plastic working. On the other hand the decrease of plastic properties of the metal limits the possibility of conducting the further plastic forming and generates the need of metal heat treatment for renewing the plastic properties and reduction of strain resistance.

The determination of yield stresses during the process of cold metal forming

It is necessary to use the experimental data about the mechanical characteristics of different metals obtained after different kinds of tests for accomplishing the engineering calculations of deforming forces during the processes of cold metal forming. These data are presented in standards for different steel grades and alloys with indication of delivery conditions and the type of heat treatment. The considerable change of mechanical properties takes place during the process of deformation. The metal hardening comes with the increase of deformation rate. For determination of energy-power characteristics at cold deformation of metals the data are needed to be presented about the mechanical properties of metals in non-cold-hardened condition (at 20ºC) and in dependence on the deformation rate ε. These data for different metals are given in reference books in the form of diagrams of dependence of conventional yield strength on total deformation rate (in the form of hardening curves). Besides that, for many steel grades and alloys the empirical formulas are given for determination of conventional yield strength as follows:

$$\sigma_{yield} = \sigma_{yield0} + a\,\varepsilon^{b},$$

where σ_{yield0} – yield strength of non-deformed (annealed) metal; a, b – coefficient and index of deformation rate ε, %.

For instance, for steel grade 45: $\sigma_{yield}=343+85\varepsilon^{0.48}$ (MPa).

For performing the calculations of metal forming processes the necessity of determination of the mean value of yield strength is arising within the specified interval of deformation from: ε_{init} (initial value of deformation rate) up to ε_{fin} (the final value of deformation rate). Medium-integrated value of yield strength within this interval can be determined as follows:

$$\sigma_{yield\ av} = \frac{\int_{\varepsilon_{init}}^{\varepsilon_{fin}} \sigma_t d\varepsilon}{\varepsilon_{fin} - \varepsilon_{init}} = \sigma_{T0} + \frac{a}{b+1} \cdot \frac{\varepsilon_{fin}^{b+1} - \varepsilon_{init}^{b+1}}{\varepsilon_{fin} - \varepsilon_{init}}.$$

The value of the yield strength at desired initial deformation rate $\sigma_{yield\ init}$ can be determined as well as desired finite degree of deformation $\sigma_{yield\ fin}$ according to the approximation formulas:

- for annealed metal and at small deformations:

$$\sigma_{yield\ av}=(\sigma_{yield\ init}+2\sigma_{yield\ fin})/3;$$

- for hardened metal:

$$\sigma_{yield\ av}=(\sigma_{yield\ init}+\sigma_{yield\ fin})/2.$$

The influence of the deformation rate on the yield strength is not taken into account during the process of cold deformation. But the very high deformation rates due to the evident metal heating yield stress of the work metal is rather decreasing during the heat evolution.

1.4. Hot metal forming

The deformation is conducted in heated state for decreasing the strain resistance and increasing the plasticity of the worked metal. The rise in temperature no higher than (0.3-0.4)T_f (T_f – the metal fusion temperature in absolute scale, ºK) doesn't bring the structure changes to the metal, but the acceleration of diffusion processes contributes to the healing of structure defects and drop of inner stresses in metal. At temperatures of heating higher than 0.4T_f the process of grain recovery takes place in the metal. The nucleuses of the new grains, which are the centers of grain recovery, are being formed at the boundaries of deformed grains. The new grains are growing due to the solution and absorption of deformed grains. The rate of the process of grain recovery depends upon the temperature of metal heating: the higher the metal temperature is, the faster the process of the grain recover is going on. The processes of structure deformation and metal hardening connected with deformation are going on simultaneously during the process of hot metal forming as well as the process of formation of new structure as the result of grain recovery following by the weakening.

The temperature of metal heating is taken higher than 0.7T_f for the process of grain recovery to be over completely during the metal forming or partially with completion after deformation finishing. This kind of metal forming is called hot forming. Within the temperature interval (0.3-0.7)T_f the metal forming is called the incomplete hot or incomplete cold forming. The mechanisms of plastic deformation are the same during the hot forming and cold forming: sliding and twinning within the grains, mutual displacement and turning of grains. At high temperatures the additional mechanisms such as amorphous-diffusion, inter-grain recrystallization and inter-phase solution-precipitation mechanisms, which play the secondary part during the process of forming enter in action.

The new grains, which have been formed after grain recovery are arbitrary oriented in space, they have approximately equal dimensions along all directions what causes the isotropy of mechanical properties of the hot deformed metal. The structure of hot deformed metal with equi-axial grains doesn't allow to determine the direction of the main deformations during the forming. The tracks of admixtures may be however remained in the structure located at the boundaries of grains of cold deformed metal before the hot forming. It causes the possibility of getting fibrous structure after hot deformation as well.

The size of grains received after grain recovery depends upon metal deformation rate conducted before grain recovery. The inner energy reserve of the metal doesn't permit to form great quantities of grain recovery centers at small deformation rates, which are called as critical. The quantity of new grains in grain recovered structure will be moderate, and the obtained structure will be coarse-grain one. This structure has the low mechanical properties and its formation is undesirable. The quantity of new formed grains is increasing with the increasing of deformation rate and the structure of the metal becomes fine-grained.

The temperature interval within which the hot forming is possible to conduct depends upon carbon content in steel and is determined in dependence on the state diagram for different metals.

The diagram Fe-C section is shown on Fig. 1.7 and corresponds to the content of carbon in steels. The temperature range within which the forming of steels with different carbon content is possible is shown by shading.

The upper limit of temperature range $t_{u.l.}$ is determined by the danger of overheating or over burning the metal. The process of collecting recrystallization with formation of very coarse-grained structure may take place in the metal in the furnace area at high temperatures and long term ageing of metal. The low plasticity of this structure makes this metal useless for forming. This phenomenon is called overheating of the metal. The overheated metal has to be cooled quickly on the air. This working is called normalization. During the process of normalization the structure of the metal is growing smaller and this metal is possible to set to production.

The oxygen penetrates to the metal very deep, the grain boundaries are oxidizing, the ties between the grains are broken at high temperatures and oxidizing atmosphere in the furnace area. This phenomenon is called over burning. This metal is damaged during the process of working.

Practically the superior limit $t_{u.l.}$ for carbon steels is located 100-200° lower than the line of solidus AE (Fig. 1.7).

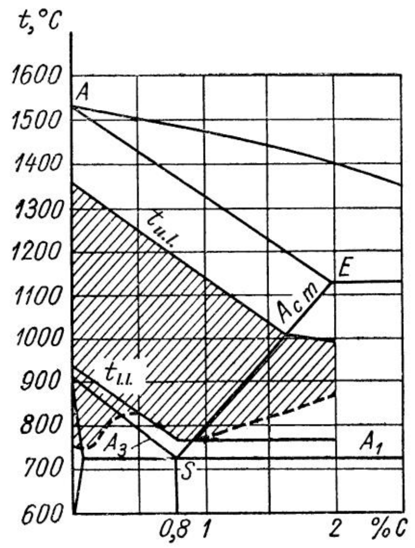


Fig. 1.7. Temperature range of hot forming of steels with different carbon content

The inferior limit of hot working temperature $t_{u.l.}$ is chosen from the condition of obtaining sufficiently fine-grain and plastic structure. For hypoeutectoid steels the optimum temperature of forging finish is A_3+(25-50°); for steels with carbon content less than 0.3% the working may be finished below the line A_3. For hypereutectoid steels the working is finished a little bit below the line SE, at the same time the separated cementite has to be present in the form of small fractured inclusions. At the lower temperatures of the working finish the plasticity of the metal is reducing.

As can be seen from Fig. 1.7, the increase of carbon content in steel causes the narrower temperature interval of working.

1.5. External (contact) friction

Resistance originated during displacement of one solid along the surface of the other is called external or contact friction. Resistance force to the relative displacement of solids is called friction force. The vector of friction force is located in the contact plane of solids and is directed to the side opposite to action of the shear.

At the presence of obstacles on the way of metal sliding along the surface of instrument the friction brings to increasing the force and irregularity of deformation as per thickness of worked metal. Thus the additional energy is used for overcoming the friction forces. The wear of instrument is increasing along with the increasing of friction forces, which may influence negatively the quality of working. The instrument surface defects leave the marks on the surface of the deformed solid and damage it. The usage of technological lubricants is the main method of decreasing the friction force and accordingly the instrument wear and decreasing of deforming force and deformation work. It makes the technological process more complicated. However in spite of negative sides of influence of external friction it is impossible, for instance, to grip the strip by rolls during the rolling without friction and accomplish the process of deformation. It is often necessary to increase artificially the friction for increasing reduction. Therefore it is necessary to manage the friction for increasing of effectiveness of the metal forming processes.

A number of factors influences on the value of external friction during the process of plastic deformation: the state of surface and chemical composition of pressing instrument, the state of surface of the worked solid, chemical composition of worked alloy, deformation temperature, the rate of relative shear of instrument and deformed solid, technological lubricants, contact pressure.

The main causes of friction forces origin are as follows:

- mechanical meshing of interaction surfaces irregularities;
- molecular seizure of surfaces in the points of contact, formation of so-called junctions of welding with their further damage;
- overcoming of shear resistance in the layer of transient formations, that is in microvolumes of isolation medium.

As it is known there are two types of friction: sliding friction and rolling friction. The sliding friction is typical for metal forming. The sliding friction is characterized by the fact that all points of surface of one solid are moving at a tangent to the surface of another solid.

Different substances in that or other quantity practically usually are located between the surfaces of interacting solids (tarnishes, lubricant, pollution, moisture, gases etc.) which properties differ greatly from the properties of the main solids. These are so-called intermediate or isolation media. The mechanism of external friction depends substantially on composition and quantity of these intermediate products.

The following types of friction are distinguished depending on the properties of isolation medium.

Dry friction. It can be observed when the surfaces of interacting solids are completely free of lubricant, pollution and molecules of environment (moisture, gases etc.). Ideally dry friction can't be met in practice. In action dry friction means the friction of un-lubricated solids.

Boundary friction. It can be observed in case of the thinnest lubricant films presence on the contact surfaces (their thickness equals to one hundredth micron parts). At the same time surface imperfections of solids are meshing directly.

Half-dry friction. It is the most widespread type of friction in the processes of metal forming. During these processes the contact surfaces of the instrument and worked metal are divided by the layer of oxides, marks of lubricant.

Semi-fluid friction. It is characterized by the presence of sectors on the contact surfaces divided by the lubricant layer which thickness doesn't exceed the height of micro-roughness of the surfaces.

Fluid friction. It takes place when the great thickness of the dividing lubricant layer is present, when all imperfections of solid surfaces don't mesh directly.

The change of friction force degree depending upon load conditions in case of half-dry friction is described by Amonton law, which is formulated as follows: the friction force is proportionate to normal load.

The notion of constant of friction is widely used as the aspect ratio.

Then the friction force T is equal to:

$$T=fP,$$

where f – is the constant friction; P – deformation force.

The average friction stress t_{av} is equal to:

$$t_{av}=fp_{av},$$

where p_{av} is the average pressure, MPa.

The constant of friction is dimensionless value. The coefficient of friction is determined by experimental methods during the process of metal forming.

The numerous factors influence on the value of friction constant: deformation temperature, metal chemical composition, material and roughness of instrument, the rate of metal sliding along the surface of the instrument, lubricants and others.

The values of friction constant are given in technical literature for specific conditions of deformation as well as formulas for estimation of friction constant.

1.6. Stress and strain state in the processes of metal forming

Every type of metal forming is characterized by the definite scheme of stresses and strains actions. For instance during the process of pressing the deformable billet and its every elementary volume is in the conditions of uniform compression. The scheme of deformation is characterized by compression in transverse location and elongation in the direction of metal extrusion in this process. The tensile stresses are acting from the action of drawing force in linear direction and compressing stresses from the side of the drawing die in transverse direction during the drawing. The scheme of deformation is similar to the process of pressing.

The following schemes of stress state are possible in different processes of metal forming (Fig. 1.8, *a*): four volumetric (*I*), three flat (*II*) and two linear (*III*). Elementary volume of deformed metal at volumetric stress state is subjected to the action of stresses from all sides. The flat stress state is the case when the stress is equal to zero at one of the directions. Linear schemes of stresses have place at ordinary elongation or compression.

The possible schemes of strain state are shown on Fig. 1.8, *b*. It is evident that the linear schemes of strain state are impossible under condition of volume preservation during the process of deformation.

The combining of stressed and strain states schemes in the specific process of metal forming is called mechanical scheme of deformation.

The schemes of stress state in the form of irregular uniform compression or opposite schemes are the most widespread in different processes of metal forming.

The friction on the contact surface of instrument with the worked metal plays the important role in formation of scheme of stressed state. Let us examine the process of setting-reduction of the billet between the flat heads at smith forging (Fig. 1.9).

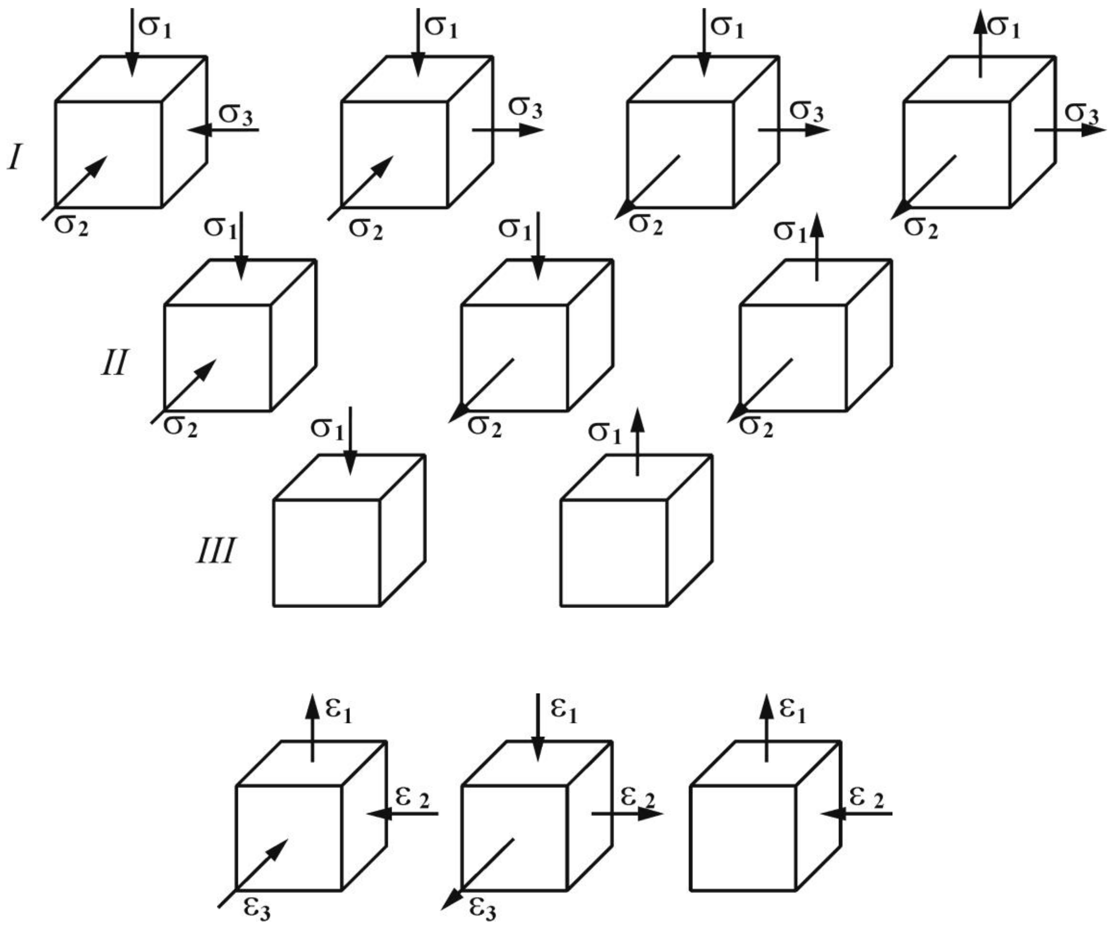


Fig. 1.8. The schemes of stress (*a*)
and strain (*b*) state

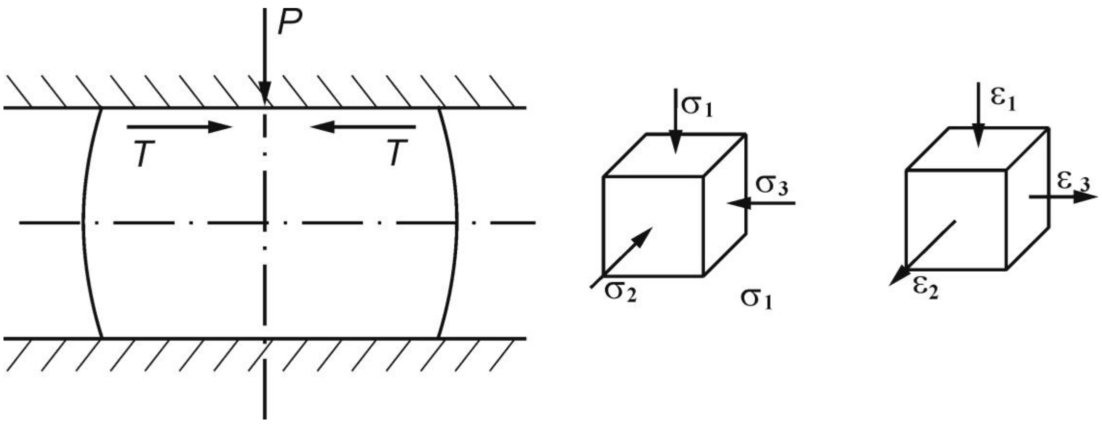


Fig. 1.9. Mechanical scheme
of deformation during setting

The height of the billet is reducing and the flow of the metal begins in transverse direction under the action of deformation force *P* and stress $\sigma_{1.}$ In this case the friction forces *T* on the contact surface resist to the flow of the metal and the side compressing stresses σ_2 and σ_3 appear. The deformed volume of the metal is to be found in the conditions of uniform compression. It can be seen from the given scheme of the strain state that the deformation direction may not correspond to the direction of stresses action.

Analogous schemes of stress and strain state appear in the process of rolling where the side compressing stresses are formed also as the result of action of friction forces on the surface of contact of rolls with worked metal.

The conditions of deformation may differ significantly in different parts of deformable solid. For instance, the side stresses in elements bordering the contact surface during the setting will be greatest in comparison to the stresses in elements, which are the farthest from the contact surface. This is the reason of different deformation of these elements: the transverse deformation of elements bordering the contact surface will be smaller than that in elements, which are distant from the surface. As the result of non-uniform deformation of the elements the shape of up setted billet becomes barrel shaped. The non-uniformity of deformation may also be caused by the non-uniformity of elements reduction resulting from the billet shape or instrument as well as heterogeneity of mechanical properties of deforming solid.

The inner stresses arise which may be the cause of metal destruction during the process or after finishing the working in case of non-uniform deformation in the volume of metal. The inner stresses in the metal after finishing of working are called residual ones. They are not desirable in many cases because the metal properties become worse: the corrosion resistance of the metal is reducing as well as serviceability; the formation of cracks on the surface is possible.

Deformation is accomplished only at separate section of the billet during many processes of metal forming. This section is called deformation zone (for instance during the drawing, rolling and some operations of free forging and others). Non-deformable parts of the billet bordering the deformation zone are called fringe zones or rigid ends. The fringe zones influence on metal flow in the deformation zone and on the deformation force. Significant deformations of shear and cut are taking place at the borders of deformation zone with the fringe zones resisting additionally during the reduction of the metal in deformation zone. Irregularity of deformation is reducing under the action of external zones. The influence of the fringe zones on the processes in the deformation zone depends upon the shape of deformation zone, which is characterized by the ratio l_d/h_{av} (l_d – the length of deformation zone; h_{av} – the average height of deformation zone). The workable metal is divided conditionally as per value of ratio l_d/h_{av} for thick strip ($l_d/h_{\text{av}}<1$), medium thickness strip ($l_d/h_{\text{av}}\approx1$) and thin strip ($l_d/h_{\text{av}}>1$).

The influence of the fringe zones on the deformation force is especially visible at the working of the thick strip and is practically absent at the thin strip working.

1.7. Strain resistance and plasticity during hot metal forming

Chemical composition influence

Ferrous alloys are undergoing the plastic working as well as non-ferrous: carbon steels and alloyed steels, bronze, brass, aluminum, copper and others. Pure metals and alloys have the highest plasticity and form solid solutions. The alloys forming chemical compounds and mechanical mixtures have the worst plasticity properties.

Carbon is the main element influencing the steel properties. The increase of carbon content in steel causes the decrease of plasticity and strain resistance increases. Steels with carbon content up to 0.5% have good plasticity and their working doesn't case any problems. However the forming of steel with content of carbon more than 1% presents great difficulties. Silicon and manganese within the limits of their content in ordinary steels (0.17-0.35% and 0.3-0.8% accordingly) don't influence much on plasticity of steel. The further increase of silicon and manganese content in steel decreases its plasticity properties and resistance to deformation is increasing.

Sulfur is presented in steel as FeS and MnS chemical compounds. It causes the red-brittleness of steel. The phenomenon of red-brittleness is connected with formation of eutectic of FeS+Fe at the boundaries of grains which (eutectic) is fusing at temperature 985ºC. The eutectic is undergone to fusion at heating of steel up to 1000-1200ºC for forging and rolling, the ties between the grains become weaker, and the cracks are forming in these places during the deformation. In case of MnS in steel the interval of red-brittleness is moved to the area of higher temperatures (1200ºC). In this connection the sulfur content in steel has to be minimum (no more than 0.03-0.05%).

Phosphorus content in steel causes cold brittleness. The separation of brittle compounds of phosphorus from the solid solution at the grains boundaries takes place at low temperatures, which may cause brittle failure during the metal pressuring in these conditions. That is why the content of phosphorus in steel has to be no more than 0.03-0.04%.

Alloying elements (chromium, nickel, tungsten, molybdenum, vanadium and others) cause the decrease of plasticity and increase the resistance for deformation in which connection the more is the content of carbon in steel, the more intensive the process is.

The temperature influence

The temperature effects substantially the mechanical properties of metals and alloys. The influence of temperature of metal heating is explained by the increase of amplitude of atoms' thermal oscillation, which causes the weakening of their ties and facilitates the process of plastic sliding. Besides that the rate of recrystallization process increases at higher temperatures and contributes to the metal softening. The resistance to deformation decreases due to increasing of metal heating temperature within the range of temperatures of hot metal forming, and the plasticity increases. But the increasing of strength and decreasing of plasticity takes place within the range of temperatures of phase change at release of new phases (it is 800-900ºC for steels).

The distinction in resistance to deformation between the steels with different carbon content becomes insignificant at high working temperatures (more than 1100ºC).

The influence of degree and the rate of deformation

The resistance to deformation is increasing due to the development of the process of strengthening with the increase of deformation degree. The strengthening (hardening) of metal takes place during the process of deformation at hot forming as well as at cold one. But the intensity of strengthening is decreasing to a considerable degree due to the development of the re-crystallization process.

The change of resistance to deformation depends upon correlation of the processes of strengthening at deformation and softening as the result of recrystallization.

Two rates have to be distinguished during the process of metal deforming: deforming rate constituting the speed of travel of working machine tool (head of the hammer, press slide etc.) and the rate of deformation presenting the change of deformation degree ε per unit time *t*.

The rate of deformation *u* is shown by the formula $u=d\varepsilon/dt$. $u_{av}=\varepsilon/t$ at constant rate as well as at average rate.

The rate of deforming during the plastic forming on presses amounts to approximately 0.1-0.5 m/sec and deformation rate amounts to 1-5 1/sec. The rate of deforming at the moment of impact at plastic forming at hammers runs up to 5-10 m/sec; in this case the whole process of deformation per one impact lasts a split second, the rate of deformation may amount to 200-250 l/sec. The more higher rates of deformation take place during the process of wire-rods, thin plates and strip rolling. The period of deformation is reduced with increase of the rate of deformation. The processes of recrystallization and the softening of metal connected with latter are accomplished to a smaller extent. The process of hardening becomes predominant and the resistance for deformation is increasing. However in order to have the more noticeable influence of deformation rate on the resistance to deformation the change of deformation rate has to be considerable.

The influence of deformation rate on metal plasticity is a little noticed. But nevertheless the increase of deformation rate and decrease of metal softening connected with it during the process of working contributes to decrease of plasticity. The plasticity of some manganese and copper alloys is decreasing especially sharply as well as plasticity of high-alloyed steel what may be explained by small rates of recrystallization.

The influence of scheme of stress

The influence of this factor may be referred only to the plasticity, because the yield strength and ultimate strength is determined only in conditions of linear stress – under simple tension and compression, though there is some difference between results of tensile and compression tests.

The compressing stress prevents the failure of intercrystallite ties. The plastic deformation takes no place under overall uniform compression due to the fact that shear stresses amount to zero. The scheme of stress under overall non-uniform compression is the most favorable scheme for passing the processes of metal forming. The metals reveal the highest plasticity in these conditions. The higher is the value of the average compression stress (hydrostatic pressure), the higher plastic properties of metals are revealed in these conditions. Plasticity is decreasing with the decrease of hydrostatic pressure and with the appearance of tension stresses. The plasticity of the metal is minimal under conditions of action of overall tensile stresses and the brittle failure takes place.

Determination of yield stress during hot metal forming

It is possible to use the laboratory data of testing obtained for different steel grades and alloys of ferrous and non-ferrous metals for practical determination of yield stress of workable metal.

The dependence of deformation resistance from chemical composition, metal temperature, degree and rate of deformation is very complicated. The test data are shown in the form of diagrams of yield strength change in dependence one of the parameters at fixed value of other parameters (for instance, dependence of yield strength on deformation degree at constant values of metal temperature and deformation rate). The value of the yield strength at specifically desired conditions of deformation has to be determined by the method of interpolation using the closest experimental data as to the conditions of deformation.

At present the method of thermo-mechanical coefficients for determination of yield strength during the process of hot metal forming has become widespread. This method is based on experimental determination of yield stress according to specified standard conditions:

- the temperature of the deformed metal t=1000ºC;
- deformation degree ε=10%;
- deformation rate u=10 1/sec.

The value of yield stress determined in these conditions is called the basic one ($\sigma_{\text{yield base}}$). The values of the basic yield strength for some steel grades and alloys are given in Table 1.1.

Table 1.1. The basic yield strength

Steel grade (alloy)	08КП	20	Ст3	45	У8	40Х
$\sigma_{\text{yield base}}$, MPa	82	83	84	86	88	90
Steel grade (alloy)	10ХН, 45ХН	12ХН3А	30ХГСА	60С2	Х18Н9Т	Р18
$\sigma_{\text{yield base}}$, MPa	93	98	103	112	120	156

The coefficients k_t, k_ε and k_u are introduced for calculating the influence of temperature, degree and rate of deformation in conditions different from basic ones. The actual value of yield strength can be found as follows:

$$\sigma_t = \sigma_{\text{yield base}}\, k_t\, k_\varepsilon\, k_u.$$

In case when the temperature of deformation coincides with the basic one, k_t=1. At higher temperatures k_t<1 and at temperatures lower than basic one k_t>1. Taking into account the influence of degree of deformation let us assume at ε=10% k_ε=1; at ε>10% k_ε>1; at ε<10% k_ε<1. The influence of the rate of deformation is calculated in the same way: at u=10 1/sec k_u=1; at u>10 1/sec k_u >1; at u<10 1/sec k_u<1.

The values of thermo-mechanical coefficients can be determined according to the diagrams shown on Fig. 1.10.

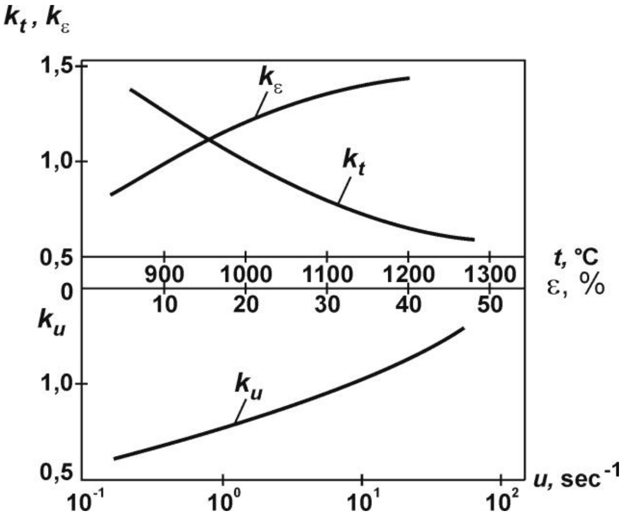


Fig. 1.10. Diagrams of changing
the thermo-mechanical coefficients

The P.L. Klimenko formulas for approximate determination of the value of thermo-mechanical coefficients may be also used:

$$k_t = 0{,}57 + 0{,}0045 \cdot (1200 - t)\sqrt{\frac{|1200 - t|}{t}};$$

$$k_\varepsilon = 0{,}82 + 0{,}082\sqrt{\varepsilon};$$

$$k_u = 0{,}80 + 0{,}065\sqrt{u}.$$

For instance, thermo-mechanical coefficients at deformation temperature t=1100°C, the degree of deformation ε=30% and the rate of deformation u=25 1/sec will be equal to: k_t=0.7; k_ε=1.27; k_u=1.125. Steel grade 45 ($\sigma_{yield\ base}$=86 MPa) will have the following yield strength:

$$\sigma_{yield} = 86 \cdot 0.7 \cdot 1.27 \cdot 1.125 = 86 \text{ MPa}.$$

1.8. Determination of deforming stress in the processes of metal forming

The beginning of the plastic deformation is connected with the increase of the level of acting stresses σ_1 up to the value called the yield strength and designated as σ_{yield} in the processes of ordinary linear tension and compression. But the action of tensions σ_2 and σ_3 influences the beginning of plastic deformation under conditions of volumetric stress or two-dimensional stress. The plastic deformation may start when deforming stress σ_1 haven't yet reached the value of yield stress or on the contrary at increasing of stress over the values of yield stress the plastic deformation never starts.

It has been found experimentally that plastic deformation begins in cases when the difference between the greatest acting stress σ_1 and the smallest stress σ_3 will reach the value of metal yield strength σ_{yield} when taking into account the correction β, considering the influence of stress σ_2:

$$|\sigma_1 - \sigma_3| = \beta\sigma_{yield}. \tag{1.1}$$

The value of the correction coefficient β, called the Lode coefficient, is within the limit $1.0 \le \beta \le 1.15$ and it has the maximum value at $\sigma_2 = (\sigma_1 + \sigma_3)/2$.

The ratio (1.1) is called equation of plasticity.

The tensile stresses are designated as «+» and compressing as «–». All stresses will be negative at scheme of uniform compression stressed state. The stresses σ_1 and σ_3 enter the equation of plasticity with the sign «–». As $|\sigma_1| > |\sigma_3|$, the difference $\sigma_1 - \sigma_3$ will also be negative. In this case we will have $|\sigma_1 - \sigma_3| = |\sigma_1| - |\sigma_3|$. In case $|\sigma_1 - \sigma_3| < \beta\sigma_{yield}$ deformation will be only elastic. The plastic deformation is impossible in case of uniform compression $|\sigma_1 - \sigma_3| = 0$ irrespective of the value of acting stress. The plastic deformation starts at ratio (1.1) in case of uniform compression, in which connection the value of the deforming stress σ_1 exceeds the value of yield stress in these conditions:

$$\sigma_1 = \beta\sigma_{yield} + \sigma_3. \tag{1.2}$$

The modulus of stress difference $|\sigma_1 - \sigma_3|$ is equal to the sum of modulus $|\sigma_1|$ and $|\sigma_3|$, and the value of the deforming stress will be less than the value of the yield stress at opposite schemes of stress state:

$$\sigma_1 = \beta\sigma_{yield} - \sigma_3. \tag{1.3}$$

Let us examine these ratios with the examples of specific processes of metal forming. The metal is situated in the deformation zone in conditions of overall non-uniform compression during the plate rolling (Fig. 1.11, *a*).

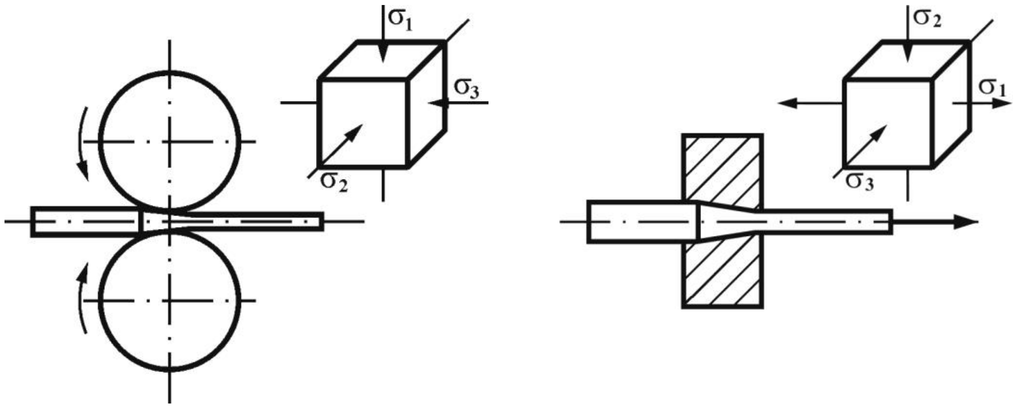


Fig. 1.11. The schemes of stress state during the rolling (*a*) and drawing (*b*)

The deforming stress from the rolls side is designated σ_1. The side stresses formed by friction forces are designated σ_2 (in transverse direction) and σ_3 (in the direction of rolling).

The ratio $\sigma_2=(\sigma_1+\sigma_3)/2$ at which $\beta=1.15$, has place during the rolling of plates. Let us suppose that the stress $\sigma_3=50$ MPa is formed at desired friction conditions which influence the resistance to the metal flow in linear direction. Then the deforming stress equal to:

$$\sigma_1 = \beta\sigma_{yield} + \sigma_3 = 1.15\cdot 100 + 50 = 165 \text{ MPa}$$

will be needed for plastic deformation with yield tensile $\sigma_{yield}=100$ MPa.

The scheme of stress state with deforming stretching stress σ_1 and compression stresses $\sigma_2=\sigma_3$ affecting the metal in deformation zone in the transverse direction (Fig. 1.11, *b*) appears during the process of deformation of material with yield strength $\sigma_{yield}=100$ MPa by means of drawing. In these conditions β=1, taking as σ_3=50 MPa, the value of deforming stress will be obtained as follows:

$$\sigma_1 = \beta\sigma_{yield} - \sigma_3 = 100 - 50 = 50 \text{ MPa}.$$

It is obvious that the scheme of stress state influences significantly on the value of deforming stress.

1.9. The main laws of plastic deformation

The law of the constant volume

The plastic deformation of the metal is accompanied by rather insignificant change of its volume consisting only 1-2% for melt metal. Practically this change of the volume may be ignored and considered that the metal volume before deformation is equal to the volume of the metal after deformation. The constant volume of the metal before and after deformation has the name of the law of volume constancy. The important consequence results from the law of the constant volume.

Let us suppose that the rectangular parallelepiped the ribs of which before deformation are equal to *H*, *B* and *L*, is undergone to compression at the direction of the rib *H* (Fig. 1.12).

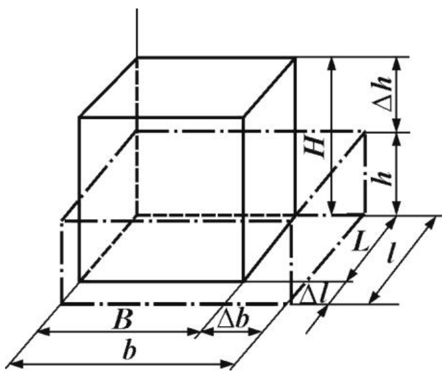


Fig. 1.12. The scheme of linear dimensions change during the deformation of parallelepiped

After deformation the parallelepiped remained as rectangular but its ribs dimensions have been changed and became *h*, *b*, *l*. The following equality results from the law of constant volume:

$$H \cdot B \cdot L = h \cdot b \cdot l$$

or

$$\frac{h}{H} \cdot \frac{b}{B} \cdot \frac{l}{L} = 1. \qquad (1.4)$$

The co-factor in this equation is called linear coefficients of deformation and designated as:

$\eta = \frac{h}{H}$ – the coefficient of altitude deformation;

$\beta = \frac{b}{B}$ – the coefficient of lateral deformation;

$\lambda = \frac{l}{L}$ – the reduction ratio.

The linear coefficients of deformation are connected by the ratio:

$$\eta \cdot \beta \cdot \lambda = 1.$$

The following result is obtained after finding the logarithm of two parts of equation (1.4):

$$\ln\frac{h}{H} + \ln\frac{b}{B} + \ln\frac{l}{L} = 0. \qquad (1.5)$$

The quantity $\ln\frac{h}{H}$ has the name of logarithmic or actual degree of deformation in the direction *h*; accordingly two other items present the actual degrees of deformation in directions *b* and *l*. Deformations along three mutually perpendicular directions are called the components of deformation. In case of designation of the components along three directions as e_h, e_b, e_l, one might record that:

$$e_h + e_b + e_l = 0. \qquad (1.6)$$

That is the algebraic sum of actual degrees of deformation along three mutually perpendicular directions is equal to zero. Consequently if two components of deformation have the same sign, the third component has to have the opposite sign (the sign «+» corresponds to stretching and sign «–» corresponds to compression).

Conditional indexes of relative deformation are widely used in plastic working. They are expressed by the ratio of linear dimension increase obtained as the result of deforming to the initial:

$$\varepsilon_h=(h-H)/H\cdot 100\%; \qquad (1.7)$$

$$\varepsilon_b=(b-B)/B\cdot 100\%; \qquad (1.8)$$

$$\varepsilon_l=(l-L)/L\cdot 100\%. \qquad (1.9)$$

They are practically equal to logarithmic ones at values of conditional relative deformation less than 10%. All computations of the billets are based on the law of constant volume as well as calculations of technological transition of shaping during metal forming.

The law of similarity

The modeling principle is used for approximate determination of deformation force and of the work spent for deformation at metal forming. It is based on the scaling law. The scaling law is formulated in the following way: the average contact pressures will be equal at plastic deformation of geometrically similar solids in physically similar conditions.

Let us examine (Fig. 1.13) two geometrically similar solids, one of which (of the greatest size) will be called the nature and the other will be called the model.

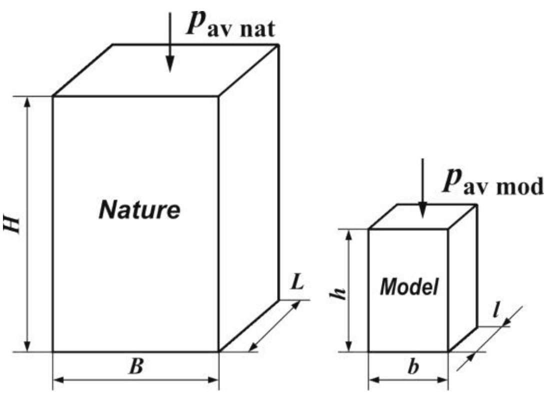


Fig. 1.13. Scheme for explanation

of the law of similarity

The following ratio has to be kept for geometrically similar solids:

$$\frac{H}{h}=\frac{B}{b}=\frac{L}{l}=n,$$

where n is the scale of similarity.

Geometrical similarity supposes the similarity of the deforming instrument shape for nature and model.

The following items are required to keep the conditions of physical similarity:

- model and nature have to be produced from the same material;
- the equality of temperatures of model and nature during the deformation process has to be kept;
- degree and rate of model and nature deformation has to be the same.

In this case we have the equality of average contact pressures of nature and model: $p_{\text{av nat}}=p_{\text{av mod}}$. Taking into account that the deformation force is equal to the product of average contact pressure on contact area we obtain the ratio of deformation force of the nature P_{nat} to the deformation force of the model P_{mod}:

$$\frac{P_{\text{nat}}}{P_{\text{mod}}}=\frac{p_{\text{nat}}BL}{p_{\text{mod}}bl}=n^2. \qquad (1.10)$$

The works used for deformation of nature and model have the following ratio:

$$\frac{A_{\text{nat}}}{A_{\text{mod}}}=\frac{P_{\text{nat}}\Delta H}{P_{\text{mod}}\Delta h}=n^3 \qquad (1.11)$$

(at equality of deformation degree of nature and model $\frac{\Delta H}{\Delta h}=n$).

The ratios (1.10) and (1.11) are the consequences of the law of similarity. They permit to determine the value of strain and expended work necessary for nature deformation according with the results of tests carried out on the model.

