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CONSTRUCTION MATERIALS ENGINEERING

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Scientific bases of the construction materials engineering are considered. Up-to-date technologies of parts manufacturing and assemblage are given. Engineering equipment and progressive operation methods are shown. Methods of technical condition estimation are also considered.

The study aid designed at the Materials Science and Technology of Metals Department of the TPU. The manual is intended for training students majoring in the direction 15.03.01 "Mechanical engineering".

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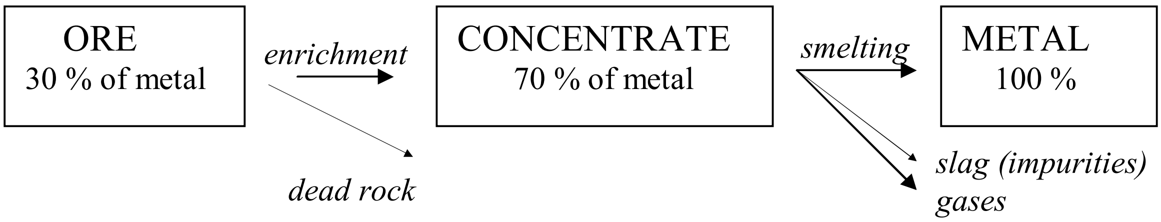
The subject of *construction materials engineering* is a technology of materials processing, which includes parts manufacturing and assemblage, engineering equipment as well as progressive operation methods.

Technology is a set of operations for product manufacturing. It is possible to say that technology includes materials, tools, equipment and the sequence of actions which are necessary to make the product. All these concepts are often designated by the English expression “know how”.

Part I Fundamentals of Metallurgy

In the earth crust metals occur in the form of ***ores*** (rocks with the high content of metal compounds). Only precious metals (gold, silver, platinum) are met in the form of nuggets. They may be extracted from gobs by *physical methods* based on differences in their densities. Active metals such as iron, aluminium, titanium, tin, zinc, etc. are found in nature only in the form of compounds from which they are recovered by various *chemical methods*.

Natural ores are frequently poor therefore they have to be enriched before melting. Any metallurgical manufacture is the gradual increase in concentration of the necessary metal:



Thus, the ***problem of metallurgical manufacture*** is reduction of metals from oxides and other compounds.

Ferrous metals, such as *cast iron* and *steel* are the most important for the technology. *Ferrous metallurgy* covers all processes for obtaining these metals.

Nonferrous metallurgy deals with copper, aluminium, titanium, and other nonferrous metals. Ores of nonferrous metals are poorer even than the iron ones: thus copper ore contains from 1 to 5 % of copper while molybdenum ore contains only 1/100 of a percentage of Mo. Their enrichment includes more operations, and the melt consists of several stages.

The ferrous metallurgy enterprises are depended on deposits of ores and coked coals. They are usually situated near the power complexes (Fig. 1, *a*, *b*).

Raw materials for ferrous metallurgy are iron ore, coke and fluxing stone.

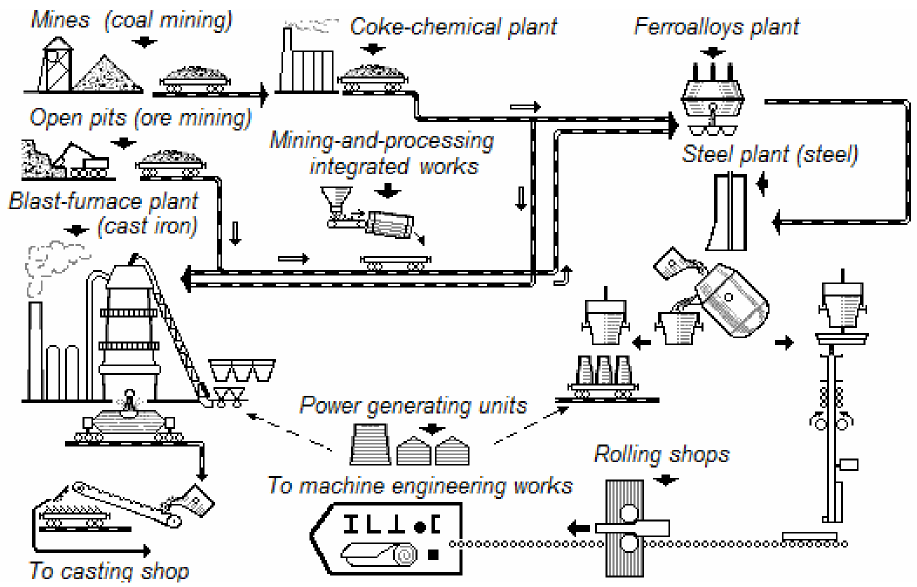
Ferrous metallurgy *production* includes *cast steel* and *iron founding*, *rolled steel* in the form of rails, beams, sheets, wire, tubes, *pig-iron* and *foundry iron*, *ferroalloys*.

Steel is the major product of all these processes therefore it is called “the bread of industry”.

The ***primary goals of ferrous metallurgy are***:

1) smelting *of cast iron* from the ore by reduction of iron from oxides in a blast furnace;

2) smelting *of steel* from cast iron and scrap metal by oxidation of impurities in steel-smelting units (converters, Martin furnaces, etc.).



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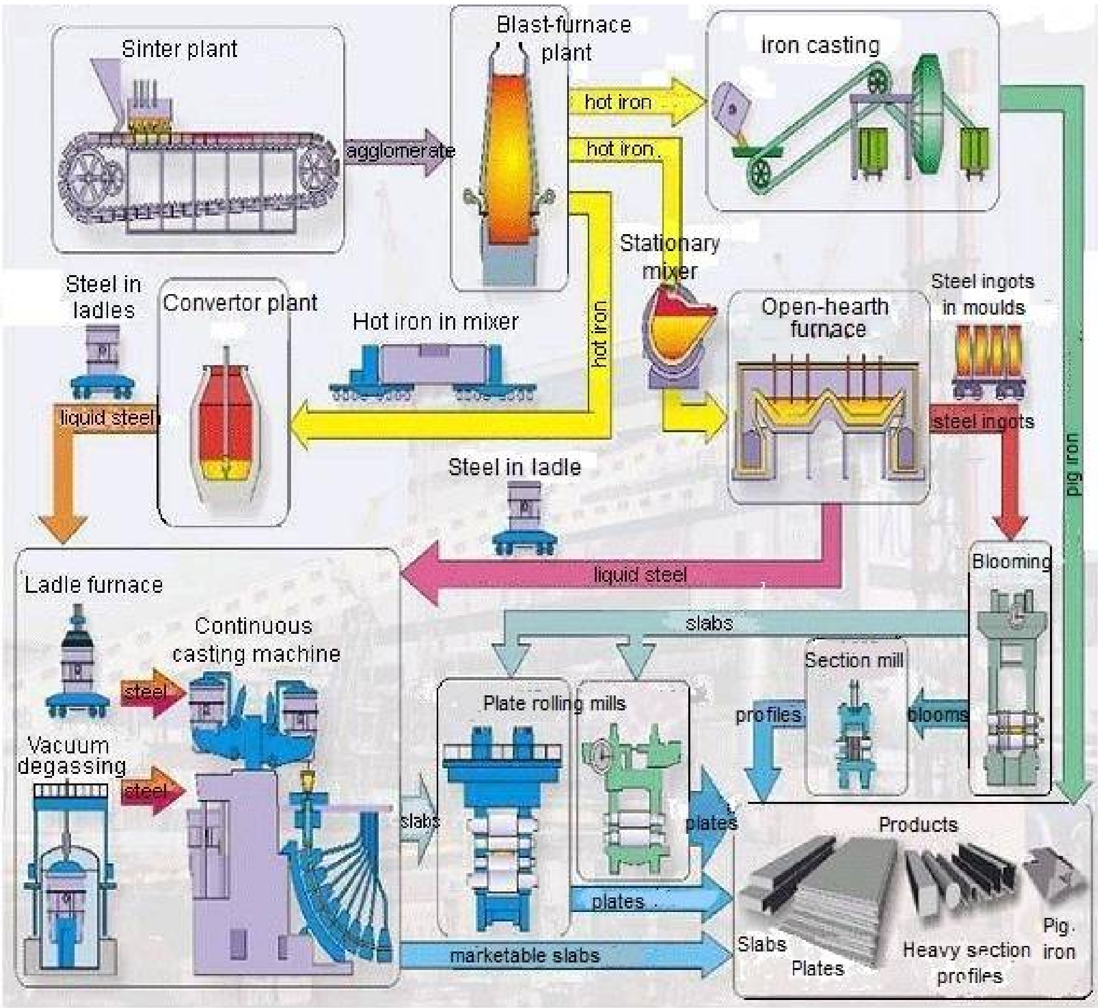


b

Fig. 1. The scheme of ferrous metallurgy

Cast iron production

Blast furnace is a vertical melting unit of shaft type. The counterflow principle is used in its operations as follows: raw materials are loaded from above; they melt and go down while hot air and gases rise upwards (Fig. 2). All materials loaded into the furnace are called *blast-furnace mixture*. They are as follows: ore, coke and flux. All these materials are subjected to preliminary processing: crushing of large pieces, sintering of small ones and enrichment. The enriched concentrate (not natural ore) is loaded into a blast furnace in the form of pieces of certain size (10–80 mm). The pieces are made by *agglomeration* (sintering) or *pelletization* (pellets or balls of 30 mm in diameter prepared of fine fractions of humidified mixture and then roasted).

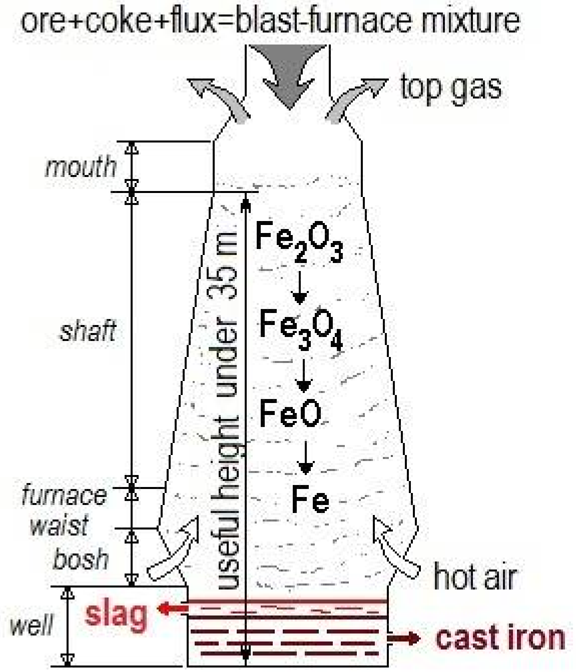


Fig. 2 The blast furnace scheme

The blast furnace contains up to 7,000 tons of raw materials (5 trains). It is the furnace of continuous action: it works without repair for 5–8 years round the clock. Outside the blast furnace is dressed by a steel casing with the thickness of 40–50 mm. Fireclay lining of the furnace has the thickness from 70 cm in the top part to 1,5 m around the well. The warmed-up *blasting* (air for the fuel burning enriched by oxygen) moves from the stove through tuyeres.

The blasting temperature reaches 1,200°C, which allows to save coke and raises productivity. Each blast furnace has hot-blast stoves, which work in turn either heating the brick cladding by waste gases (Fig. 3) or heating the blow.

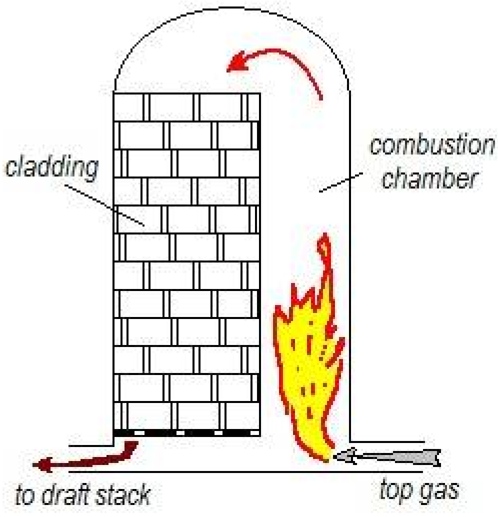


Fig. 3 Blast-furnace stove works for heating of cladding

Coke burns down thus releasing a considerable quantity of heat: the temperature in a bosh is about 2,000°C. The combustion products CO and CO_2 serve to heat blast-furnace mixture since their temperature in the top of the blast furnace is about 300°C.

The main chemical process in a blast furnace is the reduction of iron. Iron can be reduced by CO and H_2 (*indirect* reduction) as well as by solid carbon of coke *(direct* reduction). The reaction goes sequentially from high oxides to low ones:

$$Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe.$$

Besides, the impurities like silicon, manganese, phosphorus, sulfur are deoxidized too; iron actively dissolves carbon and sulfur. The alloy saturated with carbon up to ≈4 % melts, flows down into a well, and further carburizing becomes impossible: a layer of liquid cast iron is covered by a layer of liquid slag. The latter consists of oxides and is lighter than metal.

Iron-base alloy containing carbon, silicon, manganese, phosphorus and sulfur is called ***cast iron***. It is subdivided into *foundry* iron and *steel-making* iron. Foundry cast iron is poured into ingots (pigs) weighting 45 kg each or it is used for casting. Steel-making cast iron is used for making steel. Steel-making cast iron is poured from ladles into a mixer. This refractory container is warmed with combustible gas and contains up to 2,000 tons of liquid cast iron. In the mixer the averaging of makeup of pig-iron from different portions takes place that is important for correct work of steelmaking vessels.

Cast iron and the blast-furnace *ferroalloys* used for deoxidizing effect and alloying of steel are the basic products of blast-furnace process; slag and top gas are by-products.

Technical and economic indicators of the blast furnace work are as follows:

1) effective-volume utilization factor V/P [m^3/t], where V is useful volume, P *is* daily productivity;
2) specific consumption of coke $K = A/P$, where A is the coke consumption per day.