The law of least resistance

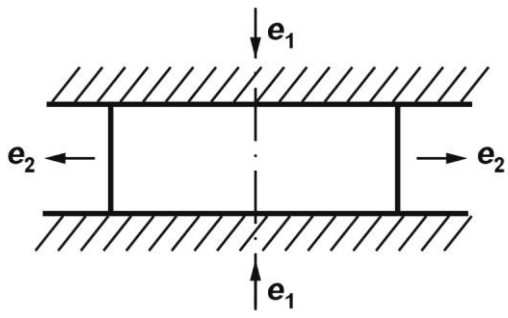
This law permits to determine the trajectory of displacement of solid points during deformation. The law sounds as following: each particle is moving at the direction of the least resistance during the process of plastic deformation in case of possibility of moving for deformed solid particles.

The displacement of solid's points is prevented by the friction forces. The bigger is the point pass is the bigger is the resistance of the friction forces. Thus each point is moving along the path of the least resistance at the direction which is perpendicular to the nearest plane.

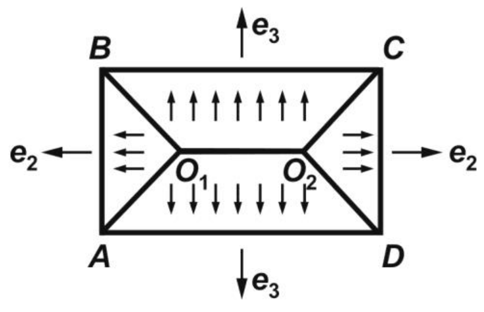
Let us examine the scheme of up setting of parallelepiped (Fig. 1.14, *a*).

The arrows show the directions of particles movement during deformation and conventional boundaries of flow BO_1, AO_1, O_1O_2, O_2C, O_2D which determine the character of metal flow (Fig. 1.14, *b*). The law of the least resistance runs that the particles flow in this case is going along the normal to perimeter. Therefore after deformation the contact surface of parallelepiped will have the shape shown on Fig. 1.14, *c*.

The greatest deformation will take place at the direction, where the majority of moving points meet the least resistance to their displacement in case of possibility of free forming of the solid at different directions. The directions of moving of deformed metal may be different in different parts of solid during



a



b

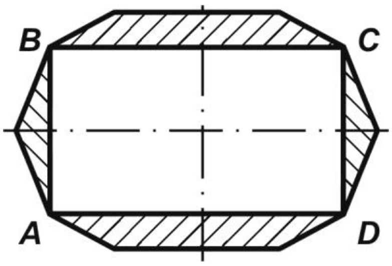


Fig. 1.14. Metal flow at the setting: *a* – direction of the flow (view from the side); *b* – direction of flow (view from the side); *c* – shape of the contact surface after setting

the complicated processes of plastic metal working. And it is necessary to know in advance the directions of metal moving for different parts of deformed solid for determination of the force conditions of the process. The law of the least resistance gives the simplified connection between metal particles moving during its plastic working and resistances to movements of these particles. The quantification of this connection is rather complicated, but for practical calculations of forming during the metal working it may be assumed at the first approximation that the movements of metal particles at different directions are inversely proportional to resistances for movement.

2. THE THEORY OF METAL FORMING PROCESSES

2.1. Lengthwise (longitudinal) rolling

Deformation zone and its geometrical parameters

The metal under the action of friction forces on the contact is drawing into the driven rolls rotating in opposite sides during the rolling. The thickness of the strip is being reduced while passing between the rolls, and the length and width increase. The metal is plastically deformed non-simultaneously along its whole length, but only at some area, which is called zone of deformation. The zone of deformation is identified as the metal volume *ABB'A'* locating between the rolls and bordered by the planes of entry *AA'* and exit *BB'* (Fig. 2.1). That is so-called geometrical zone of deformation. The parts of the strip bordering the zone of deformation, but not deformed at this moment are called external zones or rigid ends.

The arc *AB* and *A'B'* is called the contact arc or the arc of contact. The central angle α corresponding to the arc of nipping (arc of contact) is called the angle of nipping or contact angle.

Ichnography of contact arc (the line *AC*) is called the length of deformation zone l_d.

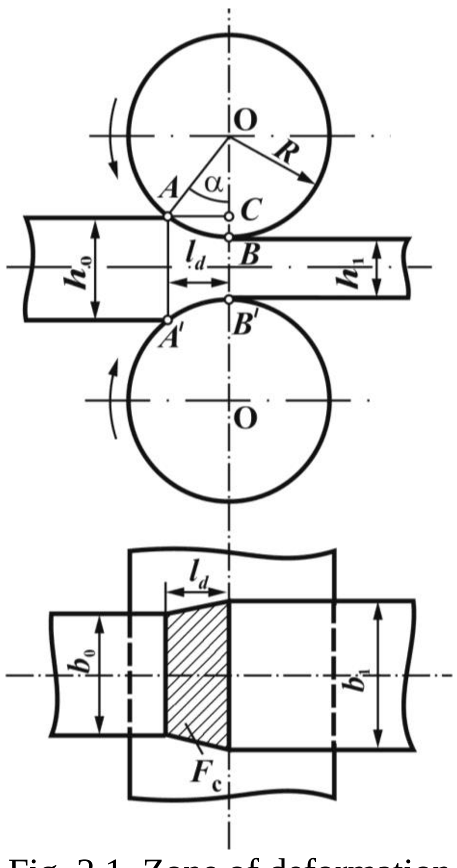


Fig. 2.1. Zone of deformation

The ichnography of the strip contact surface with rolls F_c is shown by shading at the bottom of Fig. 2.1.

The difference $h_0 – h_1 = \Delta h$ is called reduction in thickness; $b_1 – b_0 = \Delta b$ is called absolute broadening. The values Δh, R and α are connected between each other by geometrical correlation $\frac{\Delta h}{2} = R(1 - \cos\alpha)$. In that way the result will be approximately as follows:

$$\Delta h = D(1 – \cos\alpha) \tag{2.1a}$$

or

$$\Delta h = R\alpha^2, \tag{2.1b}$$

where $D = 2R$ is the diameter of the roll.

The length of deformation zone may be determined as follows:

$$l_d = AC = AO \cdot \sin\alpha = R \cdot \sin\alpha. \tag{2.2}$$

The length of deformation zone may be determined approximately with high enough accuracy by the following formulas:

$$l_d \approx AB = \sqrt{R\Delta h} \tag{2.3a}$$

or

$$l_d \approx \smile AB = R\alpha. \tag{2.3b}$$

The contact area is close by the shape to isosceles trapezium and may be determined by the formula:

$$F_c = 0{,}5(b_0 + b_1)\sqrt{R\Delta h}\,. \tag{2.4}$$

The condition of strip nipping by the rolls

The strip placed before the rolls is not always captured by the rolls for beginning of the rolling process. The nipping and the further rolling will take place only under the definite conditions. Let us examine the condition of nipping (Fig. 2.2).

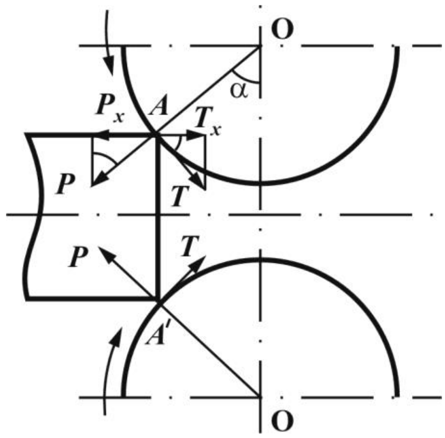


Fig. 2.2. Nipping of strip by rollers

Let us place the strip before the rolls. The forces of the normal pressure *P* and friction force *T* appear in points *A* and *A*' – the place of contact of the strip with the rolls.

P_x is the ichnography of the force *P*; that is expulsive force, it strives to push the strip out of the rolls.

T_x is the ichnography of the force *T*; it is the force drawing the strip into the rolls.

The nipping of the strip by the rolls is possible under the following conditions:

$$P_x \le T_x, \text{ but } P_x = P\cdot\sin\alpha,\ T_x = T\cdot\cos\alpha,\ P\sin\alpha \le T\cdot\cos\alpha.$$

After dividing into $P\cdot\cos\alpha$ we obtain:

$$\frac{P\cdot\sin\alpha}{P\cdot\cos\alpha} \le \frac{T\cdot\cos\alpha}{P\cdot\cos\alpha} \to \mathrm{tg}\alpha \le \frac{T}{P}.$$

Substituting $\mathrm{tg}\alpha \approx \alpha$ and $\frac{T}{P} = f$ we obtain:

$$\alpha \le f. \qquad (2.5)$$

This is the condition of the strip nipping by rolls, which is formulated in the following way: the angle of nipping has to be less or equal to friction coefficient for nipping the strip by rolls. The angle of nipping is measured in radians. The friction coefficient at hot rolling of steels is equal to 0.3-0.5.

Taking the limiting condition of friction as $\alpha = f$, using formula (2.1*b*) we will obtain the maximum reduction in the moment of nipping during the rolling on roughing mill with 800 mm rolls diameter and friction coefficient f=0.5 (the rolls with ragging).

$$\Delta h_{\max} = R \cdot f^2 = \frac{D}{2} \cdot f^2 = \frac{800}{2} \cdot 0{,}5^2 = 100 \text{ mm.}$$

The expressions (2.1*a*; 2.1*b*) denote the direct dependence of reduction during the process of rolling on the value of the angle of nipping. The increase of the angle of nipping at the given rolls diameter permits to increase the reduction, that is to increase the efficiency of the mill due to decrease of the numbers of passes. Therefore one tries to carry out the rolling with greater angles of nipping, but their values are limited by the value of friction coefficient. In production practice the artificial coarsening of the rolls (cuts, welding on etc.) is used to increase the angle of nipping and consequently the reductions. Besides the rolling speed is decreased at the moment of nipping. The cone rolling ingots are feeding forward by the thin end to facilitate the nipping. It is possible to increase considerably the nipping angle and consequently the reduction by means of forced feeding of the metal into the rolls.

The value of the friction coefficient may be determined according to the empirical formulas. The formula of B.P. Bakhtinov and M.M. Shtern is given below:

$$f = k_1 k_2 k_3 \left(1{,}05 - 0{,}0005 t^{\circ}\right), \qquad (2.6)$$

where t is the temperature of metal, ºC; k_1, k_1 and k_3 – the coefficients taking into consideration the condition of surface and the rolls material, the speed of rolling and chemical composition of the metal.

The practice of manufacturing different rolled products permitted to determine the coefficients of friction and maximum angles of nipping: the coefficient of friction amounts to 0.45÷0.52 during the rolling of blooms and ingots on the rolls with cuts or welding on, and maximum angle of nipping amounts to 26÷34º; the coefficient of friction amounts to 0.36÷0.47 during the rolling of sectional bars and maximum angle of nipping amounts to 20÷25º; the coefficient of friction amounts to 0.04÷0.06 during the cold rolling with lubricant and maximum angle of nipping amounts to 4÷10º.

The scheme of forces action in zone of deformation will be changed in case when the initial nipping has been accomplished and the deformation zone is filled by metal due to the fact that the point of application of equivalent forces *P* and *T* is displaced to the center of the contact surface. Its position is characterized by the value of the angle ψ (Fig. 2.3) and the angle α should be changed to ψ in the equation (2.5) obtained above. The condition of the metal nipping has the following form in the stable process of rolling:

$$\psi \le f. \qquad (2.7)$$

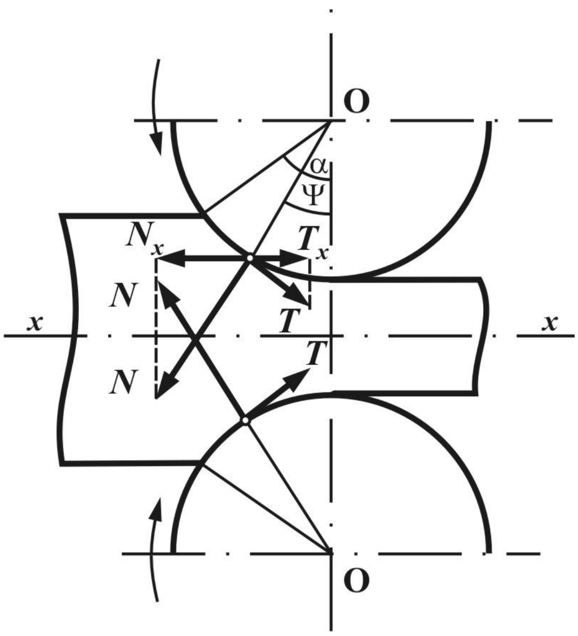


Fig. 2.3. The scheme of the force action in the stable process of rolling

Taking $\psi=\alpha/2$ we obtain the expression for determination of maximum possible angle of nipping for stable process of rolling:

$$\alpha_{\max} = 2f\,. \qquad (2.8)$$

The angle of nipping can be increased two times as compared with the condition of initial nipping. Consequently the possibilities of initial nipping limit the reduction during the rolling. The angle of nipping in the stable process of rolling may be increased two times, what corresponds to increasing of reduction ($\Delta h = R\alpha^2$) to four times if the initial nipping is ensured.

Longitudinal and lateral deformation

The height of the strip during the rolling is decreased for the value of absolute reduction Δh. The length and width of the strip has to be increased according to the law of metal volume constancy.

The increasing of the strip length is called the longitudinal deformation or stretching. The length of the strip after rolling is equal to:

$$l_1 = \lambda \cdot l_0,$$

where λ is reduction ratio, l_0 is the initial strip length.

It is necessary to distinguish the reduction ratio in every pass and the total rate of reduction.

The total reduction ratio for several passes is equal to:

$$\lambda_{\text{tot}} = \frac{l_n}{l_0} = \frac{F_0}{F_n}, \qquad (2.9)$$

where l_n and F_n are accordingly the length and cross-section area of the strip after n-th pass.

It is not difficult to prove that the total reduction ratio is equal to the product of separate reduction ratio:

$$\lambda_{\text{tot}} = \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdot \ldots \cdot \lambda_n. \qquad (2.10)$$

The increase of the strip width during the rolling is called broadening or lateral deformation. In case when the value of broadening is known the final width of strip will be equal:

$$b_1 = b_0 + \Delta b.$$

The number of formulas is proposed for broadening determination. One of them is as follows:

$$\Delta b = 0{,}5c_b\left(\sqrt{R\Delta h} - \frac{\Delta h}{2f}\right)\ln\frac{h_0}{h_1}, \qquad (2.11)$$

where c_b is the coefficient considering the influence of strip width.

The rate of stretching and broadening change during the rolling is determined by the law of the least resistance and depends on dimensions of deformation zone: its length $l_d = \sqrt{R\Delta h}$ and width b_0.

The resistance of friction forces to the metal displacement in linear direction will be greater than in transverse location and the broadening will be increased and the stretching will be decreased in case when the length of the deformation zone l_d is greater than width b_0 ($l_d > b_0$).

The resistance of friction forces to the metal displacement will be increased in transverse location if the width of deformation zone is greater than its length ($b_0 > l_d$). It will lead to the increase of stretching and the decrease of broadening.

The factors of the rolling increasing the length of the deformation zone (the increase of the absolute reduction Δh and the rolls diameter D) will increase the broadening and reduce the stretching.

The increase of the width of deformation zone (the increasing of the initial strip width) will on the contrary lead to increasing of stretching and decreasing of broadening.

Though dimensions of deformation zone change the correlation between longitudinal and transverse deformation, the greater part of metal reduced by its height, nearly 60-80%, is used for increasing the strip elongation (increasing its length), and only 20-40% is used for increasing its width.

Phenomena of the forward and backward slip at the rolling

Let us distinguish three sections in deformation zone – the section of entry, any intermediate section at the arbitrary φ, the section of exit and write down for them the condition of continuity of the metal flow passing via the deformation zone:

$$h_0 b_0 v_0 = h_\varphi b_\varphi v_\varphi = h_1 b_1 v_1. \qquad (2.12)$$

The equation (2.12) may be put to the following type:

$$F_0 v_0 = F_\varphi v_\varphi = F_1 v_1 = \text{const}. \qquad (2.13)$$

The product of the cross-section area to the strip speed (v) in the given area is called a second volume. The equation (2.13) is called the condition of the constant second volume, which is formulated in the following way: the equal metal quantity should pass through every cross-section of deformation zone per time unit.

The cross-section area of the strip is reduced as advances from the entry plane to the exit plane. The speed of the strip should increase continuously from the section of entry to the section of exit of metal out of the rolls for observance of the constant second volume, that is:

$$V_0 < V\varphi < V_1.$$

As it was shown by the experiments, the speed of the strip end coming out of the rolls is greater than the circumferential speed of the rolls. In the theory of rolling this effect is called forward slip. The longitudinal speed of the strip is compared with the horizontal projection of circumferential speed of the rolls which is equal for any point of contact arc to:

$$v_{x\text{roll}} = v_{\text{roll}} \cos\varphi, \qquad (2.14)$$

where φ is the current central angle.

The angle φ is changing from φ=α (entry section) up to φ=0 (exit section) along the contact arc. For the exit plane if φ=0 and cosφ=1 we obtain:

$$v_{x\text{roll}} = v_{\text{roll}}, \qquad (2.15)$$

that is the horizontal projection is equal to the circumferential speed of the rolls.

Mathematically the relative forward slip can be written as follows:

$$S = \frac{v_1 - v_{\text{roll}}}{v_{\text{roll}}}. \qquad (2.16a)$$

The forward slip is often determined in percentage terms:

$$S = \frac{v_1 - v_{\text{roll}}}{v_{\text{roll}}} \cdot 100\%. \qquad (2.16b)$$

The speed of the strip at the exit at the known advance (acceleration) is equal:

$$v_1 = v_{\text{roll}} \cdot (1 + S). \qquad (2.17)$$

Let as assume that v_{roll}=2 m/sec, and S=5%, then:

$$v_1 = 2(1 + 0,05) = 2,1 \text{ m/sec}.$$

It is easy to determine the speed of metal entry into the rolls using the strip speed in the plane of exit v_1 and the law of constant second volume (2.13):

$$F_0 v_0 = F_1 v_1,$$

wherefrom

$$v_0 = \frac{F_1}{F_0} v_1. \qquad (2.18)$$

The ratio $\frac{F_1}{F_0} = \frac{1}{\lambda}$ is the value opposite to the reduction ratio, therefore the speed of the metal entry to the rolls is:

$$v_0 = \frac{v_1}{\lambda}. \qquad (2.19)$$

The strip speed in the plane of entry to the rolls is less than the speed of its exit so many times as many times the area of cross-section per pass is decreasing (for the value of reduction ratio).

Let us continue the above given calculation and determine the speed of metal entry into the rolls, when reduction ratio is equal for instance to λ=1.5. We obtain from (2.19) the following:

$$v_0 = \frac{v_1}{\lambda} = \frac{2.1}{1.5} = 1.4 \text{ m/sec}. \qquad (2.20)$$

Thus the speed of metal entry into the rolls is less than circumferential speed of rolls. This phenomenon is called the backward slip.

Mathematically relative backward slip can be written down as follows:

$$S_{\text{back}} = \frac{v_{\text{roll}} \cos\alpha - v_0}{v_{\text{roll}} \cos\alpha}. \qquad (2.21)$$

The value called the backward slip characterizes the ratio of speeds in the plane of metal entry into the rolls. This term emphasizes that the speed of movement of the trailing end of the strip is less than the horizontal ichnography of circumferential speed of the rolls.

The forward slip is variable along the groove width during the rolling in grooves. It may be explained by the fact that the strip speed at the exit v_1 is the same along the whole cross-section and radius and circumferential speed of the rolls are changing along the perimeter of the groove.

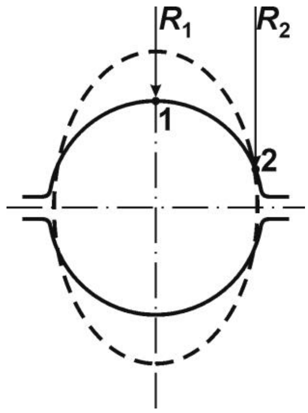


Fig. 2.4. Scheme of oval billet reduction during the rolling in the round groove

Let us examine for instance the case of the oval billet rolling in the round groove (Fig. 2.4). The speed of points 1 and 2 of the roll surface is different. As $R_2>R_1$, $v_{\text{roll2}}>v_{\text{roll1}}$. The forward slip in the point 1 and point 2 is equal:

$$S_1 = \frac{v_1 - v_{\text{roll1}}}{v_{\text{roll1}}}; \;\; S_2 = \frac{v_1 - v_{\text{roll2}}}{v_{\text{roll2}}}.$$

The coefficients of forward slip are as follows: $1+S_1=v_1/v_{\text{roll1}}$;$1+S_2=v_1/v_{\text{roll2}}$.

This implies: $\frac{1+S_1}{1+S_2} = \frac{v_{\text{roll2}}}{v_{\text{roll1}}}$, that is $S_1>S_2$.

The maximum value of forward slip in the grooves takes place in the points of the groove having the minimum roll radius (at the peak of the groove). The forward slip has the minimum value in the points of the groove with maximum radius and the negative value (the backward slip) is possible.

The change of strip speed along the deformation zone

The strip speeds were determined above only for the extreme cross-sections of the deformation zone – entry and exit of the strip out of the roll. The behavior of strip speed during the deformation zone can be determined from the condition of constant second volumes.

Let us assume that the speeds are uniformly distributed per the height of the strip, and the broadening is absent, that is $b_0=b_\varphi=b_1$; then we obtain the following:

$$h_0v_0 = h_\varphi v_\varphi=h_1v_1, \qquad (2.22)$$

wherefrom

$$v_\varphi = \frac{h_0 \cdot v_0}{h_\varphi} \qquad (2.23)$$

or

$$v_\varphi = \frac{h_1 \cdot v_1}{h_\varphi}, \qquad (2.24)$$

that is the change of the strip speed within the deformation zone may be determined using the condition at the entrance (h_0, v_0) or the condition at the exit (h_1, v_1).

The current height of the strip h_φ in any point of the arc of contact may be determined according to the following formula:

$$h_\varphi=h_1+D(1-\cos\varphi). \qquad (2.25)$$

Substituting the value h_φ into the formulas (2.23) and (2.24) for determination of v_φ we obtain the following:

$$v_\varphi = \frac{h_0}{h_1 + D(1-\cos\varphi)} \cdot v_0, \qquad (2.26)$$

$$v_\varphi = \frac{h_1}{h_1 + D(1-\cos\varphi)} \cdot v_1. \qquad (2.27)$$

As the metal speed increases continuously from the section of entry to the section of exit and at the same time the speed of metal entry into the rolls is less than the speed of rolls and the speed of exit is greater, it is evident that in deformation zone there is such a section in which the speeds of metal and rolls are equal. This section is called neutral. Its location in the deformation zone is determined by the value of neutral angle γ.

The diagram reflecting the ratio of speeds of the rolls and metal along the deformation zone is given on Fig. 2.5.

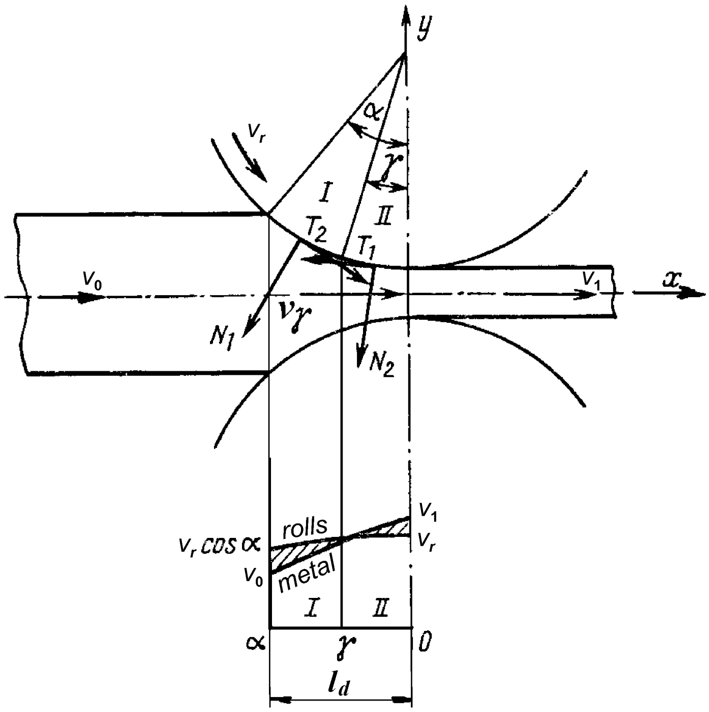


Fig. 2.5. The scheme of the acting forces
and change of speeds of the rolls
and strip in the deformation zone

The neutral section divides the deformation zone into two zones of sliding: zone of backward slip (*I*) located from the neutral section up to the section of entry and zone of forward slip (*II*) located from the neutral section to the section of exit. The speed of metal in any section of zone of backward slip is less and in zone of forward slip on the contrary, is greater than the ichnography of the circumferential speed of the rolls.

The difference of speeds of metal and rolls displacement is the evidence that the strip during rolling is continuously slipping relative to the rolls along the whole deformation zone, except of one section – the neutral section. As the result the friction forces appearing on the surface of contact of the metal with the rolls in the zones of backward and forward slip are directed to opposite sides, and support metal making its deformation more difficult.

The neutral section is the division of metal flow within the deformation zone. During the strip reduction as for height one part of metal is pressed from the neutral section forward along the run of the rolling. At that the speed of plastic shear of these particles is summarized with circumferential speed of the rolls forming zone of forward slip.

The other part of the metal on the contrary is pressed backwards from the neutral section against the run of rolling. In this case the speed of plastic shear of these particles is deducted from the circumferential speed of rolls forming the zone of backward slip.

The formula of Dresden is used for practical calculations of the forward slip value during the rolling:

$$S = \frac{R}{h_1}\gamma^2 . \qquad (2.28)$$

The forward slip increases with the increase of the rolls diameter and the angle γ and the decrease of the final height of the strip.

The angle of the neutral section γ, which is necessary for calculation of the forward slip is determined according to the formula of Pavlov I.M.:

$$\gamma = \frac{\alpha}{2}\left(1 - \frac{\alpha}{2f}\right). \qquad (2.29)$$

The angle of nipping should be determined in radians. The following formula may be used:

$$\alpha = \sqrt{\frac{\Delta h}{R}} . \qquad (2.30)$$

The knowledge of the forward slip is especially important for the correct calculation of the speed regime of rolling in the stands of continuous mills to avoid excessive tension or formation of the loop between the stands as it may cause the breakdown of the technological process as well as formation of the defects in the rolled metal.

The rate of deformation

The average rate of deformation is determined by the executed relative deformation ε realized during the time of metal flow of the zone of deformation τ_{def}:

$$u_{av} = \frac{\varepsilon}{\tau_{def}}. \qquad (2.31)$$

Approximately the value τ_{def} may be determined as $\tau_{def}=l_d/v_1$. Then we obtain the A.I. Tselikov's formula:

$$u_{av} = \frac{v_1 \cdot \varepsilon}{l_d}. \qquad (2.32)$$

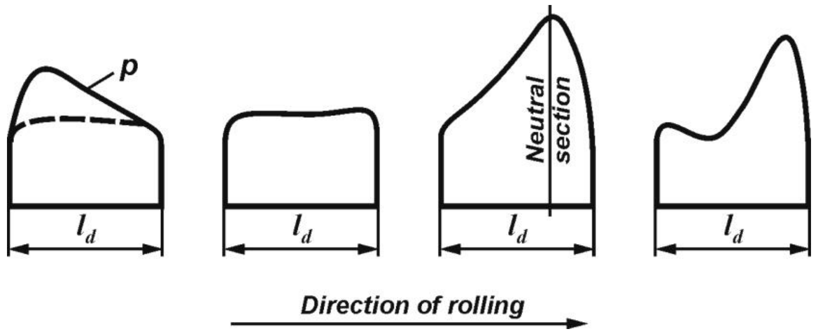
It is necessary to take into account the rate of deformation while determining metal resistance to deformation.

The distribution of pressures along the contact surface

At present the pressure distribution along the contact surface (contact pressure profile) has been well researched by means of the point load cells. It has been stated that the view of the pressure profile depends upon the conditions of rolling and first of all upon such factors as the ratio l_d/h_{av}, coefficient of friction f and contact angle α.

Under the small values of parameter l_d/h_{av} (approximately l_d/h_{av}<0.7) the pressure has the maximum value near the plane of entry (Fig. 2.6, *a*). It may be explained by the supporting action of rigid trailing end of the strip.

At higher values of parameter l_d/h_{av}, especially at l_d/h_{av}>3÷4 (thin strip) the clearly-defined peak appears on the profiles (epures) of pressure, which is located in the neutral section (Fig. 2.6, *c*). This character of pressures distribution is due to the action of friction forces. The sum of the linear supporting friction forces increases during the process of the displacement from the boundaries of deformation zone to the neutral section – consequently, the contact pressures are increasing. The peak height on the pressures profile depends upon the value of the friction coefficient.



a *b* *c* *d*

Fig. 2.6. The typical profiles of the pressure distribution along the contact arc: *a* – during the rolling of thick strip; *b* – during the rolling of medium strip; *c* – during the rolling of thin strip; *d* – at $\alpha>\beta$

In case if the contact angle exceeds the friction angle, the pressures profiles (epures) have the saddle-like form (Fig. 2.6, *d*). In this case the linear tensile stresses, which are the cause of the pressure falling on this area, appear in the rear part of the deformation zone.

The average contact pressure and the force of rolling

One of the most important energy-power indexes of the rolling process is the average contact pressure p_{av}. The implication of this value is easy enough: it is the pressure which would be under condition of the uniform distribution of pressures along the contact surface.

The force of rolling P may be presented as the product of average contact pressure on the contact square area F_{cont}:

$$P=p_{av}\,F_{cont}. \qquad (2.33)$$

The calculation of the contact square area F_{cont} in majority of cases doesn't present particular difficulties. The main problem in the theory of calculation of the rolling force is in determination of the average contact pressure.

The value of the average contact pressure depends on the yield strength of the metal to be worked and on the stress state of the metal under deformation:

$$p_{av}=\beta\sigma_{yield}\cdot n_\sigma, \tag{2.34}$$

where n_σ is the coefficient of stress state.

The value of the coefficient of stress state may be presented as the product of three coefficients:

$$n_\sigma=n_\sigma'\cdot n_\sigma''\cdot n_\sigma''', \tag{2.35}$$

where n_σ', n_σ'', n_σ''' are the coefficients taking into account the influence correspondingly of the external friction, external zones and tension of the strip ends. There are several theoretical and empirical formulas for determination of the value of these coefficients.

Turning moment, work and power of rolling

At the stable process of rolling the resultant of all forces *P* operating in the deformation zone has the vertical direction. In such a way the condition of balance of forces acting on the strip from the bottom and top rolls is fulfilled. The action of the reactive force *P* from the side of metal to be worked on the roll is shown on Fig. 2.7. The turning moment produced by force *P* relatively the center of the roll is equal to:

$$M_{roll}=P\cdot a,$$

where a is the arm of the resultant P relatively the center of the roll.

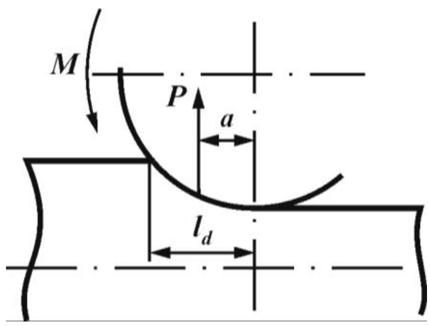


Fig. 2.7. On the calculation of rolling torque

The arm a is assumed to be determined as some part of the length of the deformation zone: $a=\psi l_d$. The value ψ is called the coefficient of arm moment or the coefficient of arm of the rolling power. Thus for two rolls we'll obtain:

$$M_{\text{roll}}=2P\psi l_d. \tag{2.36}$$

The problem of the calculation of the torque rolling is reduced to the determination of the point of application of force P that is, to the determination of the coefficient of the moment arm ψ.

The line of action of the force P is practically passing through the center of gravity of the profile of the contact pressures. Consequently the coefficient of the arm of the moment depends on the character of the pressure distribution along the contact arc. In case of uniform pressure distribution the point of application of force P is situated in the middle of the contact arc and $\psi=0.5$. During the process of the thick strip rolling $\psi>0.5$, as the maximum of pressures is sheared to the plane of entrance (Fig. 2.6, *a*). During the process of thin strip rolling $\psi<0.5$, as the maximum of pressures is sheared to the plane of exit. The value of coefficient of the moment arm may be determined strictly analytically if the law of the pressure distribution along the contact arc is determined.

If the value of the rolling torque is known, the determination of the work and power of the rolling don't present any difficulties.

The rolling work A_{roll} is equal:

$$A_{\text{roll}}=M_{\text{roll}}\varphi, \tag{2.37}$$

where φ is the angle of the rolls rotation per period of rolling the strip with the length l_1:

$$\varphi=\frac{l_1}{R\cdot(1+S)}. \tag{2.38}$$

The power spent on the roll barrel is equal:

$$N_{\text{roll}} = M_{\text{roll}}\cdot\omega, \tag{2.39}$$

where ω is the angle speed of the rolls rotation.

$$N_{\text{roll}}=M_{\text{roll}}\omega=M_{\text{roll}}\frac{\pi n_{\text{rolls}}}{30}, \tag{2.40}$$

where ω is the angular acceleration; n_{rolls} is the rolls rotation frequency, rev./min.

2.2. Continuous rolling

The main peculiarity of the process of continuous rolling consists in the possibility of correlation of the separate stands in continuous rolling mill through the strip to be rolled. Proceeding from the metal solidity condition, the rates (speeds) of the strip exit out of each mill stand as well as speeds of entry to the next stand are to be coordinated. In the case of absence of the interstand deformation these speeds as well as corresponding strip sections are equal to each other. Then the solidity condition takes the form of condition of the metal constant second volumes passing through each working mill stand:

$$\frac{F_i l_i}{t} = \frac{F_{i+1} l_{i+1}}{t},$$

$$F_i v_i = F_{i+1} v_{i+1},$$

$$F_{1,0} v_{1,0} = F_1 v_1 = \ldots = F_{i,0} v_{i,0} = F_i v_i = \ldots =$$

$$= F_{n,0} v_{n,0} = F_n v_n = \text{const.} \qquad (2.41)$$

So, the main condition of the normal work for continuous rolling mill is:

$$F_i v_i = c_i = \text{const.}$$

The condition of metal solidity specifies also the main physical peculiarity (feature) of continuous rolling process – the force (power) interaction of continuous mill stands through the strip to be rolled. Let us consider this peculiarity at the example of interaction of the stands in two-high mill (Fig. 2.8).

While analyzing the possible separated rolling of the strip in the stands with application of external forces to the strip, one needs to take into account that the speed of strip and dimensions of section of the latter at the exit out of the given stand under other equal conditions depend only on the value of external force (tension or support), and, thus, the second volume of metal is a single-valued function of longitudinal force (Fig. 2.9).

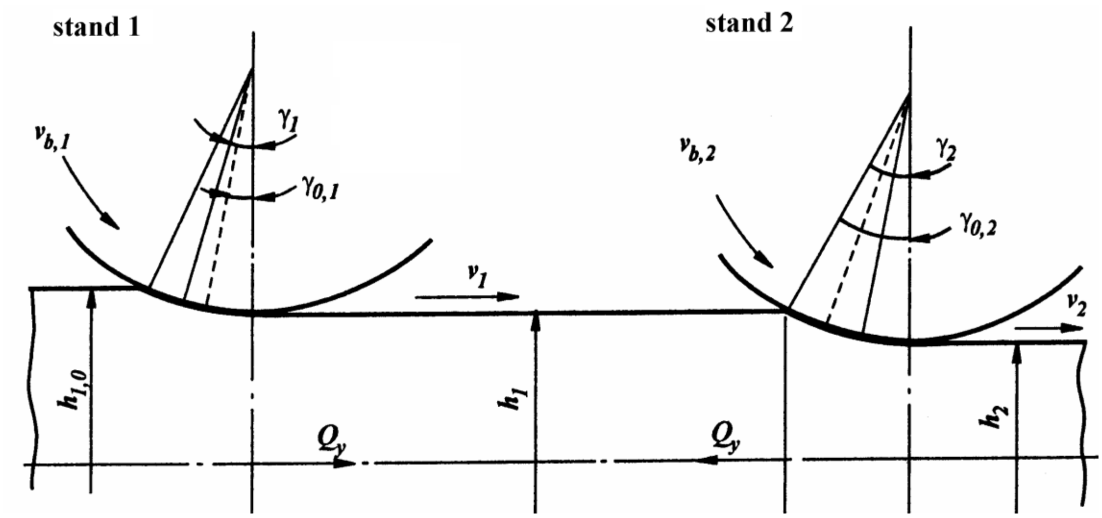


Fig. 2.8. Scheme of the rolling in two-high continuous mill

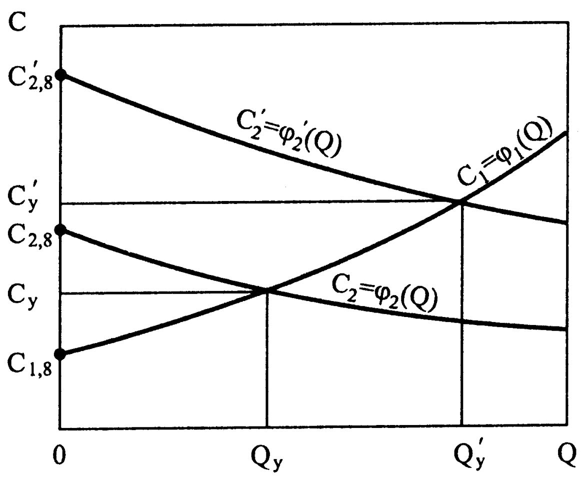


Fig. 2.9. Dependence of metal second volumes in the first (C_1) and second (C_1 and C'_2) stands of continuous mill

Let us assume that the possible (during the separate free rolling in the natural conditions) second volumes of metals passing through stands are not equal to each other:

$$F_1 v_1 = c_1; \quad F_2 v_2 = c_2; \; c_2 > c_1.$$

At the simultaneous (continuous) rolling of the strip in both stands the condition (2.41) is to be observed. Equalizing of metal second volumes passing through every stand under invariable mill set up is possible only at the expense of action of corresponding lengthwise forces.

The initial inequality of metal second volumes $C_1 \neq C_2$ leads in the process of continuous rolling to appearance of lengthwise forces in the strip.

Interaction of the stands of continuous mill through the strip to be rolled is accompanied with energy transference from one stand to another.

Because of that the lengths of forward slip zones in the interacting stands change as compared with the separate free rolling. So, in the present case, the lengthwise tensile force arises in the strip in the interstand space at $C_1 < C_2$. The scheme of rolling with front tension is acting in the first stand, and the scheme of rolling with back tension takes place in the second stand. According to it the following zones of forward slip are settled in the process of continuous rolling:

$$\gamma_1 > \gamma_{e1} \quad \text{and} \quad \gamma_2 > \gamma_{e2},$$

where γ_{e1} and γ_{e2} are neutral angles of forward slip zones in the stands in conditions of free rolling.

The rolling with tension (as compared with free rolling) evokes also the change of forces in the stands and correlation of lengthwise and cross (transverse) metal flow in zones of deformation. The elastic deformations of the stands are changing (in accordance with the stiffness modulus of the latter), as well as value of the strip thickness reduction, spreading and also, in connection with loads change, the speeds of the stand’s motors (according to stiffness of their mechanical characteristics).

The stands of continuous rolling mill, the strip to be rolled and electric drive form one complex with mutually depending and mutually conditioned phenomena. The stand stiffness characterizes quantitatively one of the most substantial dependences – dependence between rolling force and thickness of the strip at the exit of the stand. The degree of influence of the rolling moment upon velocity of rotation of the stand rolls depends on the stiffness of the drive mechanical characteristic.

Thus the equalizing of metal second volumes to the value C_y takes place at the expense of corresponding change of all the variables F_i, $v_{\text{roll},i}$, s_i):

$$F_i v_i = F_i v_{\text{roll},i}(1+ s_i) = C_y = \text{const.} \qquad (2.42)$$

The lengthwise force Q_y (Fig. 2.8) appearing in this case is an important technological factor determining rolling force, change of metal form and quality of rolled products.

To create a greater interstand tension it is necessary to establish a greater possible inaccordance of initial metal second volumes.

In the present case that can be realized by the way of establishing, for example, the greater frequency of rotation of rolls in the second stand.

Then $C'_2>C_2$, and at continuous rolling the new equal second volumes of metal C'_2 are set and the quite specific tension with the force Q'_2 (Fig. 2.9) is created here.

The value of tension (support) is evaluated by means of coefficient of tension (coefficient of plastic tension) z:

$$z = \frac{\sigma_x}{2K} = \frac{\sigma_x}{\beta\sigma_{\text{yield}}}.$$

At free rolling σ_x=0 and z=0.

Besides that, the degree of tension is evaluated by means of coefficient of kinematic tension ω, easy to determine and equal to relation of possible (at the separate rolling of strip in the stands) second volumes of metal in adjacent stands of continuous mill:

$$\omega_{i+1} = \frac{F_{i+1}v_{i+1}}{F_i v_i}.$$

At free rolling ω=1, at rolling with tension ω>1, and when ω<1 we have rolling with support.

The normal continuous rolling process is possible under condition that the lengthwise (longitudinal) stresses appearing in the metal in the interstand spaces don’t exceed the definite values conditioned with yield strength of metal, type of the mill, technological peculiarities of rolling and so on.

That is why the degree of attainment of this or that technological effect from using the rolling with tension is limited with ultimate conditions of the process.

Thus, the critical interstand tension is specified by conditions of drawing the metal in preceding stand and slippage in the following one as well as by conditions of the strip rupture. The critical (limit) support is specified by conditions of the slippage in preceding stand and drawing in the following one as well as by conditions of the loss of longitudinal stability or overfilling of the groove with metal and possibility of defects appearance (rolled kinks, back fins and so on).

The above considered connection between longitudinal forces and variables specifying metal second volumes, which are passing through the stand takes also place in multistand continuous mills. The interaction of stands in such a mill is like to considered one, but presents a much more complex picture.

The change of adjustment of any stand in continuous mill (change of the frequency of roll rotation, distance between rolls), which can be realized in the process of rolling too, evokes the corresponding change of drafts, forward slips as well as loadings and speeds of motors (drives) of all the stands in the mill including those arranged before the stand in question. As a result, the rolling mill will work (while observing the restrictions) in a new tension schedule with other technological effect.

Beside of controlling influences during the stable process the rolling parameters can be changed in connection with influence of different perturbations.

The change of temperature and strip thickness along the length, eccentricity of rolls, change of reel tension don't lead, as a rule, to breaking of the process current thanks to its ability of self-adjusting, that is to renewal of speed coordination and setting up of a new constant of continuous rolling (C).

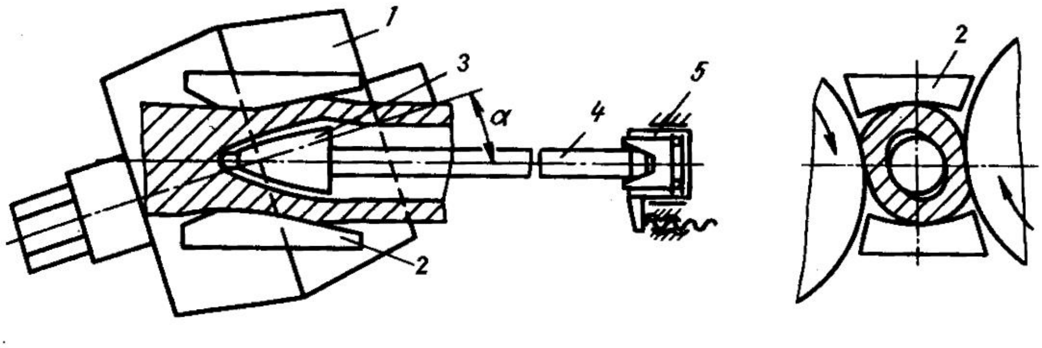
Thus the essence of the process of self-adjusting is reduced to keeping the equality of metal second volumes passing through all stands of the mill.

The process of self-adjusting is performed without controlling influences at corresponding change of variables and tension schedule.

Any perturbing influence in a given stand of continuous mill leads to change of reduction and speed of metal in this stand. In this case the change of speeds and on the whole of metal second volume in the stand affects the work of other stands through tension change in practice instantaneously.

2.3. Screw rolling

The feature of the screw rolling mills is the axial inclination of the working rolls to the axis of rolling and the same direction of the rolls rotation. Scheme of the process of screw rolling is given on Fig. 2.10 for two-high rolling mill with barrel rolls.



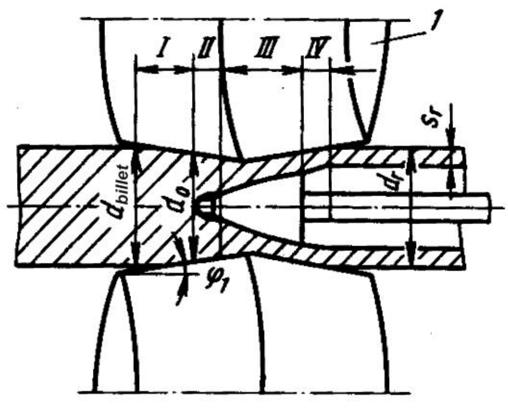


Fig. 2.10. The deformation zone in two-high piercing mill: *a* – the longitudinal sections in the plane of bars; *b* – longitudinal sections in the plane of rolls; *c* – cross section; *1* – roll; *2* – plug; *3* – guide; *4* – core; *5* – stop-adjusting mechanism

The process of piercing the round solid billet into the shell is the most widespread process in the tube manufacture. The process is realized at the mill having two working rolls *1*, guide unit in the form of two former bars *2*. The piercing is realized by means of floating plug *3* restrained in axial direction by the core *4* and stop-adjusting mechanism *5*.

The main technological angle is feed angle α. The feed angle is formed at the rotation of the roll axis around the axis OZ, which is perpendicular to the rolling axis OX (Fig. 2.11). The rolls are installed at the feed angle from 2° up to 40° in the mills of different design and purpose.

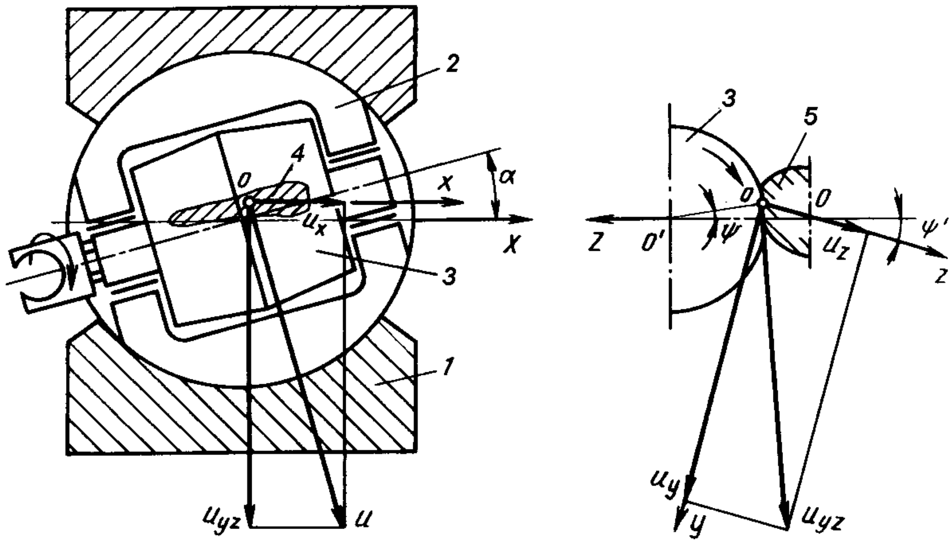


Fig. 2.11. Scheme of installation of the roll of a screw rolling mill and the decomposition of vector of circumferential velocity of the roll: *1* – the housing of the roll stand; *2* – the drum; *3* – the roll; *4* – the contact surface of the metal with the roll; *5* – under deformation

Due to the indicated rotation the vector of circumferential velocity of the roll *u* in every point of the roll contact with the metal may be decomposed into the axial component u_x, which determines the movement of the metal along the rolling axis ($u_x=u\cdot\sin\alpha$); tangential component u_y, which determines the rotation of the metal ($u_x=u\cdot\cos\alpha$); radial component u_z – the speed of the billet reduction as per diameter.

The components of metal velocity v_x, v_y and v_z differ from u_x, u_y and u_z. The sliding is arising on the contact surface and its value is characterized by velocity coefficients:

$\eta_x = \dfrac{v_x}{u_x}$ – axial velocity coefficient;

$\eta_y = \dfrac{v_y}{u_y}$ – tangential velocity coefficient.

Each point of the wrought metal is moving at axial direction and is rotating around the axis of rolling, that is traveling along the screw curve. The spiral path of displacing of the points of metal within the deformation zone has the varied pitch of the spiral due to the decrease of the radial size and stretching along the axial direction; the pitches of the spiral are constant before the entry to the deformation zone and after it. The change of the velocities under consideration is taking place along the length of the contact surface (Fig. 2.12).

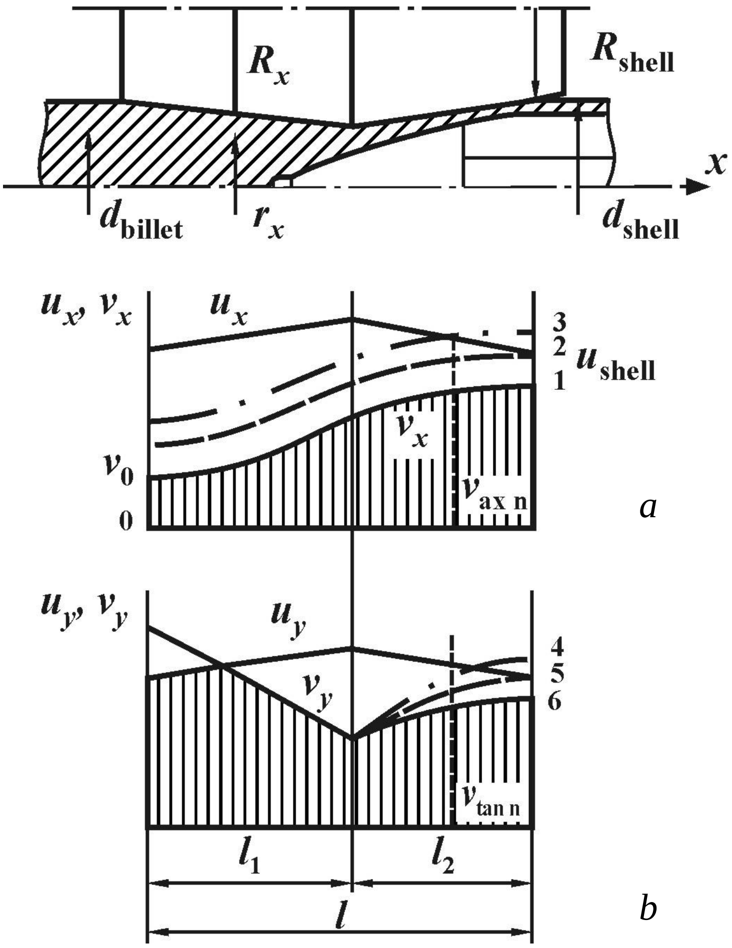


Fig. 2.12. The change of the axial (*a*) and tangential (*b*) metal (v_x, v_y) and the rolls (u_x, u_y) velocities along the length of the contact surface

The circumferential velocity of the rolls and its components u_x and u_y are changing proportionally to the radiuses R_x, which have the maximum values of the section called pinch and are decreasing towards the entry and the exit out of the deformation zone. The axial component of the metal velocity v_x is changing from v_0 at the entry up to v_{shell} at the exit of the deformation zone with the condition of the constant second volumes:

$$v_0F_0 = v_xF_x = v_{\text{shell}}F_{\text{shell}} = \text{const},$$

where F is the area of the metal cross-section.

As $\frac{v_{\text{shell}}}{v_0} = \frac{F_0}{F_{\text{shell}}} = \lambda_\Sigma$ (λ_Σ is the reduction ratio of the piercing mill) and $\frac{v_x}{v_{\text{shell}}} = \frac{F_{\text{shell}}}{F_x} = \frac{\lambda_x}{\lambda_\Sigma}$ (λ_x is the reduction from the entry up to the arbitrary section x), then $v_x = v_{\text{shell}} \cdot \frac{\lambda_x}{\lambda_\Sigma}$, that is the changing of the axial velocity of the metal along the deformation zone is proportional to the coefficient of reduction.

The coefficient of the axial velocity within the section of exit by means of what the relative axial velocity of the process is characterized, is equal to $\eta_0 = \frac{v_{\text{shell}}}{u_{\text{shell}}}$.

The coefficient η_0 may take on the values less than 1 (Fig. 2.12, *a*, curve *1*), $\eta_0=1$ (curve *2*) and $\eta_0>1$ (curve *3*) depending on the material of the rolled billet, roll pass and tools design, their surface conditions defining the friction coefficient, the tolling of the mill. The interval of its changing amounts to 0.4-1.1, but as usual it is less than one. In the case when $\eta_0>1$, there is a neutral section $x_{\text{av}\,n}$ situated on the contact surface; in this section the axial metal components of metal velocity and the roll are equal ($u_x=v_x$); the zone of the axial backward slip is located before the neutral section and the zone of forward slip is located after it.

The coefficient of the axial velocity in the arbitrary section η_x and the exit section η_0 are related by correlation, which is determined from the law of the constant second volumes:

$$\eta_x = \eta_o \cdot \frac{R_\Gamma}{R_x} \cdot \frac{\lambda_x}{\lambda_\Sigma}. \qquad (2.43)$$

The distribution of tangential metal and rolls velocities along the length of the contact surface is shown on the Fig. 2.12, *b*. The radius of the roll is growing on within the entry cone of the deformation zone (l_1) and accordingly the tangential velocity u_y is increasing proportionally to the radiuses in each section of the roll and the angle speed of the roll. On the billet the direction of the taper is opposite to the roll. The radius of the billet in the entry cone is decreasing and accordingly the tangential velocity of the metal is decreasing too. There is the tangential neutral section $x_{t.n}$ on the contact surface; in this section u_y=v_y. The character of alteration of the tangential metal and rolls velocities is changing to the opposite one in the zone of cone expansion. This may cause to appearing of the second tangential neutral section at the end of deformation zone (Fig. 2.12, curve *4*). The angle velocity of the billet is affected distinctly by the twisting of the latter under the influence of variable tangential velocity of the roll surface.

The coefficient of tangential velocity in the section of exit out of the deformation zone is designated as η_t; due to the twisting in this section the equality v_y=u_y is attained and $\eta_t = \dfrac{v_y}{u_y} = 1$ (curve *5*) or the ratio v_y<u_y and η_t<1 (curve *6*). During the process of piercing the interval of changing η_t is equal to 0.8-1.1, but usually η_t=0.95-1 if the diameters of the incoming billet and the shell are approximately equal. η_t=0.6-0.9 in the section of the nick.

The deformation zone may be divided to 4 zones along the direction of piercing (Fig. 2.10, *b*): *I* – the zone of the solid billet rolling (from the section of nipping up to the place of meeting with the plug cone); *II* – the zone of introduction of the plug cone into the metal; *III* – the zone of expansion on the plug; *IV* – the zone of the shell rounding.

The reduction of the billet diameter, expansion and ovalling of the cross-section of the metal take place within the first zone.

The deformation of the billet is going on at comparatively narrow contact surfaces in the conditions of significant influence of external zones. The non-uniform deformation leads to the appearance of lateral tensile stresses in the central layers of the metal. The peripheral ring layer is formed at the turning of the billet, which (the ring layer) is deformed more intensively than the internal one. This layer causes the growing of lateral tensile stresses σ_y in the central volume. Simultaneously the external layer increases its length along the axial direction to a greater extent than the central one. The funnel-shaped recesses appear on the face surfaces. The leveling of stretching causes the appearance of additional longitudinal tensile stresses σ_x in central zone and compressing in peripheral zone during moving away from the face surfaces.

Thus the scheme of stress state with two tensile stresses along the cross section and compressing along the direction of reduction is appearing in the central zone.

As far as the reduction of the billet is going on, the increase of σ_y may lead to destruction of the metal in the central zone and to the destruction of the cavity.

The value of the summary reduction of cross-sectional area of the diameter, at which the damage of the metal is beginning is called the critical reduction:

$$\varepsilon_{\mathrm{cr}} = \frac{\Delta d_{\mathrm{cr}}}{d_{\mathrm{billet}}} \cdot 100\% . \qquad (2.44)$$

The critical reduction is within the limits from 7 up to 16% depending on the natural plasticity and the heating temperature of different steels.

In case of reduction before the cone of the plug greater than critical one the central destruction of the metal is taking place, which causes skins creation on the inner surface of the shells and the defective tubes.

The solid billet is pierced by the cone of the plug in zone *II*. The thick wall ring formed by piercing is undergoing to reduction by the rolls.

The gradual reduction of the shell wall is going on within the narrowing nip of the rolls and the plug in zone *III* and the wall thickness of the shell is finally formed.

The metal ovality is limited by the guides along the second and the third zones. The shell has the coefficient of ovality 1.05-1.15 by the end of the third zone. The cross-section of the shell becomes more round due to the rolling by the rolls in zone four. The nipping of the metal by the rolls at the screw rolling mill is divided to two stages: initial and secondary.

The initial nipping covers the period from the initial contact of the billet and the rolls before beginning of its steady screw travel.

The supply of the billet to the rolls of the piercing mill is made by the pusher. In case when the speed and the force of pushing is too great, the width of the contact may exceed the permissible value, and the rotation of the billet will be stopped. Concurrently the condition of the axial drawing will be broken and the initial nipping will not be accomplished. The force and the speed of the pushing should be limited for accomplishing of the steady nipping.

The secondary nipping covers the period from the contact of the billet face and the plug up to the complete filling of the deformation zone on the plug. The shutdown of the axial travel of the billet with the preservation of its rotation is typical in case of the nipping break.

The value of the cross-sectional area reduction per diameter in front of the plug cone ε_0 has the significant influence on the nipping. The increase of the feeding force and the decrease of the plug resistance take place with the increase of reduction ε_0, the steadiness of the secondary nipping is increased.

The production of the shell with specified dimensions $d_{\text{shell}} \times S_{\text{shell}}$ from the billet with diameter d_{billet} may be accomplished with different mill setup. The parameters, which determine the mill setup are as follows: the distance between the rolls in nick; the extension of the plug outside the nick; mounting of the core.

The value of billet reduction in the nick per diameter is used for evaluation of the setting parameters:

- absolute value $\Delta d_{\text{nick}} = d_{\text{billet}} - d_{\text{nick}}$;
- relative value $\varepsilon_{\text{nick}} = \dfrac{\Delta d_{\text{nick}}}{d_{\text{billet}}} \cdot 100\%$.

The value $\varepsilon_{\text{nick}}$ is usually equal to 8-20%.

For rational setting it is necessary to choose the optimal reduction in front of the cone of the plug taking into account the condition of the secondary nipping and prevention of the premature opening of the cavity in front of the cone of the plug: $\varepsilon_{0min}<\varepsilon_0<\varepsilon_{cr}$.

The growth ε_0 causes the increase of the steadiness of the nipping on one side as well as the probability of defects appearing. In practice the reduction in front of the plug cone is chosen within the limits 3-8%.

At the feeding angles 8-10º the length of the contact surface in the cone of piercing (l_1) and the cone of expansion (l_2) is determined by expression:

$$l_1 = \frac{d_{\text{billet}} - d_{\text{nick}}}{2\text{tg}\varphi_1} \qquad (2.45)$$

and

$$l_2 = \frac{d_{\text{shell}} - d_{\text{nick}}}{2\text{tg}\varphi_2}, \qquad (2.46)$$

where φ_1 and φ_2 are the angles of the roll coning in zones l_1 and l_2.

The maximum width of the contact surface in the nick is determined according to the following formula:

$$b_{\text{nick}} = \sqrt{\frac{R_{\text{nick}} r_{\text{nick}}}{R_{\text{nick}} + r_{\text{nick}}} \cdot \Delta r_{\text{nick}}}, \qquad (2.47)$$

where R_{nick}, r_{nick} the radius of the roll and the radius of the billet in the nick; Δr_{nick} is the absolute partial reduction along radius of the billet in the nick.

For approximate determination of the average width of the contact surface in the cone of piercing the following formula may be used:

$$b_{1av}=0{,}67 b_{\text{nick}}, \qquad (2.48)$$

in the cone of expansion:

$$b_{2av}=0{,}8 b_{\text{nick}}. \qquad (2.49)$$

The average contact pressure in the cone of piercing is determined according to the empirical formula:

$$p_{1\mathrm{av}} = (1{,}8 - \frac{b_{\mathrm{nick}}}{2r_{\mathrm{nick}}})(1 - 2{,}7\varepsilon^2_{\mathrm{nick}})\sigma_{\mathrm{yield\ av}} \qquad (2.50)$$

in the cone of expansion $p_{2\mathrm{av}}=0{,}75\ p_{1\mathrm{av}}$.

For deformation of the average value of the yield strength of the metal $\sigma_{\mathrm{yield\ av}}$ the rate of deformation may be estimated according to the following expression:

$$u_{\mathrm{av}} = \frac{v_{\mathrm{nick}}}{2r_{\mathrm{nick}}}, \qquad (2.51)$$

where v_{nick} is the circumferential speed of the roll in the nick.

The overall stress on the roll will be equal to:

$$N = p_{1\mathrm{av}} b_{1\mathrm{av}} l_{1\mathrm{av}} + p_{2\mathrm{av}} b_{2\mathrm{av}} l_{2\mathrm{av}}. \qquad (2.52)$$

Basing on the experimental data the stress Q, having the effect on the plug amounts to:

$$Q=(0{,}2\ldots0{,}5)N, \qquad (2.53)$$

on the guide:

$$N_{\mathrm{guide}}=(0{,}1\ldots0{,}4)N. \qquad (2.54)$$

The rolling torque may be estimated approximately according to the formula:

$$M=Na, \qquad (2.55)$$

where the arm of the moment:

$$a = \frac{b_{\mathrm{av}}}{2}\left(1 + \frac{r_{\mathrm{av}}}{R_{\mathrm{av}}}\right), \qquad (2.56)$$

where $b_{\mathrm{av}} = \dfrac{b_{1\mathrm{av}} l_1 + b_{2\mathrm{av}} l_2}{l_1 + l_2}$ is the average value of the width of the contact surface; r_{av} and R_{av} – the average values of the billet radius and the roll radius.

2.4. Drawing

The drawing of the ferrous and non-ferrous metals is accomplished in overwhelming majority of cases in cold condition. The lubricant is used for reduction of friction forces.

The cold deformation is accompanied by the metal hardening – the strength properties are increasing significantly and the plasticity is decreasing. The possibility of deformation per one drawing are limited by the plastic properties of the metal and the strength of the leading end of the obtained profile passing the drawing force to the deformation zone. The drawing stress should be lower than the breaking point of the metal at the exit out of the deformation zone.

The following indexes are the most used as characteristics of the metal deformation during the process of drawing:

- reduction of cross-sectional area $\varepsilon = \frac{F_0 - F_1}{F_0} \cdot 100\%$ (F_0 – the net area of the billet; F_1 – the net area of the profile at the exit out of the drawing die);
- elongation (reduction) ratio $\lambda = \frac{F_0}{F_1}$.

The elongation (reduction) ratio may be estimated according with the formula $\lambda = \frac{d_0^2}{d_1^2}$ during the drawing of the round profiles with diameter d_1 from the round billet with diameter d_0.

The indexes ε and λ are connected between each other by the constant volume condition with the following correlation:

$$\varepsilon = \frac{\lambda - 1}{\lambda} \tag{2.57}$$

and

$$\lambda = \frac{1}{1 - \varepsilon}. \tag{2.58}$$

The value of the elongation (reduction) ratio per one drawing as usual doesn't exceed the value 1.3-1.4. The maximum drawings (1.8-2.0) may be achieved in the processes of tube drawing on the long mandrel when there is possibility of the passing the drawing force to the deformation zone via the mandrel.

The deformation becomes non-uniform at small values of the elongation ratio per one drawing and is concentrating in the outlaying layers. Therefore the minimum value of the unit strain is also limited. For the round solid profile λ_{min}=1.1-1.2.

The total reduction of cross-sectional area per *n* drawings is determined according to the following formula:

$$\varepsilon_{\Sigma} = \frac{F_0 - F_n}{F_0}, \tag{2.59}$$

where F_n is the net profile area obtained after *n*-drawing.

The maximum total reduction $\varepsilon_{\Sigma max}$ is limited by the sharp decrease of the metal plasticity. The value of the total reductions is usually equal to 40-60% and may amount the maximum value of 90-95%. It is necessary to carry out the intermediate heat treatment for recovery of the metal plastic properties and the possibility of its further deformation.

The succession of the draws accomplished up to the manufacture of the finished product or up to intermediate heat treatment is called the drawing routing. The drawing routing may be different as per the number of draws so as the used unit reduction at the same total reduction ε_{Σ}. As usual the gradual decrease of unit reductions is foreseen taking into account the metal hardening during the formation of the drawing routing. The higher reductions during the first passes cause the increase of the uniformity of deformation along the section of obtained profile.

The work of deformation and contact friction during the process of drawing is turned into the heat, that results in significant increase of the metal temperature especially at high speeds of drawing. The product temperature should not exceed 250ºC as the ageing of the metal is going on at the higher temperature. The conditions for the better heat sink and better lubricant are provided for increase of the drawing speed. At present the speed of the low carbon steel wire drawing amounts to 2400 m/min. In respect to the minimum drawing forces the optimal values are considered to be the speeds 900-1500 m/min.

Let us examine the character of the metal flow in the deformation zone according to the changes of the grid during the drawing of the round profile through the tapered die (Fig. 2.13).

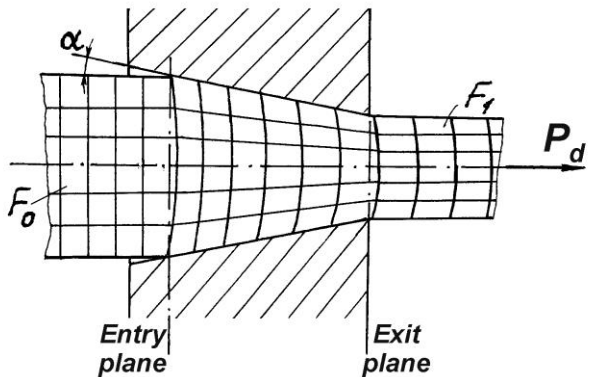


Fig. 2.13. Scheme of changing the grid in the deformation zone during the drawing

The bend of the horizontal line of the grid had place near the plane of entry and the reciprocal bend of the inclined lines to the horizontal position had place near the plane of exit place. It is the evidence of the shearing deformation at the boundaries at the deformation zone with the external zones.

The vertical lines of the grid get the camber along the drawing direction, that is the central layers of the metal are moving with the greater axial speed than outlying ones. It leads to the additional shears in all layers especially in close to contact ones. The shears in central layers are minimum ones. The action of the contact friction is the cause of the shear deformations. The value of the shears is increasing with the increase of the coning angle of the die α, reduction ε and the coefficient of friction in the die channel *f*.

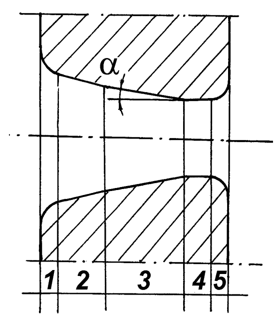


Fig. 2.14. The profile of the die channel:
1 – entry zone;
2 – lubricating cone;
3 – working cone;
4 – calibrating collar;
5 – exit zone

The die channel profile has several areas of different purposes (Fig. 2.14).

The entry zone *1* is used for protection of the billet against the scorings on the die edges. The lubricating cone *2* provides for the lubricant entry to the die channel and improves the lubricant pickup by the billet surface at the entry to the working cone. The main deformation of decreasing the cross section area of the billet is accomplished in the working cone *3*. The calibrating cylindrical collar *4* does not change the profile section dimension, but increases the die durability significantly. The exit zone *5* prevents the calibrating collar from crumbling and the out coming from the die profile from the scorings on the surface.

As usual the dies with the angle of the working cone α=5-15° are used.

There is a number of empirical and theoretical formulas for determination of the drawing force (P_{draw}) and the drawing stress ($\sigma_1=P_{\mathrm{draw}}/F_1$). One of them the most simple (Gavrilenko formula) has the following form:

$$\sigma_1 = \sigma_{\mathrm{drav\ av}} \cdot (\lambda - 1)\left(1 + \frac{f}{\mathrm{tg}\alpha}\right), \qquad (2.60)$$

where $\sigma_{\mathrm{drav\ av}} = \dfrac{\sigma_{\mathrm{drav0}} + \sigma_{\mathrm{drav1}}}{2}$ is the average value of the tensile stress of the metal to be worked before and after drawing.

It is possible to estimate the power used for drawing, if the drawing force is determined as $P_{\mathrm{draw}}=\sigma_1 \cdot F_1$:

$$N_{\mathrm{draw}}=P_{\mathrm{draw}} v_{\mathrm{draw}}, \qquad (2.61)$$

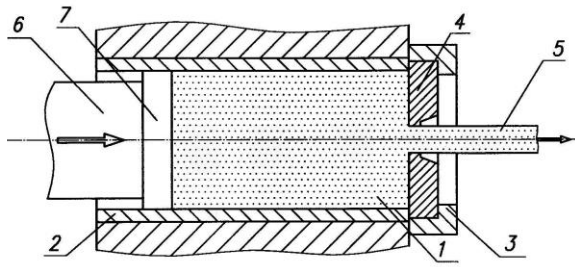
where v_{draw} is the drawing speed.

2.5. Pressing (extrusion)

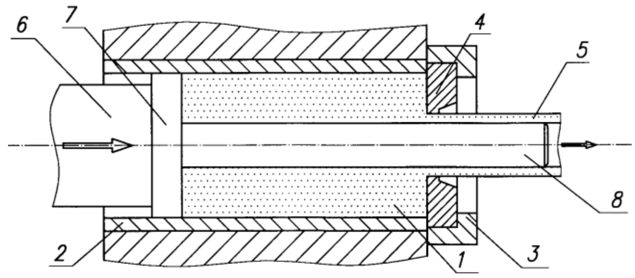
There are different methods of pressing due to the scheme of the relative displacement of the pressing tool (the ram) and profile to be extrusion: with direct, side and reverse metal flow.

The process of the forward (direct) extrusion is the most widespread in the world practice. By means of this method it is possible to produce the solid and hollow profiles of the wide size range up to the sizes close to the size of container.

Scheme of the direct extrusion is shown on Fig. 2.15.



a



b

Fig. 2.15. Schemes of the direct extrusion:
a – solid profile; *b* – hollow profile

The billet *1* heated up to the temperature of extrusion is placed into the container *2* (Fig. 2.15, *a*). The mold *4* forming the profile of the product *5* is placed at the exit side of the container in the mold holder *3*. The pressure from the main press cylinder is passed on the billet via the ram *6* and pressure pad *7*. Due to the high pressure the metal is flowing into the working mold channel forming the profile corresponding to the profile of mold channel. The tool in the form of core *8* fixed on the ram and passing through the hole in the billet is introduced into the mold channel for producing the hollow profiles. The tool in the mold channel can be retained by another method without resorting to the billet piercing.

The mold is placed on the front end of the hollow ram for backward extrusion (Fig. 2.16). The pressure of the ram brings to the metal flow out of the mold hole at the direction reverse to the direction of the ram travel.

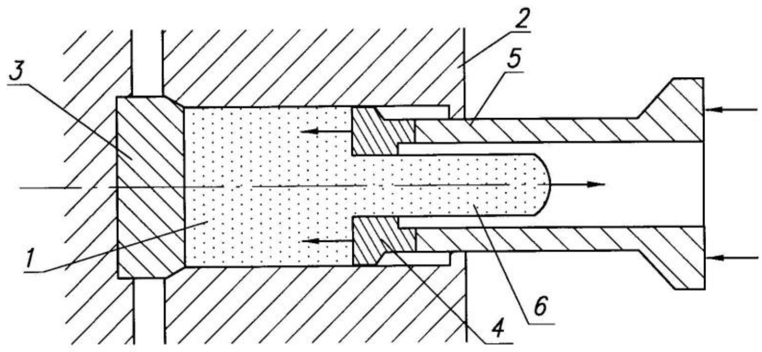


Fig. 2.16. Scheme of extrusion with reverse metal flow:
1 – billet; *2* – container; *3* – plug; *4* – extrusion die; *5* – ram; *6* – pressed product

The process of the backward extrusion is notable for the absence of friction forces on the walls of container due to the absence of the billet sliding along the container walls.

The extrusion differs from other processes of metal forming with what at different stages of the process the stress state, the metal flow and pressing force are different. The pressing process may be divided to three successive periods depending on the force and deformation conditions (Fig. 2.17):

I – pressing out (upsetting) of the billet in the container and filling of the whole container volume by the metal. The pressing force is increasing from zero up to the maximum value (in case of direct extrusion it is greater than in case of reverse one);

II – steady-state process. The force is not changed during the backward (indirect) extrusion, during the direct extrusion it is decreasing due to the reduction of the billet height and the surface of contact of the billet and the container walls;

III – the final stage of the process. The side supporting stresses are increasing with decreasing of the butt-end and the force of pressing increases sharply.

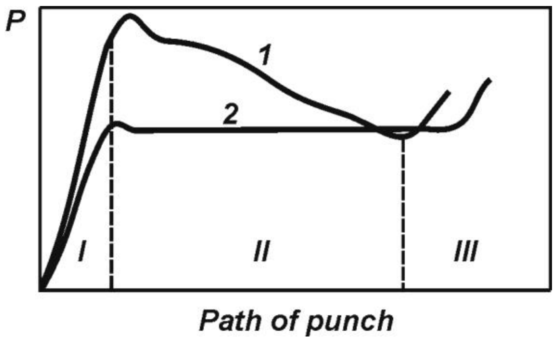


Fig. 2.17. The change of the force
during the process of extrusion:
1 – with direct flow of the metal;
2 – with reverse flow of the metal

The temperature-speed regime of pressing (extrusion) influences significantly on the character of metal flow out of container through the extrusion die channel as well as the temperature difference of the billet and the container walls and along the billet section; the conditions of friction under the ram, on the container walls and in the extrusion die channel.

Let us examine three the most typical kinds of deformation zone during the process of pressing.

The first kind (Fig. 2.18, *a*) is characterized by the fact that the deformation zone is concentrated near the extrusion die, the rest of the billet part is not plastically deformed, it is immovable during the backward extrusion or is traveling to the deformation zone during the process of direct pressing. This kind of deformation zone is observed during the backward extrusion as well as during the direct one if the coefficient of friction is low. Mechanical properties will be homogeneous along the section and the length of the pressed product.

The second kind of deformation zone is observed at average values of the friction coefficient and the presence of some heterogeneity of metal mechanical properties along the section of the billet (for instance, in case of non-uniform heating of the billet). The deformation zone is extending on the whole length of the billet (Fig. 2.18, *b*). The flow of the inner layers (volume V_1) is going on faster than of the external ones (volume V_2). The flow of the external layers is restrained by the friction forces on the container walls as well as the greater resistance to the metal deformation, sub-cooled due to the contact with the container walls. The mechanical properties are changing along the length of the pressed product.

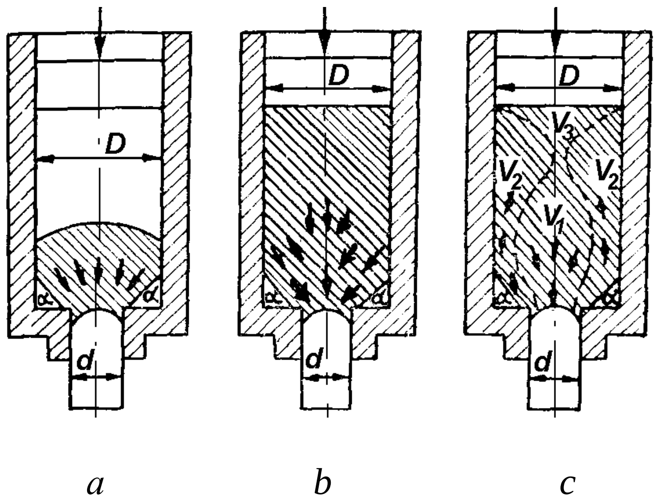


Fig. 2.18. Three types of metal flow
at the pressing (extrusion)

The third kind of deformation zone (Fig. 2.18, *c*) is observed in the conditions of pressing with the bad lubricant at the high value of the contact friction, at non-uniform heating of the billet, in the absence of the heating of the container. The deformation zone then is characterized by the high irregularity of the metal flow. The greatest intensity of the deformation takes place in the volume V_1 located immediately against the extrusion die. The volume V_2 is flowing from the periphery to the billet axis as the deformation is developing. The volume V_3 borders to the surface of pressure pad. The metal flow to the center causes the transfer of the metal from the side surface of the billet to the face of the pressure pad.

The pressure pad is approaching the extrusion die during the final stage of the pressing process. The metal volume feeding the central zone is reducing and under pressure pad the funnel-shaped hollow is formed – press-funnel where the surface defects of the billet are concentrated. The pressing (extrusion) is stopped before the approach of the front end of the funnel to the extrusion die channel to avoid the ingress of the funnel to the product. Butt-end is left and then it is cut.

The value of the deformation during the process of pressing is characterized by the following indexes:

- degree of deformation:

$$\varepsilon = \frac{F_0 - \Sigma F_1}{F_0} \cdot 100\%, \qquad (2.62)$$

where ΣF_1 is the total area of all the holes of extrusion die;

- reduction ratio:

$$\lambda = \frac{F_0}{\Sigma F_1}. \qquad (2.63)$$

The value of the reduction ratio during pressing (extrusion) usually amounts to 20…30, and while pressing for example aluminum alloys – up to 100.

The empirical L.V. Prozorov's formula became widely used for calculation of the pressing force:

$$P = nc\sigma_{ts} F \ln \frac{F}{F_1}, \qquad (2.64)$$

where σ_{ts} is the tensile strength within the pressing temperature range; F is the cross-section area of the container; F_1 is the cross-section area of the pressed product; n is the coefficient characterizing the metal friction between the billet and container and determined according to the following formula:

$$n = 1+0.08H/D, \qquad (2.65)$$

where H is the height of the billet, D is the diameter of container; c is the coefficient characterizing the friction forces and non-uniformity of stress distribution in the billet; during the pressing of the solid sections c=4, of smooth-walled tubes – c=5-6, ribbed tubes – c=7.

The pressing (extrusion) process with the other kinds of metal forming has its advantages and disadvantages.

Advantages:

- the scheme of the all-round non-uniform pressing increases the plasticity of the metal what permits to process the low plasticity alloys;
- the products with complicated configuration of the cross-section may be produced by the way of pressing (extrusion) method;
- readjusting for transition from one kind of products manufacture to another is very simple and this makes the process of pressing competitive at manufacturing of small production lots;
- the high precision of products produced by pressing.

Disadvantages:

- considerable metal loses for tailings (butt-end and press-funnel);
- non-uniform structure and mechanical properties along the section and the length of the product;
- comparatively low efficiency because of the long time auxiliary operations.

2.6. Smith (free) forging

While obtaining products by the way of smith (free) forging the primary billet (ingot) is processed by repeated action from the hammer head or press until the moment when the solid acquires the set shape and size. Smith forging is used in small-lot and individual production of forged pieces with various mass including the most heavy (up to 250-300 tons). Small and medium size forged pieces (up to 0.5 tons) are produced from the rolled billets. More heavy forged pieces are manufactured from the ingots with round, square and polyhedral section.

The value of deformation during the smith forging is determined by relative change of cross-section areas:

$$\varepsilon = \frac{F_0 - F_1}{F_0} \cdot 100\% \qquad (2.66)$$

or by forging ratio:

$$y = \frac{F_0}{F_1}, \tag{2.67}$$

where F_0, F_1 – areas of cross section of forging piece before and after deformation.

The forging ratio shows how many times the cross section of the billet changed during the forging, that it characterizes the level of the hammering of the metal. The greater is the forging ratio, the higher are the mechanical properties of the metal. The practice has stated that to obtain forged pieces of high quality from construction steels the forging ratio for ingots should be no less than 2.5-3, for rolled metal 1.1-1.3. One should take into account the forging ratio no less than 10-12 during the forging of steels containing difficult-to-break carbides and eutectics.

The hot metal forming influences essentially on the structure of metal. The primary crystals (dendrites) are crushing and stretching in the direction of the greater deformation during the forging of the cast metal. The metal obtains the grain microstructure as the result of the recrystallization processes and fibrous macrostructure due to the impurities location at the boundaries of the deformed grains. The metal becomes more strong and plastic as the result of forging. The metal obtains anisotropy in consequence of fibrous macrostructure formation. The increase forging ratio leads to the increase of metal plasticity characteristics along the fibers and their falling in transverse direction.