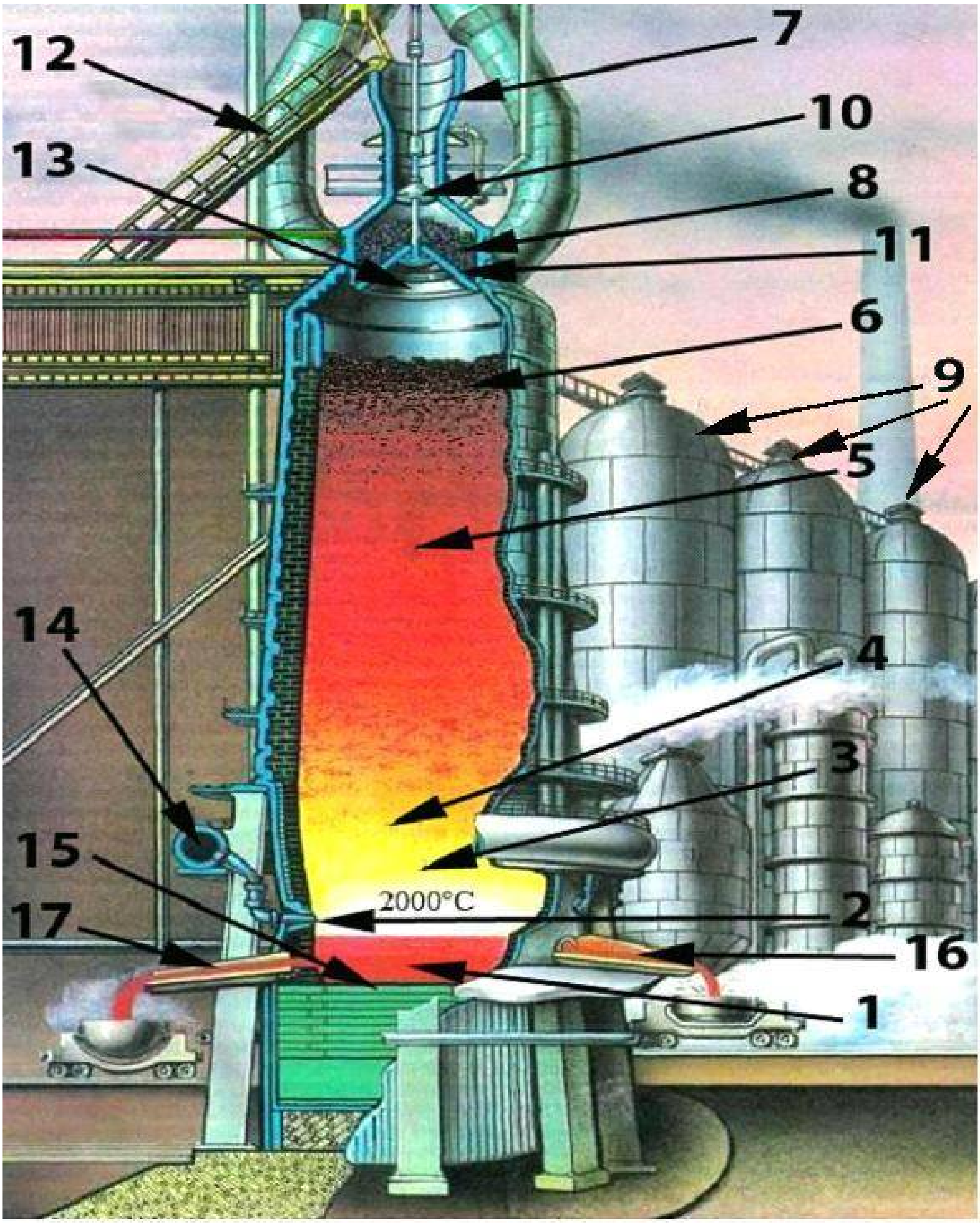
It is clear that the lower these indicators are, the more effective blast furnace is. For the best furnaces both these indicators are at the level of ≈ 0.4.

Additional blast furnace description

Blast furnace (see scheme on p. 9) is a shaft furnace. It has outside steel casing which is laid with fire-resistant chamotte bricks from inside. The working space of the furnace includes mouth 6, mine 5, waist 4, bosh 3, well 1, and bottom 15. Top charging gear 8 is placed in the top part of the mouth. It serves for loading a blast-furnace mixture into the furnace by *skip loads*. The blast-furnace mixture consists of 30–50 mm pieces of the enriched ore (concentrate), coke and flux. Small fractions of ore are preliminarily prepared by either agglomeration or pelletization. *The agglomerate* is made of small concentrate particles (less than 10 mm) sintered with coke and flux at a sinter plant. *Pellets* are compacted from dust fractions by pelletization and roasting; they are 30 mm diameter balls.

The weighed portions of mixture and coke are lifted by means of a skip hoist along the inclined bridge 12 to top charging gear 8 where the skip overturns, and mixture is poured out into the receiving bowl 7. While the small cone 10 goes down the mixture falls into bowl 11 of the big cone. Then the small cone rises, the big cone 13 falls, and mixture gets to the furnace. Such sequence of the top charging mechanism work is necessary for prevention of exhausting fumes out of the blast furnace top exit into the atmosphere.

In the course of smelting the mixture gradually lowers and new portions of mixture are constantly added. In the top part of a well there is tuyere belt 14 for heated air blowing through tuyeres 2. Hot air is necessary for coke burning. In the process of melting both liquid iron and slag are collected at the bottom; they are let out from the furnace: cast iron through metal notch 17, and slag through slag notch 16.



The scheme of blast furnace

Steel making

Raw materials used for steel making are conversion iron and *scrap metal*.

Conversion iron consists of 4 % C, 1 % Mn, 1 % Si, 0.3 % P, ≤ 0.1 % S.

Steel 1040 composition is 0.4 % C, 0.5 % Mn, 0.3 % Si, ≤ 0.05 % P, ≤ 0.03 % S.

Hence, for making steel, the content of all impurities in cast iron should be reduced approximately by a factor of 10. For this purpose it is necessary to oxidize impurities and convert them into slag (or gas).

Steel is made in steel-smelting furnaces having various design, capacity and productivity.

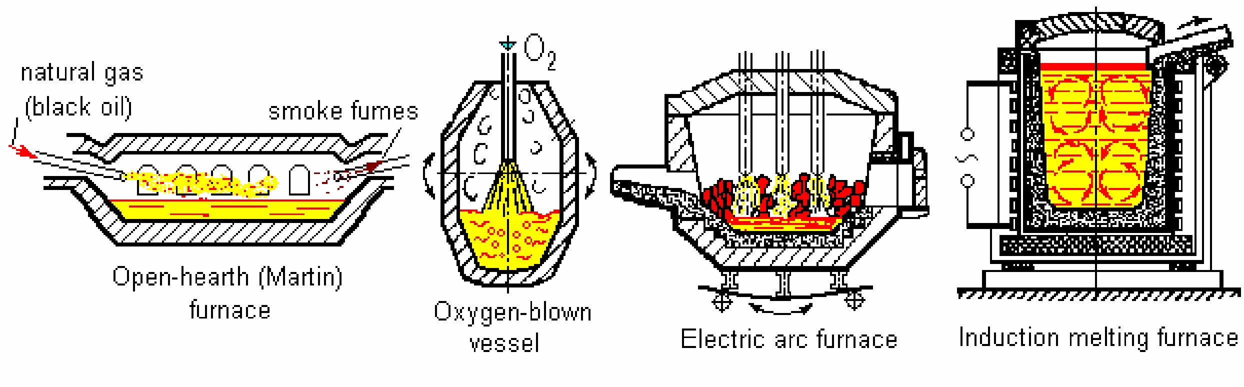


Fig. 4 Steel-making units

Steel-making units

Open-hearth, or *Martin furnace* is the largest size steel-melting unit (Fig. 4). This open-flame regenerative furnace can contain up to 900 t of liquid steel. The furnace is a bath made of fire-resistant materials. The top part of the furnace is made in the form of an arch; the charging holes are located in a front wall, while there is a metal notch in the bottom part of a back wall. The cheeks are fitted with heads for fuel feed and extraction of combustion products. Heat sources are natural gas or black oil flame torches. The gases formed on burning pass through one of the regenerators (hot-blast stoves) thus bringing heat to the brick cladding. Air for fuel burning passes through a regenerator while being heated up. Then by means of a dumper a stream of exhausting gases is directed so that the previously cooled regenerator is heated up and the blasting air passes through the regenerator that was heated before.

In order to accelerate fusion the tuyeres for oxygen injection are passed through the furnace arch.

Productivity of the furnace is estimated by value of metal pickup per 1 m^2 of furnace hearth. This indicator reaches 10 t/m^2; large furnaces with the hearth area 100 m^2 work more productively.

The furnace stands for 400 to 600 smelts (approximately 8 months) and after that it is stopped for repair. Duration of smelt in the Martin furnace is from 6 to 12 hours. Plain carbon steels and alloyed ones are melted in open-hearth, or Martin furnaces.

The share of martin steel is less than 50 % of the total steel production in the world. For the last decades its share has been decreasing, since no new Martin furnaces have been built.

Oxygen converter is the second by size steel-melting unit. It is a pear-shaped vessel (retort) made of fire-resistant bricks and dressed outside by a steel casing. The converter is mounted on legs and hinged on pins to be capable of inclining for steel and slag tapping. Capacity of converters is equal to 300–400 t of liquid steel. The sizes of converter are as follows: height is up to 9 m, diameter is not over 7 m.

Oxidation of impurities contained in the cast iron is facilitated by pure oxygen lancing of the liquid metal from the top of the converter. Chemical reactions of oxidation are exothermic and release large quantity of heat, therefore the bath is warmed up very quickly. Under the lancing the temperature of melt reaches 2,400°C. The fusion cycle takes 40 minutes only, therefore the converter is the most high-efficiency steel-melting unit. The converters are commonly used to make only plain carbon and low-alloyed steels. The content of an alloying element is no more than 3 %. Excessively high temperature promotes burning out of valuable alloying elements; therefore, sometimes alloying is made already in a ladle after the steel tapping from the converter. The share of converter steel in the world production grows; converter method supersedes the Martin one.

Electric-arc steel-melting *furnace* has capacity up to 300 t. It is a chamber made of fire-resistant bricks with the removable arch. It has a window for loading the fluxing materials and alloying elements; charging of a mixture is made from above when the arch is removed. For steel tapping the furnace has a fire-resistant trench. It can be inclined by means of a special mechanism.

Heat for chemical reactions is obtained from three electric arches ignited between graphite electrodes and the mix material. The furnace is powered by a three-phase current with voltage 600 V; the current strength is 10 kA. The electric-arc furnace allows making any atmosphere or vacuum. Electric parameters can be easily regulated so it is possible to maintain necessary temperature in the furnace.

Electric furnaces are intended for melting the high-quality alloyed steels. Fusion lasts 6–7 hours; making one ton of steel consumes approximately 600 kWh electric power and about 10 kg of electrodes.

Electric-induction furnace is the smallest unit for steel melt. Its capacity does not exceed 25 t. Such furnaces are often used at machine-building enterprises for recasting their own steel waste.

An electric-induction furnace represents a refractory crucible placed into an inductor. The inductor is executed of a copper tube wound in the shape of coil through which water for cooling is pumped over. The inductor is connected with an alternating current generator of high frequency 500 to 2,000 Hz. The current creates an alternating electromagnetic field. The field induces eddy currents, or Foucault's currents in pieces of mixture loaded to the crucible. Due to metal electrical resistance to current passage the mixture is heated up and melts; the melt is intensively stirred up.

In these furnaces it is also possible to make any atmosphere. The temperature in the furnace is not too high; therefore, there is no waste of alloying elements. There are no graphite electrodes as in the arc furnace, therefore superfluous carbon does not get into the melt. Induction furnaces are intended for melting the high-quality alloyed steels and alloys, including carbon-free ones are melted.

Stages of steel-making

In each steel-melting furnace the process of fusion includes some stages:

1) *fusion of smelting charge and bath heating*; during this period iron and impurities are oxidized and phosphorus is deleted:

$2Fe + O_2 = 2FeO$;

$Si + O_2 = SiO_2$;

$2Mn + O_2 = 2MnO$;

$CaCO_3 = CaO + CO_2$;

$2P + 5FeO + 4Ca = (CaO)_4{\cdot}P_2O_5 + 5Fe$;

2) *bath "boil"*: high carbon content in the melt is the reason behind forming CO bubbles which produce the effect of boiling; at the same time sulfur is removed according to the reaction as follows:

$2C + O_2 = 2CO$;

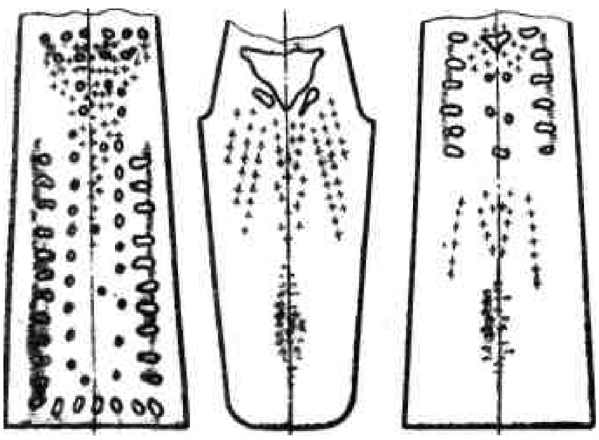
$FeS + CaO = FeO + CaS$;

3) *deoxidizing:* reduction of iron from oxide FeO by means of elements (manganese, silicon, aluminum) more active than iron:

$2FeO + Si = 2Fe + SiO_2$;

4) *alloying:* addition of necessary elements for making alloyed steel; it is carried out at the end of melting or directly in a ladle.

According to the degree of deoxidation steels are subdivided into *killed steels* (completely deoxidized with ferromanganese, ferrosilicon and aluminum), *rimming steels* (deoxidized with ferromanganese only; they “boil” in ingot mould because bubbles of CO rise) and *semikilled*, or *balanced steels* (deoxidized with manganese and silicon).



a *b* *c*

Fig. 5 Ingots of rimming steel *(a)*; killed steel *(b)*, and balanced steel *(c)*

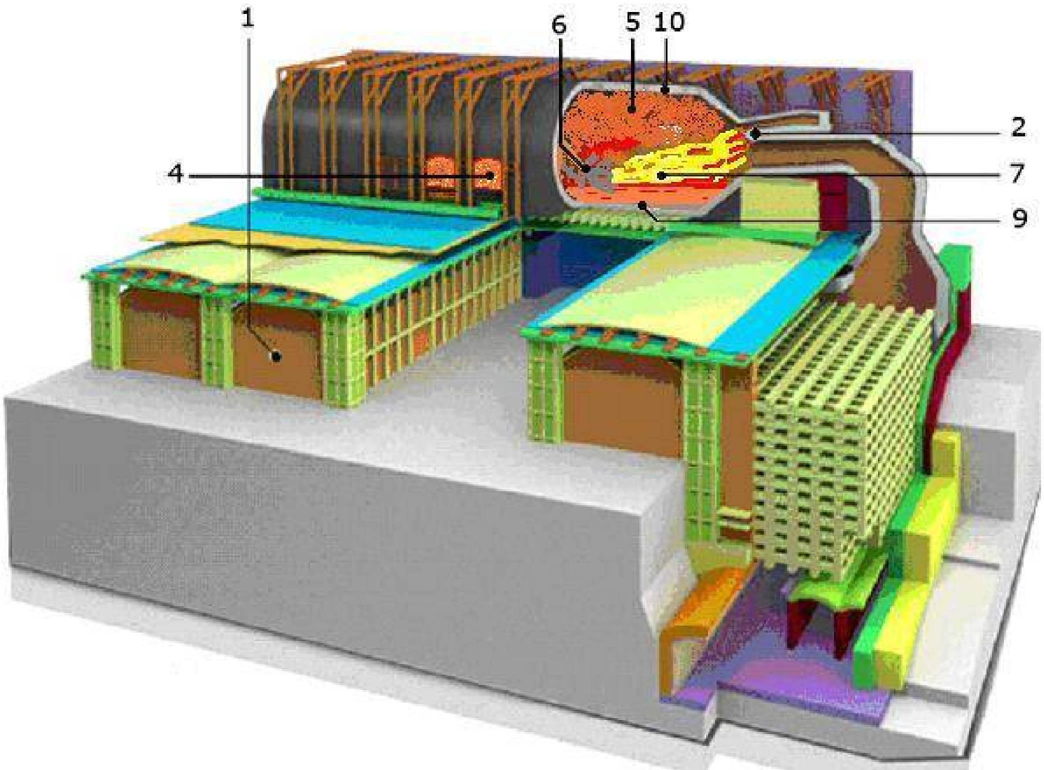
The ingot of killed steel is dense and contains a shrinkage cavity in its top part (Fig. 5, *b*). The ingot of rimming steel contains gas bubbles instead of the shrinkage cavity (Fig. 5, *a*). This steel does not contain nonmetallic inclusions and is more ductile, as it contains less silicon.