It is necessary to take into account the direction of the fibers during the development of the process of components production due to the anisotropy of the metal mechanical properties: the fibers have to turn round the component profile or to coincide with the direction of tensions action during the components' loading and where possible haven't cross each other.

The technological process of forged pieces production may be divided into the main and auxiliary operations. The main forging operations are as follows: setting, drawing, piercing, bending, cutting, twisting etc.

The drawing of the forging piece is being sketched first of all on the base of the drawing of the finished component during the process of development of the technological process of forging components production. For this purpose allowances, tolerances and if required overlaps are being chosen according to the standard.

Allowance is the provided exceeding of the forging piece dimensions in comparison with the nominal component dimensions for obtaining required dimensions and pure surface after the finishing by cutting.

Tolerance is the difference between the greater and the smallest dimensions limit of the forging (permissible deviations of dimensions).

Overlap is the increasing of the allowance making the forging piece configuration more simple due to the impossibility or inexpediency of the forging piece production according with the component contour.

The mass of the forging piece or the billet is determined proceeding from the volume calculated from dimensions indicated on the drawing. For volume calculation the forging piece is divided to parts having the simplest geometry. It is possible to calculate the mass of the billet knowing the density of the metal.

The total mass of the billet (ingot) is obtained as the sum of forging piece mass and mass of wastes in the form of removed metal and bottom part of the ingot, punching of the forged piece, loss of metal during heating and during the heating of the billet.

The cross section area of the billet is calculated according with the specified degree of upsetting.

The overall index of precision called the coefficient of the usage of forging piece metal during machining is used for comparison of different technological processes and the equipment efficiency:

$$K_{\text{mec.tr}} = \frac{G_{\text{comp}}}{G_{\text{f.p}}}, \qquad (2.68)$$

where G_{comp} and $G_{\text{f.p}}$ is the mass of the finished component and the mass of the forging piece.

This index characterizes the degree of perfection of the forging piece.

As usual $K_{mec.tr}$=0.05-0.3 for forged pieces obtained by smith forging.

Another important index characterizing the degree of perfection of the forging technology is the yield $\eta = \frac{G_{f.p}}{G_{billet}}$ where G_{billet} – the billet mass. During the forging from the ingot η=0.3-0.7, during the forging from rolled billet η=0.7-0.9.

The product $K_{m.u}= K_{mec.tr}\eta$ is the cumulative rate of the metal usage during the whole technological cycle of the ready component production. At smith forging $K_{m.u}$=0.02-0.3.

The size range of the main forging equipment (hammer, press) is determined according dimensions of the billet (ingot) and the transition diagram of forging.

The most difficult operation of the given technological process is oriented on. The press force and the mass of the hammer falling parts are determined by calculations according to the empirical and theoretical formulas given in special reference literature. The approximate data about the equipment used for hammer forging and press forging are given in Table 2.1.

Table 2.1. The approximate data about the equipment used for hammer forging and press forging

Mass of the falling parts of hammer, kg	Mass of forging piece, kg	Billet section (square side, mm)	Press force, MN	Ingot mass, t
100	0.5-2.0	50	6	0.5-2.0
300	3-10	85	10	4-8
500	8-25	115	20	15-30
1000	20-70	160	30	30-60
3000	100-320	275	60	60-120
5000	200-700	350	100	150-250

2.7. Hot die forging

The metal flow is limited by the surfaces of die cavities in case of using this method of metal forming. The die cavity (die impression) is being filled up by the metal, the cavity has the form of the product – forging piece.

The die forging if to compare with the smith (free) forging provides for higher efficiency, dimensional precision and better quality of the products' surface. The components with the most complex shape may be received by forging with considerable reduction of technological operations.

The forging tool – the die has the considerable cost and may be used for production of only one configuration forging pieces, that's why die forging becomes profitable only in case of mass serial production.

The most widespread method of hot die forging is the forging in open die with the burr (Fig. 2.19).

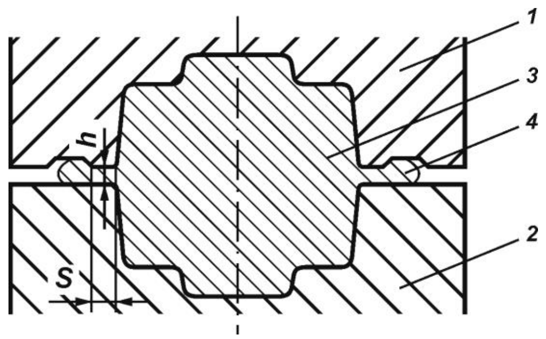


Fig. 2.19. Forging in open die with the burr: *1* – moving die; *2* – bottom die; *3* – product; *4* – burr

The essence of the burr method consists in the fact that due to the excess of metal the forging piece is produced with the burr at the place of the die parting. After finishing the plastic working the burr is removed on the shaving die. This method of forging is widely used in manufacturing, because it ensures the effective filling of the die cavity in spite of the metal losses in the form of burr.

Forging in the opened dies is characterized by the direction of the metal displacement into the burr slit perpendicular to the direction of the die movement. The burr thickness is reducing during the process of forging. The filling of the die impression by the metal may be divided into several stages (Fig. 2.20).

The free upsetting of the billet is going on during the first stage. In case of complex shape of the die the partial piercing or extrusion of the metal into the recesses of the cavity is possible.

The second stage of forging begins from the moment of the billet contact with the side walls of the die. The deformation force at this stage is increasing due to the supporting action of the side walls of the die and the appearance of friction forces on the side surface of the impression. This stage of forging is finished by the moment of beginning of the burr formation.

Only the angles of the die cavity remain unfilled by the metal by the beginning of the third stage. The surplus metal of the billet is displaced into the groove. That time the burr is accomplishing its main function, which consists in closing the die cavity. Now the resistance to the metal flow into the unfilled angles of the die cavity is becoming less than into the groove. The die impression becomes filled by the end of the third stage.

In case the forging piece by the moment of the impression filling has the height greater than it is necessary, fourth stage of the process – additional forging is required during the process of which the excess of metal will be displaced into the burr.

It is necessary to take into account that the stages of forging of complex shape forging pieces are non-simultaneous along the perimeter of the forging piece. At the beginning the angles of the die are being filled only in separate places.

a

b

c

d

e

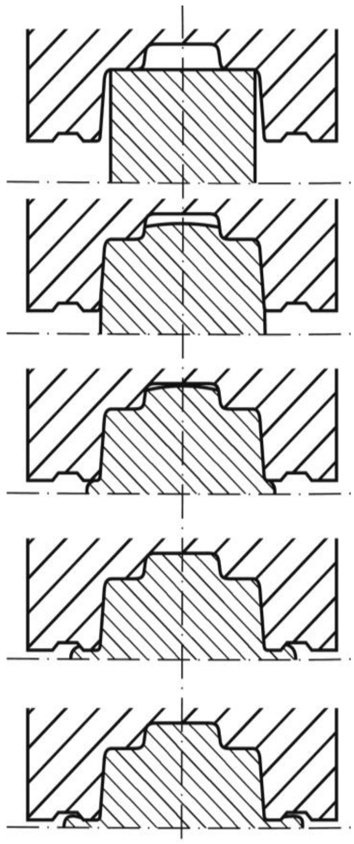


Fig. 2.20. The stages of metal flow during the filling of the opened die: *a* – initial position of the billet in the die; *b* – position of the billet at the moment of the first stage finishing; *c* – finishing of the second stage; *d* – finishing of the third stage; *e* – the forth stage – additional forging

Demolding of the forging piece presents some difficulties due to retaining of the latter by the friction forces in the die cavity. The side walls of the cavity are made with the inclination to facilitate the demolding of the forging piece and the forging piece is produced with the lap, though it is connected with the forging piece shape distortion and additional metal consumption.

The dies have to be lubricated thoroughly, what gives the possibility to decrease their inclinations and laps on the forging pieces. The lubricant is necessary for increasing the die strength.

Deforming force P, which is necessary for deformation accomplishing at the final moment of forging, presents the sum of force necessary for metal deformation in the die and the force necessary for the burr deformation.

For the elongated forging pieces having the form similar to rectangular with the long side a:

$$P=\beta\sigma_{\text{yield}}[(1+f_\sigma s/h)F_{\text{burr}}+(2f_\sigma s/h_{\text{burr}}–0{,}25+1{,}25\ln a/h_{\text{burr}})F_{\text{p}}], \quad (2.69)$$

where s is the width of the bridge; h_{burr} is the thickness of the burr; f_σ is the index of friction; F_{burr} is the area of projection of the burr bridge; F_{p} is the square of the forging piece projection.

For the forging pieces having the form similar to the round with the diameter d:

$$P=\beta\sigma_{\text{yield}}[(1{,}5+f_\sigma s/h_{\text{burr}})F_{\text{burr}}+(2f_\sigma s/h_{\text{burr}}–0{,}375+1{,}25\ln d/h_{\text{burr}})F_{\text{p}}].(2.70)$$

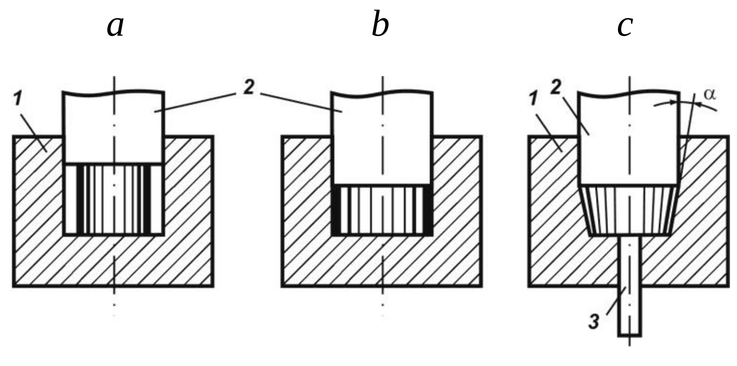


Fig. 2.21. Schemes of forging in closed dies

Burr-free forging in closed die method consists in billet placing into the die cavity *1*, to which its another part *2* enters as into the guide (Fig. 2.21, *a*, *b*). In this die the whole volume of the billet metal remains in the forging piece. The exit for the burr is not provided for. This die doesn't provides for the free forging piece removing from the impression. The forging piece is removed from the die cavity by the pusher *3* (Fig. 2.21, *c*) or the female composite dies are used.

The forging angles α of relatively small sizes are used for decreasing the pushing force. In case of composite dies usage the inclinations are not necessary.

The variations of the billet volume should be insignificant during the forging in the closed die. The smaller than required billet volume leads to the underflow of the die angles and forging pieces defects. The greater billet volume leads to the thrust of the die, decrease of its longevity and may bring the die damage.

The burr formed in the split at the place of the die joint is insignificant; its thickness is not changed during the process of forging and the direction of the run-out coincides with the direction of the die movement.

The billet processing may be accomplished in one or several impressions during the opened forging as well as during the closed one. In case of multi- impression forging the billet is changing gradually during the transition from one impression to the other and in the finishing pass it is finalized as to the shape and dimensions.

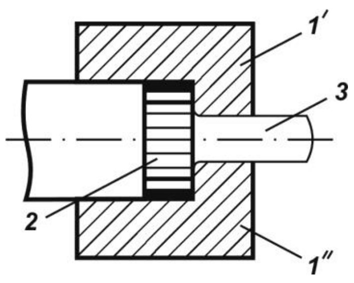


Fig. 2.22. The scheme of the forging by extrusion: *1*', *1*" – the composite parts of the die; *2* – the body of the forging piece; *3* – the core part of the forging piece

The essence of the process of extrusion consists in the following: the billet is positioned in the cavity of the closed die having the outlet, which the part of the metal is extruded through beyond the bounds of the main cavity (Fig. 2.22).

The wastes are not envisaged here, excluding the excess part of the billet volume formed during out-of-tolerance cut of the metal for billets. Unlike the cavities in the closed die, for the forming of shape separate elements the die for extrusion has the open cavities with the outlet.

The obtained forging piece consists of the body located in the main part of the cavity and the core part extruded through the hole in the die cavity.

The extruded forging pieces have the higher quality, the absence of the cracks and other defects due to the plasticity increasing in the conditions of uniform compression at the high hydrostatic pressure.

Every method of forging described above has its advantages and disadvantages, but the forging in the closed dies is more rational as only the small size burr is possible during this process (0.5-1%), the quality of the forging pieces is higher than from the opened dies. The main disadvantage of the method of forging in the closed dies is in its non-universality and limited nature of rational shapes of the forged pieces.

2.8. Sheet metal stamping

Sheet metal stamping is used for manufacturing the products from sheet, plate and strip material without any significant change of the billet thickness. All technical metals and alloys having good plasticity are used for sheet metal stamping. Metal deformation is usually carried out in the cold state and only for processing of the plates with the thickness more than 100 mm and low-plastic alloys it is accomplished in hot or warmed-up state.

The variety of the products' shapes and sizes manufactured by sheet metal stamping is determined by significant number of stamping operations differing by the character of the billet shape changing and by the conditions of the stress. They may be divided to two categories: separating (cutting, blanking, punching) and shape changing (bending, stretching, reduction, burring, shaping and others).

The cutting operation consists in separation of the billet part along the open contour. Mostly cutting is the blanking operation. Cutting of the metal is accomplished by the shears with parallel blades or incline blades as well as by circle shears.

The separation of the billet part along the closed contour is called blanking. The separated part is intended for further processing. The operation is called punching in case when the remained part of the sheet undergoes the further processing. The operations of punching and notching are accomplished in the dies. The effort *P*, which is necessary for punching and notching is determined according the following formula:

$$P=1.3\cdot\Pi\cdot H\cdot\tau_{av}, \qquad (2.71)$$

where Π is the perimeter of the contour, which the punching or notching is accomplished along; *H* is the thickness of the sheet; $\tau_{aver}=(0.8\text{-}0.9)\sigma_{ult}$ is the value of the shearing strength.

The operation changing the shape provide for the manufacture of spatial component with the required shape and dimensions. Let us examine some the most often met operations of shape changing.

The bending in dies is widely used for manufacturing the different products. The bending process is accompanied with the stretching of the external fibers of the bending material and compression of the internal ones, at that the value of the relative deformation is increasing along with the decreasing of the bending radius. The minimum internal value of the bending radius depends on the metal plasticity and is taken within the limits $r_{min}=(0.25\text{-}0.3)h$, where *h* is the plate thickness.

The elastic properties of the metal lead to the changing of the bending value for the angle of springing, which may be 6-12° for steel during the bending for 90°.

The effort *P* during the bending may be determined according the following formula:

$$P=0{,}7\frac{Bh^2}{r+h}\sigma_{ult}, \qquad (2.72)$$

where *B*, *h* is the width and thickness of the bending billet; *r* is the radius of bend along the internal contour.

The stretching presents the operation of transformation of the flat or hollow billet into the hollow body (cap, cup) accomplished without thinning as well as with thinning of the wall. The process of stretching may be accomplished for several successive operations in a number of dies with gradual decreasing of the cup diameter. The stretching (Fig. 2.23, *a*) is accomplished in a die under the pressure of the punch *2* on the center part of the billet *1* placed above the hole of the die *3*. Passing through the die hole, the center part of the billet is pulling the remaining part of the billet, what leads to its folding and reduction of the diameter. The compression stresses appear in a circular direction during this process and they may lead to the loss of the flange stability and riffles formation. To exclude this effect the ring holders of different constructions are used (Fig. 2.23, *b*).

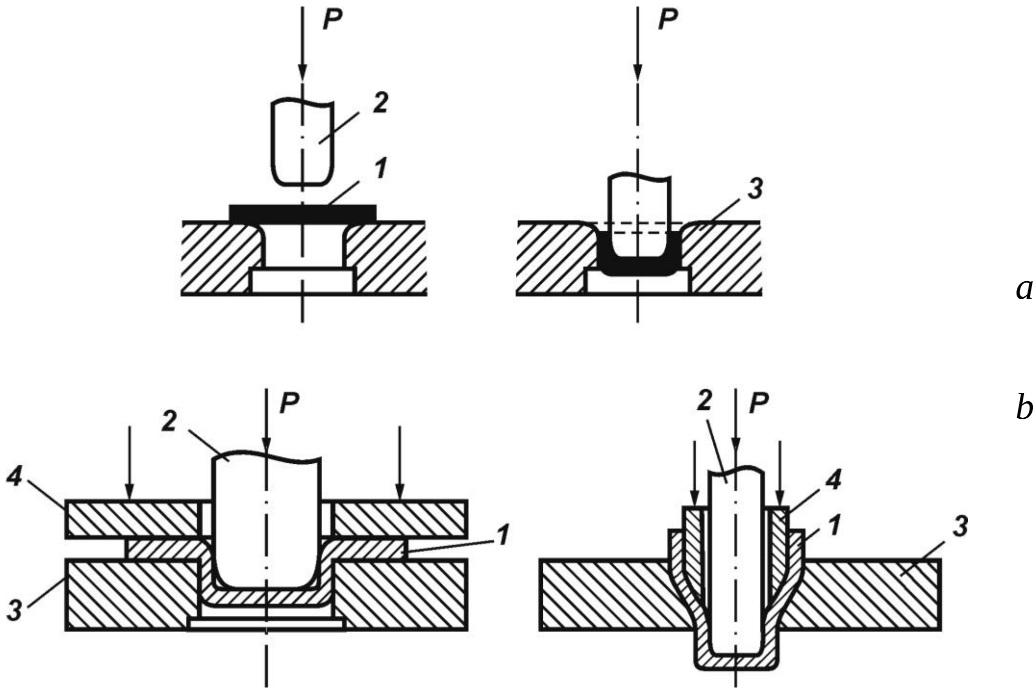


Fig. 2.23. The scheme of stretching operation:
a – without holder; *b* – with holder;
1 – billet; *2* – punch; *3* – die; *4* – holder

The value of the force *P* acting from the side of the punch is limited by the strength of the walls and bottom of the manufactured product. The work-hardened low-alloyed steel permits the production of the cup with diameter 1.8-2.0 times less than the billet diameter per one pass. The possible decreasing of the diameter is smaller to 1.2-1.4 times during the next operations of stretching due to the decrease of plasticity.

The edges of the punch and the die are rounded by the radius equal to: r_{punch}=(4-6) h; r_{matrix}=(5-10)h to reduce the stresses and possibilities of the billet damage.

As a rule the stretching is accomplished with the use of lubrication of the contact surfaces of the die and the draw ring. Different oils are used as lubricants, in many cases with fillers (graphite, chalk, talc) as well as soap greases.

Inward flanging is used in those cases when it is necessary to produce the neck at some place of the flat billet with the hole (Fig. 2.24).

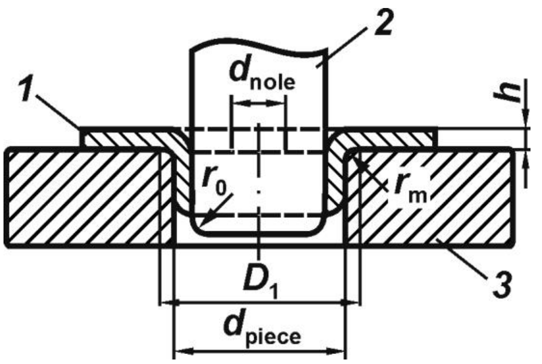


Fig. 2.24. The scheme of inward flanging:
1 – billet; *2* – punch; *3* – die

It can’t be permitted the increase of the hole diameter more than 1.4-1.5 times to avoid the appearance of the cracks along the edge of the hole.

Several operations are combined in one die to increase the efficiency during the manufacturing of the components by the methods of sheet metal stamping (separating, shape changing in this or that combination: cutting and notching, cutting and bending, punching and stretching etc.) – so-called combined stamping.

3. PROCESSES AND EQUIPMENT OF ROLLING

3.1. Classification of the rolling mills

The rolling mills are classified according the following basis: the number and arrangement of the rolls in the roll stands; the arrangement of the roll stands; purpose.

The number and arrangement of the rolls in the roll stands

The stands differ according to above mentioned basis as follows (Fig. 3.1):

- two-high mill stand (duo);
- three-high rolling stand (trio);
- four-high stand (quarto);
- multi-high stands (six-high, 12-high, 20-high etc.);
- universal mill stands;
- special construction mill stands.

Two-high-, four-high- and multi-high mill stands may be of reversing type (with variable direction of the rolls rotation) as well as irreversible (with the constant direction of the rolls rotation). The rolling is accomplishing only between two working rolls in the quarto and multi-high stands, all the rest of rolls are backup rolls and are used for reduction of the working rolls deflection and taking up the pressure during the rolling.

Two-high mill stands (duo) are the most widespread. The reversible stands are used for rolling the large shapes (blooms, slabs, beams, rails and others), thick plates. Irreversible stands are used for rolling the billets, sections, tubes.

The rolling of hollow sections and plate profiles may be realized in three-high rolling stands (trio) in two directions without changing the direction of the rolls rotation.

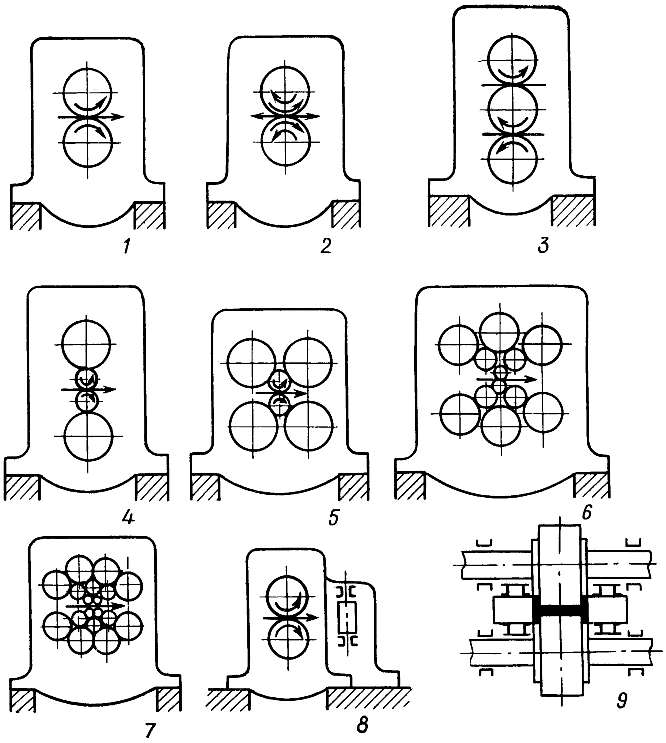


Fig. 3.1. The rolls arrangement
in the working stand of the rolling mill:
1 – two-high mill stand (duo) irreversible; *2* – two-high mill stand (duo) reversible; *3* – three-high rolling stand (trio); *4* – four-high stand (quarto); *5* – six-high rolling stand; *6* – 12-high rolling stand; *7* – 20-high rolling stand; *8* – universal mill stand; *9* – beam universal mill stand

Four-high stands (quarto) are widely used for the hot rolling of plates and sheets.

Multi-high stands are used for cold rolling of thin strip and band in coils. These stands are equipped by winders (reels) and re-coilers.

Universal mill stands have the horizontal and vertical rolls, which ensure the reduction of metal from four sides: along the thickness by horizontal and along the width by the vertical rolls. Universal mill stands are used for rolling slabs, thick plates, wide flange beams with the height 600-1000 mm with parallel flanges.

Special construction mill stands are used for rolling the wheels, bands, rings, balls, seamless tubes, irregular sections, gears and others.

Layout of the roll stands

The following types of mills are differed as to layout of the roll stands: single-stand mill, linear operation mill, successive mills, continuous and combination (mixed type) mills (Fig. 3.2, 3.3).

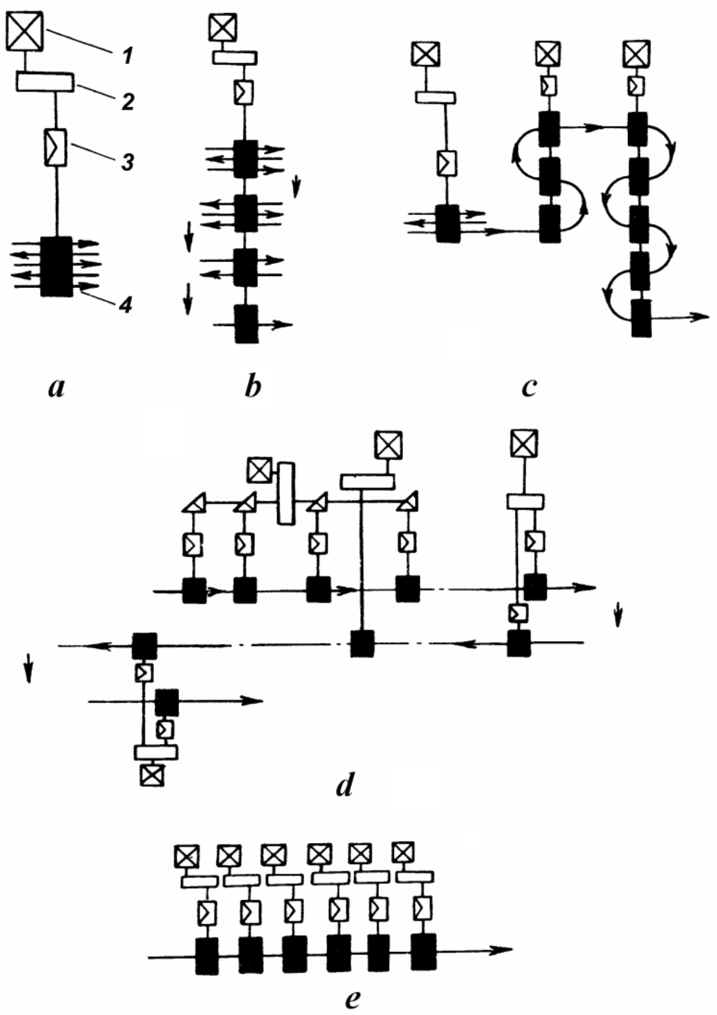


Fig. 3.2. The main types of the rolling mills (on the basis of the stands arrangement): *a* – single-stand mill; *b, c* – linear (one- and three-stage); *d* – successive; *e* – continuous; *1* – engine; *2* – drive; *3* – pinion stand; *4* – roll stand

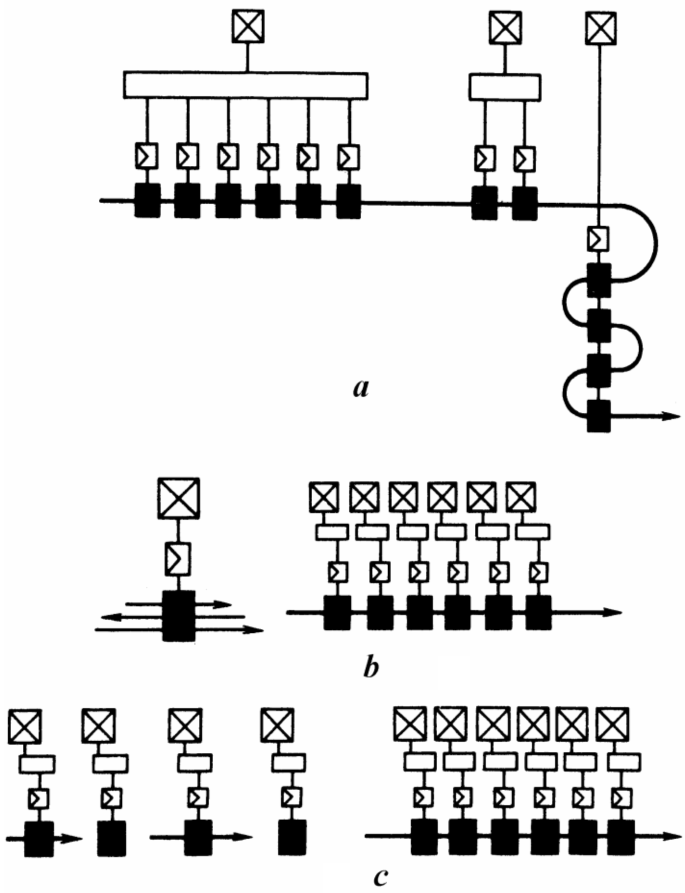


Fig. 3.3. The rolling mills of mixed type (combined):
a – semi-continuous mill with the linear group; *b* – semi-continuous with reversible roughing stand; *c* – successive-continuous

Single-stand mills (Fig. 3.2, *a*) are mostly reversible ones, because it happens to make several passes within one stand. Single-stand mills – there are bloomings, slabbings, universal and plate mills.

Linear operation mills (Fig. 3.2, *b*, *c*) differ from other ones by the roll stands arranged in one line with the common drive from one engine. The mill may have one (Fig. 3.2, *b*) or several (Fig. 3.2, *c*) stands. These mills are used mainly as billet mill, heavy and medium section mills.

There significant disadvantage is the same, unchangeable speed of rolls rotation in all stands that prevents to the necessary increase of rolling speed as the length of the rolled strip increases.

Successive arrangement of the stands (Fig. 3.2, *d*) includes several roll stands arranged successively one after another. The strip is passing through each stand only one time moving ahead all the time, that's why the number of the stands should correspond to the maximum number of passes and the speed of the rolls rotation and the distance between the stands should increase from the first stand to the last one.

Continuous mills (Fig. 3.2, *e*) also have the successive arrangement of the stands, but the stands are installed close to each other and during the stable process the strip is rolled simultaneously in all the stands. It is necessary to follow the law of the constant second volume for the stable process of continuous rolling, that is the quantity of the metal passing through any stand per time unit has to be constant:

$$F_1 v_1 = F_2 \cdot v_2 = \ldots = F_n v_n, \quad (3.1)$$

where F_1, F_2, …, F_n is the area of the cross section of the strip in first, second and the last stand; v_1, v_2, …, v_n is the speed of exit of the strip from the first, second and the last stand.

Continuous mills are the most high-speed, automated and high efficient plants.

Mixed type mills (Fig. 3.3) as a rule include the continuous group and some of the other group of stands (linear, or with consequent arrangement of the stands, or reversing stand). These mills are called semi-continuous.

Classification of the rolling mills as to their the purpose

The rolling mills are divided into cogging-billet mills, section mills, sheet mills, tube mills and special purpose mills (Table 3.1).

Breakdown mills – blooming and slabbing mills – are used for rolling large ingots to the heavy billets – blooms and slabs. The billets of smaller sections are rolled from blooms and small ingots at billet mills.

Table 3.1. Classification of the rolling mills as to their the purpose

Rolling mills	Rolls sizes, mm	Typical kinds of products, mm
Cogging:	Diameter	
Bloomings (bloom)	800-1500	Blooms 200×200-400×400
Slabbings	1100-1250	Slabs 100-300×600-2000
Billets mills	500-900	Billets 50×50-150×150
Section mills:	Diameter	
Structural	750-900	Railway rails, beams №20 and greater and others
Heave-section	500-800	Rounds 50-150, beams №10-30 and others
Medium-section	300-550	Rounds 30-80, beams №10-12, angles 50×50-100×100 and others
Light-section (merchant bar)	250-350	Rounds 10-30, angle 25×25-50×50 and others
Wire (rod)	150-250	Rod 5-12
Skelp	300	Strips 3-8×100-500
Sheet	Barrel length	
Plate	1800-5500	Sheets with thickness more than 4, width 600-5300 mm
Thin-sheet	900-2800	Sheets with the thickness less than 4, width 600-2500 mm
Hot-strip	1200-2800	Strip with the thickness 1-16 at hot rolling mills, 0.1-4 at cold rolling mills; width 600-2500 mm
Strip	Up to 1000	Strip with thickness 0.5-10, width up to 600 mm
Band	Up to 800	Bands with the thickness 0.05-2, width up to 300 mm

Breakdown mills – blooming and slabbing mills – are used for rolling large ingots to the heavy billets – blooms and slabs. The billets of smaller sections are rolled from blooms and small ingots at billet mills.

Thus cogging and billet mills are used for manufacturing of semi-finished product.

All the rest mills are used for finished products manufacturing.

Standard and structural shapes such as round, square, angle, beams, channel, rails and others are rolled at section mills.

Sheet mills are of the following main types: plate, thin sheet and hot strip rolling mills.

Tube mills are divided into mills (plants) for production of seamless and welded tubes.

The special purpose mills are as follows – roll-forming machines, railway-wheel-and-tyre-rolling mills, ball-rolling mills.

The main index characterizing cogging-billet and section mills is diameter of the rolls of the last finish stand; sheet mills are characterized upon by the length of the roll barrel, which the possible width of the rolled sheets (strip) depends on; tube mills are characterized by the maximum outside diameter of the rolled tubes.

3.2. Equipment of the rolling shops

All equipment is divided to two groups: the main and the auxiliary equipment.

Equipment used for carrying out the main technological operation – metal plastic deformation is called the main equipment. The line along which the main equipment is arranged is called the main line of the rolling mill.

Equipment intended for carrying out all the rest technological operations is called auxiliary equipment.

The following technological operations may be referred to as the auxiliary ones: metal heating in heating furnaces and pit furnaces; cooling of the rolled metal on different construction cooling beds (tables); metal cutting on shears and saws; straightening of the rolled metal in straightening machines; roller conveyers for strip transportation; manipulators for strip traveling along the rolls; side tilters (tilting) and others. The complex of the main and auxiliary equipment for metal deformation into the rotating rolls is called the rolling mill.

The components of the main equipment of the rolling mills

The following main equipment is situated on the main line of the rolling mill: working stand, driving gears used for transition of rotation from the engine to the rolls; engine (Fig. 3.4).

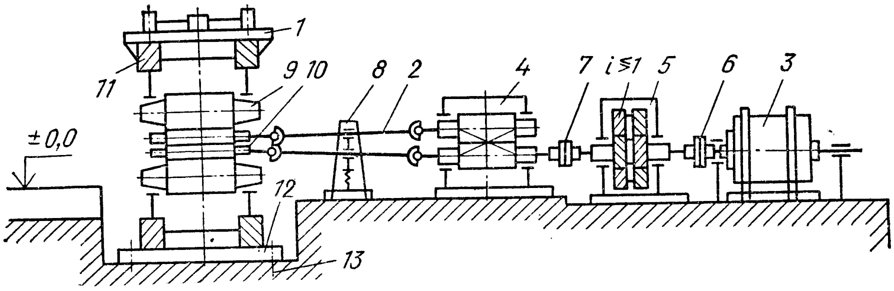


Fig. 3.4. The scheme of the main line of four-roll stand:
1 – roll stand; *2* – universal shafts; *3* – electric motor (the main drive); *4* – pinion stand; *5* – gearbox; *6* – motor spindle; *7* – lead spindle; *8* – springing balancing spindle unit; *9* – support idle rolls; *10* – work driven rolls; *11* – housing; *12* – mill shoe; *13* – anchor bolt

Roll (work) stand (*1*) – is used for plastic deformation of the metal into rotating rolls.

Coupling spindles (*2*) – are used for transition of rotation to the work rolls from pinion stand.

Pinion stand (*4*) – is used for dividing the turning moment (torque) from one engine between the rolls.

Lead spindle (*7*) – is used for transition of rotation to the shaft of the driving gear of the pinion stand from the gear box shaft.

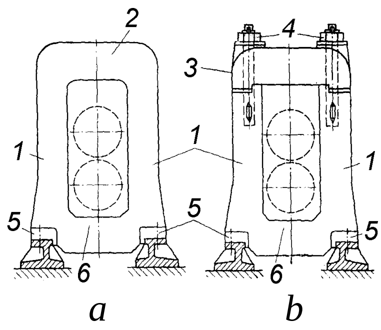
Gearbox turning (*5*) – is used for changing the moment and the number of engine revolutions during transition of rotation from the engine to the work rolls.

Motor spindle (*6*) – connects the engine shaft with the drive shaft of gearbox.

Electric motor (*3*) – forms the turning moment (torque) and power necessary for plastic deformation of the metal.

The working stand of the rolling mill is the main unit, in which the rolling of the metal takes place. The working stand consists of the following components: two housings (Fig. 3.5) (excluding multi-roll and special stands) connected between each other and installed on the bed plates; rolls with chocks and bearings; setting mechanisms for adjustment of rolls position; roll fittings and others.

Fig. 3.5. The housings of the roll stand:
a – closed; *b* – open; *1* – vertical support; *2* – top-housing; *3* – cover; 4 – bolts; *5* – horizontal shoes; 6 – bottom-housing (mill separator)



The rolling roll consists of the following main components: barrel, which presents the center part of the roll, which the contact of the roll with the rolled metal takes place along; two roll necks situated at both sides of the barrel by means of which the roll is installed in the bearings units; blades or wobblers situated on both sides of the rolls and used for connection of the roll with coupling and spindle for rotation of the roll.

Wear-resistance and strength are the main service properties of the roll.

The rolls are produced from the cast or forged steel grade 45, 55X, 60XH, 90XФ and others for blooming, slab, cogging stands of the section mills and cold rolling mills. Cast-iron rolls including Cr- and Ni-alloyed ones as well as rolls (hardened) with chilled surface layer are used for section and sheet hot rolling mills when the high wear-resistance is required.

The bearings of the rolling rolls. The rolls of the rolling mills are resting upon the bearings by their necks. The roll chocks with bearings are installed in the housing openings. The bearings are the high-duty components in the roll stand of the mill, they are loaded several times more than it is permitted in the bearings of the other machines, and the precision of the rolled shape depends upon their strength as well as mill efficiency, the cost price of the products. The bearings of the rolling mills may be divided into two groups: sliding bearings and antifriction bearings.

The rolling antifriction bearings and liquid friction bearings are installed on modern mills.

The roller multiple-row bearings are easy-to-work and don't need sealing, they are well self-aligning and have long term of service. The coefficient of friction is small in roller bearings and is equal to 0.001-0.005. Liquid friction bearings consist of the conical plug tightly fixed on the roll neck and babbit-lined bearing, which is carefully treated. The refined lubricating liquid comes under the pressure into the gap between the plug and bush. The principle of operation of these bearings lies in the following: the oil film is usually kept between the neck of the shaft and the bearing, owing to this the roll neck as if is floating in the bearing.

The liquid friction bearings provide for the accurate adjustment of the mill, have the low friction coefficient (0.001-0.008) and are practically wear-free.

The friction bearings (bronze, brass) and fabric ones were used for the mills of the old design. Fabric bearings are used also now at cogging mills, they are economical, are lubricated and cooled by water and have the low friction coefficient (0.003-0006), however they are worn out very fast, what affects negatively the precision of the rolled products.

Mechanisms and facilities for the rolls installation

It is necessary to adjust the corresponding distance (gap) between the rolls to provide for the required reduction in each pass. This distance has to be changed from the pass to pass at the rolling mills where several passes take place in one stand. The mill adjustment has to be changed due to the wear of the rolls at the mills where in each stand only one pass takes place (multi-stand continuous and semi-continuous mills and others).

The distance between the rolls is changing by means of displacement of the upper roll or by means of displacement of two rolls – bottom and upper – in two-roll stands; by displacement of upper and bottom rolls in three-roll stands (trio); by displacement of the upper roll in four-roll stands (quarto).

All kinds of machinery for rolls installation may be divided to the following groups.

1. Pressure mechanisms.
2. Balancing mechanisms for the upper rolls.
3. Axial rolls adjustment mechanisms.

The roll stand of the continuous billet mill is shown on Fig. 3.6.

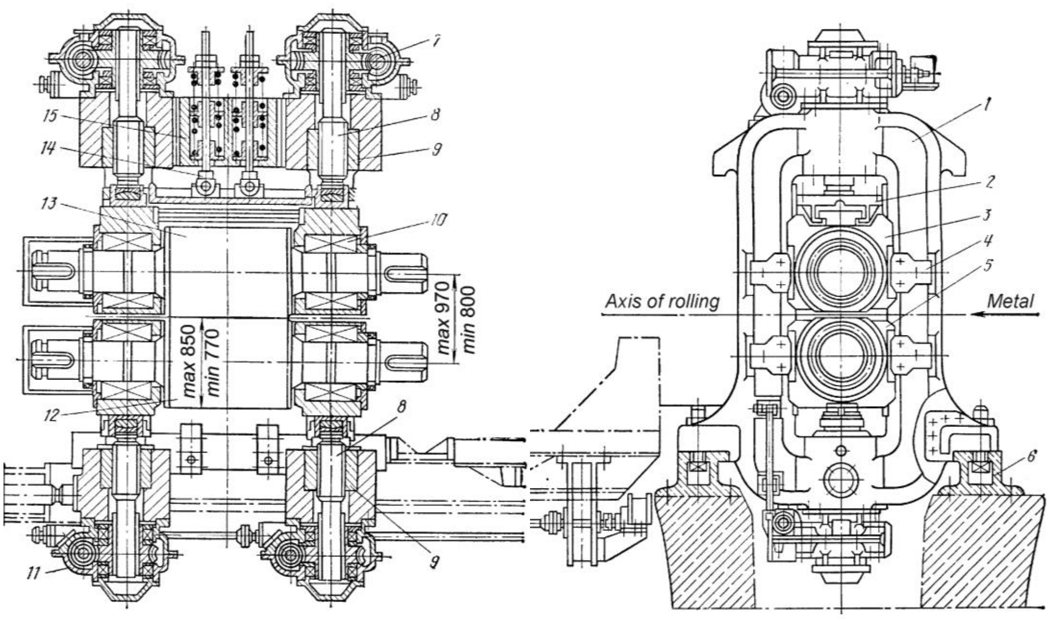


Fig. 3.6. Working stand with horizontal rolls
of continuous billet mill 850/700/500:

1 – housing; *2* – chock attachment point of the upper roll to the rods of spring balancing mechanism; *3* – chock of the upper roll; *4* – plates for axial adjustment of the rolls; *5* – chock of the bottom roll; *6* – mill shoe; *7* – drive of pressure mechanism of the upper roll; *8* – pressure screw; *9* – nut of the pressure screw; *10* – four-row conical roller nearing; *11* – drive of the pressure mechanism of the bottom roll; *12* – bottom roll; *13* – upper roll; *14* – spring balancing mechanism; *15* – cross-bar

The vertical adjustment of the position of the upper and bottom rolls of the roll stand (Fig. 3.6) is accomplished by means of the pressure mechanisms. The pressure mechanism consists of the nut *9* fixed in the housing of the stand *1* and pressure screw *8* resting on the chock *3* of the upper roll *13*.