Additional Martin furnace description

Martin furnace is a flame reverberatory furnace (see the scheme below).

The furnace works using gaseous or liquid fuel (natural gas or black oil). It has working space 5 limited by hearth 9 from below, by arch 10 from above, and by forward and back walls from the sides. The hearth has the shape of bath. The refractory lining of the furnace can be basic or acid type. If basic oxides prevail in the slag while melting, then the process is called *basic martin process* (lining should be basic). If acid oxides prevail, the process is called *acid martin process* (lining should be acid). The lining of the basic martin furnace is made of magnesite bricks, and the top working layer of the hearth is filled with dead-burned magnesite grain. In a front wall of the furnace there are charging holes 4 for loading mixture into the furnace. In a back wall of the furnace there is a notch for steel. Before fusion the notch is closed with refractory clay.

The furnace has two regenerators 1 for air heating if the fuel is gaseous. The regenerator represents the chamber in which the refractory lining is made of fire-resistant bricks with channels between them. The temperature of gases exhausting from the furnace is about 1,500–1,600°C. Passing through regenerators, they heat the lining up to 1,250–1,280°C. On cooling to 500–600°C the gases leave for pipe 8. Hot air is supplied to furnace head 2 where it mixes with fuel and forms torch 7 directed on mixture 6.



The scheme of Martin furnace

__Pouring of steel__

Melted steel is tapped out into a teeming ladle and then poured into iron moulds for producing ingots of the necessary weight and shape. For pouring a stopper ladle is used. Ingot moulds are filled *from above (top casting)* or *from below (uphill casting)* (Fig. 6). Uphill casting means that some moulds are filled simultaneously. In this case metal loss is greater, but the quality of an ingot is better as filling of a mould with metal goes gently without splashes. Solidified splashes form small solid particles on the ingot surface. They are called metallic shots and complicate further processing of ingots. Carbon steels of ordinary quality are poured by top casting, and alloyed fine quality steels undergo uphill casting.

The most efficient method of steel pouring is *continuous casting* (Fig. 7). Metal from a ladle is tapped into an intermediate pouring device and then goes to a copper crystallizer. The crystallizer has double walls; cold water is pumped over between them; it takes away heat from metal. Passing through the crystallizer aperture, the fused metal begins to solidify. At the output a partially solidified ingot is grasped by pulling rollers and goes to additional cooling with water from spray jets. Speed of pulling out is about 1 m/minute. Finally, solidified shapes are cut into measured pieces using an acetylene-oxygen cutting torch.

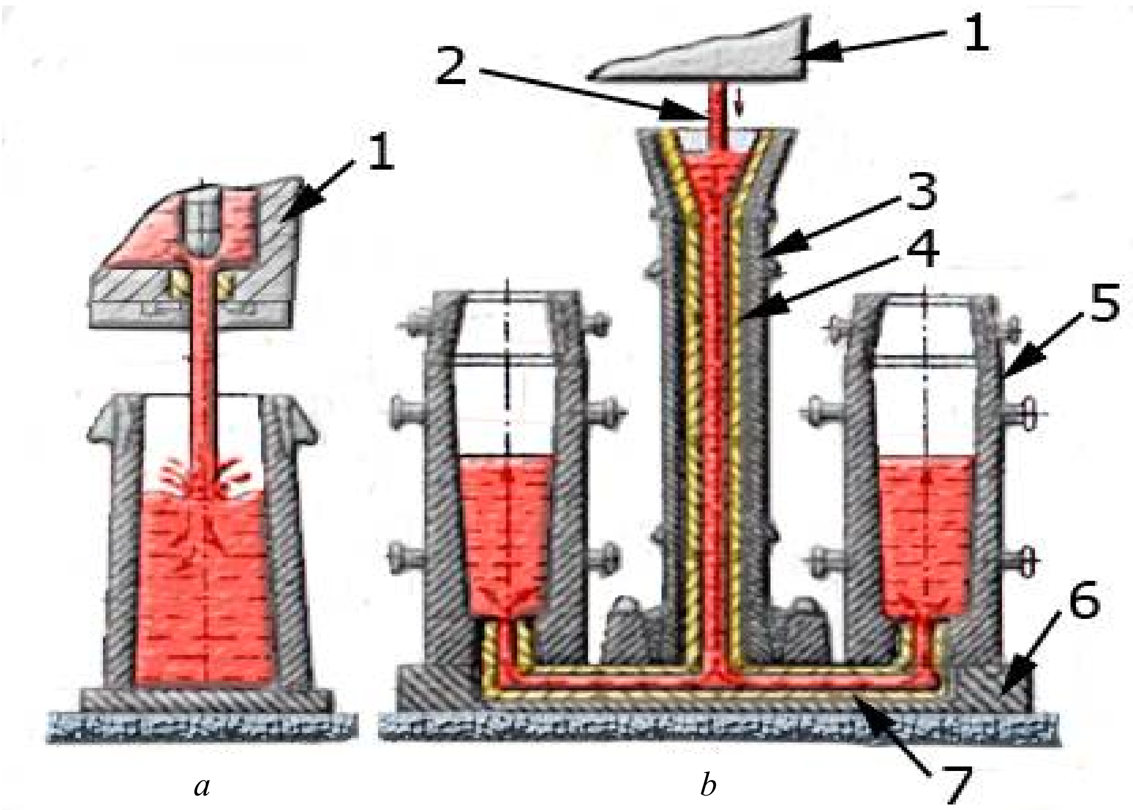
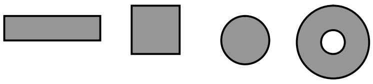


Fig. 6 Normal ingot making: *a* – top casting; *b* – uphill teeming;
1 – ladle; 2 – liquid steel; 3 – central gate; 4 – pipe lining; 5 – ingot;
6 – bottom plate; 7 – fused channel

Continuous-casting machines for steels may have radial, horizontal or vertical design (in compliance with the direction of ingot drawing). The product yield makes almost 98 % for continuous casting. The ingot has a dense, fine-grained structure. The section of any shape can be produced as shown below:



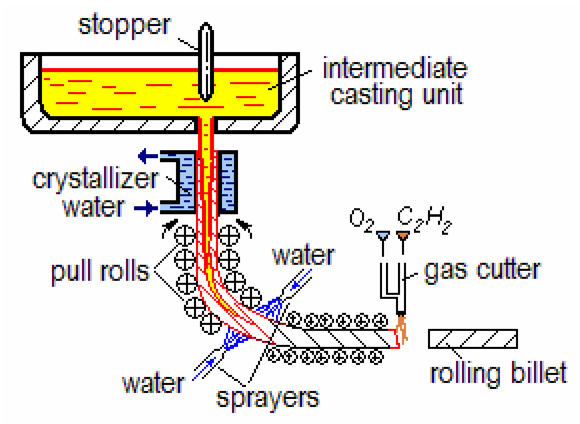


Fig. 7 Continuous casting of steel

Improvement of steel quality

Improvement of steel quality means reducing detrimental impurity content. Harmful or detrimental impurities are sulphur, phosphorus and gases.

Ways of improving steel quality:

1) *Processing by synthetic slag* in a ladle. The fused slag of special composition is poured onto the ladle bottom and then the steel is tapped out to the ladle. Heavier liquid metal falls on the bottom, and slag emerges, thus its particles grasp non-metallic inclusions and gas bubbles. Besides, slag components form compounds with sulphur and extract sulphur from the metal.

2) *Vacuum degassing* in a ladle. When pressure declines above the liquid metal, gas bubbles float up and carry away oxides and other non-metallic impurities from the melt to the slag. Vacuum degassing may be carried out during metal overflow to a mould, to another ladle, or to an intermediate pouring device.

3) *Double remelting: electroslag remelting* (Fig. 8), *vacuum-arc remelting, plasma-arc remelting, etc.* With each of these methods the ingot is gradually melted and small droplets of liquid steel travel either through a liquid medium (slag) or through vacuum. Thus steel becomes clean of gases and non-metallic inclusions. Then metal crystallizes again. Alloyed steels only, especially high-quality ones are subject to double remelting because the process is very expensive.

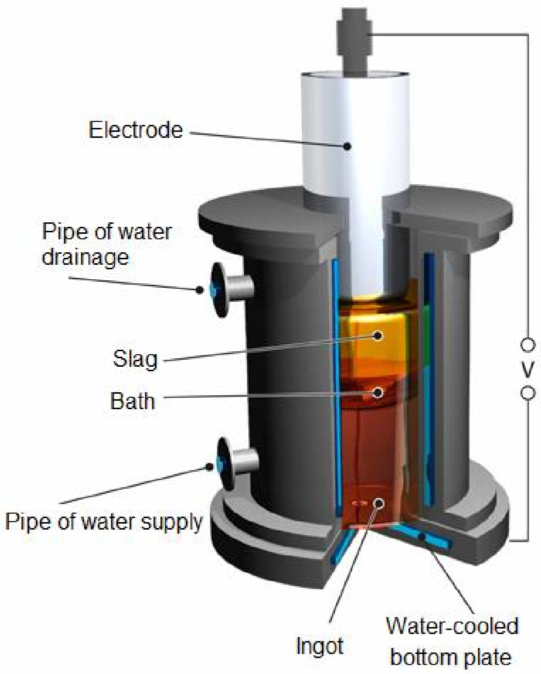


Fig. 8 Electroslag remelting

Reduction of iron from ore out of blast furnace

Reduction of iron out of blast furnace is the most promising trend of ferrous metallurgy development. During last decades there was a necessity to replace the traditional double conversion with the more advanced process. The reasons are as follows.

1) Resource base of coked coals is exhausted.

2) Two auxiliary processes, agglomerate and coke production, considerably surpass the blast-furnace practice in capital intensity, complexities and occupational hazards.

3) Raw materials transportation for the long distances is necessary because resource areas around powerful metallurgical complexes are mined out. (Only two Siberian metallurgical plants demand 15 million tons of ore per year.) Apart from all things ecological balance is upset around the metallurgical centres.

Solution to this problem is a gradual replacement of blast-furnace and steel-melting manufacture for direct steel production from ore and then with continuous metallurgical process "ore – rolled metal".

Till now this problem has not been resolved completely although there is equipment for ore pellets reduction out of a blast furnace as well as the ways of continuous casting and rolling of steel are developed. The idea is simple as to learn how to make continuous melt of steel. Chemical reactions rate does not allow implementing it in modern furnaces.

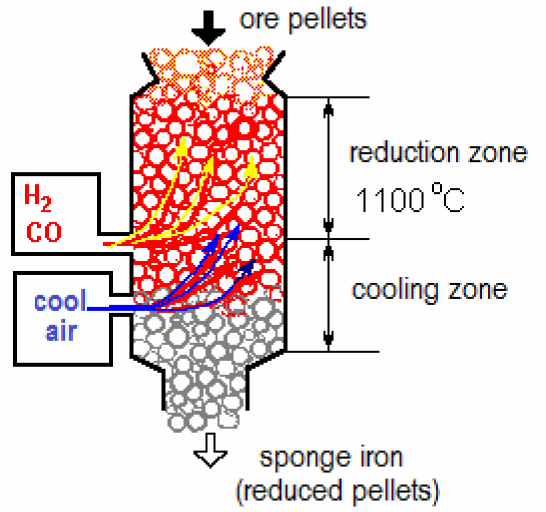


Fig. 9 The scheme of iron pellets manufacture in a shaft counter-flow furnace

Tomsk region has huge potential to become the centre of iron ore mining and possibly steel production. Resources of the Bakchar ore deposit are estimated at level of 12 billion tons. This is enough for 700 years of mining. Hydraulic mining by boreholes is aimed at working out of deposit. Being washed away by a stream of water, the ore (*pulp*) will move to metallurgical plant by pulp feed-line.

Shaft counter-flow furnace (Fig. 9) is an example of successfully working equipment for iron reduction out of a blast furnace. The furnace looks like a shaft into which ore pellets are loaded from its top part. The top part of the furnace is a reduction zone. It is heated up to 1,100°C. Gases CO and H_2 (products of natural gas conversion) move upwards. They reduce iron from oxides contained in pellets. The bottom part of the furnace is a cooling zone where cold air is delivered to. The output product is the sponge iron in the form of pellets (balls). Sponge pellets contain approximately 95 % of iron; the rest is impurities such as manganese, sulfur, and phosphorus. These sponge iron balls are remelted in electric furnaces into steel. Steel produced by this way contains under 0.2 % C.

There are also other ways of reducing iron out of blast furnace: boiling bed reduction, capsule reduction (in the shape of concentric layers).

Part II Metal Forming

Metal forming allows producing metal blanks and parts of machines by methods of plastic deformation.

About 90 % of metal products undergo plastic working when manufactured. The level of usage of metal forming in mechanical engineering specifies the level of this branch as a whole.

Forged products includes both the heaviest and most sophisticated articles (rotors of turbogenerators, screw propellers of sea crafts, reactor vessels of the atomic power stations) and the small goods of day-to-day demand: nails, fixtures, aerosol cans, rivets and buttons.

The reason for that is the following advantages of metal forming in comparison with other kinds of processing:

1) low metal expense;

2) high productivity (it is especially important in mass production of cars, agricultural machinery, consumer goods);

3) high accuracy of sizes and quality of the surface;

4) pressure shaping improves structure and raises mechanical characteristics of metal.

Essential parts of machines such as wheels and axes of railway cars or rotors of turbines undergo pressure shaping without fail.

Forging of native metals has been applied since 8000 year BC. An example of ancient smith skill is the iron column in Delhi, the capital of India. This cylindrical forged column about 42 cm in diameter has not been exposed to corrosion throughout many centuries.

Physical grounds of metal forming

Metal forming is possible due to unique ability of metals to be plastically deformed that is to change the shape without fructure.

Under the loading, the intensity of stress in metal arises. *Stress* in mechanics is a ratio of load *P* applied to the cross-sectional area *F* of a specimen:

$$\sigma = \frac{P}{F}.$$

Pressure growth causes first elastic deformation of metal, then plastic deformation, and, finally, fracture.

Elastic deformation is reversible. Atoms are displaced from their balance positions, and when load removes, they come back to the places. Elastic deformation disappears after removal of loading.

Plastic deformation remains after loading removed. Atoms are displaced at a considerable distance and occupy new steady positions. Metal layers are displaced with regard to each other; a sliding of layers occurs.

When some value of pressure is achieved the interatomic bonds become torn, a crack arises and grows, that is a *fracture* occurs.

In the course of metal forming, it is necessary to reach the value of stress sufficient to start plastic deformation. But the stress must not exceed the value at which the fracture begins. Flow stress is different for each metal and alloy. It is called *yield strength* and is designated as σ_y or σ_{02}. The maximum value of stress which metal maintains without fracture is called *tensile strength* and it is designated as σ_{max}. Magnitude of stress for metal forming should be above the yield strength but below the tensile strength: $\sigma_y < \sigma < \sigma_{max}$.

Laws of plastic deformation

1) The law of conservation of volume: The volume of a body before deformation is equal to its volume after deformation (Fig. 10, *b)*. It is used to calculate the dimensions of blanks.

2) The law of the least resistance: Each point of a deformable body is displaced in the direction of the least resistance. It is used to define product shape after metal forming (Fig. 10, *a)*.

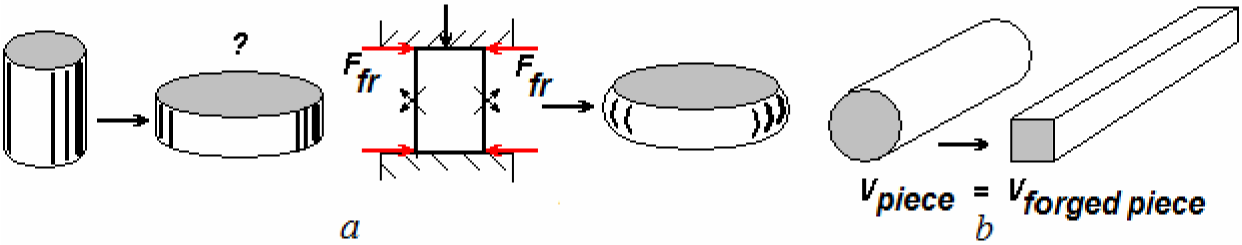


Fig. 10 Barrel shape of a forged piece is caused by friction forces which act between the piece and a hammer block *(a)*; volumes of a piece and a forged piece are equal *(b)*

3) The law of shear stress: Plastic deformation will begin only when shear stress in a deformable body reaches the certain value depending on the nature of a body and conditions of deformation. It is used to calculate the necessary force, or capacity of equipment.

Cold and hot plastic deformation

While heating the metal resistance to deformation considerably decreases i. e. the yield strength decreases. For successful metal forming, it is necessary to control precisely the heating temperatures.

There is a certain temperature for each metal and alloy, named *recrystallization temperature* T_r. It is available in directories, but also can be defined using temperature of melting T_m by the following formulas:

$$T_r = 0.4 \cdot T_m \text{ – for metals,}$$

$$T_r = (0.6 \div 0.7) \cdot T_m \text{ – for alloys.}$$

Note: $T_m = t_m + 273$. (T – temperature in Kelvin, t – temperature in Celsius.)

The recrystallization temperature is a boundary between areas of hot and cold deformation. Deformation at temperatures below t_r is called ***cold deformation*** and above t_r ***hot deformation***.

Values of t_r for some materials:

pure iron – 450 ºC,
carbon steel – 550–650 ºC,
copper – 270 ºC,
led – –33 ºC.

As a result of cold plastic deformation the crystal structure of metal becomes distorted: grains are elongated in one direction; strength increases and ductility decreases. This phenomenon is called *mechanical*, or *cold working hardening*. To deform the hardened metal both higher force and more powerful equipment are necessary. Therefore, cold working is applied rarely, only for the most ductile metals or billets of small section (sheet, wire). Drawing and sheet-metal stamping are usually carried out as cold working. The dimensional accuracy and surface finish are thus reached. There is a possibility to influence on properties of a product by means of different degree of cold working.

In the course of hot working, mechanical hardening is not so important, i.e. metal is not work-hardened. Resistance of metal during hot plastic deformation is approximately 10 times less that of obtained during the cold one. Therefore, it becomes possible to obtain the high strain levels. But in the course of heating scale (a layer of oxides) is formed on the metal surface that affects the surface quality and accuracy of the sizes. Rolling, forging, pressing, die forging are usually carried out as a hot working treatment.

Temperature range of metal forming

To provide deformation in a hot state it is necessary both to begin and finish the processing above the recrystallization temperature. While being forged or rolled, the metal continuously cools down, and it is important not to allow it's cooling below t_r. Therefore, for each metal and alloy they usually define *the temperature range of metal forming* i.e. the onset and end temperatures of hot deformation.

Temperature at the onset of deformation should be 100–200º lower the melting temperature. If this rule is broken (temperature overriding), reject is possible: *overheating* is grain growth in metal over acceptable values; *overburning* is oxidation of grain boundaries. The last kind of reject is irreversible.

Temperature at the end of deformation should exceed the temperature of recrystallization by 50–100º to avoid hardening.

Temperature ranges for metal forming:

Carbon steels – 1,200–900ºC,
Copper – 1,000–800ºC,
Bronze – 900–700ºC.

Billets, especially the large ones, should be heated up slowly because the stress rise due to the temperature difference in the centre and on the perifphery of the billet which may lead to cracking. (A 40-ton ingot must be heated for 24 hours!)

Sometimes to avoid scale formation heating is carried out in protective atmospheres.

Heating of billets

1) The oldest heating device is *forge (hearth, devil)*. Metal is heated up in it in direct contact with the burning fuel such as coke, coal, or charcoal. Now forges are applied only in repair shops.

2) *Chamber flame furnace* (Fig. 11) has identical temperatures throughout the whole working space. Heat source is a flame torch formed by combustion of natural gas or black oil.

3) *Continuous flame furnace* (Fig. 12) consists of several zones with gradually rising temperature. Billets in the furnace move ahead with the help of pusher mechanism or the conveyor.

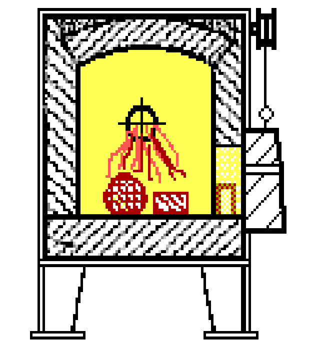


Fig. 11 Chamber furnace

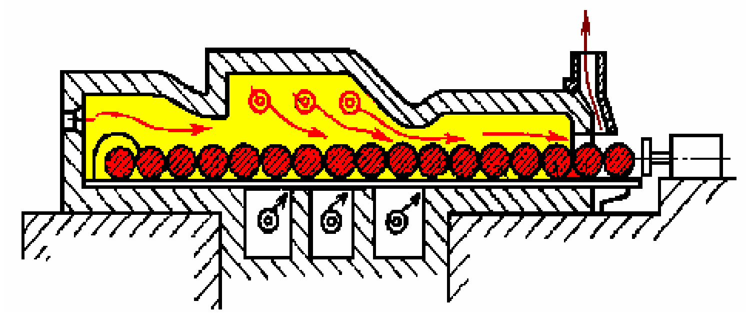


Fig. 12 Continuous furnace

For very large billets *car furnaces* are used: they have a sliding hearth. Loading and unloading is made by means of a frame-crane. *Furnace-wells* are applied for heating ingots weighting ten tons in rolling shops. Their working space is located under the shop floor and a cover – at floor level.

4) *Electric resistance furnaces* have heaters in the form of strips or spirals along all furnace laboratory. The temperature range is supported automatically. By design they can be both chamber and continuous. There is less scale formation in them than in flame furnaces.

5) *Electric heating devices* are based on induction or contact heating (Fig. 13). They are used for heating big parties of identical billets, usually having simple geometrical shapes.

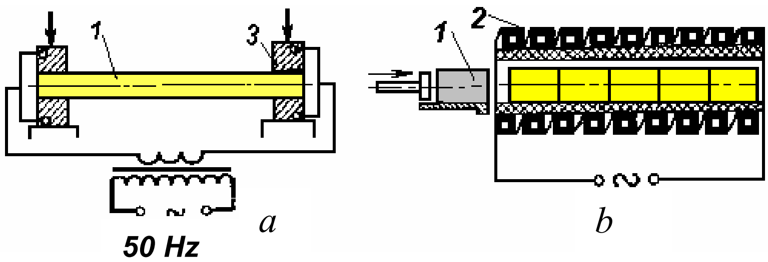


Fig. 13 Electric contact *(a)* and induction *(b)* heaters:
1 – billet; 2 – inductor; 3 – copper contact

Metal forming classification

Metal forming

- Fabrication of shapes
  - rolling
  - pressing
  - drawing
- Fabrication of billets and machine parts
  - forging
  - hot die forging
  - cold sheet-metal stamping

Machine-building shape is a lengthy product with the certain form of cross section. The length of the product significantly exceeds cross-section sizes. Examples are rails, beams, bars, pipes, and wire.

Rolling production

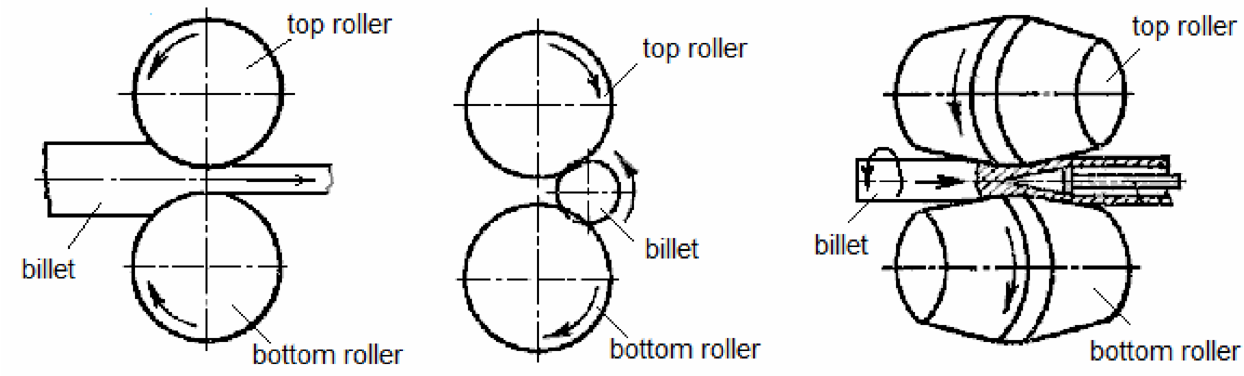
Rolling is a method of metal forming when a metal billet is plastically deformed between the rotating rollers. In this case *friction forces* between rollers and the billet pull the last into the roll space, and *normal forces* perpendicular to the roller surface produce deformation of the billet.

Schemes of rolling

1) ***Longitudinal rolling***: a work-piece is deformed between two rollers rotating in the opposite directions; it moves perpendicularly to the rollers axes (Fig. 14, *a*).

2) ***Cross rolling***: axes of the rollers and a work-piece are parallel; rollers rotating in the same direction impart rotation to the work-piece in the opposite directions (Fig. 14, *b*).

3) ***Helical rolling***: rollers are positioned at an angle to each other and impart rotational and translational movement to a work-piece. Rollers rotate in the same direction (Fig. 14, *c*).



a *b* *c*

Fig. 14 Schemes of rolling:
a – longitudinal; *b* – cross; *c* – helical

Rolling deformation and forces

The metal volume in which plastic deformation occurs during a given moment of time is called *deformation zone*.

Cross-section area *ABCD* of the deformation zone in a drawing plane is shown in Fig. 15. In process of roller rotation the deformation zone moves along with the metal being rolled.

Arch *AB* along which the roller is contacting to the billet metal is called *arch of contact*, and angle α between radiuses of the roller based on the arch of contact is called *angle of nip*.

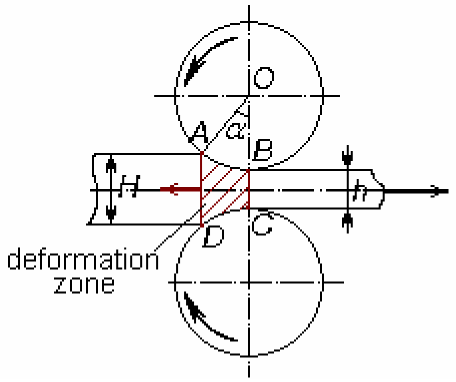


Fig. 15 Rolling deformation zone

A billet is exposed to the action of friction force T directed tangentially with respect to the roller cross section view. It draws the billet into the roll opening (Fig. 16). Normal supporting force N directed along the roller's radius pushes the billet out. For the billet to be drawn into the roll opening the condition should be satisfied $T_x > N_x$, i.e.

$$T \cdot \cos\alpha > N \cdot \sin\alpha;$$

friction force $T = N \cdot k_{fr}$, therefore

$$N \cdot k_{fr} \cdot \cos\alpha > N \cdot \sin\alpha;$$

$$\boxed{k_{fr} > \text{tg}\alpha.}$$

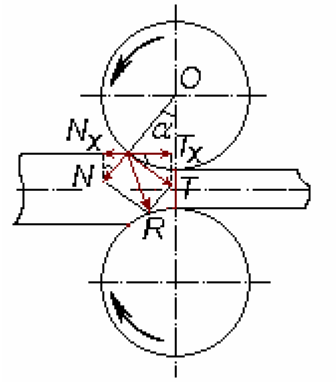


Fig. 16 For calculation condition of nip

Condition of roller bite of metal: the coefficient of friction between the rollers and a billet should be higher than tangent of the angle of nip.

Then friction forces will draw a billet into the rollers opening, and a rolling will start. Otherwise, the rollers will push away the billet.

In the course of hot rolling of steel an angle of nip makes from 15 to 24°, and at cold rolling – from 3 to 8°. It means that hot rolling allows reducing height of billet H in a greater extent as compared to cold rolling since friction force in hot deformation is higher than that of in the cold one.

Deformation in the course of rolling is defined by two factors: relative squeezing ε and draft coefficient μ.

Relative squeezing is calculated as $\varepsilon = \dfrac{H-h}{H} \cdot 100\%$, where $\Delta H = H - h$ is reduction in thickness, mm;

draft coefficient $\mu = \dfrac{l}{l_0} = \dfrac{F_0}{F}$, where l_0 and F_0 are length and cross-section of a billet before rolling, l and F – after rolling.

Relative squeezing is usually 40–60 % for rolling, and draft coefficient μ = 1.2–2.0.

Tools for rolling

Tools for rolling are *rollers* (Fig. 17). The working part of a roll is called *body*; *roll necks* serve as support for bearings; a shaped projection named *roll wobbler* is necessary for transferring rotation from a drive to the roller. Rollers are a twin tool: a rolling mill stand consists of two or more rolls (but not of one).