The pressure mechanism is driving from the electric motor installed on the housing by means of the worm reducer. The position of the rolls in axial direction is adjusted by means of plates *4* with the bolt joints or by means of special levering devices.

Balance mechanisms provide for the constant pressure of the upper roll chocks to the mill housing screw. The easiest ones accomplish the balancing by means of springs and rods passing through the holes in the housings. The large diameter rolls as well as spindles are balanced by cargo gear and hydraulic units.

Coupling spindles are used for the transmission of rotation from the pinion stand to the rolls.

Besides that they can transmit the rotation from the rolls of one stand to another stand in case of linear arrangement of the stands.

Universal spindles are used at modern rolling mills, designed according to the principle of Hooke. They permit to transmit the rotation to the rolls at significant deviation of gear and rolling rolls axes resulting from the upper roll raising (Fig. 3.7).

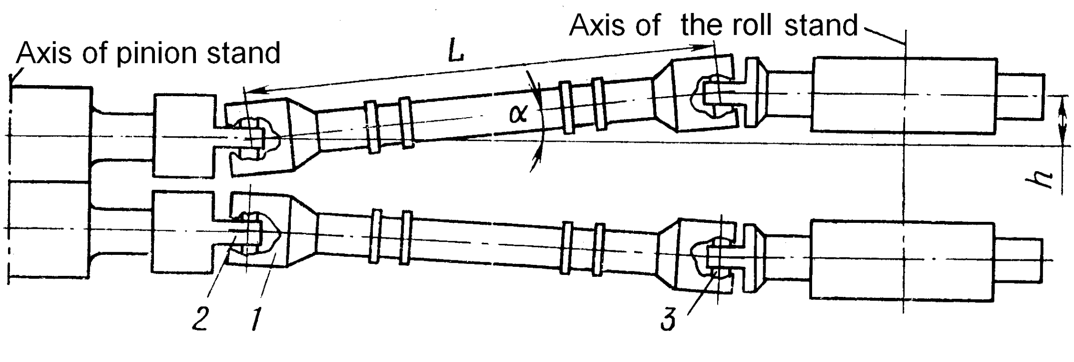


Fig. 3.7. Scheme of universal spindles layout

The universal spindles are working smoothly without any impacts.

The hinge of the spindle consists of the head of spindle *1*, wobbler *2* at the end of the roll or gear roll, bronze bush *3* and sliding block connecting them. One of the spindle hinges is fixed at the end of the driving shaft of the pinion stand and the other from the side of the roll and may travel in axial direction during the upper roll travel up and down.

The length of spindle L is determined from the permissible angle of inclination α and the required maximum distance between the axis of roll and the axis of driving shaft $L=h/tg\alpha$.

4. SECTION AND SHEET MANUFACTURING

Steel smelted in steel plants is being poured into moulds where the ingots are being formed during the cooling and solidification processes. They are the raw material for all kinds of rolling manufacturing.

The technological process of rolled products manufacture out of ingots consists of two stages: the rolling of the ingot into the semi-finished product (billet) and the rolling of semi-finished product into the finished rolled product.

All rolling mills are divided into two groups: cogging blooming mills, slabs and billet mills – for semi-finished products manufacturing; sheet mills, section mills, tube mills and special purpose mills – for production of finished products.

The flat billet called slab is used at sheet mills. The square or close to square rectangular billet is used at section mills. The round billet is used at tube mills.

At present production of semi-finished product (billet) by the continuous steel casting method at continuous casting machines became the most widespread. It gives the possibility to exclude the large cogging blooming mills, slabs and billet mills from the technological scheme.

4.1. Rolled-products range

Cross-section form of the rolled metal is called shape (profile). The range means all shapes rolled at the given mill. The whole range of the rolling manufacturing is divided to four groups: sheet rolled products, section products, tubes, special types of rolled products.

The sheet rolled products are divided to thin sheets (thickness less than 4 mm) and thick sheets (plates) (thickness more than 4 mm).

Tubes are divided into seamless and welded tubes.

Section rolled products include square and round shapes, channels, flanged beams, angles, rails and others.

The shapes for the special fields of industries are the rail-way wheels, balls, tongues, rail-way wheels axes, window frame crosses) die-rolled sections and rolled-formed shapes. The shapes with variable cross-section along the length of rolling are called die-rolled sections.

The unified technical requirements for suppliers as well as for consumers have been established to guarantee the quality of the products. These norms are called standards and they have the force of the law (ДСТУ, ГОСТ). The requirements to the rolled products dimensions, chemical composition, mechanical properties, and surface quality are stipulated in the state standards as well as the rules of acceptance of the finished products, test methods, marking and others are given.

The suppliers and the customers develop technical conditions (ТУ) in cases when the products have the special purpose and the requirement to it is not included to the standards.

The fulfillment of these conditions is obligatory. The shapes of the branch purpose are accepted according to the technical conditions.

Different steel grades are used for rolled products manufacturing. Steels are divided into three types as for the content of the detrimental impurities (sulfur and phosphorus): common quality steel (the maximum content of sulfur and phosphorus 0.05-0.055%), fine steels (0.04-0.045%) and extra-fine steels (0.03%). Steels are divided into two main groups as for the chemical composition: carbon steels and alloyed steels.

Carbon steels are the alloys of iron and carbon and have some quantity of unavoidable impurities – silicon and manganese as well as detrimental impurities – sulfur and phosphorus.

The special alloying impurities such as chromium, nickel, tungsten, molybdenum, vanadium and others as well as manganese and silicon in quantities more than 1.0-1.5% are contained in alloyed steels except indicated elements. The alloying impurities give the special properties to steels.

Steels are distinguished as structural steels, tool steels and special steels according to their purpose. Structural, carbon and alloyed steels are the most widespread.

The elements entering the steel composition are indicated by the following Russian lettering according to standard:

Aluminum – Ю	Copper – Д	Cobalt – К
Vanadium – Ф	Molybdenum – М	Silicon – С
Tungsten – В	Nickel – Н	Manganese – Г
Niobium – Б	Titanium – Т	Chromium – Х

Conventional notations of steel grades are also correspondent to the system determined by the standards. Each steel grade is identified by the combination of figures and letters. According to this system the first two figures indicate the average carbon content in steel grade in hundredth parts of the percent for structural steels and in tenth parts of the percent for tool steels. The letters indicate the corresponding alloying element in steel and the figures following the letters indicate the average content of this element in percents if its content is greater than 1.5%.

Besides that the marking is applied to some steel grades indicating the purpose of steel. For instance the Russian letter Ш before steel grade indicates that the given steel is ball-bearing steel, the Russian letter Р indicates rapid steel, the Russian letter У indicates tool steel and letter А at the end indicates extra-fine steel.

The following steel grades have the greatest weight in the rolling products range: Ст.1-Ст.7, steels 05, 08, 10, 15, 20, 25, 35, 40, 45, 50, 55, 60, 65, 70, 15Х-40Х, 18ХГ-40ХГ, 20ХГСА-35ХГСА, 20ХН-50ХН, 30ХНВА, 38ХНВА, 40ХНВА, 40ХНМА, 30Х18Н10Т.

4.2. The main technological operations in the rolling shops

Metal preparation for rolling, metal heating, rolling itself, cooling and finishing of the rolled product are the main technological operations during the manufacturing of sheet, section and tube rolled products.

Preparation of ingots and billets for rolling consists in removing different surface defects such as flaws, sinks, cracks, nonmetallic inclusions and others. The removing of the defects is made by different methods such as gauging by pneumatic chisels, flame scaling, abrasive discs. The total removing of the surface layer of metal by planning, milling, treatment on the special lathes is made in case when especially high quality surface is required.

Metal heating before rolling is necessary for increasing the metal plasticity and decreasing the value of deformation resistance and power consumption. Heating of ingots and billets before deformation is made in the furnaces of different types and design. The pit furnaces or box furnaces are mostly used for heating of large ingots. Continuous furnaces are widely used for heating of billets. The heating temperature for low carbon steels (0.1-0.2% C) is 1200÷1280º; for high-carbon (1-1.5% C) – 1000÷1150º; for corrosion resistant (stainless) steels – 1100÷1180º.

Hot rolling. The quality of the rolled products, their mechanical characteristics, rolls wear, rolled products surface smoothness, precision of the finished rolled products dimensions, and energy consumption for deformation is determined by the heating rate.

Metal cooling after the process of rolling is accomplishing in stacks or on the coolers on the air. The delayed cooling rate or accelerated cooling rate is used for some kinds of rolled products. Then the special thermal installations are to be created.

Rolled product finishing includes operations such as straightening, cutting, defects skinning, marking and others. Straightening as a rule is accomplished at roller straightening machines and straightening presses. Thick plates are straightened in hot condition.

4.3. Cogging-billet production

Cogging and billet mills are installed in those cases when smelted steel is poured into ingots. Semi-finished products in the form of blooms and billets are produced out of the ingot at cogging (blooms) and billet mills, and they are used as the raw material at the final rolling mills.

Blooms (*bloomings*) are the cogging mills. They are intended for production of large breakdown bars of square or rectangular (close to square) section with dimensions from 250×250 up to 450×450 mm by means of ingots cogging. These breakdown bars are called blooms.

Blooms (bloomings) are one-stand reversing mills with two horizontal rolls. Mills with variable roll rotation direction are called *reversible* ones. Bloom rolls diameter is 950-1300 mm. The rolling is accomplished in the following way: the rolls are stopped after each pass and are switched on for rotation in the reverse direction. The rolling is going on in forward direction in each odd 1-3-5-7 pass and in reverse direction in each even 2-4-6-8 pass.

The upper roll is going down after each pass (odd or even) for the value of the absolute cogging Δh which is equal to 60-100 mm depending on the roll diameter. The ingot rolling is carried out at bloom into the rolls having square passes (Fig. 4.1).

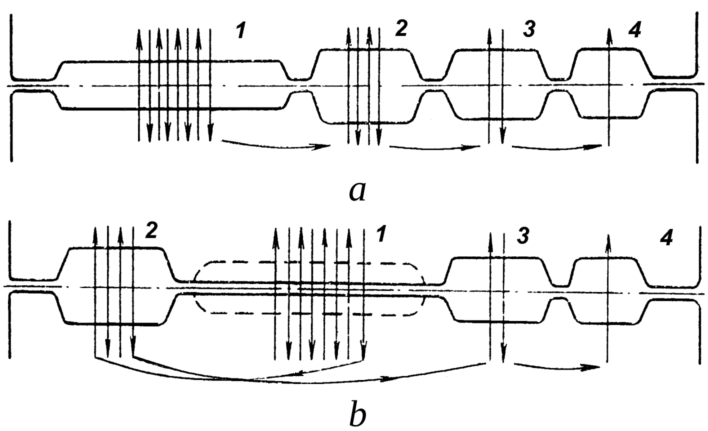


Fig. 4.1. Continuous in-line (*a*) and equally-spaced (*b*) arrangement of the passes on the bloom rolls

The square passes are often called *box grooves*. The rolling directions and the quantity of passes in each groove are shown by the arrows. For production of square section blooms the breakdown bar is moved by special rulers (manipulators) along the roll barrel from one box groove into another having smaller cross section. The breakdown bar is turned over (turned around the longitudinal axis for 90º) before rolling in the next groove. The total quantity of the passes at bloom has to be odd and is of 9-17 passes.

Billet mills are used for bloom rolling into the semi-finished products of smaller sections from 60×60 up to 170×170 mm, which are called billets. It is inexpediently to roll sections less than 250×250 mm at bloom, because its efficiency is sharply decreased due to the increase of quantity of passes. The usage of billet mills permits to increase the final section of blooms and to enlarge its efficiency. The possible efficiency of blooms with 1300 mm rolls is about 6 million tons per year. Continuous-billet mills (CBM) are used at modern metallurgical plants with the big production volume of section products. They are installed immediately after bloom and work without intermediate blooms heating. In case of production of a large volume of large size round billets with diameter 90-350 mm, tube-billet mills (TBM) are installed after bloom where the square billet is also rolled. Continuous billet cast machines are highly widespread at present what allows to exclude the usage of blooms and billet mills.

Continuous-billet mill consists of 14 irreversible two-roll stands with individual roll drive. Only one pass is accomplished in each stand. The stands are combined in two groups. There are 8 stands in the first group, two of them with 900 mm diameter of horizontal rolls and 6 stands with 700 mm roll diameter, 4 of these stands with horizontal rolls and two stands with vertical rolls. The second group has six stands with 500 mm roll diameter. In this group three stands have horizontal rolls and three stands have vertical ones.

After pouring in steel plants the hot ingots with temperature 800-900ºC are transported on the rail-way platforms to the department of the heating furnaces of bloom. The ingots are charged into the furnaces and are heated up to the temperature of rolling, which is 1260-1300ºC. Heated ingots are extracted out of the furnaces and loaded on the ingot car. After that they are delivered along the circle route to the receiving roller conveyor and transported to the bloom 1300 for rolling. After rolling blooms are passed to the scarfing machine for removing the surface defects and are delivered to the shears where the defect ends of bloom corresponding to the head and bottom parts of ingot are cut. Then the bloom with section 360×360 is forwarded by the conveyor for rolling in stands of the continuous-billet mill. The billet with section 190×190, 170×170, 150×150 mm is produced after rolling in the first group of stands, which is sent along the bypass table to the shears for cutting.

The head end of the ingot (defect) is cut at the shears *7* before rolling in the second group of stands. 150×150 mm billet is used for rolling in the 2nd group. The billet with 125×125, 100×100, 80×80 mm sizes is produced after rolling in the 2nd group. The system of box (rectangular) grooves is used in the first group of stands, the system of diamond and square grooves is used in the second group.

4.4. Continuous casting billets manufacturing

The method of casting with the help of machines for continuous billet casting is widely used at present. Continuous casting is intensively introduced in practice in ferrous and non-ferrous metallurgy replacing pouring into moulds. Up to 90% of smelted metal is poured by the method of continuous casting in many developed countries. The major advantage of this method is the reduction of metallurgical cycle. The necessity of technological operations of billets casting, removing them from the moulds, rolling at cogging mills and forging at expensive equipment is no more relevant. The quality of the produced billets is much higher due to their homogeneity. The continuous casting provides for the high efficiency and significant increase of metal yield (for 15% and more) as the result of decrease of technological wastes during the further processing. The billets of square and rectangular sections are produced by continuous casting as well as round shapes and H-sections.

The advantages of the continuous casting are even greater in the case of combination of continuous casting machine with rolling mill into one complex, which is called foundry-rolling plant.

The process of continuous casting (Fig. 4.2) consists in the following: the liquid metal from the ladle *1* comes to the heated up to 1200-1300ºC intermediate ladle *2* and from it to the copper water cooled crystallizer *3* where the dummy ingot serves as the temporary bottom.

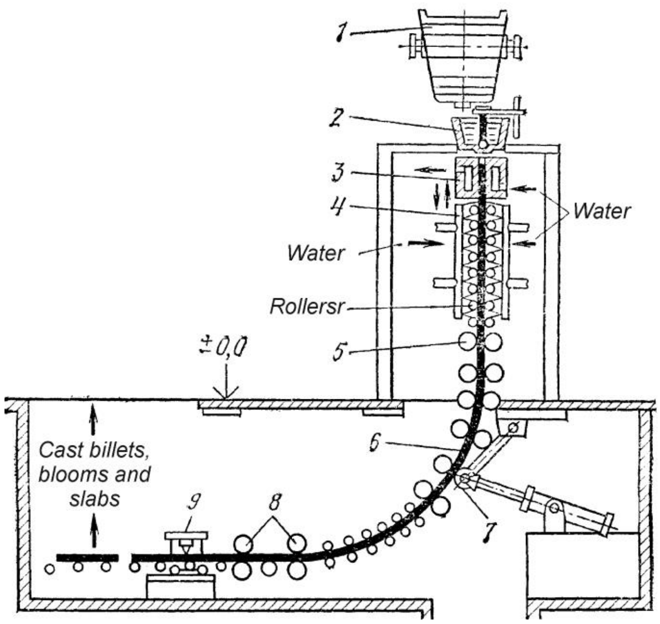


Fig. 4.2. Scheme of continuous billet casting machine:
1 – ladle with liquid metal; *2* – intermediate ladle with constant level of liquid metal; *3* – copper water-cooled crystallizer; *4* – secondary cooling system; *5* – supporting and pulling rollers; *6* – continuous cast billet; *7* – forming roller; *8* – straightening-pulling rollers; *9* – moveable device for billet cutting-to-length

The solid coating of the billet is being formed in crystallizer. Crystallizer is accomplishing alternate/reciprocal motions along the axis of the billet to avoid sticking of the coating to the inner surface of crystallizer. The dummy ingot together with solidified billet is pulled out of crystallizer by the pulling rollers *5*. The metal at the same time is passing the secondary cooling zone *4* where it is intensively cooled by water up to complete solidification along the whole section.

At present "S"-type continuous casters became widespread. Their total height is reduced due to the usage of crystallizer and secondary cooling zone bent along the arc of constant radius.

The machine is equipped by the corresponding devices for bending and further straightening of the billet. The billet is cut at the exit by movable device. Modern continuous casters have from two to four strands, that is the liquid steel is continuously being fed from the high capacity ladle to two-four crystallizers behind which the corresponding equipment is installed. The usage of multi-strand plants installed after high capacity steelmaking units (converters, high capacity electric-arc furnaces) increases significantly the efficiency of the process.

4.5. Shape and bar production

The types of section mills

Section shapes are conditionally divided into four groups depending on their size: large shapes, medium-size shapes, light shapes and rod. Consequently the mills producing these groups of shapes are divided into heavy section mills, medium section mills, light section mills, wire mills. Besides there are rail rolling mills, beam rolling mills or structural mills and strip rolling mills.

The main characteristic of section mills is the rolls diameter. As section mills are multi-stand one, as a rule it is accepted to indicate the diameter of the rolls in the last finishing stand after the name of the mill: for example, structural mill 850. The types of the mills and their approximate size range of general purpose shapes are given below.

1. *Structural mills D*=800÷850 mm. The following products are rolled at these mills:

- rails of the broad gauge P43, P50, P65, P75;
- flanged beams with the height 200÷600 mm (No. 20÷60);
- channel with the height 200÷400 mm (No. 20÷40);
- angles 180×180÷230×230 mm (No. 18÷23).

2. *Heavy section mills D*=600÷750 mm. The large shapes are rolled at these mills:

- rounds with diameter 50÷100 mm;
- square shapes 50×50÷100×100 mm;
- angle shapes 80×80÷200×200 mm;
- flanged beams with the height 120÷220 mm (No. 12÷22);
- channel with the height 120÷220 mm (No. 12÷22);
- mine rails P15, P18, P24, P33. The weight of one running meter is indicated by the figures;
- strip h=14÷50; b=100÷120 mm.

3. *Medium section mills D*=350÷500 mm. Medium size shapes are rolled at these mills:

- rounds with diameter 30÷75 mm;
- squares 30×30÷80×80 mm;
- angle shapes 40×40÷80×80 mm;
- flanged beams No. 10÷20;
- channel No. 5÷12;
- hexagonal steel 20÷75 mm (diameter of inscribed circle);
- strip h = 45÷60; b =6÷40 mm.

4. *Light section mills D*=250÷350 mm. Light sections are rolled at these mills.

- rounds with diameter 8÷40 mm;
- squares 8×8÷40×40 mm;
- angle shapes 20×20÷40×40 mm;
- reinforcing steel.

5. *Strip mills D*=300 mm. Strip with 2÷12 mm thickness and width 200-400 mm are rolled at these mills. The strips are the raw material for welded tubes production.

6. *Wire mills D*=150÷250 mm. The rods with diameter 5.5÷10 mm are rolled at these mills.

The fundamentals of the roll pass design

The cross section of the strip is called *the shape*.

Section shapes are produced by rolling in the rolls having on their working surface the cuts or fluting, which are called *grooves*. The grooves of two (three) rolls combined along the vertical axis are forming *the pass*. The strip section coming from the pass is taking the form of the pass (Fig. 4.3).

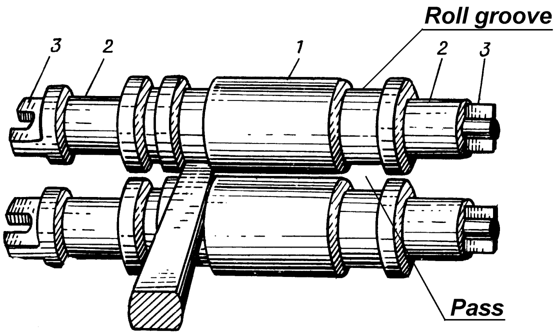


Fig. 4.3. Section roll:
1 – roll barrel; *2* – roll neck;
3 – wobbler

The choice of form and dimensions of the transition sections, consequence of their arrangement providing for obtaining the required shape from the given billet production during the rolling process is called *shape sizing* and the order of the chosen passes on the rolls arrangement is called *roll pass design.*

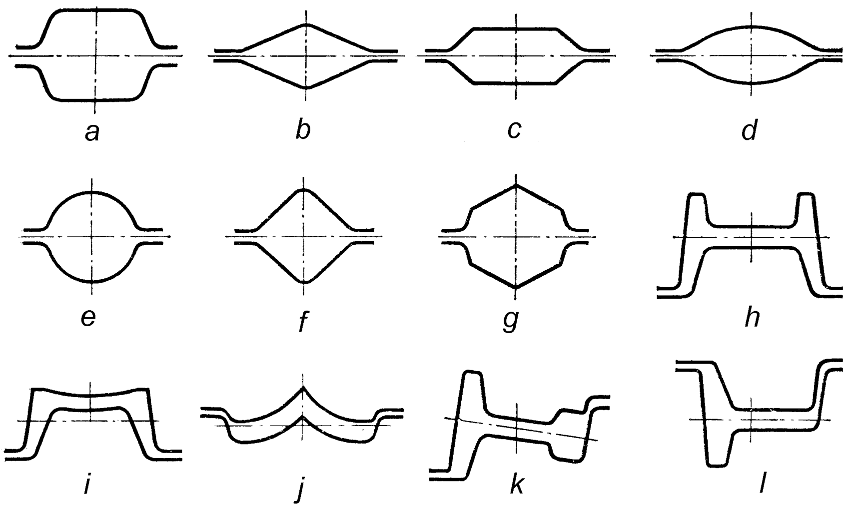


Fig. 4.4. Classification of the passes according with their shape: *standard shape*: *a* – box pass; *b* – diamond pass; *c* – hexagonal pass; *d* – oval pass; *e* – round pass; *f* – square pass; *g* – hexahedral pass; *flange shape*: *h* – beam pass; *i* – channel pass; *j* – angle pass; *k* – rail pass; *l* – tee form pass

The passes are classified according to their shape as *standard* and *flange* ones (Fig. 4.4).

The standard passes have the contour of simple geometrical figures. They have two symmetry axes: vertical and horizontal (Fig. 4.4, *a-g*). Flange shape passes have either one symmetry axis or may be completely non-central (Fig. 4.4, *h-l*).

The passes arrangement in the working rolls

The passes are classified as *open*, *closed*, *semi-closed* and *diagonal* according with their arrangement in the rolls (Fig. 4.5).

The horizontal gap between the rolls collars is situated within the limits of the pass height in open passes (Fig. 4.5, *a*); in the closed – the gap is situated out of the pass limits (Fig. 4.5, *b*); in semi-closed passes – closer to the basement or the top of the pass (Fig. 4.5, *c*); in diagonal passes the gaps between the collars are situated bias (Fig. 4.5, *d*).

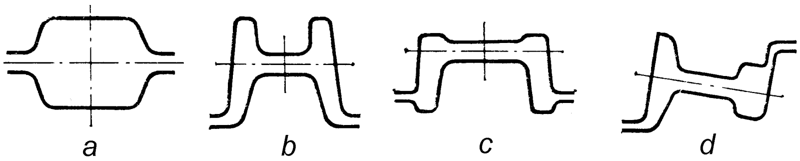


Fig. 4.5. Passes classification according with their arrangement in working rolls

Breakdown (stretching) passes are used for reduction of the cross section area of original ingot, bloom or billet for production of the billet for further forming of the required shape. These passes are used for rolling at blooms and billet mills and also during the first passes at section mills.

Uniting of alternate passes of one or two types is called *the pass system.* The name of the system includes the types of the alternate passes. The alternate passes of simple shape are used as breakdown (stretching) passes.

The following systems of passes are the most widespread ones: box (rectangular) passes (Fig. 4.6, *a*), diamond-square (Fig. 4.6, *b*), oval-square (Fig. 4.6, *c*), hexagon-square (Fig. 4.6, *d*), oval-vertical oval (Fig. 4.6, *e*).

The square or rectangular billet is produced after rolling in breakdown (stretching) passes; the cross section area of latter significantly (to 3-5 times) exceeds the area of the finished shape.

Pre-leader passes. As usual the section shapes are rolled of square or rectangular billet differing from the form of shaped section. Shaped section may be produced by means of consequent rolling of the billet in several passes in which the shape and sizes of the strip cross section are changing up to the finished shape.

The reduction of the area of cross section and stretching of the strip takes place in the pre-leader passes. The pre-leader passes are arranged after breakdown (stretching) passes at section mills.

Finishing pass is the last pass along the rolling process. The finished shape with the final geometry and sizes is coming out of it.

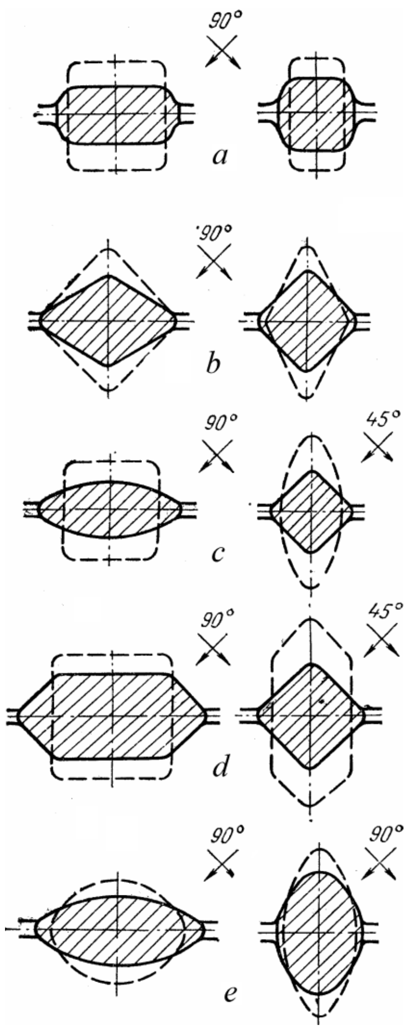


Fig. 4.6. The system of breakdown passes:
a – box (rectangular); *b* – diamond-square; *c* – oval-square; *d* – hexagon-square; *e* – oval-vertical oval

The last pre-leader pass previous to finishing pass is called pre-finishing or the leader pass. They differ regarding the shape and sizes from the finishing passes insignificantly. The degree of the finishing pass filling and the size of the finished shape depend on the shape and the sizes of pre-finishing pass. The arrangement of the listed types of passes in the general scheme of the passes is given on Fig. 4.7 by the example of angle shape rolling.

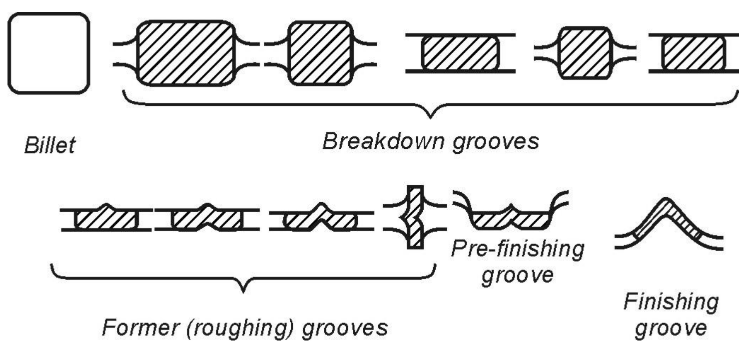


Fig. 4.7. Scheme of the angle steel rolling

Shapes production

The special rail-beam (structural) mills are used for rolling of the rails of the broad gauge P43, P50, P65, P75, heavy beams No. 20÷60 and channel No. 20÷40.

The working stands are arranged in two lines. The cogging stand, the reversing one, the two-roll stand with rolls diameter 950 mm (small bloom) are situated on the first line. Two roughing stands and three-high stands with common roll drive from one motor and one finishing two-roll irreversible stand with individual roll drive are situated on the second line.

The blooms with section 250×250-320×320 mm are used for rail rolling which are heated up to the temperature 1180-1200ºC in continuous furnaces. The heated blooms are rolled in reversing stand for 5-7 passes in box and channel passes. After that the unrolled metal (process work–piece) is continuously rolling in the first and second roughing three-high stands with rail passes. The last pass is being accomplished in the finishing pass (Fig. 4.8).

The first four passes are called *tee-shape* ones. The rail flange is being formed in them during the rolling of rectangular billet. The process work-piece after tee-shape passes comes to so-called slitting rail pass (the fifth on Fig. 4.8). The elements of the rail are being formed out of tee-shape section in the slitting pass, namely head, neck and flange. After the slitting pass

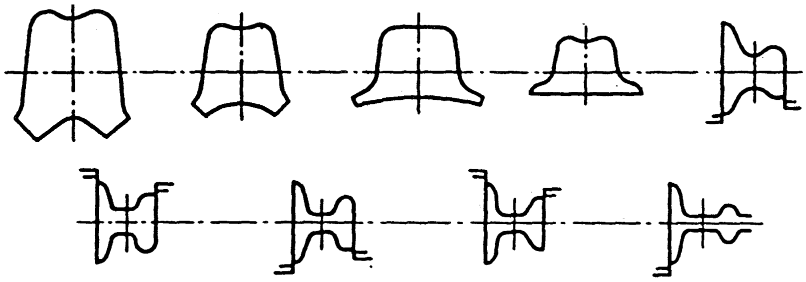


Fig. 4.8. The sizing scheme for rails rolling

the rolling is going in the pre-leader rail passes (6th, 7th and 8th) where the gradual rail forming takes place. The last pass along the flow of the rolling is called finishing one. The finished 75 m rail comes from it. The rail is being cut by the shuttle saws (*6*) to 25 m measured lengths. After that the rails are marked, and then they are bent for flange to reduce the warp during cooling on the cooler. In case the rails are not bent previously it might happen that they will be bent for the head after cooling.

The rails are taken from the cooler at 600ºC and sent to isothermal furnaces where they are kept for 2 hours at 600ºC for prevention of flakes appearance which are the main defect during the process of rail manufacturing. After getting cold the rails are entering the rail finishing department where they are straightened at roller straightening machines and presses, and the rails ends are milled. Three holes from each end of the rail are drilled for their joining. To increase the wear resistance of the rail head it is quenched. The quenching of the rail ends and the volumetric quenching is used.

The universal stand is installed instead of finishing two-high stand for rolling of beams and channels.

Flanged beams No. 10÷20, channels No. 10-20, equal-sided angle steel No. 8-16, L-bars No. 8/5-8/11, round with diameter 50-120 mm, square 50-100 mm, strips with thickness 14-50 mm and width 100-200 mm, steel mine timbering 18A, 18B, 28A and 28B, the rails of narrow gauge and other shapes are produced at *semi-continuous large section mill 600*.

The mill consists of 17 working stands arranged in three parallel lines. There are two groups of continuous stands in the first line between which the conveyer roller-hearth maintaining furnace is installed. The stands are arranged continuously in-line at the distance enough for the process work-piece placing in the second and third lines. The transfer of the process work–piece between the lines is accomplished by transfer mechanism. The last 17th stand used for beams and channels rolling may be replaced with universal stand.

The raw material is bloom with 300×300 mm section, length from 5.5 up to 6 m produced at bloom 1150. Three heating furnaces with capacity 110-120 tons per hour each are used for bloom heating.

The installations for hydraulic and steam de-scaling are provided for ensuring the good surface of the finished sections. The turners are installed before the stands, the hot shears with the cutter load of 8 MN for dividing the process work–pieces into parts are installed behind the conveyer furnace.

All stands are being set in motion from the individual engines. The speed of the process work-piece exit out of the last stand is 10 m/sec. One stationary and nine movable drop saws with discs having diameter 1800 mm are installed for shearing the finished strip to lengths from 6 up to 24 m.

After cutting the strips are being fed to the coolers. There are altogether four coolers located in pairs with the length 44 m and width 24 m each. Each cooler at the width consists of two sections with the length 12 m, which can work conjointly or independently of one another.

Four lines of cold finishing section are connected between themselves by roll-tables. Each line is equipped by movable straightening machine, cold saw, rope transfers, section stackers and other machines providing for the complete mechanization of finishing, handling and packing the finished products.

Semi-continuous medium-section mill 350 consists of 15 two-high stands located in three parallel lines. 10 stands are installed in the first line. The first stand is installed separately, it is followed by the first six-stand group including three horizontal and three vertical stands. The first group is followed by the second three-stand continuous group, the intermediate stand has the vertical rolls.

Crank drop flying shears are installed at the exit from the first continuous group for cutting the process work-piece's leading end before feeding into the second continuous group. The process work-piece is tilted before feeding. Two separately standing horizontal stands are installed in the second line; the third continuous group of stands is installed in the third line, the first stand is vertical, the others are horizontal. The billets with 150×150, 160×160 mm section are being heated in four continuous furnaces with end fit and discharge. The shears are installed in front of the first stand for cutting the leading end in case of need and dividing the billet in half. The strip is delivered from one line to another along the repeaters during the process of rolling.

The maximum speed of rolling in the last stand is 15 m/sec. The process work-piece is being cut into parts by flying shears after rolling according to the length of cooler. The finished steel is moving along the roll-table and is directed with the help of regulating mechanism to one or another side of the double racking type cooling bed, it is straightened then and cut to measured lengths. Shaped and large sections are cut by profiling tool or by saws. The following sections are rolled at the mill: round 35-65 mm steel, rebars No. 36, 40, angle steel equilateral and non-equilateral with the length of flange from 45 up to 90 mm, flanged beams and channels No. 10.

Double-strand small-section mill 250 (Fig. 4.9) includes the continuous seven-stand roughing group (*7*) equipped by horizontal duo-stands and two continuous finishing groups of stands (*9*), consisting of eight alternate stands each – vertical and horizontal duo. The mill is equipped by safety flying shears located in front of the roughing group (*6*) and behind it (*8*) for cutting the process work-piece's leading end and safety shear for the process work-piece cutting during the buckling in the finishing group. The flying shears (*10*) for dividing the process work-piece into lengths corresponding to the length of the cooler (125 m) are installed in each line behind the finishing groups.

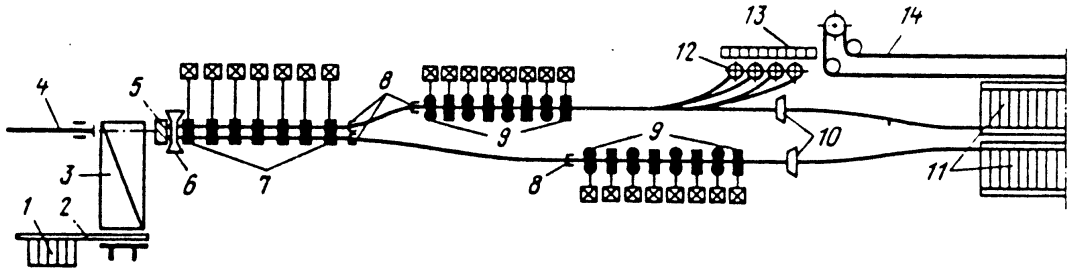


Fig. 4.9. Layout of continuous small-section mill 250:
1 – charging grid; *2* – inlet roll-table; *3* – heating furnace; *4* – pusher; *5* – distributing device; *6* – shears; *7* – roughing group of stands; *8* – flying shears; *9* – finishing groups of stands; *10* – cooler; *12* – reels (coilers); *13* – coil transporter; *14* – coil conveyor

In the roughing group of stands the rolling is realized in two strands (two billets) simultaneously. One strand (one billet) is rolled in each finishing group.

80×80 mm section and 5-11.7 m length billet is heated in continuous furnace with side loading and unloading. Distributing device delivers the billets unloaded from the furnace in turn along two parallel lines of rolling into the roughing group. It is possible to accomplish two technological schemes of cooling and finishing. The first scheme is the *work to the reels* with winding of round sections with diameter 18-20 mm in four reels (*12*). The wound coil is pushed to the transporter (*13*), then it is delivered to the hook conveyor (*14*) for cooling, after that the coil is bundled and delivered to the stock of the finished products by means of stripper and bundling machine. The second scheme is the *work to cooler*. In this case the process work–piece is cut to lengths corresponding to the cooler length after finishing stand and is delivered to two-sided cooler (*11*). The cooled strips are straightened on straightening machines, they are cut then by cold sheares to measured lengths, gathered and bundled.

The round 10-24 mm steel, 16 mm square steel, angle steel with flange 25-40 mm and strip steel is rolled at this mill.

Wire mills

The rods are rolled to the large mass coils from 200×200 mm section billet with the speed up to 100 m/sec. at modern wire mills with capacity up to 1 million tons per year. These speeds are possible due to the usage of finishing and pre-finishing units including from four to ten (arranged with 120º angle to each other) three-roll or two-roll stands. The rolls having the overhanging discs type with diameter 150 mm are made of tungsten carbide. The discs are arranged with the 45º angle to the horizontal line and the axis of each next pair of discs – with the 90º angle to the previous axis.

The continuous wire mill 150 is used for rolling rods of high carbon and alloyed steel in coils with mass equal to 2 tons (Fig. 4.10).

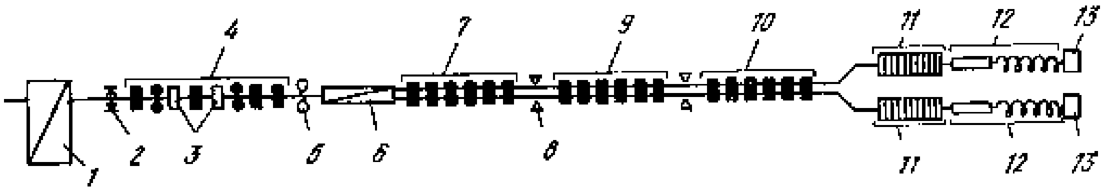


Fig. 4.10. Layout of continuous wire mill 150:
1 – walking beam heating furnace; *2* – scarfing machine; *3* – thermo-milling machine; *4* – cogging group of stands; *5* – flying shears; *6* – duplex roller furnace; *7* – break-down group of stands; *8* – shears; *9, 10* – the first and the second intermediate groups of stands; *11* – finishing stand blocks; *12* – two-stage cooling devices; *13* – wire wraps collectors and coil compactors

The incoming billet with 200×200 mm section is rolled after heating in walking beam furnace in cogging group of stands where the scarfing is made by two thermo-milling machines from four sides. The process work-piece after heating in pusher-type duplex-roller furnace up to 1200ºC is rolled in two strands in break-down and the first intermediate group and in one strand in two second intermediate groups and two finishing blocks (ten stand ones). The speed at the exit is equal to 60 m/sec. The rods are passed two-stage cooling. The process work-piece is cooled in tubes by high pressure water (2 MPa) up to 630ºC at the first stage. The process work-piece is laid by special device named laying head on the traveling conveyer in the form of the loose-wounded strands by means of tube carrier (Fig. 4.11).

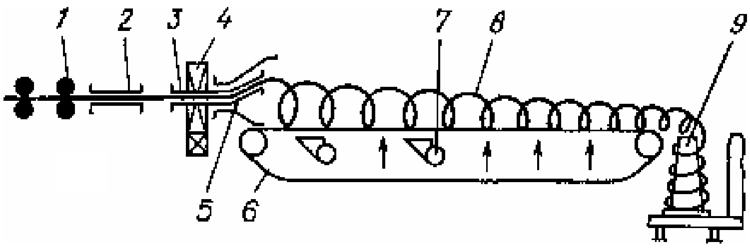


Fig. 4.11. Layout of two-stage regulated rod cooling device:
1 – last finishing stands of the wire mill; *2* – tubes for water cooling of rod; *3* – conductor pipe; *4* – the drive of tube carrier rotation; *5* – tube carrier; *6* – transporter; *7* – ventilator; *8* – scattered coil annular wraps of the hot rod; *9* – cone plugs on the turn-table for coil forming

At the end of transporter the rod cooled up to 300ºC is delivered to the coils packer where the laps are gathered again into the coil, which is compressed by hydraulic press and delivered to the finger conveyer.

At present the new rolling mills have been produced with the rolling speed up to 120 m/sec.

4.6. Sheet production

Classification of the sheet rolled products

All the sheet rolled products are divided depending on the thickness into two main categories: thick plates with thickness 4 mm and more; thin sheets with thickness less than 4 mm.

The sheet rolled products are classified according to many features.

Depending on the width of plates:

- wide strip with 600-700 mm width and more. Maximum width of the rolled strip is 2300-2500 mm. The mills where the wide strip is rolled are called *wide strip rolling mills*;
- narrow strip with less than 600-700 mm width. Strip with the width less than 300 mm is called *band*.

Depending on the chemical composition the following steels are distinguished:

- carbon steels: low-carbon (C up to 0.3%); medium-carbon steels (C up to 0.6%); high-carbon steels (C up to 1.5%);
- alloyed steels (the alloying components are Cr, Si, Ni, Mn, Mo, V); low-alloyed ones with alloying components (up to 4%); medium-alloyed (up to 10%); high-alloyed (up to 45%).

Regarding the purpose steels are classified as follows:

- structural steels (carbon and low-alloyed);
- corrosion-resistant (stainless) steels. They have a great content of Cr and Ni or only Cr in their composition;
- electric steels(dynamo and transformer). They have a great content of Si (1.0-3.5%) and very low content of C (less than 0.01%). Electromagnetic properties of these steels are improved due to increase of Si content and decrease of C content.

Regarding the methods of rolling they are distinguished as follows:

- hot rolling of plates;
- hot rolling of sheets and strips;
- cold rolling of thin strips.

Production of plates

The following products are produced at plate mills:

- plates with thickness h=4-50 mm; width b=200-1050 mm; length l=5-18 m;

- plates (armor) with thickness h=50-380 mm; width b=600-5000 mm; length up to 28 m.

The plates with h=50-380 mm are rolled of flat square ingots. The mass of ingots may exceed 100-250 t.

The sheets with the thickness less than 50 mm are rolled of slabs. Slab is the flat rectangular section ingot with ratio of width and thickness b/h=3-12.

Slabs may be rolled and cast at continuous casting machine. Rolled slabs are produced by rolling at cogging mills – slabs or blooms. The thickness of the rolled slabs is h=100-300, width b=600-2500 mm, length l=1.5-14 m. The mass of slab exceeds 10-14 t.

Slabs with thickness h=80-250 mm are cast at continuous casting machine. Casting at continuous casting machine is considered to be the most contemporary method of slab production.

Replacement of slabs with continuous casting machines decreases the production price up to 8%, increases the efficiency up to 7-8% and metal yield on average up to 8-12% for carbon steels and up to 15-20% for alloyed steels.

The types of mills for plates rolling

Two types of mills are used: one-stand and two-stand mills.

One-stand mills. Reversible four-roll mills are considered to be modern ones. They have two working rolls and two backup rolls, which diameter is greater than that of working ones. The backup rolls decrease the bending of the working rolls. Four-roll mills are called quarto mills.

The maximum size of the working rolls at these mills is $D_{w.r}$=1200-1400 mm, backup rolls $D_{b.r}$=2000-2400 mm. The rolls barrel length is up to L_b=5500 mm. One-stand mills are used for rolling sheets and plates with thickness h=20-250 mm and width up to 5500 mm.

Two-stand mills with in-line arrangement of stands. The distance between the working stands is greater than the length of the process work-piece coming from the first stand with in-line arrangement of stands. The first stand along the rolling direction is called *a break-down* one and the second is called the finishing one.

Reversible two-roll stands (duo-stands) or reversing four-roll stands (quarto-stands) are used as the break-down stands at modern two-stand mills.

Reversible stands quarto or reversing universal quarto stands are used as finishing stands. The universal working stands have horizontal rolls as well as vertical arranged rolls, which are used for cogging the sheet edges.

The biggest two-stand mills have the quarto stands with working rolls $D_{w.r.}$=1000-1200 mm, backup rolls $D_{b.r}$=2000-2200 mm and the roll barrel length up to L_b=4800 mm.

Two-stand mills have the higher efficiency and the better quality of surface if to compare with one-stand mills. The stand with vertical rolls $D_{v.r.}$=900-1100 mm is installed at plate mills (one- and two-stand mills) in front of the first working stand. This stand is used as de-scaling mill for removing the furnace scale from the surface of slab (ingot). The scale is loosened and then it is removed by water descaling.

Technological operations during plates rolling

Technological process includes the following main operations.

Preparation of ingots or slabs for rolling. It includes inspection of the surface and removing of surface defects (skins, blisters, cracks, non-metallic inclusions etc.).

Heating of slabs and ingots. Slabs and small ingots are heated in continuous furnaces with the walking beams. The large ingots are heated in chamber traveling-hearth furnaces. The temperature of heating before rolling depends upon the chemical composition of the metal and amounts as usual to 1150-1280ºC. The heated slabs (ingots) are delivered to the roll-table one by one and transported to the mill for rolling.

Descaling of the slab (ingot) surface before rolling. The scale breaker with vertical rolls is installed with this purpose in front of the mill (one-stand or two-stand). The heated slab comes first to scale breaker. The scale is loosened due to the side cogging and its removing from the surface is made easier with water jet under the high pressure (water descaling). Unevenness of slab width and side taper of ingot is eliminated simultaneously.

Rolling. All breakdown and finishing passes are accomplished in one stand at one-stand mill. The total quantity of passes has to be odd. The process work-piece is returned to the scale breaker after the second and the fourth passes for removing the side camber by the vertical scale breaker rolls. Two slabs are being rolled simultaneously at two-stand mills: one in breakdown stand and the second in finishing stand. Slab is rolled first in breakdown stand. The process work-piece is returned to the scale breaker after the second and the fourth passes for removing the the side camber. The number of passes in breakdown stand amounts to 5-11. The process work-piece is delivered to the finishing stand for further rolling after finishing of rolling in the breakdown stand. The next slab is fed to the breakdown stand at the same time. The further rolling is going on simultaneously in breakdown and finishing stands. The number of passes in finishing stand amounts to 5-9. The regime of deformation in breakdown and finishing stands is calculated in such a way that the time of rolling in these stands would be equal. In this case the efficiency will be higher.

The straightening of the sheets. The sheets are straightened in the hot state at the surface temperature equal to 700-750ºC at roller straightening machines (7-13 rollers). The sheets with thickness more than 50 mm are straightened in the cold condition at hydraulic presses.

Cooling of sheets and their lay-out. The sheets are cooled after straightening on the coolers of the following types: roller one with washers, with walking beams, link-and chain transfer type.

The inspection of the sheet surface from two sides takes place after cooling on the inspection tables where the uncovered surface defects are marked for their further removing.

The layout of the sheet is being made from all four sides.

Cutting of the sheets. The cutting of the leading end and sheet trailer with thickness of sheets from 25 to 50 mm is accomplished at guillotine shears (cutting to length). Side-lay edges are cut at guillotine shears also (longitudinal cutting). The strip ends cutting is accomplished by guillotine shears for strip cutting to length with thickness up to 25 mm. The edges are cut by circular shears. The plates are cut by flame cutter.

Heat treatment of the sheets. It is made for metal structure and mechanical properties improvement. The following kinds of treatment are used: normalization, annealing, tempering, temper hardening. The sheets are straightened in cold condition after heat treatment.

Production of sheets at two-stand plate mill 2800

The length of the roll barrel is the main characteristics of the plate mills. The figures (number) following the name of the mill indicate the length of the rolls barrel. Thus the name "plate mill 2800" indicates that this mill has the length of the roll barrel equal to 2800 mm.

The layout of equipment of two-stand plate mill 2800 is given on Fig. 4.12.

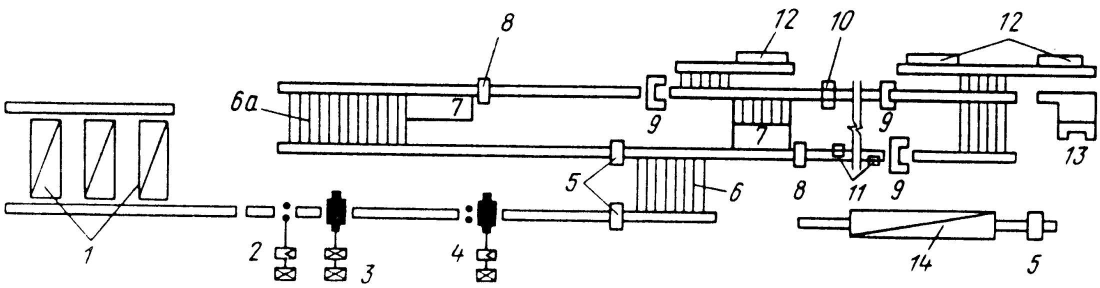


Fig. 4.12. The typical layout of two-stand plate mill 2800: *1* – continuous heating furnaces; *2* – stand with vertical rolls; *3* – breakdown reversing stand duo; *4* – finishing reversing universal stand quarto; *5* – roller-straightening machines; *6, 6a* – cooling tables; *7* – inspection tables with tilter; *8* – dimensioning trolleys; *9* – guillotine shears of cutting to length; *10, 11* – circular guillotine shears; *12* – gathering pockets; *13* – separate standing guillotine shears; *14* – heat treatment furnace for plates

The mill is used for rolling plates with thickness 4-50 mm, width up to 2500 mm, length up to 20 m.

The starting ingot for plate rolling is a slab with thickness 125-250 mm, width 700-1600 mm, length 2500-6000 mm.

Slabs are heated in three continuous furnaces *1*. The rolling mill includes the rough scale breaker with vertical rolls *2*, the roughing two-roll stand *3* and finishing universal four-roll stand *4* (quarto stand). All stands are reversing ones. The roll dimensions are as follows: in stand *2* D=950-1000 mm, the length of the roll barrel L_b=600 mm; in roughing duo stand *3* D=1100 mm, L_b=2800 mm; in finishing universal stand *4* the diameter of the working rolls is $D_{w.r}$=800 mm, the diameter of backup rolls is $L_{b.r}$=1400 mm, the length of the rolls barrel is L_b=2800 mm.

The slabs heated in the furnace are delivered by the roller table to the scale breaker. Slab is rolled first in rougher for several passes and then in finishing stand. The quench is installed after the finishing stand for cooling plates by air-water mixture for obtaining the fine grain structure of the metal and high mechanical properties. After rolling plates are straightened in roller straightening machines *5*. The first straightening machine is used for hot straightening of sheets with thickness from 4 to 25 mm, the second one is used for straightening of sheets with thickness 25-50 mm.

Sheets cooled on the cooler *6* sheets are delivered to the second technological line of the mill and then through the cooler *6a* – to the third line. The sheets are inspected here on inspection table *7* and laid by means of special trolley *8*. Cutting of sheets to length takes place on guillotine shears *9* and the side trimming – on the circular shears *10*.

The side trimming of rolled sheets with the thickness more than 25 mm is made on longitudinally arranged guillotine shears *11*; with this purpose sheets are delivered from the third line back to the second line. The finished sheets are gathered in the pockets *12*.

The additional cutting may be arranged at separate standing shears *13*. The furnace *14* is used for heat treatment of the products.

Hot rolling of the light sheet steel

At present 50-70% of light sheet steel is produced at strip rolling mills. The products manufactured at continuous mills are characterized by high quality of the surface and high precision. The annual capacity of continuous wide-strip hot rolling mills exceeds 4.0-6.0 million tons.

Due to the high efficiency and high level of mechanization and automation the finished product price is significantly lower than the price of products produced at the other strip mills.

Continuous wide-strip mill 2000

The layout of the modern continuous wide-strip mill 2000 is given on Fig. 4.13.

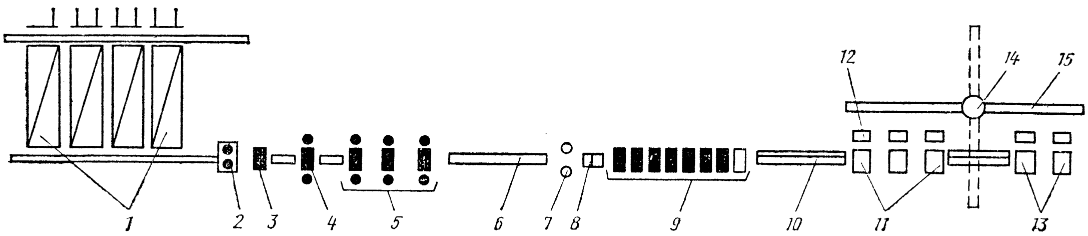


Fig. 4.13. Layout of continuous wide strip mill 2000: *1* – heating furnaces; *2-5* – working roughing stands; *2* – vertical roughing two-roll stand scale breaker; *3* – two-roll stand; *4* – universal four-roll stand; *5* – continuous three-stand sub-group of universal four-roll stands; *6* – intermediate roller table; *7* – flying drum-type shears; *8* – the finishing scale breaker; *9* – continuous finishing group; *10* – collecting quenching roller tables; *11* – 1.2-4 mm strip reels; *12* – trolley with coil tilter; *13* – 4-16 mm strip reels; *14* – rotary table for coils; *15* – coils conveyer

The mill is used for rolling the coiled steel strip with thickness 1.2-16 mm and width 1000-1850 mm. The cast and rolled slabs with thickness up to 300 mm, length up to 10.5 m and mass 15-20 t of carbon and low-alloyed steels are used as the raw material. All stands of the mill are divided into two groups: roughing (stands 3-5) and finishing continuous (stands 9).

The roughing group consists of one stand with horizontal rolls *3* and four universal stands with horizontal rolls with diameter $L_{h.r}$=1600 mm and vertical rolls with diameter $D_{v.r}$=1000 mm (stands *4* and *5*). The feature of this mill is the fact that the last three stands are combined into continuous sub-group *5* in the finishing group. It has permitted to decrease the length and to improve the temperature regime of rolling due to decrease of heat loss.

The continuous finishing group *9* includes seven four-roll stands (quarto stands) with diameter of the working rolls equal to $D_{w.r}$=800 mm and backup rolls $D_{b.r}$=1600 mm. The roughing scale breaker *2*, which provides for the primary breaking of the furnace scale and formation of the precise dimensions of slab regarding the width is installed in front of the first stand of the roughing group. The loosened scale is removed by hydraulic scaling under the pressure of 15 MPa from the slab surface.

Slabs are heated before rolling in four continuous walking beam furnaces up to the 1150-1280ºC.

The heated slab is pushed out of the furnace and is delivered by the roller-table in the roughing scale breaker and than to the stands of the roughing group. Vertical rolls of the universal stands are cogging the side edges of the strip avoiding the formation of the side camber and as the result the damage of the sheet edges during the rolling. After roughing group the strip with the thickness 30-50 mm is delivered by the intermediate roller table *6* to the finishing group. In front of the finishing group the flying shears *7* are installed intended for cutting the leading end and the strip trailer as well as the roller finishing scale breaker *8*, which is loosens the air scale and by water jets under high pressure water jets removes it from the process work-piece surface.

The temperature of the metal at approaching of the process work-piece to the finishing group is as usual 1050-1100ºC and it is 850-950ºC at the exit from the last finishing stand. The strips are intensively cooled up to the 600-650ºC by quenching in the area from the finishing stand to the reel to reduce the temperature of the strip during the reeling and to improve the metal structure of the strip coiled on one of fifth roller-drum reels. The strip with thickness 1.2-4.0 mm is coiled on the reels *11* and 4-16 mm strip is coiled on the reels *13*.

The coiled strip is delivered for rolling to the shop of cold rolling or to the finishing, which includes the unrolling of the coils, cutting to length for separate sheets and stacking or slitting of strip to separate bands, which are coiled into the bundles.

Foundry-rolling complexes (units)

The success in production of modern continuous casting machines (CCM) with high level of automation and managing together with the achievements in smelting of fine steel, avoiding its dirt during the continuous casting as well as metal defects during crystallization has permitted to deliver the cast billet without inspection to the continuous mill (direct rolling) retaining the casting heat. The possibility of combination of continuous casting and hot rolling into one unit called foundry-rolling complex (FRC) has appeared.

The main complexity in creation of FRC is concluded in the power difference of CCM and rolling mill. FRC for production of light hot rolled strip of continuous cast slabs obtained the industrial development.

The main technological schemes of FRC for production of hot rolled strip is given on Fig. 4.14.

The technology of the sheet production from thick slabs is presented on Fig. 4.14, *a*. Slabs after casting on CCM are cut by shears *2* and delivered after quality inspection to the heating furnace of the rolling mill. In this case the heat of the hot fit of slabs is partially used. The cutting of the slab strip after casting permits to run the process of casting and rolling of slabs independently. This scheme is similar to the standard scheme of sheet production at continuous wide-strip rolling mill.

FRC with the light slab technology of light hot rolled strip production (CSP process) is given on Fig. 4.14, *b*. The casting of light slabs (with thickness 50-90 mm) permitted to increase

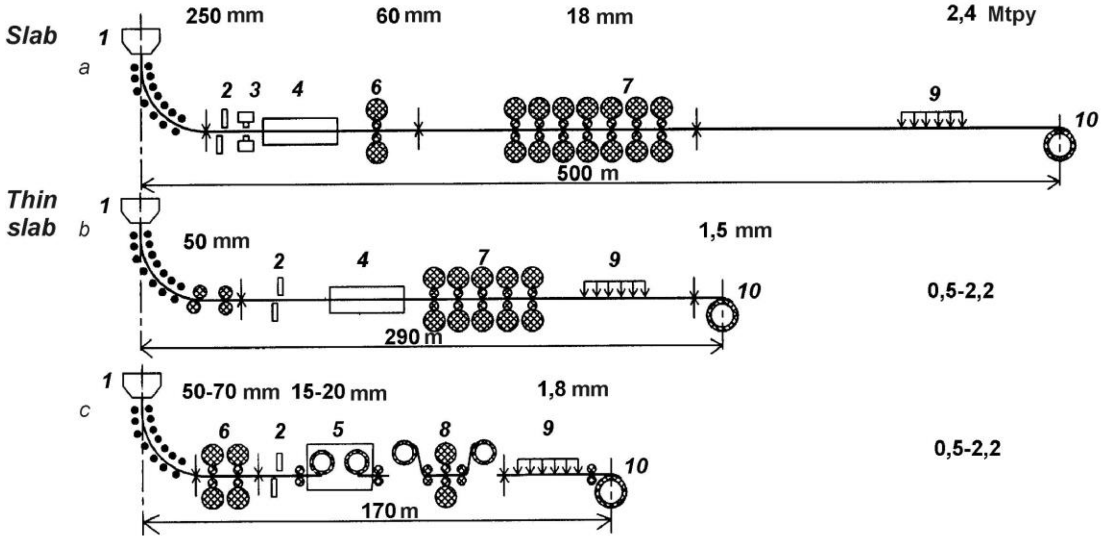


Fig. 4.14. The development of the technological schemes of FRC for production of flat hot rolled strip:
a – slab technology; *b*, *c* – light slab technologies, CSP and ISP accordingly; *1* – CCM; *2* – shears; *3* – quality inspection; *4* – furnace; *5* – coil box; *6* – roughing mill; *7* – continuous mill; *8* – Steckel mill; *9* – cooling device; *10* – reel

the casting speed and to reduce significantly the number of stands in the line of the rolling mill excluding or significantly decreasing the number of stands in roughing group. The process of casting and rolling are being accomplished in uniform technological line. The slab strips are delivered for heating into the long (up to 200 m) tunnel oven *4* after cutting by shears *2*. This oven is the buffer between the CCM and rolling mill presenting the continuous finishing group of stands.

The feature of the scheme given on Fig. 4.14, c (ISP technology) is the casting of the light sheet slab using the cogging of ingot with the liquid core in roller guides of CCM as well as in roughing stands quarto (2-3 stands) installed just at the exit of CCM. It permits to produce the strip with thickness 15-20 mm, which is being reeled into coil by the reel in reheating furnace *5* (coil-box). The following rolling permits to produce thin hot rolled strip in the finishing group of stands *7* or at Steckel mill *8*.

The usage of the processes of the direct strip casting causes great changes in production of hot- and cold rolled strip.

The scheme of steel pouring into the rolls located under the pouring ladle is given on Fig. 4.15. The liquid steel contacting the cooled rolls is crystallizing. The cogging of the metal takes place in two-phase state (soft cogging) that is the continuous casting is combined with the rolling within one unit. Run-out of the melt from the ends of the roll is prevented by the side seals. The fast consolidation during the strip casting decreases micro-segregation and provides for more fine distribution of inclusions, as the result the quality of the metal is improved.

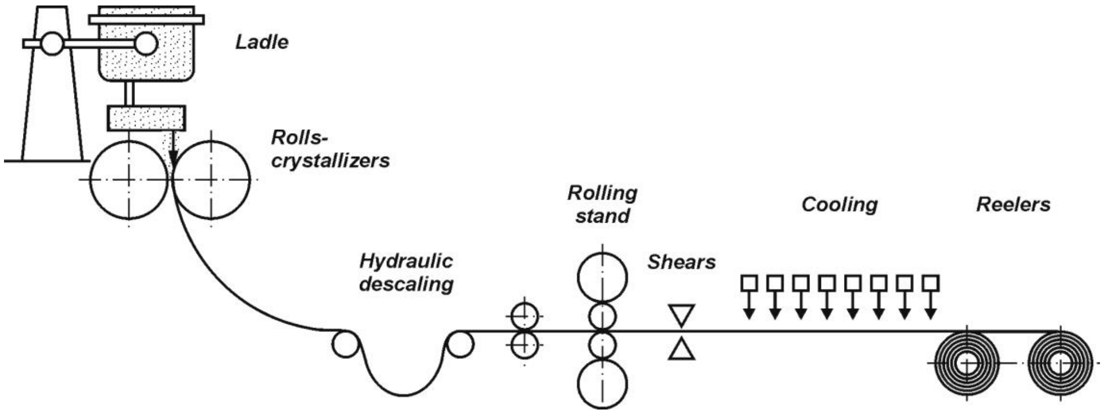


Fig. 4.15. Layout of the roll type foundry-rolling unit

The thickness of strip is usually 1.5-5.0 mm at this method of casting. The strip is run-out of the rolls with the temperature about 1300ºC. The in-line installation of the rolling stands for production of especially thin strip is possible. The short length, the moderate investments and production flexibility are the most important advantages of two-roll casting-rolling units.

Cold rolling of thin strip and sheets

The process of cold rolling is more power-consuming if to compare with the hot rolling process. The metal is being hardened, becomes hard-to-deform during the cold rolling and requires the additional energy consumption for restoration of plastic properties, that is for accomplishing of annealing.

Besides the technological process of cold rolling is more complicated in comparison with the hot rolling and includes the whole series of additional operations requiring the usage of complex and various equipment such as continuous pickling lines, annealing devices for metal hardening, tempering mills, shearing units for sheets and strip, units for protective coating application etc.

However the cold rolling has many advantages if to compare with the hot rolling:

- the possibility to produce thin and especially thin strip and sheets with thickness less than 0.8-1.8 mm up to several microns 0.002-0.003 mm;
- high quality of the surface of strip and sheets, high precision of geometry. It is possible to produce by the process of cold rolling the sheets with any degree of roughness from mate to mirror due to the special treatment of the rolls surface;
- the possibility to produce cold rolled strip with required physical-mechanical properties.

The wide usage of cold rolling was determined by these advantages.

At present the share of cold rolled sheets in the total mass of thin sheets amounts to 50% approximately. The following goods are produced by cold rolling: automobile sheets with thickness 0.25-2.5 mm; sheet iron with thickness 0.38-0.80 mm; tin with thickness 0.16-0.36 mm; foil with thickness 0.001-0.005 mm as well as the rolling of corrosion resistant (stainless) steel and electric steel – dynamo steel and transformer steel.

The range of cold rolled sheet products is as follows: sheets with thickness 0.2-0.4 mm, width – 510-2300 mm, length from 1200 up to 5000 mm; strip in coils with thickness 0.2-4.0 mm, width – from 200 up to 2300 mm; bands in coils with thickness 0.05-3.6 mm and width up to 600 mm.

The types of mills for cold rolling of thin strip and sheets

Two types of mills are used:

- one-stand reversing mills with 4-6-12-20-32 rolls number;

▪ continuous mills with 4-5-6 stand number.

One-stand multi-roll reversing mills are used for rolling of small lots of wide range sheets especially of hard-to-deform steel grades. The mills setting is simple, the rolling may be accomplished with any number of passes. The quarto mills and 20-roll mills are mostly often used in ferrous industry.

Two methods of rolling are used at one-stand mill. The rolling per sheet is accomplished in quarto stand. The initial ingot is the hot rolled pickled sheet with thickness 3-10.5 mm; the final thickness of the rolled sheets is up to 1.5 mm.

The rolling of coiled strip is accomplished at 20-roll mills with working rolls diameter $D_{w.r.}$=3-150 mm and the length of the barrel L_b=60-1700 mm.

The thin strip with the thickness 0.57-0.60 mm and width up to 1700 mm is included to the range of these mills. The initial billet is pickled hot rolled coil strip with thickness 3-4 mm. The initial billet for rolling the bands with thickness 0.002-0.10 mm is cold rolled strip with thickness 0.03-1.0 mm passed the bright annealing.

One-stand reversible mills are equipped by reels from the front and back side. The rolling is being accomplished for several passes rewinding the strip from one reel to another with high tensions of the strip between the reels and the working stand with compulsory use of technological lubricants for reduction of influence of friction forces on the rolling force. The scheme of 20-roll mill of cold strip rolling is given on Fig. 4.16.

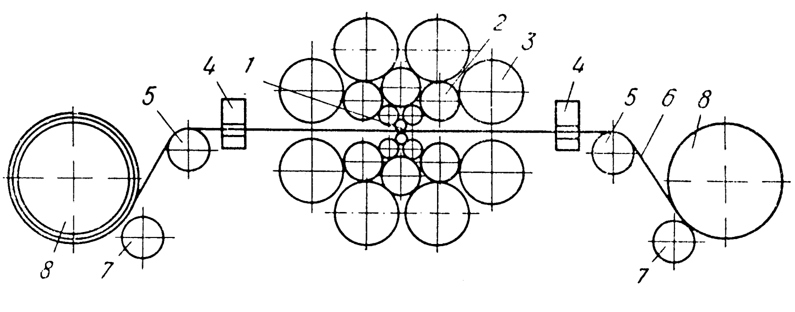


Fig. 4.16. Layout of 20-roll mill for cold strip rolling: *1* – working rolls; *2* and *3* – intermediate and backup rolls; *4* – strip thickness gauge; *5* and *7* – tension devices; *6* – strip; *8* – reels' drums

The mill has only two working rolls deforming the strip. The rest of the rolls are backup ones and are used for reduction of the working rolls bend. The continuous mills for cold rolling of thin strip are used for production of large volumes of relatively small strip range. The modern continuous mills consist of 5-6 irreversible stands quarto and the strip is located in all stands simultaneously. Only one pass is accomplished in each stand. Continuous mills are supplied with de-coiler on the front and the reel at the back side.

Hot rolled coils pickled in advance with lubricated surface serve as the strip plate for continuous cold rolling mills. Hot rolled coil strip is received from the continuous wide-strip hot rolling mills. The thickness of the strip plate is 2-6 mm depending on the thickness of the finished product.

The great pressure of metal on the rolls during the cold rolling originates due to the metal hardening in the process of deformation and a great influence of outside friction forces. The cold rolling of the coil strip is being accomplished with significant tension of the strip between the stands and between the last stand and the reel with compulsory usage of technological lubricants. The strip tension provides for significant reduction of metal pressure on the rolls and permits to roll the strip with high reductions per each pass and contributes to tight reeling of the strip on the reel and its steady position between the rolls, the strip is not displaced along the roll barrel. The usage of technological lubricants causes the reduction of the influence of the friction forces and reduction of the metal pressure on the rolls.

The strip with thickness 0.2-3.5 mm is rolled at 5-stand continuous mills and strip with thickness 0.18-1.0 is rolled at 6-stand mills. The width of the strip rolled at these mills is up to 1200 mm.

Two methods of rolling are used at continuous mills: individual coil rolling and endless rolling of coil strip. The pickled hot rolled coils are delivered from stock by crane to the conveyer in front of cold rolling mill and after that one after another the coils are delivered to the decoiler at individual coil rolling. The arm with electromagnet is going down, the magnet is drawing the end of the strip, lifts it and deliver to the feed rollers. These rollers are feeding the strip further into the threading guide, which is blocking it and feeding into the rolls of the first stand.

The process of rolling is starting at slow leading-in speed 0.5-1.0 m/sec. The strip is fed to the first stand, passed through the rolls of all stands and sent to the drum of the reel. The mill is raced up to the working speed equal to 30-40 m/sec. after forming of two-three coil laps (wraps) on the reel drum. The speed is decreased again during the strip trailer passing through the rolls. The greater part of the strip is rolled with variable speed and it causes the change of the rolling conditions, rolling force, stand resilience, and leads finally to the change of the strip thickness along its length.

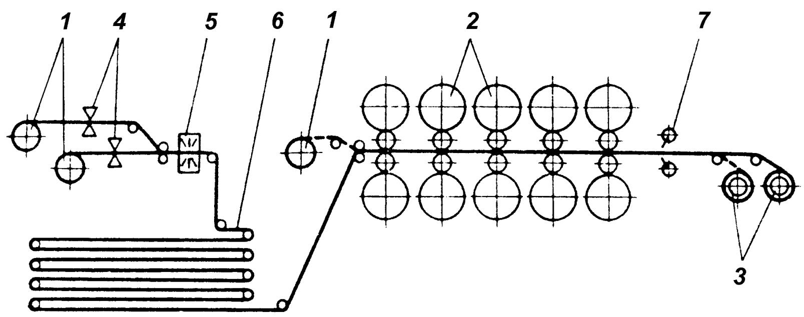


Fig. 4.17. Layout of continuous endless rolling mills: *1* – de-coiler; *2* – working stands; *3* – reels; *4* – shears; *5* – butt-welding machine; *6* – looping unit; *7* – flying shears

The significant improvement of the strip quality is achieved at endless rolling mills (Fig. 4.17) where the ends of the coils prepared for rolling are being welded in line in front of the mill. As the result the operations of the leading end feed are reduced, the speed of rolling is reduced only during the welded seams passing through the rolls; the efficiency is increased and metal discharged coefficient is being reduced correspondingly. The continuity of the process in the moment of welding the ends of the adjacent coils ends requiring the strip stop is secured by the loop accumulator *6*. When the process of coils welding is finished the loop accumulation of strip is produced again; the strip is cut by flying shears *7* at the exit from the last stand and is reeled on the reels *3*.

Technological operations during the cold rolling at one-stand and continuous mills

The technological process is accomplished in the following succession.

The pickling of the strip is made at continuous units with the usage of water solution of sulphuric or hydrochloric acid. Recently the preliminary mechanical removing of the scale from the hot metal surface before pickling of the latter has been started.

The considerable part of scale is removed in special installations where strip is processed by steel or iron shot simultaneously from two sides. The strip is subjected to acid pickling after mechanical processing. The combined method of cleaning provides for reduction of metal loss during descaling up to 1% instead of 2%, besides the installation occupies considerably smaller area.

Hot rolled strip, which is covered by scale after cooling, is the initial billet for cold rolling.

It will be pressed into the metal making the surface quality worse if not to remove it.

Cold rolling. The coils are lubricated and delivered for rolling after pickling. The total reduction during the cold rolling at 5 stand mill is 50-80%.

The annealing of coils is made for relieving of strengthening (cold-hardening) during cold rolling. The higher the deformation degree is, the more strengthened becomes metal, and its plasticity is reducing. The re-crystallization annealing at 650-730ºC is used for renewal of plastic properties. Annealing may be final when the rolling is accomplished and intermediate one between the stages of cold rolling. In case the significant deformation has to be produced during the cold rolling it is usually divided to several stages with intermediate annealing. The bell-type furnaces or continuous annealing units are used for annealing the developed strip. The annealing is made in protective gas medium (90-97% of nitrogen and 3-5% of hydrogen).

The temper rolling. It is the cold rolling with relatively small 0.8-1.5% reductions. The temper rolling is used after rolling and annealing are finished and it is the final operation of cold rolling.

Cold rolled sheets are after used for the subsequent stamping and applying of protective coatings. The yield lines are being formed on the surface, it becomes roughly uneven and the so-called orange skin (peel) is formed during the stamping of annealed cold rolled plates without tempering. This surface is of little use for applying of coatings as well as for enameling. The surface layer is only strengthened during tempering, the inner layers remain the plastic ones, non-deformed and the appearance of plastic shear lines on the surface is being stopped due to this fact. One- or two stand irreversible mills quarto is used for tempering. The tempering is accomplished for one pass.

The necessary roughness of the strip surface is obtained during tempering if required. The required degree of roughness is marked on the rolls for that reason.

Finishing of cold rolled strip. Cold rolled strip is shipped to the customers as coils or separate sheets. In the latter case coils are delivered to continuous units for cutting to length where strip is cut to sheets. The wide strip is slit at slitters to narrow bands for further reeling into coils.

Protective coatings application is accomplished on strip and plates for protection in aggressive medium. All kinds of coatings may be divided into metallic and non-metallic ones. Tin, zinc, aluminum, chromium, nickel, copper, titanium and others are used as metallic coatings. Plastics, varnishes, paints are used as non-metallic coatings.

5. TUBE AND PIPE MANUFACTURING

5.1. Tube and pipe range

The range of tubes and pipe is very wide: it includes tubes with diameter from the tenth part of millimeter up to 2.5 meters with the wall thickness from hundredth part of millimeter up to 50 mm. Regarding the ratio of diameter to wall thickness (D/S) tubes and pipe are classified as especially thick-walled tubes (D/S<5,5), thick-walled tubes (D/S=5÷9), standard tubes (D/S=9÷20), thin-walled tubes (D/S=20÷50) and especially thin-walled tubes (D/S>50).

The following tubes are produced: round, oval, rectangular, square, ribbed, tapered and tubes with variable wall thickness.

Tube and pipe are widely used in construction of gas- and oil pipelines, chemical engineering, building projects, components of different units and mechanisms.

There are general and special purpose tubes and pipes.

All tubes and pipes are divided into 2 kinds – seamless and welded – according with the method of production.

Seamless tubes are divided in their turn into hot deformed (produced by rolling or pressing) and cold deformed manufactured of hot deformed or welded tube billets by means of rolling in cold state at cold-rolling mills and cold-rolling roller mills (cold-rolled) and cold drawing (cold drawn). Seamless hot rolled tubes are produced with diameters D=16÷630 mm and wall thickness S=1.5÷50 mm.

Tubes with diameter from 25 up to 245 mm and wall thickness S=2.5÷30 mm are produced by hot pressing. Hot pressed tubes are often produced of low-plastic hard-to-deform steel grades.

Cold deformed tubes are produced with diameter D=0.2÷450 mm and wall thickness S=0.03÷35 mm.

Welded tubes are divided into electric-welded (D=5÷2520 mm, S=0.03÷32 mm) and welded in furnaces (D=10÷140 mm, S=1.8÷5.5 mm).

Seamless tubes take about 40% and welded tubes about 60% in total volume of tubes and pipes.

The comparative analysis of the range and characteristics of electric welded and hot deformed tubes and pipe shows the following:

- range of diameters of electric welded tubes is wider than that of hot deformed tubes, but regarding steel grades it is greatly smaller;
- precision of electric welded tubes regarding the wall thickness is higher than that of hot deformed tubes;
- electric-welded tubes can be produced with the smaller wall thickness if to compare with hot deformed tubes with equal diameters;
- electric-welded tubes produced by pressure welding have the burr as the result of seam welding salient on the inner surface up to 0.5 mm (the burr is removed from the outside surface).

5.2. Seamless hot rolled tubes production

There are several methods of hot rolling of tubes. Each of these methods includes three operations of plastic working accomplished in the following succession:

- piercing of solid round billet into thick walled tube called the shell;
- expansion of the shell into rough tube;
- sizing or reduction of the rough tube into finished tube with final dimensions as for diameter and wall thickness.

The piercing of solid round billet into shell is the first technological operation. The main methods of piercing are screw rolling and press piercing.

The additional installation of elongating mill is necessary in case of piercing at piercing presses. As to construction that is the screw rolling mill with fixed plug (similar to piercing mill type). The shell is produced in two operations. The first is the piercing of the billet at the press, after which the shell is produced as the thick walled cup with solid bottom. The second is the rolling of the cup at elongating mill. The length is increased during the rolling, the bottom is pierced and the shell is produced.

Expansion of the shell into the rough tube. The produced shell is rolled between the rolls having round grooves and the plug located inside of the tube. The tube with dimensions close to the final ones is produced out of shell in the process of reduction of diameter and wall thickness. These tubes are called rough tubes.

Two methods of expansion are used for shell expansion into the rough tube: expansion on short fixed plug (Fig. 5.1, *b*) and on movable long mandrel, which is moving together with the tube in the rolls (Fig. 5.1, *a*).

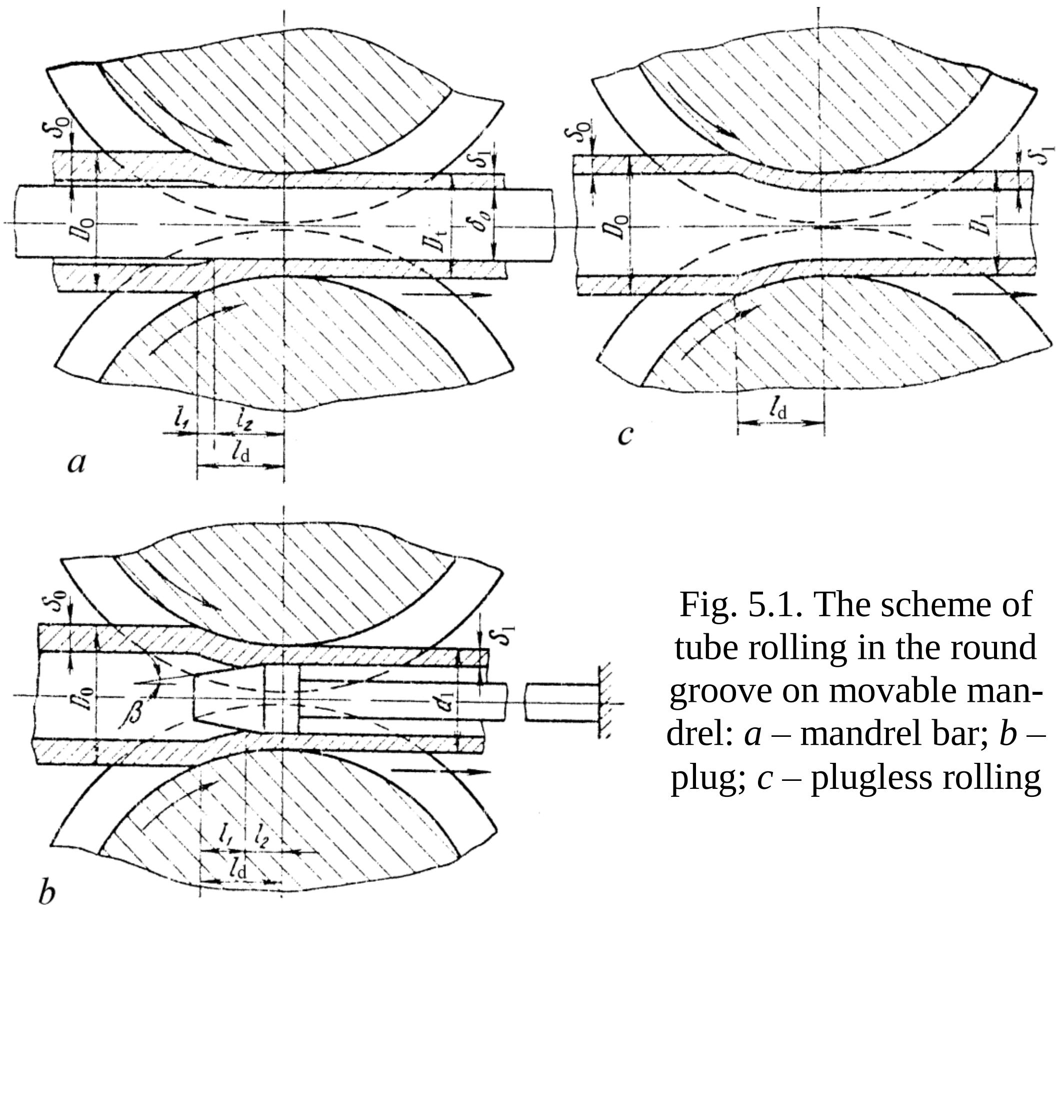


Fig. 5.1. The scheme of tube rolling in the round groove on movable mandrel: *a* – mandrel bar; *b* – plug; *c* – plugless rolling

The expansion of the shell into the rough tube on the plug is accomplished at plug mills and 2-stand tandem mills of lengthwise rolling. The expansion on the mandrel is accomplished at continuous lengthwise mills, pilger mills, three-roll reelers and rack-type draw benches.