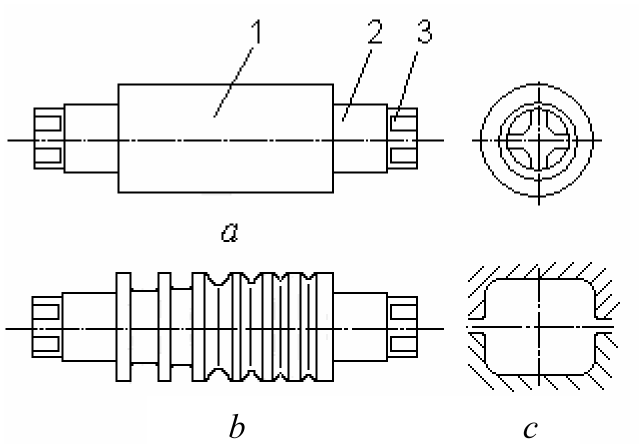
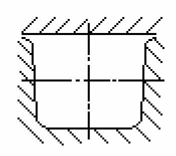


Fig. 17 Rollers: flat *(a)* and grooved *(b)*:
1 – body; 2 – roll neck; 3 – roll wobbler; *c* – pass

Depending on the working part's shape, the rollers can be *flat* (Fig. 17, *a*), step and *grooved*

(Fig. 17, *b*). Flat rollers serve for rolling sheets. Grooved rollers have grooves on their lateral surface. When top and bottom rollers interlock their grooves form a gap of the certain shape called *pass* (Fig. 17, *c*). The cross-section of a billet being rolled takes the shape of a pass. Grooved rollers serve to manufacture sectional bars.



A pass shown in Fig. 17, *c* is called *open pass* as the split line of rollers goes through the pass; in the opposite case (the split line of rollers goes out of the pass) a pass is *closed*.

Equipment for rolling

A set of rollers with mill housing forms a *working stand*. The working stand with a transfer mechanism and an electric motor is *a working line of a rolling mill* (Fig. 18). The transfer mechanism consists of a reducer, a pinion stand, spindles and clutches. The reducer decreases the number of revolutions of the electric motor, the pinion stand transfers rotation from one shaft to two spindles for driving both rollers. The screwdown structure regulates the position of the top roller, i.e. roll setting.

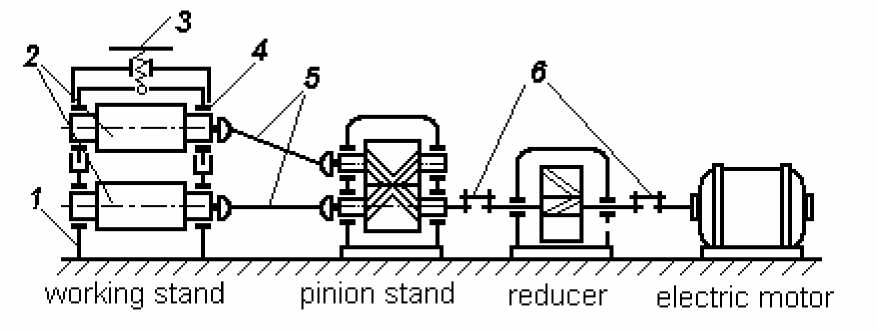
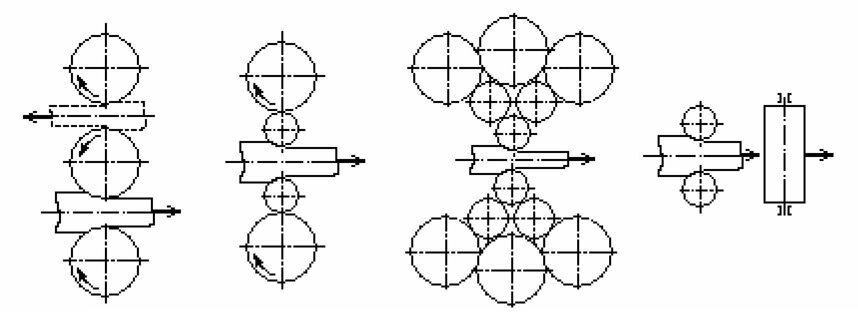


Fig. 18 Single-stand rolling mill:
1 – mill housing; 2 – rollers; 3 – screwdown structure; 4 – bearings;
5 – spindles; 6 – clutches

<u>Depending on the number of rollers</u> the rolling mills stands can be divided into *two-high (duo)* stands, *three-high (trio)* stands, *four-high (quarto)* and *multi-roll* stands (Fig. 19).

In a three-high stand a billet is rolled first between bottom and average rollers and then in the opposite direction, between average and top ones.

If there are four rollers in a stand, two of them are work rollers, and two others bigger in diameter are supporting rollers. They are necessary to reduce the deformation of work rolls.



a *b* *c* *d*

Fig. 19 Stands of rolling mills:
a – trio stand; *b* – quarto stand; *c* – multiroll stand; *d* – universal stand

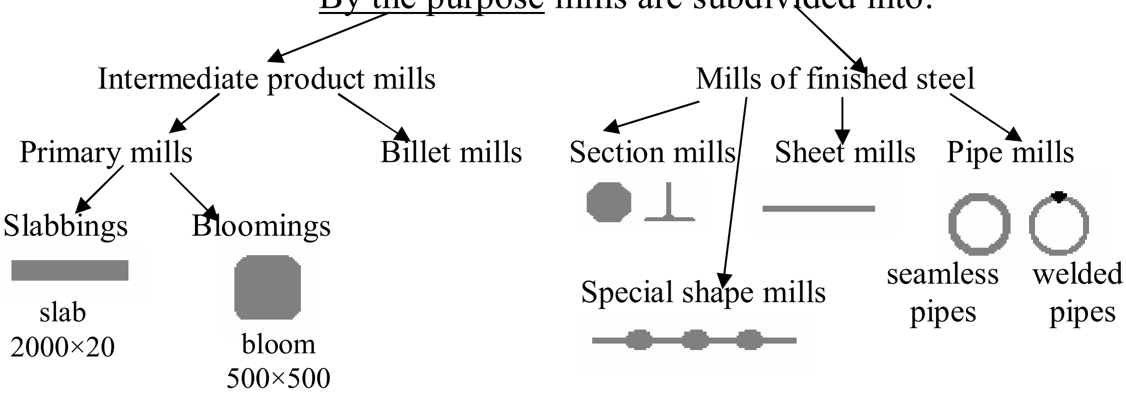
In multiroll stands the work rolls are driveless so that rotation is transferred to them by drive rollers, and the latter, in turn, rest on big supporting rollers. In such a way the minimum deformation of work rolls and a pinpoint accuracy of the billet sizes are reached.

Universal stands with two pairs of rollers, one of which is located horizontally, and another – vertically, allow processing lateral faces of a billet. It is necessary for thick sheets, plates and wide I-beams.

The most powerful rolling mills, such as blooming and slabbing have the *reversing* stands where the direction of rolls rotation is changed after each pass.

According to the number of working stands the rolling mills can be divided into single-stand mills and multistand mills. *Multistand continuous mills* are the most up-to-date equipment. A strip of metal is rolled simultaneously in the several stands on them.

By the purpose mills are subdivided into:



The blank parts for manufacturing all sorts of roll stock are ingots which are rolled to blooms or slabs on primary mills. Then blooms go to billet mills, and after that billets go to the section mill or the pipe mill. Slabs are rolled to sheet steel on the sheet mills. Periodic roll stock is fabricated from intermediates of the appropriate cross-section; piece blanks (rings, wheels) are rolled from separate castings or stamped pieces. Balls are made from bars.

Products of rolling shops

The whole variety of rolled sections is called *assortment*. The assortment is divided into four groups:

1. *Sectional iron* includes simple and shaped sections (Fig. 20).

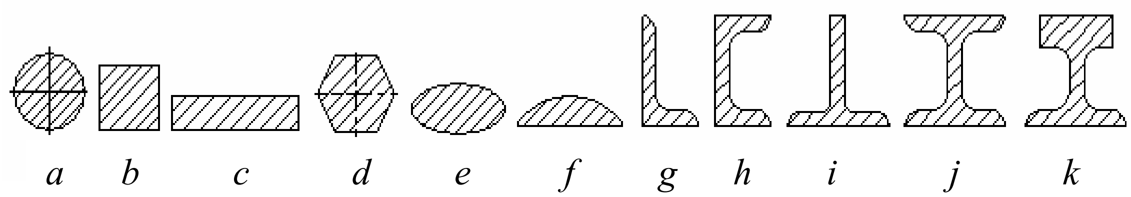


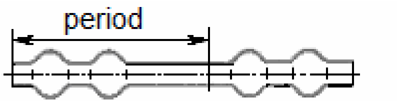
Fig. 20 Sections of rolled metal – simple *(a–f)* and shaped *(g–k)*:
a – circle; *b* – square; *c* – strip; *d* – hexagonal steel; *e* – oval; *f* – segmental steel; *g* – angle; *h* – channel; *i* – T-beam; *j* – I-beam; *k* – rail

2. *Rolled sheet* includes thick sheet (more than 4 mm in thickness), thin sheet of thickness less than 4 mm and foil of thickness less than 0.2 mm. The maximum thickness may be 160 mm (armor plates).

By application the rolled sheets are subdivided into automotive sheet steel, Armco iron, core iron, roofing iron etc. The sheets can be covered with zinc, tin, aluminum, or plastic.

3. *Pipes* may be *seamless* (30 to 650 mm diameter, wall thickness 2 to 160 mm) and *welded* (5 to 2,500 mm diameter, wall thickness 0.5 to 16 mm).

4. *Special shapes* are rings, balls, gears, wheels, periodic shapes. Periodic shapes are used for producing stamped pieces and cutting parts with minimum waist.



Lecture 5

Pressing

Pressing is a process of product manufacture by extrusion of hot metal from the closed cavity (*container*) through a tool's hole (*matrix*, or *die*). There are two ways of pressing: direct and reverse. In the course of *direct pressing* (Fig. 21, *a*) metal is squeezed out in the direction of punch movement. In the course of *reverse pressing* (Fig. 21, *b*) metal flow direction coincides with that of the punch movement.

The part blank for pressing is an ingot or a hot-rolled bar. In order to obtain a surface quality after pressing the billet may be lathe machined and even grinded.

Billets are heated in induction devices or in bath furnaces in melted salts. Nonferrous metals such as alumimium or copper can be pressed without heating.

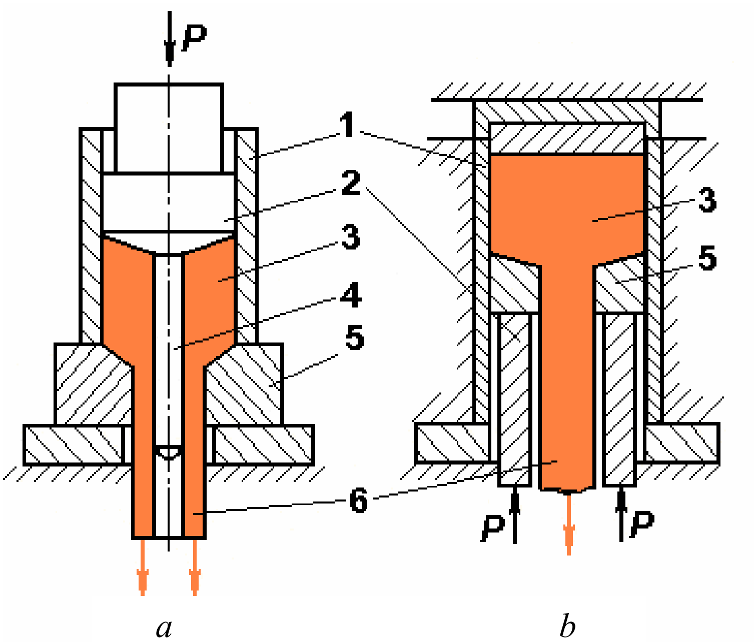


Fig. 21 Direct pressing *(a)* and reverse pressing *(b)*:
1 – container; 2 – punch; 3 – work-piece; 4 –needle; 5 – matrix; 6 – section

Pressing deformation

For pressing the scheme of all-round non-uniform compression is realised, thus there are no tensile stresses in a metal. Therefore, it becomes possible to press even the low ductility alloys, for example, tool steels. Even such brittle materials as marble and pig-iron can be pressed without cracking. It means that by the use of pressing it is possible to process materials which cannot be deformed by other methods because of their low ductility.

The draft coefficient μ may reach 30–50 for pressing.

Tools for pressing

The tools are a container, a punch, a matrix, and a needle (for producing of hollow shapes). The shape of a product is defined by the shape of a hole in a die; the cross section of a hole in a profile is defined by one of a needle. Tool service conditions are severe and characterised by high contact pressure, wear, temperatures up to 800–1,200°C. Therefore, tools are made of high-quality tool steels and heat resistant alloys.

To reduce friction solid lubricants are applied being chosen from a row as follows graphite, nickel and copper powders, molybdenum disulphide.

Equipment for pressing

These are hydraulic presses with a horizontal or vertical arrangement of a punch.

Pressing production

Pressing gives simple profiles (a circle, a square) from low ductility alloys, and profiles of very complex cross-sectional shapes which cannot be produced by other methods of processing by pressure (Fig. 22).

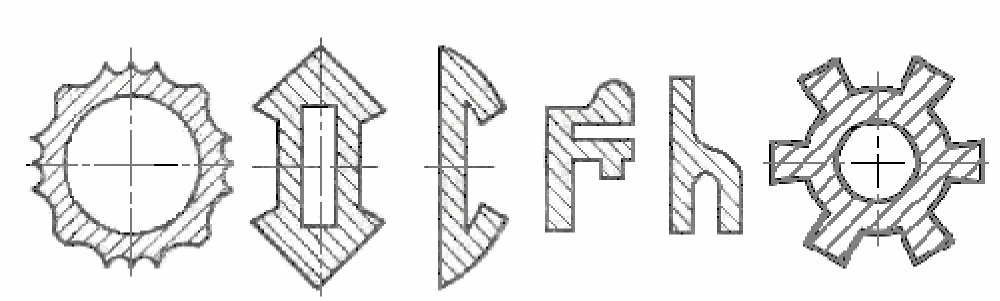


Fig. 22 Pressed sections

Advantages of pressing

Size accuracy of pressed sections is higher than that of rolled ones. It has been already mentioned above, that it is possible to make profiles of the most complex cross-sectional shapes. Process is versatile in the sense that change over from one size to another and from one shape to another can be easily carried out because change of the tool does not take much time.

The process is highly efficient due to the fact that high strains are achieved in combination with speed of pressing as high as 5 m/s and even higher. Ready item is produced for one stroke of the tool.

Disadvantages of pressing

The large waste of metal (*press rest* is about 10–20 %) as all the metal cannot be squeezed out from the container; non-homogeneity of deformation in the container; high cost and severe wear of the tool; necessity to be provided with powerful equipment.

Drawing

Drawing is manufacturing of shapes by pulling a billet through gradually narrowing aperture in the tool which is called as drawing die.

A part blank for drawing is a bar, a thick wire or a pipe. The part blank is not heated up, i.e. drawing is a cold working process.

The end of a blank is pointed, pulled through the drawing die, then clumping device grasps it and stretches (Fig. 23).

Drawing deformation

In the course of drawing metal is stretched by tensile stresses. Metal should be deformed only in the narrowing channel of a die; outside of the tool deformation is inadmissible. Reduction per pass is insignificant: draft coefficient μ = 1.1÷1.5. For producing the necessary shape the wire is drawn through a set of dies having successively smaller diameter.