Sizing and reduction of tubes is the final technological operation for obtaining finished tubes from rough tubes with final dimensions as to diameter and wall thickness.

Sizing of tubes is realized at continuous sizing lengthwise rolling mills with 3-12 stands. The rolling is accomplished within the system of round passes without any plug (Fig. 5.1, *c*). The working stands are irreversible, more often they are 2- or 3-roll ones. The sizing purpose is to produce the tubes with precise outside diameter. It is achieved due to the small reduction of tube as to the outside diameter to 3-5% in each stand of the mill. Sizing is accomplished without any tension of tube between the stands. That is why the thickening of the wall to 4-15% takes place after sizing. Sizing stands are installed with the inclination by turns to different sides at 45° angle to the horizon. The neighbor stands form the 90° angle. Thick walled and especially thick walled tubes with ratio $D/S<12.5$ are undergoing sizing.

Reduction of tubes is accomplished at continuous reduction lengthwise rolling mills in oval grooves without any plug.

Reduction mills are used for significant reduction (decrease) of the outside diameter of tubes. Decrease of the outside diameter of tubes is called reduction. The number of stands in reduction mill is increased up to 28. The 3-roll stands are mainly used.

The rolling is accomplished with tube tension at reduction mills in contrast to the sizing mills. It permits to increase the reduction of the tube as to diameter in each stand up to 10-12% without loss of tube stability (crumbling) and the total reduction of the outside diameter is up to 75-80%. Besides the rolling with tension permits to regulate the wall thickness depending on the value of tension keeping the previous one or reducing it.

The reduction mills installation widens significantly the range of produced tubes relieving at the same time the main equipment, where rough tubes are produced. Thin walled tubes with ratio $D/S<12.5$ are mainly subjected to reduction.

Hot rolled seamless tubes production at tube rolling plants (TRP) with automatic mill (Stiefel mill)

The main characteristic of the tube rolling mills is the maximum diameter of the rolled tubes. That is why the number indicating the maximum diameter of tubes to be rolled is used after the name of mill: for instance, automatic mill 140.

The plants are divided into three types of sizes depending on the range of diameters of the rolled tubes: small – TRP-140, medium – TRP-250, big – TRP-400.

The tubes with diameter 70-140 mm and wall thickness 3.0-3.5 mm are rolled at TRP-140; the tubes with diameter 76-250 mm and wall thickness 3.5-4.0 mm are rolled at TRP-250; the tubes with diameter 159-400 mm and wall thickness 4.5-6.0 mm are rolled at TRP-400.

The technological process of production at installations with automatic mill

Let us consider the succession of technological operations during tube rolling at small automatic installations TRP-140. The scheme of the technological process is given on Fig. 5.2.

The round billet is heated in the circular furnace with rotating bottom up to the 1000-1270ºC. The heated billet is delivered for piercing into the shell to the piercing mill of screw rolling.

Diameter of the billet differs from the shell diameter within the limit ±10%. The round billet with 70-150 mm diameter is obtained from bar or section mills.

The butt end of the billet is centered before piercing by pneumatic centering machine to reduce wall thickness deviation of the shells. The reduction ratio in the piercing mill is equal to $\lambda=1.5\div6.0$ depending on the tube size and wall thickness.

After piercing the shell is delivered to automatic mill. The working stand of the automatic mills is two-roll and irreversible. 5-12 round passes are cut along the barrel length. Each pass is intended for rolling only one tube size.

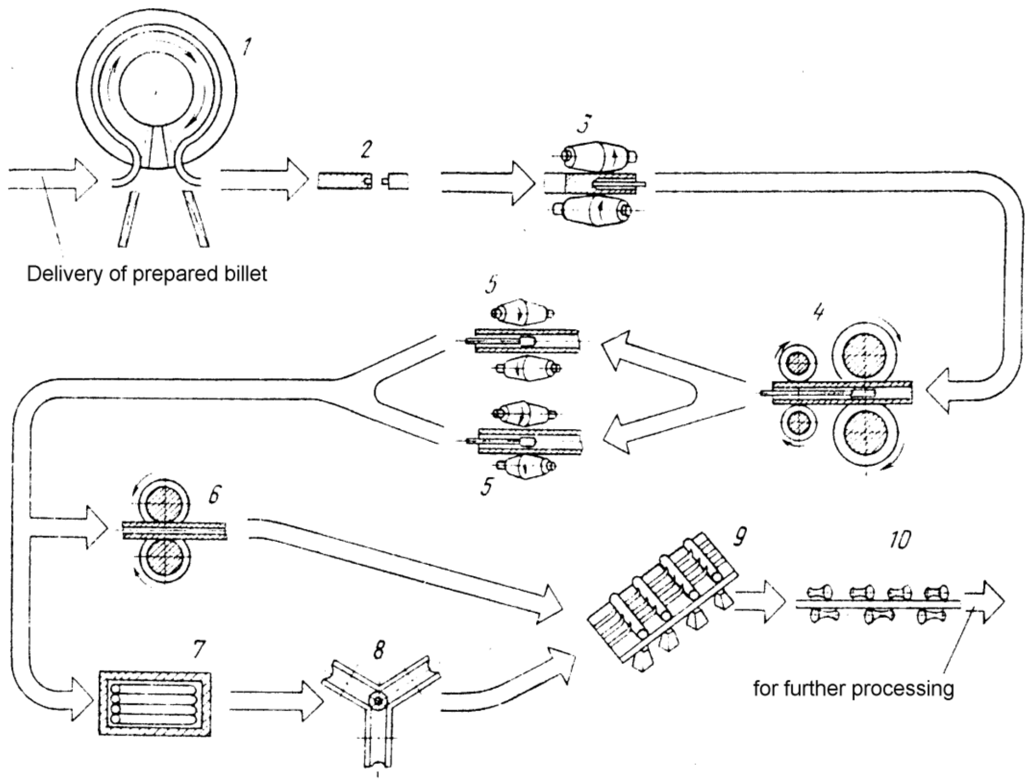


Fig. 5.2. Scheme of the technological process of tube production at installations with automatic mills (with one piercing):
1 – delivery of prepared billet and its heating; *2* – centering of the billet; *3* – piercing of the billet; *4* – rolling of the shell into the tube at automatic mill; *5* – tube expansion; *6* – tube sizing; *7* – intermediate heating of tubes; *8* – tube reduction; *9* – tube cooling; *10* – tube straightening

The rolling of the rough tube is accomplished between the rolls with passes and fixed plug installed in the rolls' groove. The shell is rolled into the tube in two passes. The scheme of the rolling is shown on Fig. 5.3.

The first pass is accomplished from the front side of the mill. The upper working roll *2* and the bottom roller of return delivery *7* are lowered down before rolling. At the moment of shell bite reduction of the latter by rolls is taking place as to diameter and wall thickness. The upper roll is loosened after the first pass and goes up under the action of balancing unit. At the same time the bottom roller of return delivery *7* goes up and the tube is returned on the front side of the mill (Fig. 5.3, *b*). Then one accomplishes the change of the plug, which diameter is

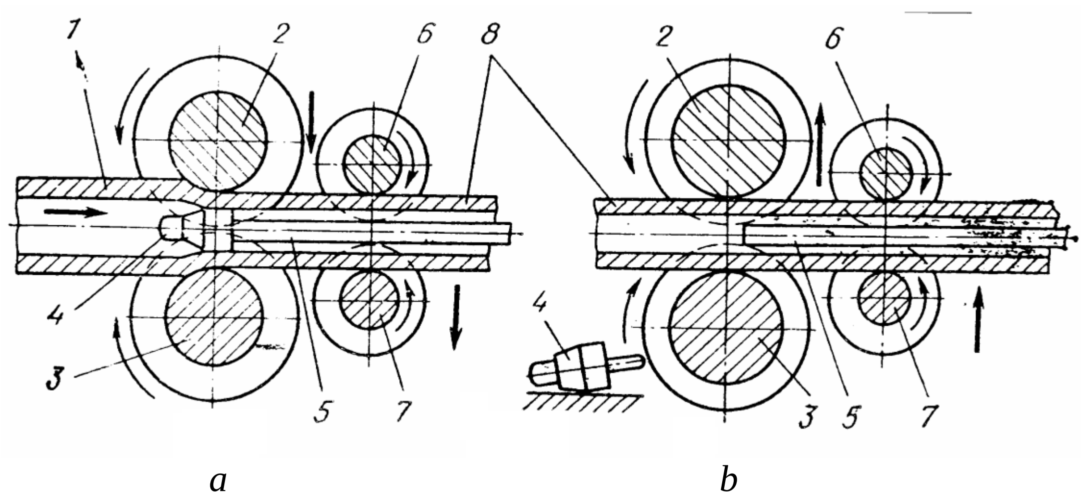


Fig. 5.3. Scheme of tube rolling at automatic mill:
a – rolling; *b* – tube returning; *1* – shell; *2* – upper roll; *3* – bottom roll; *4* – plug; *5* – stopper rod; *6* – upper roller of return delivery; *7* – bottom roller of the return delivery; *8* – tube

1-2 mm greater than diameter of the plug during the first pass. The second pass is accomplished from the front side of the mill. Tube is turned over for 90º before feeding. The total reduction ratio for two passes has not to exceed $\Sigma\lambda_{1,2}$=2 to avoid the fracture of the tube. The maximum tube length is 10-15 meters after automatic mill.

The tube has some ovality after rolling at automatic mill, called wall thickness deviation (thickening of the wall at the place of groove outlet), the formation of the notches on the inner surface of tube is possible due to the sticking of the metal particles on the plug. The rough tube is delivered for rolling to the reeling mills (Fig. 5.2, *5*) to remove these defects. The construction of reeling mills is similar to piercing mills' construction: the reeling of tube is accomplished between two barrel-shaped rolls and the plug. The reduction of wall thickness is 5-10% at the reeling mills, the metal volume displaced during deformation is flowing mainly at tangential direction increasing the diameter of tube. The capacity of the reeling mill is 1.5-2 times lower than that of the main mills – piercing and automatic ones. That is why two reeling mills are installed for leveling the throughput of all sections. The tube with $t \cong 600°C$ after reeling mills is delivered for sizing into continuous sizing mill *6* (Fig. 5.2) and then to the cooler *9* and straightening at straightening machine *10*.

The rough tubes after reeling mills are heated up to the 1000-1100ºC in the furnace *7* for obtaining significantly smaller diameters of tubes and then they are rolled at reduction mill *8*, whence they are delivered to the cooler for cooling and the further straightening and finishing.

TRP-250 with automatic mill has the same equipment as TRP-140 excluding the reduction mill, which is not installed as usual.

TRP-400 includes two circular furnaces and two piercing mills. The second piercing mill is elongating mill.

The production of tubes at TRP 30-102 with continuous mandrel mill

The mill includes *9* two-roll irreversible stands with individual drive. The stands are arranged at 45º angle to the horizon and 90º to each other. One pass is accomplished in each stand. The shell expansion into the rough tube is realized on the movable mandrel. The length of the mandrel is 19.5 m.

Continuous mandrel rolling is commonly used for production of thin walled tubes of carbon and low-alloyed steels. The main advantage of the process is the possibility to roll rough tubes of greater length (up to 33 m) with high rolling speed (up to 7 m/sec). The total reduction at the mill is 60-80%, the total reduction ratio $\lambda=3\text{-}7$. Tubes have good quality of outside and inside surface and low non-uniformity of wall thickness. As usual the tubes of one-two diameters with different wall thicknesses depending upon the diameter of mandrel are rolled at continuous mills and the production of tubes with wide range of diameters and wall thicknesses is achieved by rolling at multistand reduction mill. The scheme of the lengthwise shell rolling on the long cylindrical mandrel at continuous mill into the rough tube is shown on Fig. 5.4.

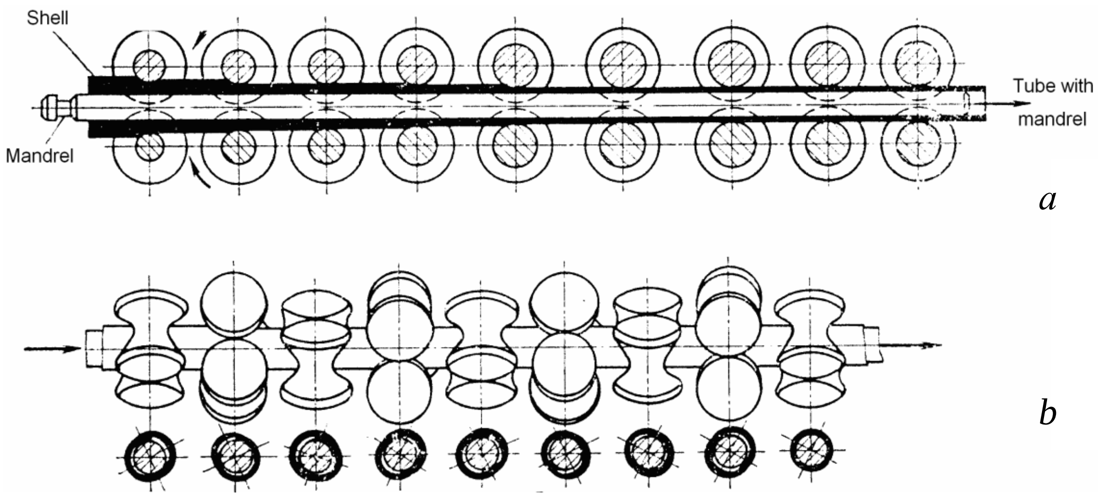


Fig. 5.4. Scheme of the lengthwise shell rolling on long cylindrical mandrel at continuous mill into the tube (*a*) and location of rolls of nine-stand mill (*b*)

The continuous plant includes the following equipment: two circular furnaces, piercing mill of screw rolling, 9-stand continuous mill, induction heating furnaces, 11-stand sizing mill, 24-stand reduction mill.

The succession of the technological operations is as follows. The round 140 mm diameter billet with measured length 0.6-1.0 m is unloaded after heating up to t=1170-1250°C out of the circular furnaces and after centering is delivered to the inlet trough of the piercing mill. The billet is pierced at the piercing mill of screw rolling into the shell in one pass and then it is delivered along the inclined racks to the feeding conveyer of continuous mill. On this conveyer a pre-lubricated long cylindrical mandrel is introduced into the shell by means of the automatic pusher. Then the shell together with the mandrel is fed into the first stand of continuous mill. After rolling the tube with mandrel is delivered to the double mandrel extractor. Mandrels extracted out of the tubes are delivered to the bath for cooling from 400° up to 150°C and then to the unit of lubricant application. The lubricated mandrels are delivered to the trough in front of continuous mill. During the extraction of the mandrel the tail end of the tube is retained in the rest, the leading end of the mandrel is clamped by pincers of the pulling trolley, which pulls the mandrel out of the tube. The ragged tail end of tube is cut by shears after the mandrel extraction. The tubes with diameter 76-102 mm are delivered for sizing and the tubes with diameter less than 76 mm are delivered for rolling at stretch-reducing mill. The heating in induction furnace is provided for up to t=1000°C before sizing or reducing. The tubes are cut to measured length and cooled after rolling at sizing and reducing mill. After that the tubes are straightened and delivered for finishing.

5.3. Cold rolling of tubes

The tubes with diameter from 3 up to 450 mm and wall thickness 0.08-35 mm are produced by method of cold rolling of carbon and alloyed steels and alloys of non-ferrous metals.

The cold rolling of thin walled tubes is accomplished at pilger die tube mills called CTR in abbreviated form. At present there are two-roll mills of cold rolling, roller mills and planetary mills. Two-roll mills became the most widespread.

Cold rolling tube mill presents two-roll mill with periodic mode of working. Alternate-reciprocal motion is imparted to the working stand by crank and connecting-rod assembly (Fig. 5.5).

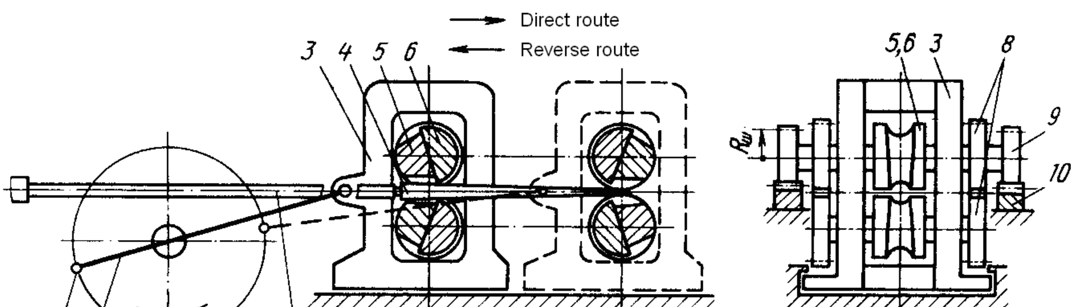


Fig. 5.5. Scheme of driving mechanisms for displacement of the working stand and turning of CTR rolls:
I and *II* – the end and the front extreme position of the stand; *1* – crank; *2* – connecting rod; *3* – working stand housing; *4* – mandrel; *5* – roll; *6* – half-disc groove; *7* – mandrel bar; *8* – driven gears; *9* – driving gear; *10* – rack

The working rolls installed in the stand on the supports are accomplishing the rocking motion during the process of rolling by means of gear wheels fixed on their necks. The extreme gears are engaged with racks on the bottom roll. The racks are fixed motionless on the side walls of the housing.

At the starting position of the working stand (*I*, Fig. 5.5) the tube shell is traveling due to the special mechanism in the direction of rolling for 3-18 mm distance, which is called "feed". The reducing of the fed shell area as to diameter and wall thickness is realized in the gradually reducing circular gap formed by the groove of pass and the mandrel during traveling ahead of the working stand.

The tail end of the shell is fixed and motionless at the axis direction during the rolling.

The turning of the rolled shell takes place together with the mandrel for 60-90º (*II*, Fig. 5.5) at the extreme front position of the working stand.

The treatment of the rolled area of the tube is realized by the passes during the reverse travel of the working stand to form the regular circumference of the required dimension. The rolling of the shell taper part of variable cross-section (called the working taper) takes place on the mandrel. As the result the backward slip (lagging) of the inner surface of tube from the mandrel takes place in the working taper due to some metal flow into the side tapers of the pass. It facilitates the traveling of the shell ahead relatively the motionless mandrel at the next "feed". The operations are repeated then.

There are recesses on the passes at the beginning and the end of the groove called gaps. They release the shell and the tube from the contact with passes at feeding and turning (these moments are shown on Fig. 5.5).

The form changing of the shell during the rolling is going on according with the scheme given on Fig. 5.6.

The metal deformation is accomplished due to the passes rolling over (Fig. 5.5). The grooves have the form of half-discs fixed in the notches of the working rolls. The variable cross-section working groove is cut along the half-circumference of the pass. The taper mandrel is fixed at the end of motionless rod

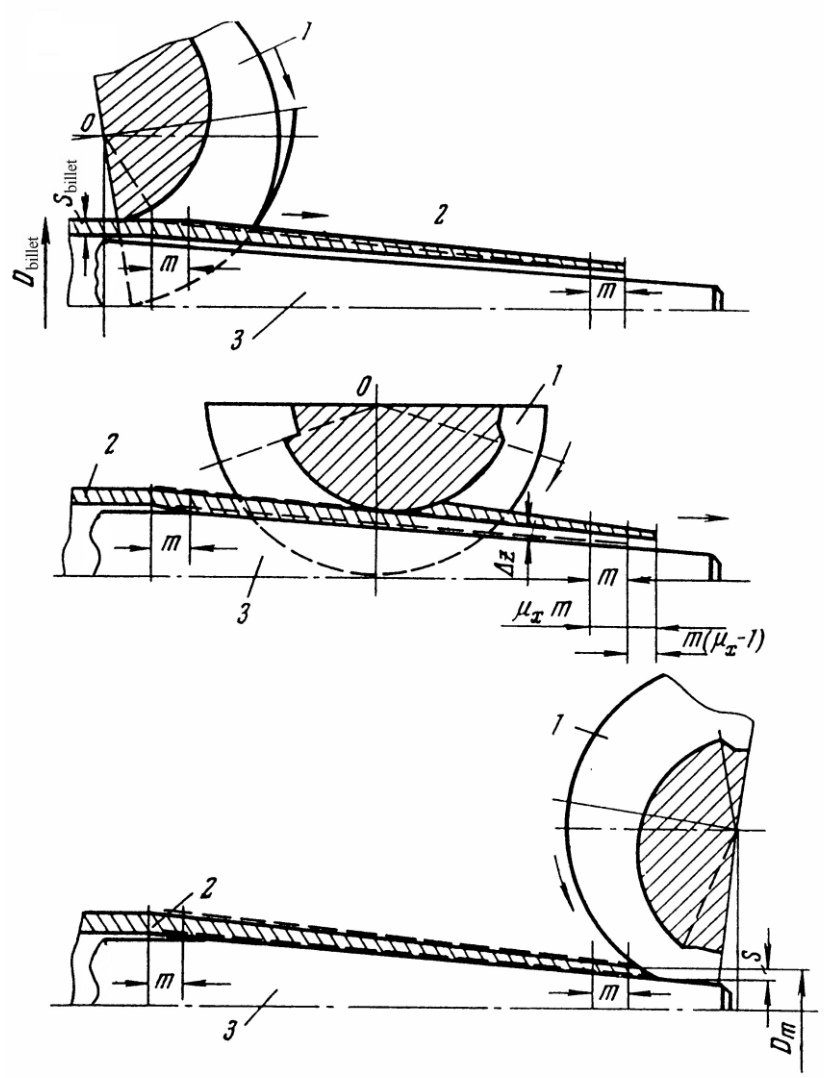


Fig. 5.6. Scheme of metal form changing during the cold rolling of tubes:
a – the extreme back position of the stand; *b* – the moment of the working travel; *c* – the extreme front position of stand; *1* – groove; *2* – working taper; *3* – mandrel

and installed in the gap formed by the grooves of upper and bottom rolls. The deformation of the feed portion of the metal begins with reducing the tube diameter with a very insignificant increase of the wall thickness. When the inside surface of the working taper contacts with the taper mandrel the deformation along the tube diameter begins to be accompanied by the reduction of the tube wall.

The calculation of roll pass design includes the determination of the mandrel dimensions, the choice of lengths of sections of the working part of the groove, the determination of the permissible groove taper, reducing and calculation of the form of the crest profile and the groove flare.

The operations of forming the initial billet into the finished tube take the most important place in the process of manufacturing the cold deformed tubes. The billet deformation is carried out during one or several cycles depending on its geometrical parameters, plastic properties of the used metal, method of deformation, dimensions and requirements to the quality of the finished tubes. Each cycle except deformation includes the operations of heat treatment of tubes for restoration of the plastic properties as well as chemical treatment for surface preparation for the successful realization of a new cycle.

The main advantages of the tube rolling at cold rolling mills are as follows: the minimum metal losses in the crop; the possibility to achieve the high reductions of the tube as to the wall thickness (up to 75-85%) and the diameter (up to 65%) using taper mandrel, what allows to reduce significantly the deformation cycling; significant reduction of wall thickness deviation and tolerances regarding the tube wall thickness; production of the wide range of the finished tubes from the limited number of billets' size types; the high quality of outside and inside surface of tubes, their precision.

The technological scheme of tube cold rolling depends on the steel grade or alloy, which the tubes are produced from as well as on the size and the purpose of tubes. The tubes may be produced as the finished products at cold rolling mills. They may be rolled at one, two or three mills successively or they may be delivered for cold drawing after rolling.

Hot rolled, pressed and welded tubes may be used as the billets for manufacturing the cold rolled tubes.

The technological process of cold rolled tubes production consists of several successive operations (preparative, the main ones and finishing). The tube billet is delivered from the stock *1* to inspection tables *2* (Fig. 5.7) where it is inspected and rejected in case of non-quality product. The accepted billets are collected into packs *4*.

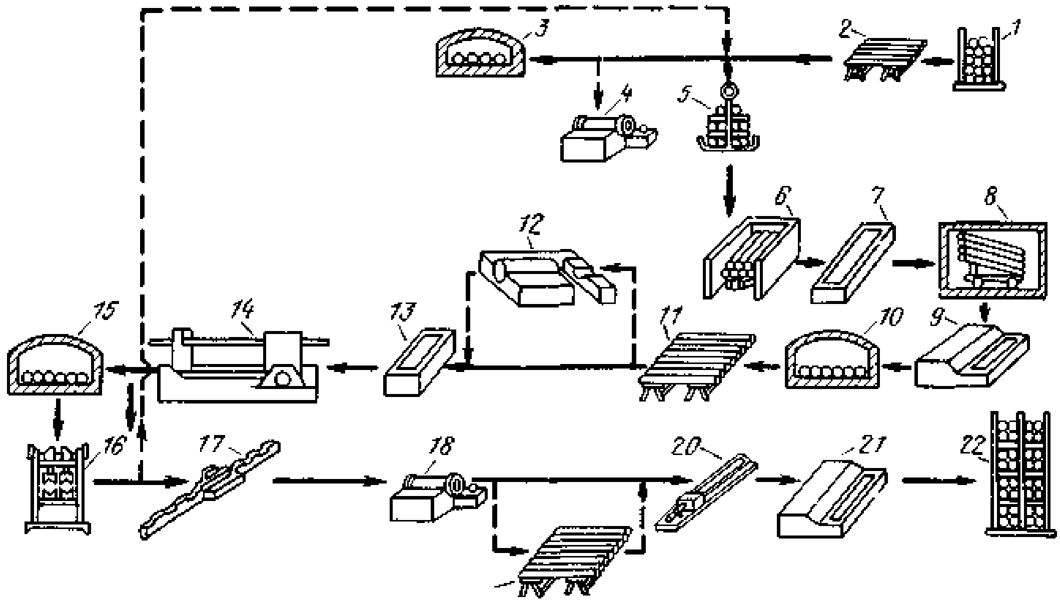


Fig. 5.7. Scheme of technological process
of manufacturing the cold deformed tubes

In case of necessity the tube ends are cut at tube cutting machines *3*, as only the billets with good cut ends are required for rolling. The billet is cut if its length exceeds the permissible length, which can be accepted by the mill. The billets are pre-annealed in the furnace in case of tube production of special steels. As the result the strength is reduced and the plasticity is increased, the structure non-homogeneity is removed, residual stresses in the metal are released from. The collected packs of tubes *4* are pickled by acid solutions in the bath *5*, washed in the bath *6* with hot water and then with stream of cold water supplied under pressure in the chamber *7*. Then they are neutralized in the alkaline solution in the bath *8*. After that the billets are dried in the furnace *9* and inspected on the tables *10*. The billets with the defects are repaired at the grinding machines *11* and are rejected finally. The solid coatings (phosphating, oxalating, copper plating) and lubricants are applied on the accepted billets in the bath *12*. Then billets are delivered for rolling to the mills *13*.

5.4. Production of welded tubes

All welded tube sizes are produced from a flat billet (sheets or strip) according to the one technological scheme including the following basic operations.

The flat billet is rolled up first into the cylindrical billet. This operation is called skelping. The next operation is the welding of the edges of the tube billet. Sizing and reducing of the welded tubes is the final operation.

These operations are combined into the one cycle and are carried out in continuous regime of equipment work. The change of the billet type (sheet or coiled strip) is possible depending on the diameter of the welded tubes, their purpose and steel grade as well as on methods of forming and edges welding.

Depending on the tube diameter one distinguishes small diameter (8-114 mm), medium diameter (114-513 mm), large diameter (530-1620 mm and more) tubes.

The initial billet for the small and medium diameter tubes is the coiled strip. The forming of the tube billet is carried out at continuous roll tube forming mill. The method of edges welding is called the pressure welding. The pressure welding is accomplished by means of heating tube billet edges up to the temperature of welding and their following compression. The edges may be welded by arc electric welding.

The hot rolled thick plates with measured length are used as the initial billet for production of large diameter pipes. The forming of the tube billet is carried out in bending rolls, at presses and continuous forming mills.

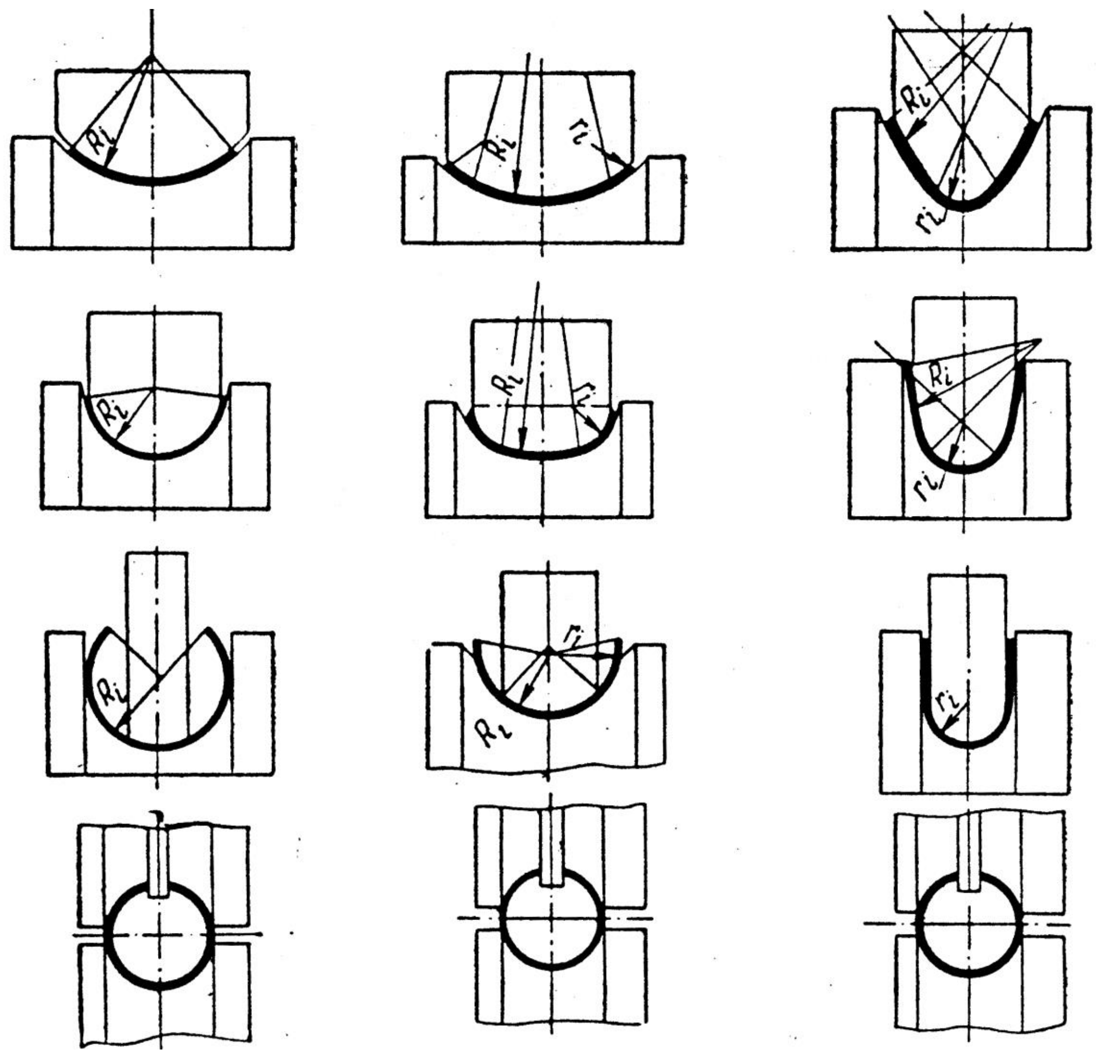
Production of small and medium diameter electric welded tubes

The range of small and medium diameters tubes is from 8 mm and 0.2 mm wall thickness up to 530 mm diameter and 12 mm wall thickness. The cold rolled annealed coil strip is used as the initial billet for production of welded tubes with wall thickness 1-2 mm. Hot rolled pickled strip is used as the initial billet for production of welded tubes with wall thickness more than 2 mm. The forming of the tube billet is realized at continuous tube forming mills. The forming mill includes from 6 up to 12 driven two-roll irreversible stands with horizontal rolls. The vertical rollers or idle stands with vertical rolls are installed between the stands.

The forming of the tube billet is accomplished in horizontal stands. The rolls in these stands have the passes intended to the gradual rolling of strip into the cylindrical tube billet.

The function of the stands with vertical rolls or rollers is to prevent the un-springing of the rolled strip.

Roll pass design of the forming mill is given on Fig. 5.8.



a *b* *c*

Fig. 5.8. The scheme of tube billet forming in roll forming mills

Single radius pass (Fig. 5.8, *a*) or double radius passes (Fig. 5.8. *b*, *c*) are used for tube billet forming. Combination of these types of passes is possible.

Technological scheme of tube production at continuous plant is given on Fig. 5.9.

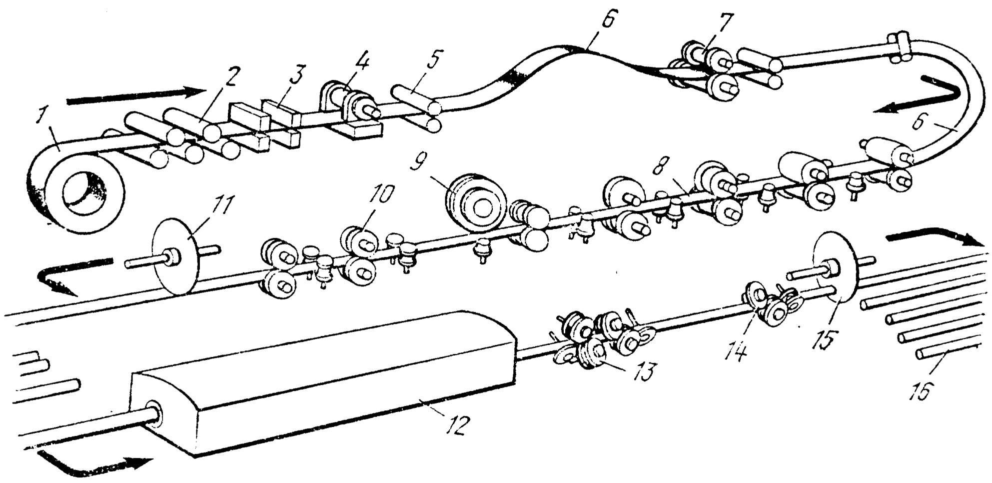


Fig. 5.9. Technological scheme of continuous plant for longitudinal tubes resistance electric welding:
1 – decoiler; *2* – straightening machine; *3* – guillotine shears; *4* – electric butt-welding machine; *5* – pulling rollers; *6* – the loop accumulator of strip; *7* – circular shears for strip edges cutting; *8* – continuous forming mill; *9* – electric welding machine with rotary transformer; *10* – sizing mill; *11* – flying cutting device; *12* – heating pusher-type furnace; *13* – continuous mill of hot stretch-reducing of tubes; *14* – hot sizing mill; *15* – flying cutting device; *16* – cooler

The technological process is accomplished in the following succession.

The coil delivered to the mill is uncoiled in decoiler *1* and is delivered for straightening to the 7-9 roller machine *2*. The strip after straightening is delivered to the guillotine shears *3* where the adjacent ends of two coils are cut for obtaining the even butts and then they are welded in butt-welding machine *4* into the endless strip. The welding of the ends requires the stoppage of the strip and for avoiding the continuous operation mill stoppage the stock of the strip is produced in the form of the loop *6*. The strip is delivered to the circular shears *7* where the side edges are cut for obtaining the strip of specified width after leaving the looping device. Then the strip is delivered to the continuous forming mill *8*. The edges pressure welding is carried out at the electric welded tube mill *9* installed just after the continuous forming mill. Tube welding mill has two driven stands with vertical rolls having round passes which diameter is a little bit smaller than the diameter of the tube billet. The heating of the edges up to the welding temperature 1430-1440ºC is carried out at tube welding mill. Different methods of edges heating are used such as high frequency current, induction heating, heating by the direct current and other. The outside burr is removed by cutters after welding and the tube is delivered to the sizing mill *10* for sizing and further to the straightening machine for the preliminary straightening. The tubes are divided to measured lengths or loops by the flying shears *11*, they are heated in heating pusher-type furnace *12* up to *t*=1000ºC, are reduced at continuous reducing mill *13* for tube diameter reduction and are sized at continuous sizing mill *14*. The tube coming out of the sizing mill is cut to measured lengths by flying shears *15* and delivered to the cooler *16* for cooling.

At the finishing section the cooled tubes are straightened, their ends are faced on special lathes, tubes are undergone to hydro-testing for checking the solidity of the welded seams.

The tubes with spiral weld are widespread as their production advantageously differs from longitudinal welded tubes production because the simpler equipment is required for it and the metal waste is decreased. Universality is the feature of the method of spiral weld tubes production. That is the possibility to produce different diameter tubes from the sheet of the same width making only the mill change-over according to the changed angle of the spiral and on the contrary it is possible to produce the tubes of the same diameter from sheets and strips of different width.

Forming, welding and cutting without stopping are the main operations during spiral seam tubes welding. That is why the spiral welding mill consists of three main mechanisms: feeding; forming and welding; cutting.

The feeding mechanism of the mill uncoils the coil preparing the strip edges (cleaning and flanging) and delivers the strip with the required force and at the definite angle into the forming and welding mechanism where the strip is rolled into the spiral tube and then it is welded along the edges in continuous seam. As the process of forming and welding is running continuously the cutting to the measured lengths with cutting torch is making without any stops. The whole cycle of the cutting, that is switching on the cutting torch and ejecting device, switching off the cutting torch and withdrawal of all mechanisms of the cutting device to the starting position is accomplished automatically during one turn of tube, that is for one spiral pitch.

The cut tubes are undergone to finishing operations (ends sizing etc.) and hydro-testing methods.

The efficiency of this mill is 60-80 meters of tubes per hour.

Tube welding mill of spiral welding may be traveling, installed on transporting machines. It permits to use the mill in the field conditions, for example, for production and laying gas pipeline tubes.

6. DRAWING, PRESSING AND DIE FORGING PRODUCTION

6.1. Drawing

The technological process of drawing besides the proper drawing includes operations of preparing metal surface for drawing, intermediate heat treatment and finishing of the manufactured products.

The preparing of metal surface for drawing includes descaling as well as applying the special layers on the metal for lubricant fixing and producing insulation between the surfaces of the metal and the die.

The removing of the scale is carried out by following methods:

- mechanical method by means of bending, twisting, stretching, shot blasting and others;
- chemical method by pickling in sulphuric, hydrochloric, nitric, phosphoric acids; alkaline pickling in alkali dip, gas pickling (pickling in the gas medium);
- electro-chemical method by anode or cathode pickling.

The surface has to be cleaned after pickling in hot water to remove the acid remains, salts and slime (mud) by means of the strong cold water jet. Then the operation of applying the bottom sub-lubricating layer comes. This layer consists of the active molecules of isolating substance weakening the cohesion between the metal and the die. The following bottom sub-lubricating layer may be used:

- sulling (corrosion) – applying the $Fe(OH)_2$ layer by water sprinkling of the pickled metal;
- copper plating in copper sulfate ($Fe+CuSO4 \rightarrow Cu+FeSO4$) solution;

- phosphating – deposition of the insoluble salts of phosphoric acid on the metal surface;
- oxalating (for high alloy steels) – deposition of oxalates.