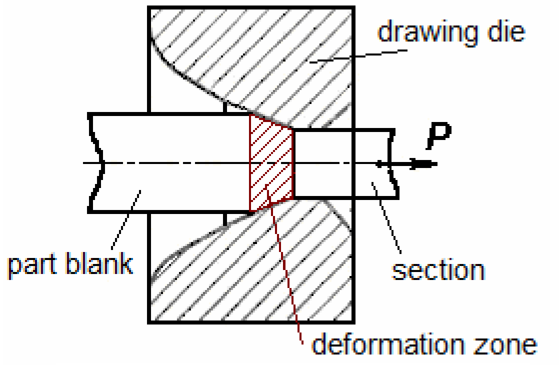


Fig. 23 Scheme of drawing

Since deformation is carried out under ambient temperatures, the metal becomes cold-worked, its strength and hardness increase with deformation. Therefore it is necessary to carry out *annealing* (heating above the recrystallization temperature) in tubular furnaces before drawing through the next smaller diameter dies. Annealing relieves cold-working hardening so that annealed metal becomes ductile again and capable of further deformation.

Tools for drawing

The tool is a *drawing die*, representing a ring with a profiled hole. Drawing dies are made of hard alloys, ceramics, and technical diamonds, the latter are used for drawing very thin wire less than 0.2 mm in diameter. Friction between the tool and a billet is reduced by means of grease lubricant. To obtain hollow shapes mandrels are applied.

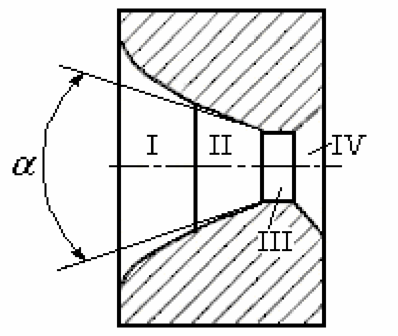


Fig. 24 Drawing die

The working hole of a die has four characteristic zones along its length (Fig. 24): I – inlet area, or lubricant zone, II – deforming, or the work zone, with angle $\alpha = 8 \div 24°$, III – calibrating zone, IV – a dieback.

The average wire diameter tolerance is about 0.02 mm.

Equipment for drawing

There are *draw benches* of various designs including drum-type, rack, chain, with a hydraulic drive, etc.

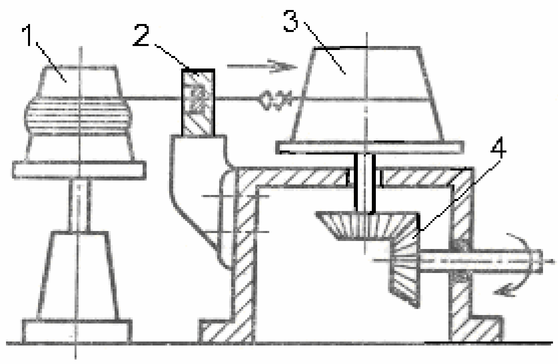


Fig. 25 Drum-type drawing bench:
1 – whirly with a coil of wire;
2 – die; 3 – dram; 4 – gear transmission

Drum-type benches (Fig. 25) are applied for drawing wire, small diameter bars and pipes which can be wound in coils. Drum-type bench of continuous drawing includes 2 to 20 drums; between them there are drawing dies and annealing furnaces. Speed of wire drawing is between 6 and 3,000 m/min.

Chain draw bench (Fig. 26) is intended for making bars and pipes with the large cross section area. The length of a product obtained is limited by the length of a bed (up to 15 m). Drawing of pipes is carried out using mandrels.

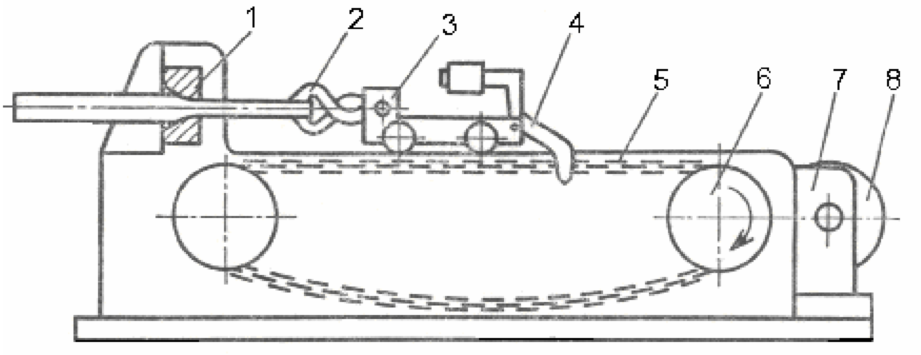


Fig. 26 Chain draw bench:
1 – die; 2 – draw vice; 3 – slide; 4 – draw hook; 5 – chain;
6 – drive sprocket; 7 – reducer; 8 – electric motor

Drawing production

Drawing is used for manufacturing 0.002 to 5 mm diameter wires, as well as bars, shaped sections (guides, keys, spline shafts) and pipes (Fig. 27).

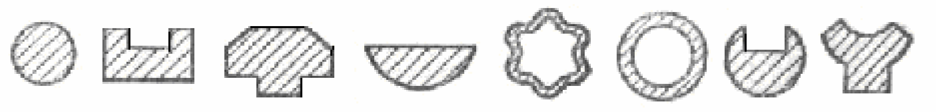


Fig. 27 Drawn sections

Advantages of drawing

They are as follows: high dimensional accuracy (tolerances not more than 100-th share of mm), low surface roughness, feasibility of thin-walled shapes, high efficiency, small quantity of waste. Process is versatile enough to replace the tool simply and quickly, therefore it is widespread.

The important feature is that it is capable of changing the properties of products made by means of cold-working and heat treatment.

Disadvantages of drawing

Inevitability of cold-work and necessity of intermediate annealing makes the process tedious. Reduction per pass is limited to small values.

Lecture 6

Forging

Forging is manufacturing of products by consecutive deformation of a heated billet by blows of a universal tool – hammer heads. The obtained so workpiece or finished article is called *forged piece* (Fig. 28).

Part blanks for forging are usually ingots or blooms, sectional rolled metal of a simple shape. Billets are heated in the chamber furnaces as a rule.

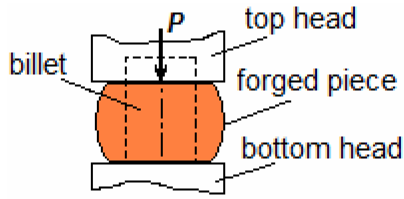


Fig. 28 Scheme of forging (upsetting)

Forging deformation

Deformation in the process of forging is accomplished by free plastic flow between the tool surfaces. Deformation is carried out sequentially on separate parts of a billet; therefore, the area of billet surface can exceed considerably the area of heads.

Setting ratio is a measure of deformation: $SR = \frac{F_{max}}{F_{min}}$,

where $F_{\max}$ and $F_{\min}$ are initial and final cross-section areas of a billet; it should be kept in mind that the ratio of a bigger cross-section to a smaller one is always used, therefore, forging reduction always exceeds 1. The higher the setting ratio is, the more severe metal is forged. Some of the forging operations are shown in Fig. 29.

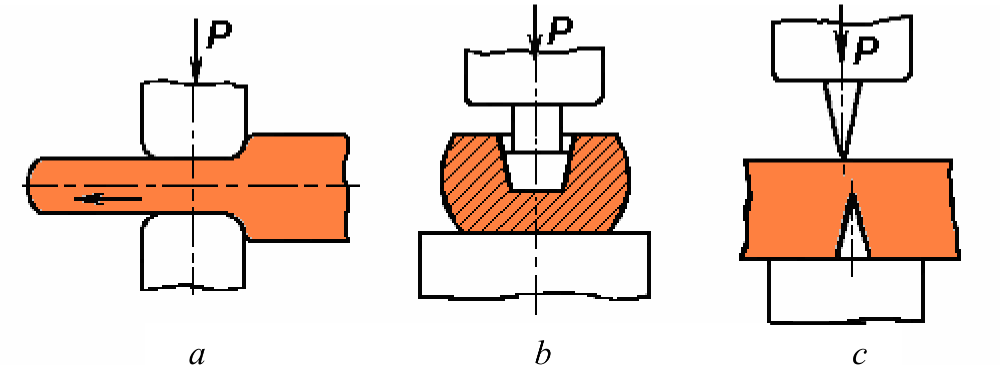


Fig. 29 Forging operations:
a – draw; *b* – piercing (making a hole); *c* – chipping (division onto parts)

Tools for forging

Forging tools are versatile and can be applied for forged pieces of various sizes and shapes: flat heads or cutout ones and a set of laid under tools (mandrels, necking, piercing mandrels etc.).

Equipment for forging

Forging is carried out by machines of dynamic or impact action – *hammers* and static action – *hydraulic presses*.

Hammers are subdivided into *pneumatic* hammers with the mass of dropping parts below 1 t, and *the air-steam* hammers with mass of dropping parts below 8 t. Hammers transmit their kinetic energy to a billet by impacting it for a fraction of a second. A working medium used for driving hammers is either compressed air or steam.

Hydraulic presses may develop force about 100 MN and intended for machining the heaviest ingots. They hold a work-piece between heads during tens of seconds. The working medium in them is a fluid (water emulsion, petroleum oil).

Forging production

Forging is often applied in individual and small-scale manufacturing, especially for production of heavy forged pieces. Forging is the only way to make products from 300-ton ingots. These are shafts of hydrogenerators, turbine disks, crankshafts of ship engines, rollers of rolling mills.

Advantages of forging

First of all, it is the versatility of the process, which allows to get various products. No complex shaped tools are required for forging. Forging improves the metal structure in a manner that fibres in a forged piece are located favourably to sustain loading during exploitation, the cast item grain structure is refined.

Disadvantages of forging

Disadvantages include low productivity of the process and necessity of considerable allowances for machining. Finished forged pieces are characterized by a low accuracy of sizes and a high roughness of the surface.

Hot die forging

Hot die forging is a process of metal parts manufacturing by plastic deformation of a heated billet using a special tool called *stamp (a die)*. The stamps are designed to confine the metal flow by the hollows made in halves of a stamp which form a closed cavity when impacting each other through the work-piece.

Part blanks for hot die forging are usually sectional rolled metal of a simple shape. The product obtained is called *a stamped piece*.

Die forging may be carried out using both open and closed stamps. *Open stamp* (Fig. 30, *a*) has a backlash along all the perimeter of a cavity – *a fin groove* where up to 20 % surplus of metal is extruded.

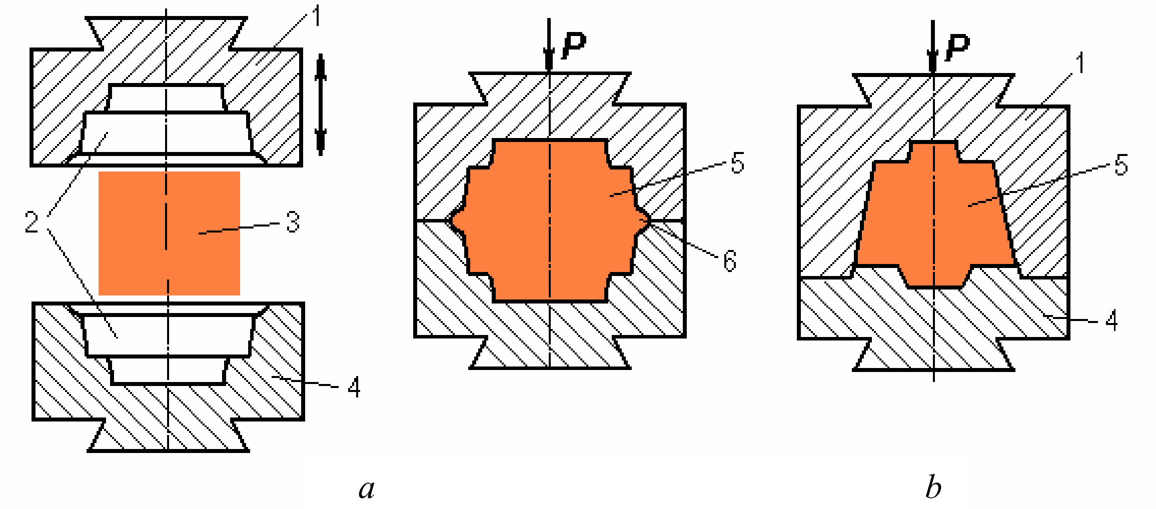


Fig. 30 Scheme of open die forging *(a)* and closed die forging *(b)*:
1 – top die; 2 – hollows; 3 – billet; 4 – bottom die;
5 – stamp cavity; 6 – fin groove

The surface of a stamp splitting is flat. In the course of stamping a split-hair accuracy of metal cutting is not required. The volume of a billet is higher than the volume of a stamped piece by the value of a fin which is cut off afterwards. The narrow bridge of a fin groove guarantees filling of the whole stamp cavity with metal as it creates the greatest resistance to the metal flow.

For die forging in *closed dies* (Fig. 30, *b*) the billet volume is equal to the volume of a forged piece since no the fin groove is present. It is necessary to maintain precisely the sizes of a billet and place it strictly on the stamp centre, otherwise stamp halves will not be closed, and there will be no complete filling of the whole cavity. The surface of a stamp splitting is more complex with a conic guide part.

Closed die forging is more advantageous as compared to the open one: metal is saved (there is no fin), and fibres are located more favourably, rounding the outline of a piece, they are not cut while the fin is being removed.

But the design of closed stamps is more complex, their manufacturing is more expensive and durability is lower.

Die forging deformation

Deformation is carried out simultaneously on the total surface area of a billet, it is impossible to deform only its part. Therefore, the value of the setting ratio rarely exceeds 2–3.

Tools for die forging

A stamp or a die is a special tool. A drawing has to be developed for each forged part when making the stamp. Allowances for machining and shrinkage while cooling are to be provided. For free removal of a forged piece from a stamp 3–10º tapers are specified. Surfaces are conjugated by their radiuses.

Using a stamp with one splitting it is impossible to make a through hole, it is only marked. After forging it is necessary to cut off a fin in special stamps and to punch a scab.

The stamp is fastened to the slider of a stamping hammer or a press by means of a ledge named "dovetail" and wedges.

Equipment for die forging

1) *Steam-air die hammers* are similar to forging ones. Hammers make 3–5 blows for filling of the stamp cavity with metal.

2) *Crank stamping presses* (Fig. 31) have higher efficiency as compared to that of hammers. Die forging is conducted for one blow as the length of a slider stroke is strictly regulated. The presses are more expensive.

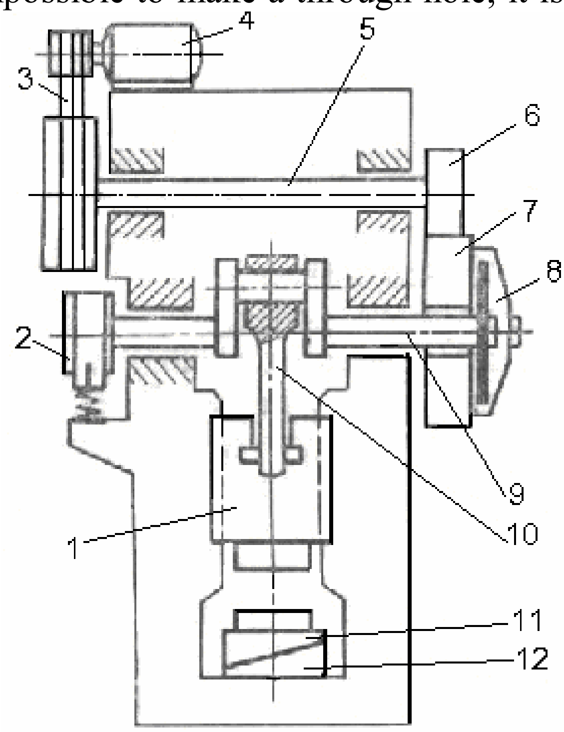


Fig. 31 Crank stamping press

From electric motor 4 movement is transmitted by V-belts to pulley 3 and shaft 5. Gearwheels 6 and 7 by means of frictional disk clutch 8 can be linked with crank shaft 9. The shaft transfmits movement to a connecting rod 10, the rod transforms rotary motion to back-and-forth motion of slider 1. Brake 2 is necessary to stop the rotation of the crank shaft. The height of plate 11 can be regulated by wedge 12 establishing a stamp in the necessary position.