The upper sub-lubricating layer forms the film between the metal and the die and acts as the mechanical isolation. The upper sub-lubricating layer applying is accomplished by liming in water solution of Ca $(OH)_2$ for neutralization of the acid remains and washing off the fat lubricant as well as coating by borax and liquid glass. The drying at 300-350ºC takes place in the chamber after applying sub-lubricating layers for moisture removing and corrosion stopping as well as for removing the hydrogen diffusing into the metal what causes brittleness from pickling.

The drawing of the wire and small diameter tubes is carried out in drum single- and multiblock machines (Fig. 6.1, *a*). To introduce the billet into the die the leading part of the billet is worked in such a way that dimensions of the first would be smaller than dimensions of the die inlet. The billet is pressed through the die and with help of the holder on the flexible cable it is fixed to the drum. Then the drive of the drum is switched on at a small speed and several coils of the wire are winded; after that the holder is disconnected and later on the driving force is provided only at the expense of friction forces between the coils of the wire and the drum. The released leading end of the wire is fed to the coiler (reeler) or to the next drum in multiblock machine having passed it previously through the next die.

The products of limited length and large cross section are drawn at chain mills (Fig. 6.1, *b*). The chain mill represents housing between the side frames of which the Gall's chain is traveling on two star-wheels. The dies are installed in a special stop from the side of non-driven star-wheel. The trolley with the hold and swivel hook for coupling with the Gall's chain is rolling along the guides of the housing. The leading end of the billet is put through the die and clenched with the holder installed on the trolley. By means of the swivel hook the trolley is hooked for the traveling chain link and the billet is being drawn. After the tail end's exit out from the die the hook is disconnected automatically with the chain and the product is released from the holder. The trolley is rolled back to the initial position.

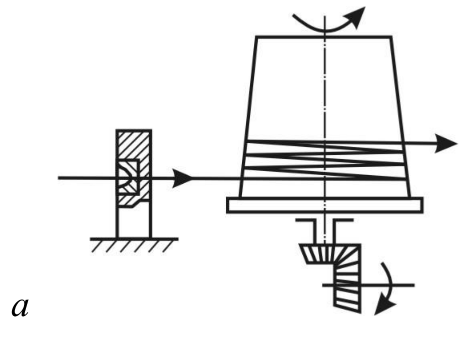
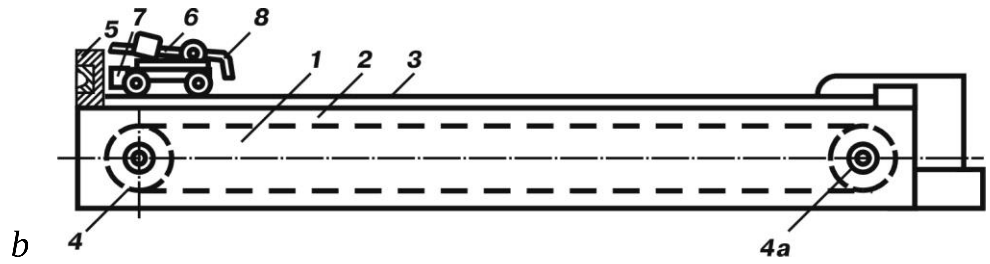


Fig. 6.1. Scheme of drawing: *a* – the drum drawing mill; *b* – the chain drawing mill (*1* – bed; *2* – Gall's chain; *3* – guides for the trolley; *4* – non-driven star-wheel; *4a* – driven star-wheel; *5* – die; *6* – trolley; *7* – holder for the billet; *8* – hook for the trolley and chain coupling)



There are many special kinds of drawing besides conventional one: with backward pull, with support, with heating, with vibrations, through the rotating dies etc.

The methods of cold tube plug (mandrel) drawing and sink drawing are shown on Fig. 6.2. The tubes of steel and alloys with diameter from 0.2 up to 765 mm with wall thickness from 0.015 up to 40-50 mm and with length more than 50 m are produced by drawing.

Drawing on stationary straight plug fixed on the rod is the most widespread method (Fig. 6.2, *a*). It is used for drawing tubes with diameter more than 8-10 mm when diameter and the wall thickness of the tube should be reduced simultaneously. The drawing of smaller diameter tubes by this method is limited by the strength of the out-coming tube to the end of which the pulling draw force *Q* is applied and a smaller diameter of the rod, which the plug is fixed to.

Different methods of mandrel (plug) and sink cold drawing of tubes are used. Mandrel drawing is used for reduction of tube diameter and wall thickness.

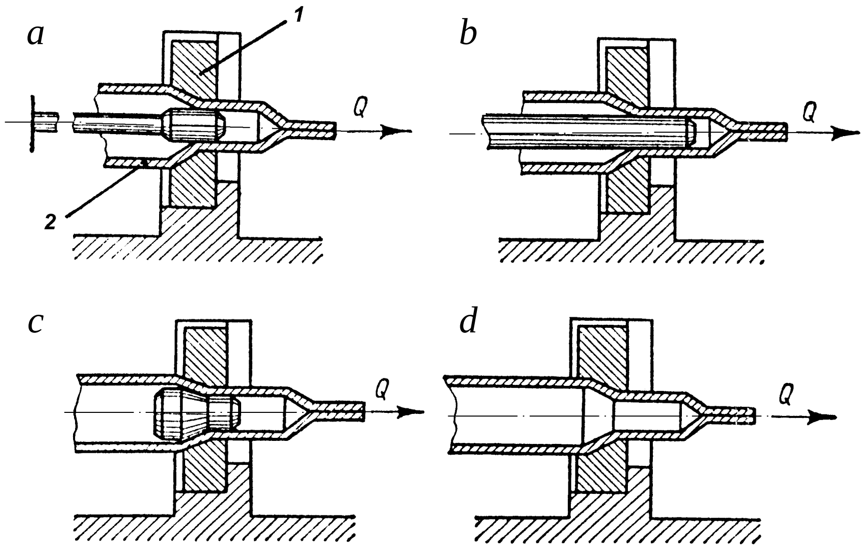


Fig. 6.2. Methods of tube drawing:
a – on plug; *b* – on mandrel; *c* – on floating mandrel; *d* – sink drawing; *1* – die; *2* – tube; *Q* – drawing pull

Drawing on the moveable mandrel displacing together with the tube is used for production of especially thin walled tubes with diameter less than 8-10 mm with the high precision of the geometrical parameters and high quality of inside and outside surface (Fig. 6.2, *b*). This method is the only one used for production of tubes with diameter less than 3 mm and capillary tubes of stainless steel with diameter les than 1.0 mm with wall thickness from 0.2 up to 0.015 mm. The disadvantage of this method, which limits its wide use is difficulty with the extraction of the mandrel out of the tubes, especially of thin walled tubes. The mandrel is tightly enveloped by tube and special operations have to be used to facilitate the extraction of the plug.

Drawing on the self-centering mandrel is used mainly for production of long length tubes up to 100 m and longer in case of drum drawing when diameter and the wall thickness of the tube should be reduced simultaneously. The stretching per pass is 1.2-1.8. The form of the mandrel is chosen such as the forces affecting the mandrel during the drawing process should pull it into the deformation zone. That is why it is not necessary to fix the mandrel on the rod (Fig. 6.2, *c*). The self-centering mandrel is called sometimes floating mandrel.

Sink drawing is used in those cases when only diameter of tube should be reduced (Fig. 6.2, *d*). Sink drawing is also used as the final operation after rolling on cold rolling mills (CRM) or after mandrel drawing. The stretching with this method doesn't exceed 1.5 and is limited by the strength of the outcoming tube and stability of cross section in the deformation zone (the tube has not to be crumpled).

The round and shaped tubes: square, rectangular, hexahedral, oval and other shapes, are produced by drawing.

There are two types of multi-die (multi-block) machines: without wire slipping on the pulling drum and with slipping. The scheme of the multi-die machine without slipping with wire accumulation on the drums is shown on Fig. 6.3, *a*.

a

b

c

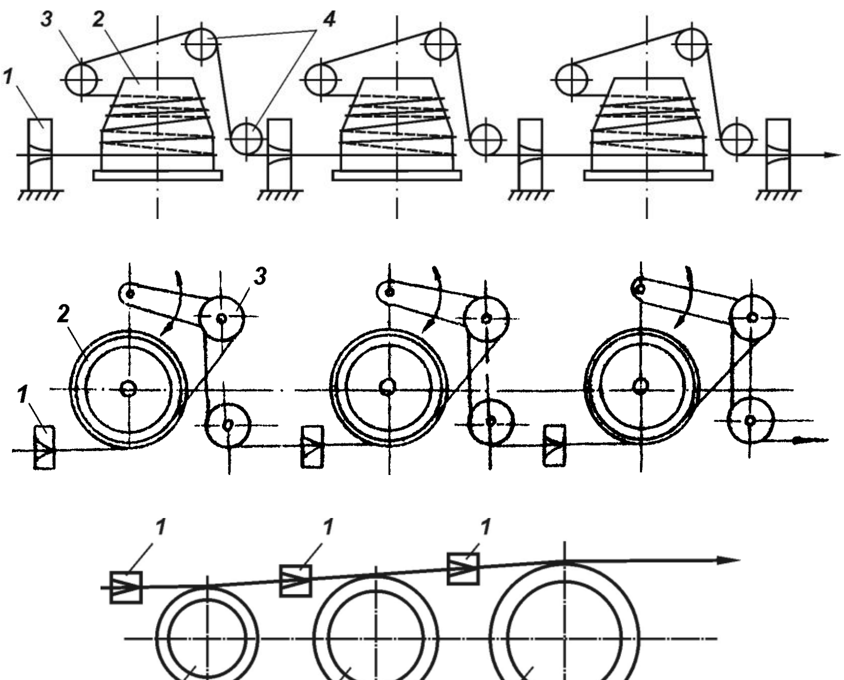


Fig. 6.3. Scheme of multiple drawing mills:
a – multiple drawing mill without slipping (*1* – die; *2* – pulling drum; *3* – device for wire taking away from the drum; *4* – guide rolls); *b* – looping type machine (*1* – die; *2* – pulling drum; *3* – tension roller); *c* – multiple drawing with slipping (*1* – die; *2* – fleet sheaves)

The speed of the drums is chosen in such a way that the previous drum had the stock of the wire. In case if the condition of synchronization of wire and drums speed is not observed, there is the possibility to compensate the fault of synchronization with the help of device *3* without mill stoppage due to the use of the wire stock.

The multiple drawing is perforemed at looping type mills without slipping with synchronization of the wire and drums speed (Fig. 6.3, *b*).

To prevent wire slipping on the drums the speed of latter is adjusted automatically during the process of drawing in such way as to avoid the wire accumulation. The adjustment is realized by means of the loop enveloping the tension roller. The turns of the drums are changed depending on position of the roller. If electric motors with soft mechanical properties will be used for pulling drums drive, the regulation of the drums speed may be done automatically due to the influence of the tension forces of the wire. The change of tension causes the change of the torque moment on the shaft of the motor and respective change of the rotating speed of the pulling drum.

The scheme of the multiple drawing with slipping is given on Fig. 6.3, *c*.

The wire is winded around the working drums one or several times depending on the diameter of the wire and the mill construction. The number of winds should provide for the nominal drawing force and exceed of the latter should cause the slipping of the wire winds on the drum. The slipping amounts 3-6% on the draught pulley (except receiving one) during the normal drawing process.

As the rotary velocity of pulleys (according to elongation) is increasing downstream the drawing, the relative downstream slipping has to be decreased from 6 to 3%.

The advantages of multiple drawing with slipping are as follows:

- machines have simple construction and are convenient in loading;
- pulleys and wire are placed into the liquid lubricant providing reliable lubrication and heat sink, high speeds of drawing.

The high wear of pulleys is the disadvantage of the drawing with slipping, it may cause the bad quality of the wire surface.

The relative slipping downstream the drawing should be decreased from 6 to 3% as the rotary velocity of the sheaves is increasing downstream the drawing.

6.2. Pressing (extrusion)

The technological process of manufacturing the pressed (extruded) products consists of the number of successive operations beginning from billet preparation up to removing the butt-end of the billet and cleaning the container and tools.

It is economically feasible to use the large billets. It is possible to produce long length sections out such billets saving the time for preparative operations. It is connected with the increase of the press tonnage (power), its overall dimensions as the increase of extrusion ratio leads to the significant increase of the pressing force. That is why one tries to decrease the diameter and to increase the length of the billet in order to reduce the extrusion force. It causes however the increase of the working stroke and the press lengthwise dimensions, complicates the lubricant applying. At present the steel billets are used with the length approximately equal to 2.5-3 diameters. The calculation of the permissible pressure on the tools is carried out in order to determine the maximum possible diameter.

The surface of the billet has to be clean and smooth for production of the goods with high quality. That is why for certain materials the billets undergo the turning and even the grinding. The billets, which are to be pierced undergo centering to reduce the wall thickness variation during the process of pressing. The piercing (sometimes boring) is performed strictly in the center producing the small inside diameter, and then the expanding takes place. Sometimes it is necessary to process the face plane of the billet according to the shape of the die cone.

Four groups of metals are distinguished depending on the temperature regime of pressing:

- under 500ºC – aluminum, magnesium, zinc, lead alloys;
- from 500 up to 900ºC – copper alloys;
- from 900 up to 1300ºC – nickel, iron, titanium and other hard-to-deform metals and alloys;
- above 1300ºC – especially high-melting point metals.

At present the method of cold pressing is used more and more widely for aluminum, titanium and other alloys.

The general requirement is to assure the uniform temperature of heating of all the billet volume. In this connection the heating of the inner layer lower for 30-80ºC is expedient taking into account the cooling of the surface.

The overheating (for 60-80ºC higher than at other methods of metal forming) is useful in many cases of alloyed steels pressing. The increase of the grain during this heating doesn't affect the quality of the product at the high elongation ratio.

The lubrication of the tools causes the decrease of friction, makes the process of the billet surface cooling slower and allows to increase its length, deformation degree and the speed of pressing. Besides that the lubricant preserves the tools from overheating and increases the wear resistance of the latter. The use of lubricant has also however its disadvantages like the additional operations for removing the lubricant remains from the metal surface.

Different lubricants are used for pressing the different metals. The type of lubricant depends upon the temperature of pressing. The most often used lubricant is the liquid one – engine oil with fillers (graphite, talc, bentonite, kaolin and others). Aluminum, magnesium, and copper alloys are pressed however in the most cases without any lubrication of the container in spite of the advantages of using lubricants. Pressing (extrusion) without lubricant leads to significant breaking of the surface layers of the billet, to appearance of the high shear deformations spreading deep into the billet. It causes the renewal of the metal layers, which the surface of the pressed product is formed from.

The entry of the defects from the surface of the billet into the surface of the product in this case is practically excluded and the defect part of the metal is removed with the remainder of the billet.

The process of hot pressing of ferrous metals has become possible due to using the technological lubricants: at first graphite-oil ones and then the glass ones.

The technology of the glass lubricant application consists in the following. The glass washer mould of the pressed glass grains is being put on the die heated up to 150-200ºC. The liquid glass is used as the bond, which is gluing the mass of the grains at 400-500ºC. The heated billet contacting with the glass washer makes its surface to melt and takes the melted layer into the hole of the die. Thus the zone of deformation is supplied with lubricant due to the glass washer. Besides the billet is lubricated due to the application of the layer of the glass grains onto the inclined table along which the billet is rolling down after discharging from the furnace. The glass grains are melted by the billet, which is rolling down this layer and is being covered with the layer of lubricant. The lubricating of the inner hole of the pierced billet is provided by the portion of the glass grains, which is put inside by means of a special spoon.

It is necessary to produce the definite pressure in the main cylinder and through the stem and press washer to force the billet to enter the container for realization of the pressing process. The scheme of construction of the bar and shapes extrusion press with direct flow of the metal is given on Fig. 6.4. The die fastened in the die holder *2* of sliding or rotary type is installed in fixed front platen *1*. During the process of extrusion the die adjoins the container *3* and after finishing the extrusion it is taken away from the container for removing the butt-end of the billet by means of device *4*. The stem *6* is fastened on the movable ram *5*. It realizes the extrusion of the metal out of the container through the channel in the die by the force produced in the main hydraulic cylinder. The press is equipped with the oil accumulator *8* with the motor and control system.

Layout of the plant with horizontal hydraulic press for production of steel tubes by method of extrusion is given on Fig. 6.5.

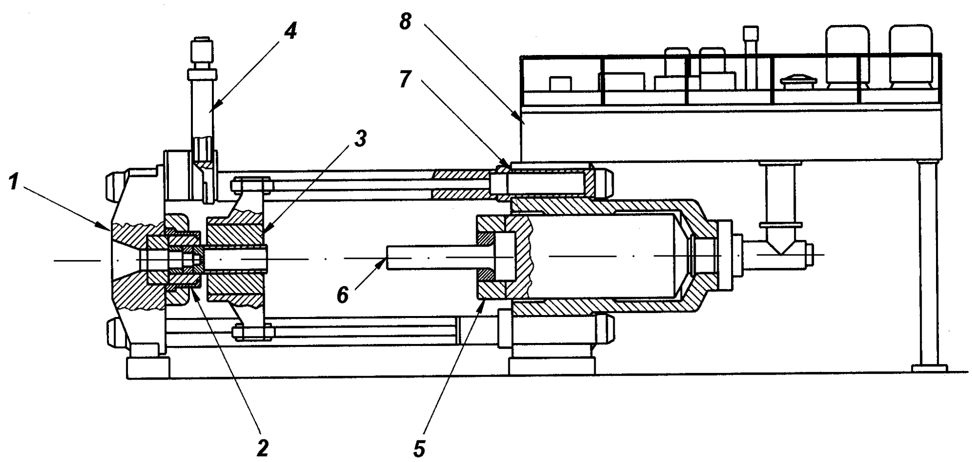


Fig. 6.4. Scheme of the construction of the bar and shape press with direct flow:
1 – the front platen; *2* – sliding or rotary die holder; *3* – container; *4* – device for removing the butt-end of the billet; *5* – ram; *6* – stem; *7* – back cylinders; *8* – oil accumulator with the motor and control system

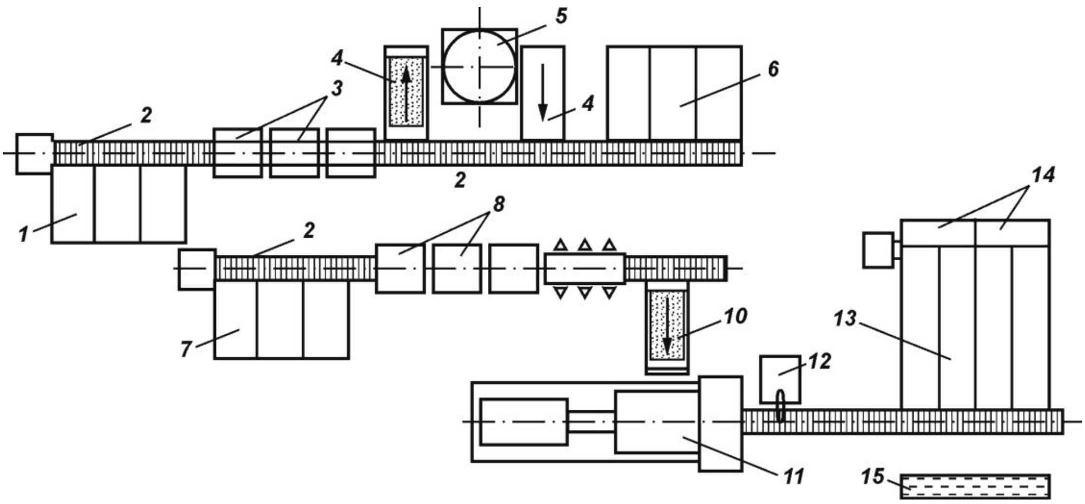


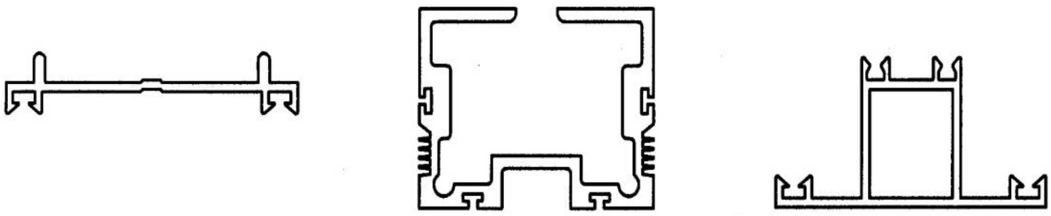
Fig. 6.5. Technological scheme of the tube extrusion process
1 – receiving stand; *2* – conveyer; *3* – induction furnace (50 Hz); *4* – the inclined table for glass lubricant; *5* – piercing press; *6* – pockets for the pierced shells; *7* – receiving table for shells; *8* – induction pusher-type furnace (500 Hz); *9* – descaler; *10* – table for glass lubricant; *11* – hydraulic press with 1600 t force; *12* – hot saw; *13* – cooler; *14* – pockets; *15* – quenching bath

The prepared billets are supplied to the receiving stand *1* and then along the conveyer *2* to the induction furnace *3*. Passing its three inductors the billet is being heated up to 1180-1220°C. After that the billet is supplied to the inclined table *4* and rolls along it covering itself by the glass grains and comes to the container of the piercing press *5*. The process of piercing includes pressing-out, piercing of the cup and punching the hole of the bottom. Then the shell is pushed out of the container and delivered by the conveyer to the pockets *6*. The shells after cooling are put into the cartridges and are traveled to the pickling. The shell is pickled to remove the remains of the glass lubricant at the pickling area, clarified, controlled and undergoes to the repair.

After that the shells are delivered to the receiving stand *7* of the main line and heated in the push-type induction furnace *8*, passed the hydraulic descaler *9*, inclined table for glass lubricant *10* and enter the press *11*. The speed of pressing at presses with 16 and 31.5 MN is 400-500 mm/sec, the elongation ratio is 6-20.

After removing the butt-end of the billet (by means of saw *12*) the products are transported to the cooler *13* and then again for pickling and straightening (tubes are straightened at the roller straightening machines and the shaped products are straightened at the stretching machine).

The process of extrusion permits to obtain the products with different (including complicated one) shape of the cross section (Fig. 6.6). In many cases it is not possible to produce the long length shapes by other methods of metal forming. The combination of the wide possibilities of obtaining the long length products of various cross-section shapes with favorable properties of material (especially in hot condition) makes the extrusion process the first one for production of shapes, for instance of aluminum alloys. Aluminum alloys extruded shapes are the universal construction material with unique properties. Thin-walled high strength shapes of aluminum alloys, for instance alloyed by scandium, determine in many aspects the development of aerospace engineering and transport machine building. The reduction of the weight of the carriers provides for significant reduction of energy consumption and harmful emission to the environment. The use of the aluminum shapes in construction has opened up the wide possibilities of the development of modern urban architecture.



a *b* *c*

Рис. 6.6. Types of shapes:
a – solid; *b* – semi-hollow; *c* – hollow

6.3. Smith forging

The necessary blacksmith operations, their succession as well as tools depend upon the configuration of the forged piece and technological requirements, which are to be satisfied. In the most of the cases in production of the forged pieces the alternation of upsetting and stretching takes place with predomination of that or another operation depending on the shape of the forged piece. The flat die is the most multi-purpose forging tool. The cut dies are usually used for forging on plugs or for stretching of low-plasticity metals.

The chamber furnaces are the most widespread in the forge shops. The billets of the same type are heated in continuous furnaces in case of forging. The adjusting of the heating regime is accomplished according to the chemical composition of the metal and temperature interval of the plastic working for the latter.

The heating of the billets as well as cooling the forged pieces are the important operations of the technological process of the forged pieces production. The very quick cooling of the forged pieces as well as the non-uniform one may bring to their buckling and even to the cracks formation. The cooling of the forged pieces produced of alloyed steels requires the special attention. The small forged pieces are usually cooled on the air in piles and the large ones are cooled in the holes with sand, in the furnaces and pits.

The choice of the equipment for forging is to be made taking into account the thermo-mechanical regime of processing the given metal or alloy connecting the speed of deformation with heating temperature and the speed of re-crystallization. High-alloyed steels (especially tool ones), heat-resistant and some non-ferrous alloys have the low speeds of re-crystallization as well as the low plasticity and don't allow the high speed of deformation. It is recommended to use the presses, but not the hammers to forge these metals.

The mass and the shape of the produced forged piece influence the choice of the equipment. The small and medium mass forged pieces (up to 2-3 t) are usually produced on hammers and the large up to 200-300 t are produced at presses.

The main characteristic of the hammers is the mass m of the falling parts. The impact energy will be equal to $E_{\text{imp}}=mv^2/2$ when the speed v of the falling parts of the hammer in the moment of impact is equal to 5-8 m/sec. The hammer impact energy is used for deformation not completely (part of it is wasted for elastic deformation of the forged piece, for shaking of the basement and the hammer etc.). The useful impact energy A_{def} used for plastic deformation of the forged piece is determined by the following expression: $A_{\text{def}}=E_{\text{imp}}\eta_{\text{imp}}$ ($\eta_{\text{imp}}\approx 0{,}8$ – coefficient of efficiency of the impact).

Hammers have mainly the mass of the falling parts equal to 1-5 t and are used for production of medium mass forged pieces from the small ingots, blooms and rolled ingots. The small forged pieces are produced of rolled sections on the hammers with the mass of the falling parts equal to 0.1-1.0 t.

The main types of the hammers for smith forging are driving hammers – pneumatic and steam-air hammers. The hammers differ by the type of the frame and may be single frame and double frame, arch and bridge ones.

Pneumatic hammer has two cylinders – compressor and working ones. The plunger in compressor cylinder is set into alternate-reciprocal motion and compresses air by turns in the upper and the bottom cylinder chamber up to 2-3 atmospheres after switching on the motor. The compressed air is used in the working chamber for lifting and lowering of the hammer block connected with the working plunger. The control of the air diffuser allows to run the forging by isolated impacts, to hold the block hanging, to accomplish idling etc.

Steam-air hammers are put into action by the steam or compressed air with the pressure 7-9 atm. The control of the steam-air hammers is accomplished by means of the steam diffuser regulating the entry of the steam into the working cylinder and its exit out of the cylinder.

The coefficient of efficiency of the hammer impact depends upon the correlation of the mass of the anvil block M and the mass of the falling parts of the hammer m. The mass of the anvil block is taken 15 times more than the mass of the falling parts for the forging hammers.

The heavy forged pieces are produced of ingots at hydraulic presses with the tonnage up to 150 MN.

The hydraulic presses are put into action by means of liquid (water, oil). The pressure of the liquid more often is produced by means of plunger pumps during the press working. Air-loaded accumulators and dead weight accumulators are used for keeping the liquid pressure in the system and reducing the required drive power of the drum.

Some types of the hydraulic presses have the system of low pressure (up to 12 atm) produced by the pump with accumulator and of high pressure (up to 200-500 atm).The high pressure is produced by multiplier working due to the steam or the air, hydraulic pump or mechanical transmission increasing the pressure to 40-60 times.

6.4. Die forging

The general technological process of the forged pieces production by the drop stamping includes the number of operations as follows: cutting of bars to the billets, heating, pressing, cutting of the burr, straightening, heat treatment, descaling and sizing. The rolled steel of different section shapes is used as the billet for drop stamping. The different methods of cutting are used: at crank-type press shears, cutting by saws, breaking, gas and anode-mechanical cutting. The choice of the method of cutting depends upon the size of billet section and technological features of different steel grades.

The stamping hammers differ regarding construction from the hammers for smith forging. All stamping hammers have double frame. The motion of the hammer block is going on in the regulated guides. The frames are installed on the anvil block and connected with it by means of bolts with springs. It provides for the necessary precision of coincidence of the die figures. The correlation of the anvil block mass to the mass of falling parts is equal to 20 and sometimes it is up to 30 at the stamping hammers.

The hammer die presents the massive block consisting of two parts, which are often called the upper and the bottom dies.

The dies may be sub-press dies and the bed dies. The sub-press dies are used in small-lot production in the forge shops. The stamping is accomplished only in the bed die at the stamping shops. Hammer dies as a rule are opened ones and stamping with the burr is accomplished in them.

The hammer dies usually have only one (finishing) groove or at worst two grooves (roughing and finishing) grooves for stamping the forging pieces of simple configuration.

The hammer dies for the complicated configuration forging pieces have two groups of grooves: the blanking (fuller, edger, pinching, forming, bending etc.) and stamping (roughing and finishing).

The dies for drop stamping work in the heavy-load conditions as they are influenced by the sharply changed temperatures and impacts. The wear of dies is accompanied by the appearance of the fire cracks, flattening of the working edges. The die steel must have high durability, hardness, impact strength, high fire resistance, wear resistance, good hardening capacity, high resistance for tempering. The dies are produced of steels alloyed by chromium, nickel, tungsten, molybdenum, vanadium, titanium etc. to ensure these properties.

The usage of the presses comparing with the hammers gives the following important advantages such as a less shaking of the earth, smaller basements, higher coefficient of operation efficiency, higher productivity, higher precision of the forged pieces, smaller stamping inclines etc.

The conditions of the metal deformation at the presses differ from those on the hammer. The first is due to the great difference in speeds of deforming tools (hammer speed is 5-8 m/sec and the press speed is 0.5-0.6 m/sec) and the second is that due to the strictly fixed value of the slider stroke. Using of special measures, for example of non oxidating heating, is necessary during the pressing process for descaling. Otherwise the scale may be stamped into the forging piece.

Almost all types of the stamping work including multi groove stamping (excluding blanking work in fuller and edger grooves) may be accomplished at crank drop stamping presses during production of the forged pieces with the mass up to 100 kg. The presses with the tonnage from 6.3 up to 100 MN are used.

Kinematics of crank hot press is given on the Fig. 6.7.

The flywheel *3* located on the intermediate shaft *4* is rotating from the electric motor1 by means of V-belt drive *2*. The rotation from the shaft *4* through the gear transmission *5* is being sent to the crank shaft *6*. The slide block *10* connected by means of the connecting rod *7* with the crank shaft *6* receives the alternate-reciprocal motion. The upper (moveable) part of the die is fixed to the slide block *10* and the bottom (immovable) is fixed to the press table *9*. The pushers are placed in the slide block and in the table used for removing the forging piece from the die. Switch on and off of the crank gear mechanism is accomplished by the friction sleeve *8* and the stoppage by the band brake *11*.

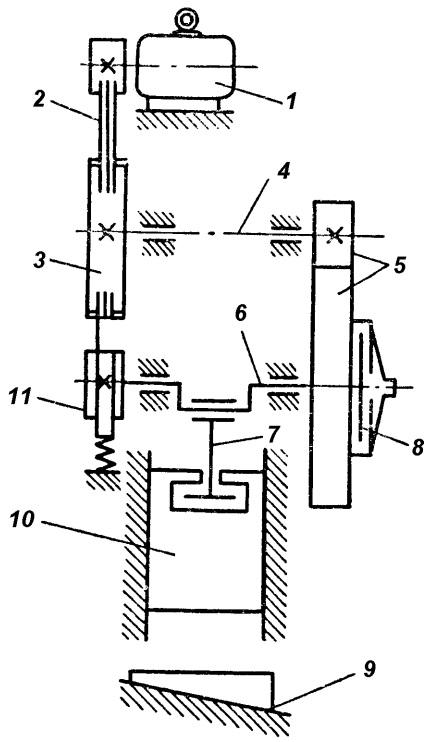


Fig. 6.7. Kinematics of crank hot press

The screw friction presses combine the impact action and the static pressure that's why they are considered to be the intermediate types of machines between the hammers and presses. These presses are constructed with the force 0.4-6.3 MN. The mass of the forged pieces processed at these presses exceeds 20 kg.

Hydraulic forging presses don't differ in principle from the forging ones as to their construction.

Horizontal forging machines are the crank-lever-cam mechanisms. The main point of the stamping at these machines consists in clamping of the billet and up-end deformation of the latter. There are two mechanisms in this machine: clamping and deforming one.

The following main operations may be accomplished on horizontal forging machine:

- up-end swaging and upsetting of the middle part of the billet;
- deep piercing with expansion towards sides;

- through piercing of the holes;
- bending;
- cutting of the forged piece from the rod billet.

The upsetting operations are mainly accomplished on horizontal forging machines. The forging is usually accomplished in several passes from one heating in consequence of what the volume of the billet remains unchanged in all passes. The forging on horizontal forging machines has the following advantages:

- the possibility of forging in the closed dies (without the burr);
- the possibility of zero-draft forging;
- the high productivity (up to 900 pcs. per hour).

The high efficiency automatic machines are operating according to the principle of the horizontal forging machines accomplishing the cold upsetting work. All fastening components including bolts, nails, screws etc. are produced by cold upsetting. Calibrated metal mainly with round section and diameter from 0.6 up to 38 mm is used as the billet for cold upsetting. The metal wastes are absent or extremely small during manufacturing of products by cold upsetting.

6.5. Sheet metal stamping

The production of the parts by hot and cold sheet metal stamping is accomplished at specialized shops having different machines and lathes. These are parallel, inclined and disc shears, crank (or eccentric) single-acting presses, double-action presses, triple-acting presses, hydraulic presses as well as the installations used for straightening and bending of sheets, bands shaping etc.

There is only one slide block at the single-acting press, which the punch is fixed at. These presses are used for blanking, bending and some drawing operations, etc. The double-action presses have two slide blocks (Fig. 6.8). The outer slide block *4*, which the blank holder *3* is fixed to, provides for necessary pressing of the sheet blank to the die *1* during the process of stamping. The inner slide block, which the punch *2* is fixed to, provides for accomplishing the main stamping operation (drawing). The pressure of the blank holder is achieved by the device usually consisting of rollers *5* and cam *6* in crank and eccentric presses. The hydraulic presses pressure is transmitted onto the blank holders from the main cylinder through the springs or rubber or from especially installed hydraulic or pneumatic cylinders.

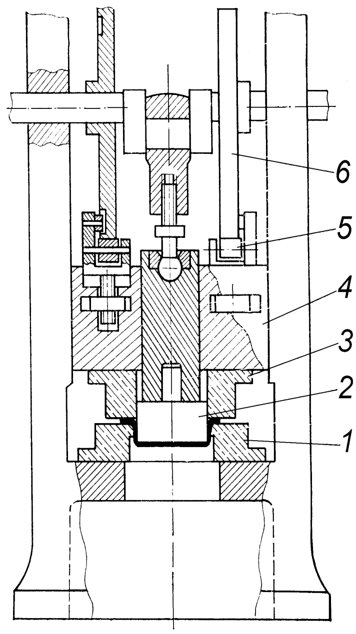


Fig. 6.8. Scheme of operation of double-action press

The triple-acting presses, the presses with three sliding blocks, in case of stamping products with complicated configuration if the necessity of the backward drawing arises. In this case the operation of two upper slide blocks is analogues to the double-operating presses and the third bottom sliding block has the direction of the working stroke opposite to the upper sliding blocks.

The crank presses – single-frame, single- or double-crank, opened and closed, double-frame and others – obtained the widest spreading. Crank presses for sheet metal stamping are produced with the force developed by the main slide block during the stamping operations from 1 KN up to 20 MN and more, hydraulic presses are produced for the same purpose with the force of compression equal to 70 MN.

The main tool for the sheet metal stamping is the die (blanking, bending, drawing etc.) which consists of working components (punch and mould) and the number of auxiliary components.

The part of the die having the punch is fixed to the slide block of the press and the part of the die having mould is fixed on the table. The fastening is usually realized by means of the bolts with the help of a number of accessories. To speed-up the change of the punch and the mould their fastening is made on the intermediate iron or steel plates (cushions). It makes the design of the punch and the mould simpler, reduces their sizes and as the result leads to the saving of the die steel and facilitates the carrying out of the heat treatment.

The coincidence of the mould *1* and the punch *2* axes is a rather important condition of the die operation (Fig. 6.9).

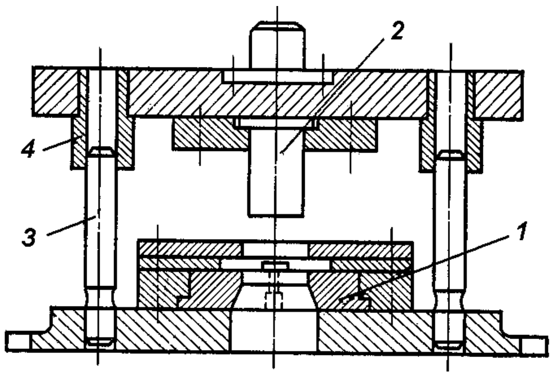


Fig. 6.9. The single-action blanking die

It is provided with the guide posts *3* situated as usual along the diagonal of the die. The traveling of the upper plate in the vertical plane is accomplished in this case into the bushes 4 along these posts. They take upon themselves the bending forces arising in the die during the shear of the center of the pressure. The guide plates are used for supplying metal into the die. Besides that the necessity to have removers, pushers and other devices arises for many dies.

The dies are classified depending on the number of operations accomplished in the die. There are plain dies accomplishing only one operation of sheet metal stamping and multi-operational ones accomplishing successive and combined operations. In successive operation dies (serial work dies) the operations follow each other at successive traveling of the billet from one punch to another. For instance, the hole is punched first and then the blanking is accomplished for production of the washers in this kind of die.

In the mixed action dies several operations of sheet metal stamping are accomplished per one stroke of the punch. For instance, the blanking of the circle is made first for production of the cup and then at the same stroke of the punch the drawing is made. Five and more operations may be accomplished in multi-operational dies.

The processes of sheet metal stamping are well mechanized and automated while using the coil billets as well as the piece blanks. The mechanical feeding of the strip to the die is more often accomplished by the rollers which are turning at regular intervals at the necessary moment at the definite angle providing for traveling the strip for the value of the required pitch. There is the great variety of devices for automatic supply of the piece blanks to the working tools. The feeding mechanism has to ensure the definite orientation of the blank in the space and ensure its next supply to the working tools. The "mechanical arms" of different design are widely used for sheet metal stamping using mechanical and automatic clamps whose work is strictly synchronized with the work of the main equipment.

The following equipment may be referred as to the auxiliary equipment of the stamping presses: cartridge devices feeding the presses by the billets, mechanisms for removing the parts from the dies, devices for applying the technological lubricant before stamping, the mechanisms for removing the wastes, the finished products counters.

It is advisable in many cases to arrange the production equipment (necessary for accomplishing the technological operations and products quality control) of the sheet stamping shop as the continuous conveyer lines for ensuring the high productivity at the all-around automation of the manufacturing.

QUESTIONS FOR EXAMINATION

1. What is the cause of the metal hardening during the cold plastic deformation?
2. What processes accompany the hot plastic deformation?
3. What does the method of determination of the yield strength of the processed metal at the hot plastic deformation consists of?
4. Explain the role of displacements in the metal plastic deformation mechanisms.
5. Explain the influence of the stress scheme on the deformation strain and the plasticity of the metal.
6. At which conditions does the initial bite of the strip by the rolls take place?
7. Explain the notion of the coefficient of the force lever during the rolling.
8. How the setting ratio is determined in the processes of the smith forging?
9. Compare the advantages and disadvantages of the processes of smith forging and die forging.
10. List the main operations of the sheet metal stamping.
11. Name and explain the purpose of the components of the main line of the rolling mill.
12. What are the advantages of the multi-roll mill design.
13. Name the main components of the technological process of the rolling manufacturing.
14. What are the advantages of the continuous mills?
15. What does the foundry-rolling complex represent?
16. Indicate the types of the section mills and the range of the rolled products.
17. Indicate the types of the plate hot rolling mills and the range of the rolled products.
18. Indicate the types of the plate cold rolling mills and the range of the rolled products.

19. Give the characteristic of the small section continuous mills.
20. Give the characteristic of the wire continuous mills.
21. Name the methods of seamless tube and pipe production.
22. Name the methods of welded tube and pipe production.
23. Give the characteristic of the cold rolling tube mills.
24. Name the methods of tube production by drawing.
25. Give the characteristic of the continuous mandrel mill.
26. Name the types of the continuous drawing mills.
27. Indicate the features of the deformation during internal extrusion.
28. Name the advantages and disadvantages of the forging in the closed dies.
29. Indicate the features of the press construction in sheet metal production.
30. Name the technological operations in press-forging production.

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Text-book

N. A. Koriaka, Translation
Yu. Zh. Shpak, Computer Design

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The characteristics of the shop equipment for metal forming and technology of the main metal forming methods have been given in separate sections.

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The fundamentals of metal forming theories, the theories of processes of metal forming, forging and stamping as well as drawing and pressing (extrusion) have been given. The characteristics of the shop equipment for metal forming and technology of the main metal forming methods have been given in separate sections. The text-book is intended for students of higher educational institutions, specialty "Metallurgy".

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