3) *Upsetting machines* (Fig. 32) are applied for forging of parts in the shape of a bar with a flange, a barrel, and a ring. They make it possible to obtain the through-holes because stamp consists of three parts such as floating die, fixed die, and punch.

4) *Hydraulic presses* are applied on heaviest forged pieces (under 3 t).

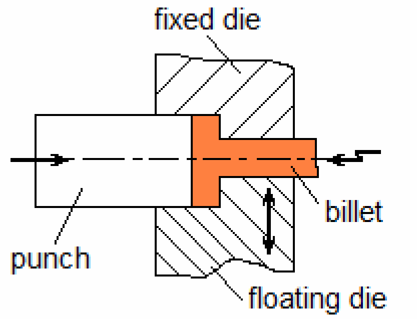


Fig. 32 Scheme of upsetting machine die forging

Application of die forging

Die forging is used for a large-scale production of forged pieces.

Advantages of die forging

In comparison with forging, die forging provides both higher productivity and pinpoint accuracy with allowances being lower by a factor of 2–3.

Disadvantages of die forging

Disadvantages include are high cost of the tools and necessity for having high capacity equipment. Die forging does not allow deforming heavy ingots of ten and hundred tons' weight.

Also there is ***cold massive forming***. It comprises processes *of cold expression* (like pressing) for manufacturing cylinders and tubes from ductile metals, *cold heading* (manufacturing of nails, bolts, rivets) and *stamping* (mint coins, medals, badges).

Cold sheet-metal stamping

Cold sheet-metal stamping is a process of making both flat and volume products from metal sheets, strips, tapes.

Part blanks usually have thickness not more than 10 mm.

Operations of sheet-metal stamping are distinguished as *shearing operations* (the integrity a billet is broken) and *forming operations* (no broken integrity is admissible).

Examples of shearing operations are die cutting and punching. They are carried out according to the same scheme (Fig. 33, *a*), but *die cutting* forms the external perimeter of a blank, and *punching* forms internal one. A stamp consists of a punch (top die) and a matrix (lower die). From their sharp edges the propagation of cracks begins. Cracks meet, and a part of the blank separates.

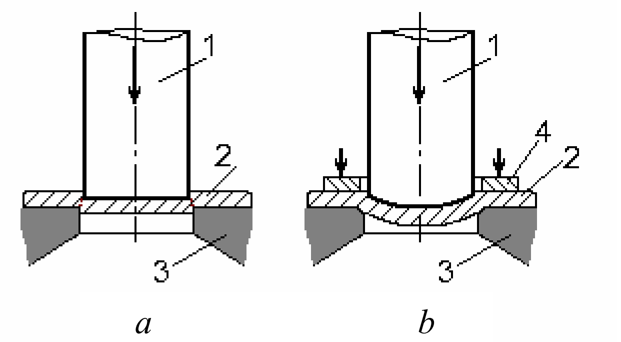


Fig. 33 Scheme of die cutting *(a)* and cupping *(b)*:
1 – punch; 2 – metal sheet; 3 – matrix;
4 – hold-down tool

Example of forming operation is *cupping* – making a volume product from a flat blank (Fig. 33, *b*). The punch and the matrix for cupping have rounded edges. The clip (hold-down tool) excludes formation of folds on a flange. In the course of cupping it is possible to reduce the thickness of a wall approximately by 2 times, but the product bottom remains of the same thickness.

Cold sheet-metal stamping deformation

Cold deformation leads to metal hardening, therefore sometimes it is necessary to anneal the cold worked pieces. Cold sheet-metal stamping is applicable only for ductile metals and alloys: low-carbon steels, alloys based on aluminium, copper, titanium.

Tools for cold sheet-metal stamping

It is necessary to use a special tool for each operation and for each size of a product. The tools are matrixes and punches of the suitable shape.

Equipment for cold sheet-metal stamping

Crank stamping presses and hydraulic presses (for thick sheets) are used for cold sheet stamping. Methods of high-speed sheet stamping with the use of energy of explosion or the electric discharge are developed too.

Application of cold sheet punching

Cold sheet-metal stamping is applied for fabrication of low weight products, but having both high durability and rigidity. It is widely spread in aircraft engineering or in manufacture of cars and tractors.

Brief description of methods of metal forming is given in Table 1.

Table 1

Methods of metal forming

Name	Place of defor-mation	Tool	Equipment	Billet	Heating	Deformation value	Products
Fabrication of shapes							
Rolling	Roller opening	Rolls or rollers	Rolling mill	Ingot, bloom, slab, in-termediate product	Hot deforma-tion as a rule	$\mu \le 2$	Sections, sheets, pipes, special shapes
Drawing	Hole of drawing die	Drawing die	Drawing bench	Bar, pipe, hot-rolled wire	Cold deforma-tion	$\mu \le 1{,}5$	Wire, gauged bars and pipes, shaped sections
Pressing	Matrix hole	Matrix, needle	Hydraulic press	Ingot, hot-rolled wire	Usually hot deformation	$\mu = 30 \div 50$	Simple and shaped sections, tools
Fabrication of billets and machine parts							
Forging	Between heads	Heads, laid un-der tools	Hammers and presses	Ingot, bloom, sections of simple shape	Hot deforma-tion	$FR \le 20$	Wide range of forged pieces not over 300 t
Die forging	Die cavity	Die (stamp)	Hammers and presses, crank stamping press, upsetting ma-chine	Sections of simple shape	Hot deforma-tion more of-ten	$FR \le 2 \div 3$	Stamped pieces of series manufacture not over 3 t
Cold sheet-metal stamping	Gap between punch and ma-trix	Punch and ma-trix	Crank stamping press, hydraulic press	Sheet, strip, tipe	Cold deforma-tion	-	Flat and volume parts having small mass and high strength

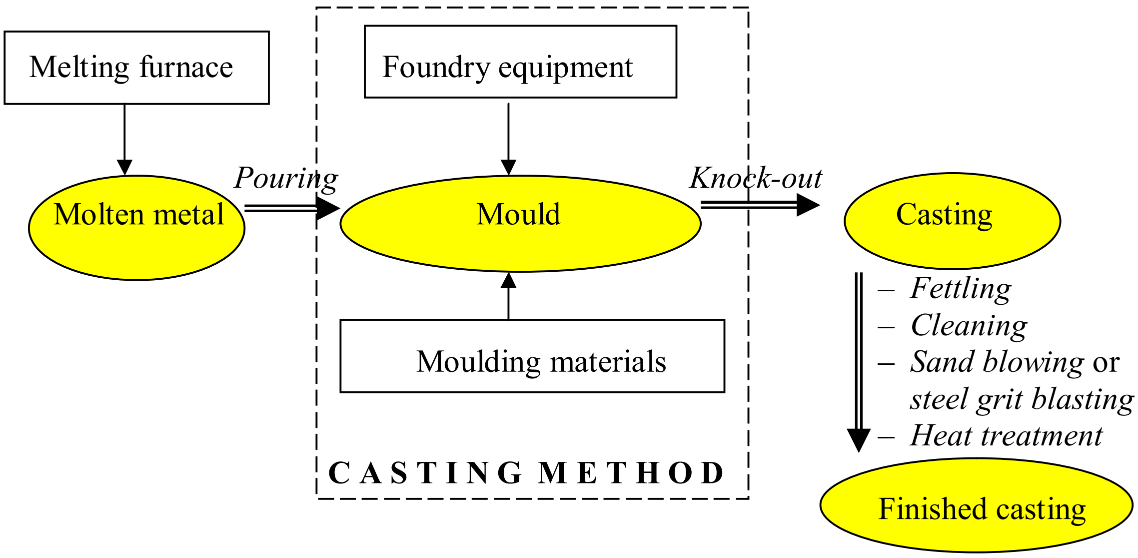
Part III Foundry Production

The problem ***of foundry production*** is manufacture of billets and machine parts by pouring fused metal into a casting mould, whose cavity has the shape of the billet. After crystallization the solid metal keeps the shape of the cavity. The billets are called *castings*.

Castings may be of variety weights and sizes. The heaviest castings weigh below 300 t; the maximum length is about 20 m, and walls thickness is less than 500 mm.

There is a set of ways of moulding distinguished on the basis of material of the mould, operations for its manufacturing, variants of liquid metal pouring into the mould and other signs.

Scheme of casting process



Casting characteristics of alloys

There are wrought alloys intended for making products of using plastic deformation (metal forming methods), and there are cast alloys which can be preferentally used only for making as-cast components. Also there are alloys, which are suitable both for moulding and for metal forming, for example, bronze. Cast iron is intended for foundry only.

The cast alloys should possess the good running quality, small linear and volume shrinkage, no susceptibility to cracking and formation of gas voids and porosity.

1. *Running quality (fluidity)* is the ability of a liquid alloy to flow along the mould channels, fill all its cavities and reproduce precisely the casting shape.

Running quality is determined by pouring a liquid metal in a technological spiral test (Fig. 34). The measure of running quality is the length in millimetres of the spiral channel filled with the metal. There are alloys which are capable of flowing along the mould channels easily like water, while others alloys are viscous and flow slowly like honey.

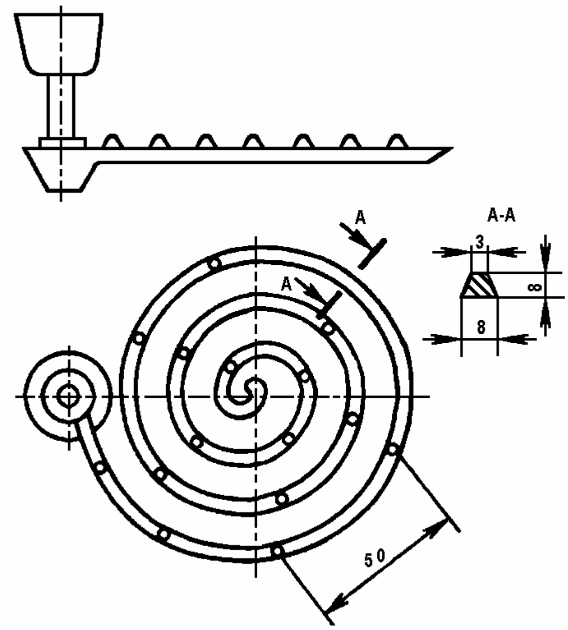
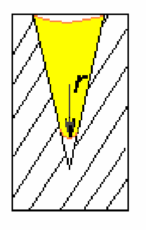


Fig. 34 Technological test for running quality determination

Running quality of the best foundry alloys – grey cast irons – reaches 1500 mm; magnesium alloys fill only 200 mm.



For the estimation of the running quality in the course of art moulding the wedge test is carried out: the less *r*, the better fluidity.

To improve the fluidity it is possible to overheat the alloy strongly before casting or to pre-warm the mould.

2. *Shrinkage* is the reduction of the linear sizes and alloy volume upon cooling.

All metals (except Bi) reduce their volume upon crystallization; it is known that while cooling the solids are compressed due to decreasing the average interatomic distances. Shrinkage is an inevitable phenomenon; therefore, it is important to consider properly its effect on the casting's sizes when designing the foundry equipment.

Shrinkage is expressed in relative units:

linear shrinkage $\varepsilon_l = \frac{l_m - l_c}{l_c} \cdot 100\%$,

where l_m и l_c – linear sizes of a mould and a casting at 20 °C;

volume shrinkage $\varepsilon_v = \frac{v_m - v_c}{v_c} \cdot 100\%$,

where v_m и v_c – volume of a mould and a casting at 20 °C.

Calculating the volume shrinkage each time when needed is not necessary, since it is usually assumed that $\varepsilon_v \approx 3\varepsilon_l$.

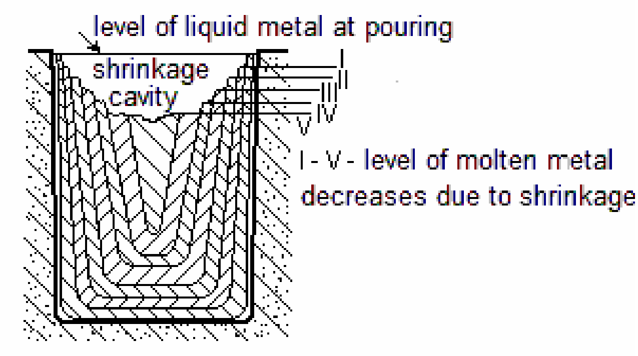
Good foundry alloys like cast iron and silumin give shrinkage far below 1 %,whereas shrinkage of both steels and copper alloys is in the range 2.5–3 %.

Shrinkage increases due to the high overheat of metal before pouring and by means of the high heat conductivity of the mould.

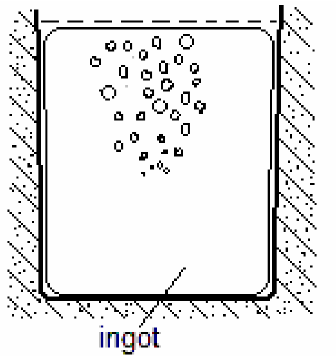
Shrinkage can lead to occurrence of defects such as shrinkage cavity, cracks, distorting.

The shrinkage cavity is a large cavity formed in the part of casting which solidifies last (Fig. 35, *a*).

Sometimes there is not one large cavity but a claster of small ones; it is *shrinkage porosity* (Fig. 35, *b*).



a



b

Fig. 35 Shrinkage cavity *(a)* and shrinkage porosity *(b)*

To prevent formation of shrinkage cavities *lost heads* are applied. They are massive tanks with the fused metal which feed metal to the casting until the crystallization has finished (Fig. 36).

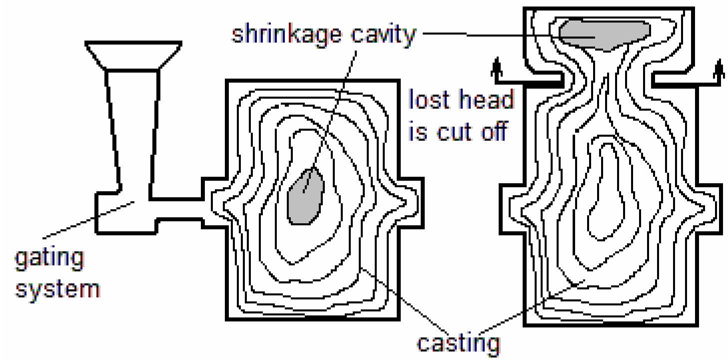
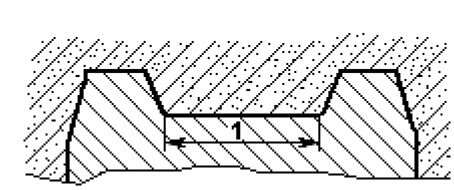


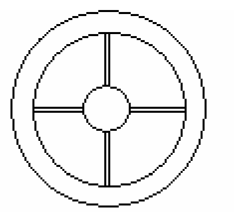
Fig. 36 Shrinkage cavity concentrates in lost head

3. *Propensity to formation of cracks*

Thick and thin parts of a casting undergo non-uniform contraction upon solidification and sometimes the mould itself can interfere with the shrinkage. In Fig. 37, *a* it is shown that ledge 1 does not allow shrinking of the solidified metal. In Fig. 37, *b* thin stiffeners will crystallize first and stop the further reduction in size of massive casting parts.



a

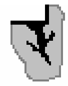


b

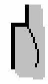
Fig. 37 Shrinkage is prevented by mould *(a)*; non-uniform shrinkage *(b)*

As a result internal stresses occur in the as-cast metal. If their value exceeds the strength of an alloy, cracks can be formed.

Hot cracks arise at the onset of solidification. Usually they are wide, ragged, and show the oxidized black surface. Their formation is caused by detrimental impurities such as gases and sulphur, high metal pouring temperature, non-uniformity of the cross section areas of the casting, and acute angles. For prevention of hot cracking it is necessary to get rid of all abovementioned reasons.



Cold cracks arise after full solidification. They are thin and have a clean surface. Being nearly invisible, they are especially dangerous. Shrinkage proceeds in a solid condition too, therefore stresses may grow. Detrimental impurity, especially phosphorus, the complex shape of casting, sharp differences of section cause occurrence of cold cracks. It is necessary either to provide uniform cooling or anneal the castings by holding them in the hot furnace and then cooling slowly together with the furnace.



If the internal stress level is below the tensile strength, but exceeds the yield strength of an alloy, distorting is developed thus causing deformation of the casting shape, especially in the thin-walled ones.

4. *Propensity to formation of gas bubbles and porosity*

The molten metals always contain dissolved gases and the higher is the temperature of the molten metal, the higher is their solubility. Metals grasp gases from atmosphere and during evaporation of moisture from the sand mix. Gases form bubbles in a casting body. Big bubbles are called blow-holes, small ones are pores. Moulds and cores must be dried up properly before using; also vent pipes (channels) are necessary for the gas removal. Increasing the pouring temperature is not required. The most effective way is metal degasification before pouring.

Moulding materials

Moulding materials are quartz moulding sand and foundry moulding clay. By mixing them together *sand mixes* are prepared with the addition of moisture and some other substances.

Requirements to sand mixes:

1) *Fire resistance*. The mix should not be softened and melted during the contact with the fused metal.

2) *Strength*. The mix should not collapse during pattern removal, transportation of the mould and pouring.

3) *Plasticity* is the ability to reproduce pattern outlines precisely in the course of moulding.

4) *Gas permeability* is the ability of the mix to pass gases formed during pouring to a mould surface.

5) *Compliance*. The mix should not hinder shrinkage of casting.

6) *Durability*. The mix should keep the properties when used repeatedly.

Kinds of sand mixes

By their application the forming mixes are subdivided into facing, backing and uniform mixes. From *facing mix* a working layer is formed which will contact with the molten metal. *Backing mix* is used for filling the rest of the mould (Fig. 38). *Uniform mixes* are applied in machine moulding.

Core mixes should have advanced properties compared to mixes for moulds because they work in more difficult conditions and are surrounded with fused metal from all sides.

In modern foundry production *special mixes* are widely used for manufacturing of cores and moulds.

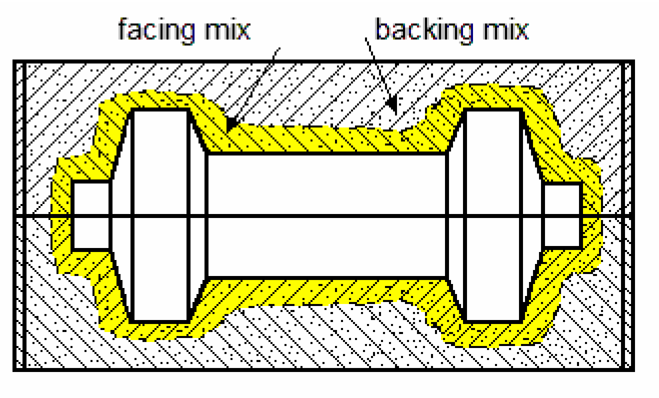


Fig. 38 Filling of the mould with a facing and backing mix

Examples of special mixes:

1) *Mixes hardening in heated up equipment*. Such mixes consist of 95 % sand and thermosetting resin. During contact with pattern heated up to 250–300°C resin acquires a viscous-flow state and envelopes the sand particles, then it is cured to form the ready mould.

2) *Liquid self-hardening mixes*. These mixes consist of 90 % sand, binding substance, a hardener and a surfactant. During stirring the mix the foam is formed which encapsulates the sand grains and thus improves the mix fluidity. The mix fills the mould cavities, and hardens in 20 minutes.

3) *Soluble silicate mixes*: sand and liquid glass. The mix hardens by blowing carbon dioxide through of the mould for 50 minutes approximately. Only up to 70 mm thickness working layer of the mould is made of such mixes.

4) *Cold setting mixes*. They consist of sand, epoxy resin and a hardener. Hardening lasts about 30 minutes, full strength is reached in a day.

Casting equipment

The *casting mould* is an equipment having a working cavity which is filled by the molten metal during pouring thus forming a casting.

Let us consider parts of a casting mould and equipment necessary for its manufacturing. For making the majority of castings, the sandy mould is used which consists of two halves joined to obtain the foundry flask with a moulding cavity in the shape of the pattern.

Flask is a framework mostly made of metal for holding a sand mix. *Pattern* is an appliance having outlines and sizes of the casting with the account of allowances for metal shrinkage necessary for making a print in the sand mix. Patterns are made of metal, plastic, and wood. A flask with the compacted sand mix and a print of pattern is called *mould half*.

However, the pattern repeats only external contours of the future casting. For making holes and cavities in castings *cores* are used; they are made of special core mixes. For manufacturing of cores, the *core boxes* are applied, usually they are metal. The core box should be open to remove a ready core.

Metal supply to the mould is carried out through the *gating system*. These are channels and cavities to provide filling of the mould with the molten metal, feeding of casting with liquid metal before full solidification and also removal of slag. To make these channels, models of parts of gating systems are moulded together with the casting pattern.

There are various variants of gating systems. Feeding with molten metal is more preferable from one side or from below without falling of metal stream from the big height not to wash away a sand mix.

The basic parts of the gating system are provided below (Fig. 39):

Pouring basin, or *trumpet* 1, is necessary to avoid spatter of metal and flowing on a mould surface. Sometimes ceramic *filters* 9 are used: they serve for retention of oxide particles, insoluble impurities, pieces of pouring ladle lining. *Pouring gate* 8 is a vertical channel for pouring the liquid metal extending to the splitting plane of mould 4. *Slag catcher* 7 is a cavity where slag (oxides and other nonmetallic particles) is collected. *Feeder* 6 brings metal to the *mould cavity* 5. *Vent pipe* 2 is intended for discharge of gases. Compacted sand mix 3 is shown by shading.

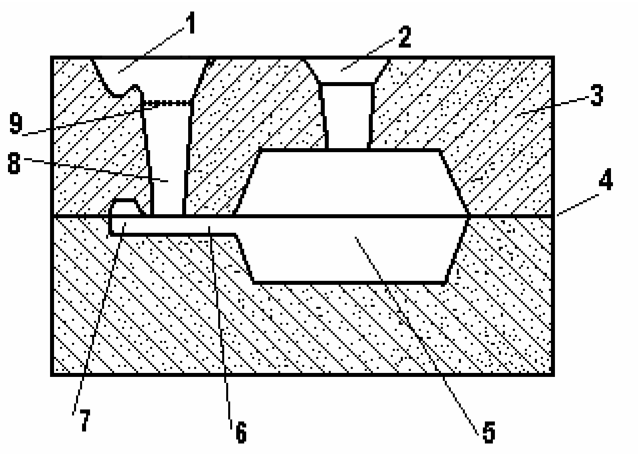


Fig. 39 Gating system:
1 – pouring basin; 2 – vent pipe; 3 – sand mix; 4 – mould splitting; 5 – working cavity; 6 – feeder; 7 – slag catcher; 8 – pouring gate; 9 – ceramic filter

Thus, according to an item drawing (Fig. 40, *a*) the casting drawing (Fig. 40, *b*) is developed. This casting differs from the real item by sizes (the sizes of casting are bigger by value of allowances 1 for machining) and by shape (tapers 2 and fillets of angles 3 are necessary for easy removal of a pattern from the mould without damaging it).

According to the casting drawing the pattern (Fig. 40, *c*) consisting of two halves is made. The split is carried out along the symmetry plane. The pattern halves are fastened by conic pins 4. Instead of a hole the pattern has projections as shown in Fig. 40, *c – core marks* 5. The core will be put inside the print on the basis of these marks. The sizes of the pattern exceed the sizes of the casting by shrinkage value.

Having molded the halves of the pattern in two flasks, we get the top and bottom half-moulds. Then the pattern halves are removed, and their prints remain in a sand mix.

Separately in a core box (Fig. 40, *e*) a core (Fig. 40, *d*) having outlines of the casting hole is made. The core is longer than the real hole by the size of core marks 6, and its cross-section is greater than cross-section of the hole by shrinkage value.

In Fig. 40, *f* the complete mould (the feeder is behind the drawing plane) is represented.

Hand moulding

Molding is a manufacture of moulds. *Hand molding* in pair flasks using a split pattern is presented in methodical instructions for laboratory work "Manufacturing of expendable casting mould". Study individually!

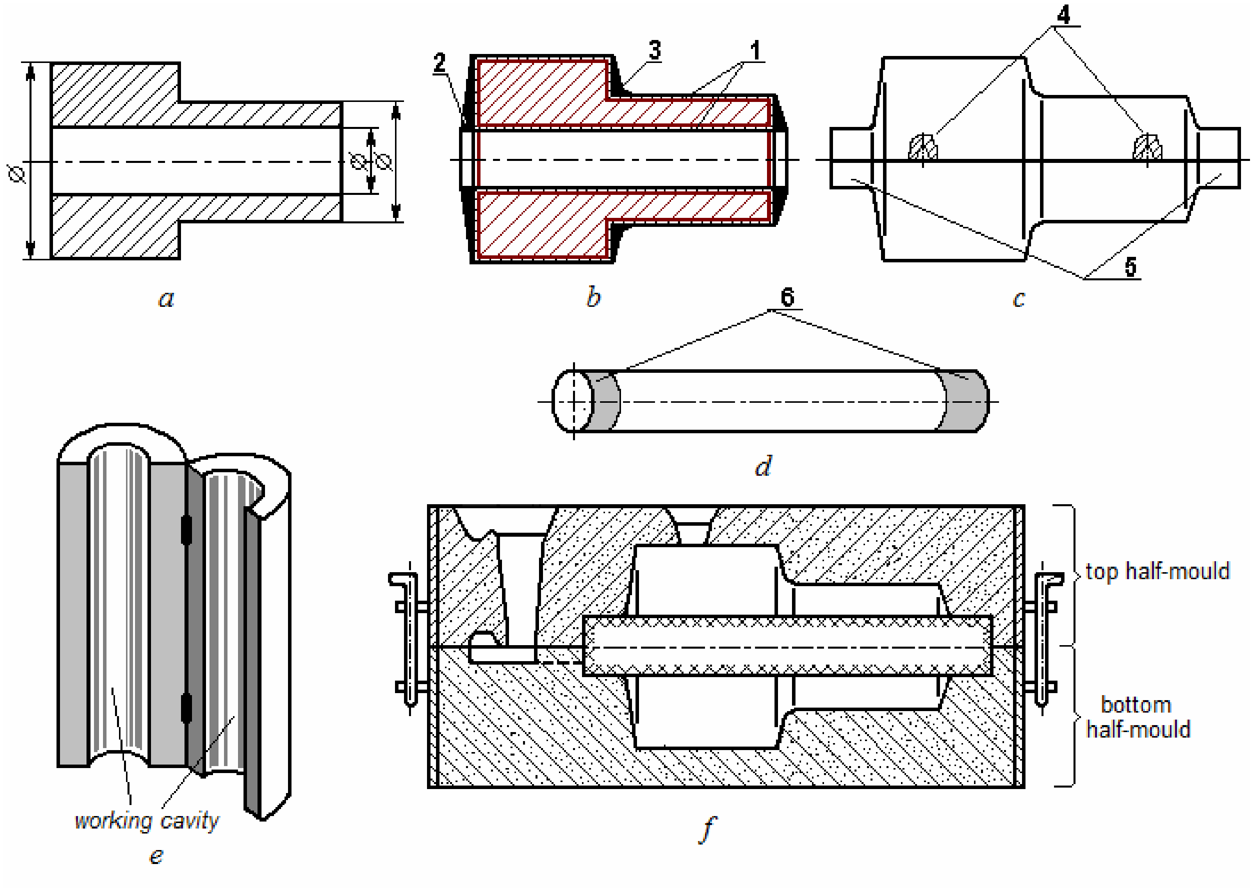


Fig. 40 Sequence of casting manufacture:
a – part drawing; *b* – casting drawing; *c* – pattern; *d* – core;
e – core box; *f* – complete mould for manufacture of casting

Lecture 8

Machine moulding

To increase productivity and improve working conditions in a batch production of casting the machine moulding is applied. The following operations are carried out mechanically:

– placing flasks onto a pattern plate,
– compacting a mix,
– removal of patterns,
– assemblage of moulds,
– transportation of complete moulds.

Moulding machines compact a mix by various ways.

Compacting by pressing (Fig. 41)

Moulding mix 1 from a bunker is filled onto the pattern plate 3 with pattern 2 and into flask 5. Then the flask is closed with pressure squeeze board 6, and the pattern plate under the influence of compressed air 7 rises along guiding 4 up to level *a-a*, moving the pattern into the flask. Thus mix compacting occurs. When flask is removed the pattern print remains in it. This method is called *bottom pressing*.

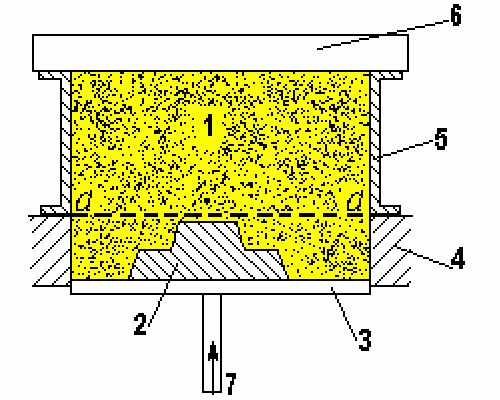


Fig. 41 Compacting of sand mix by bottom pressing

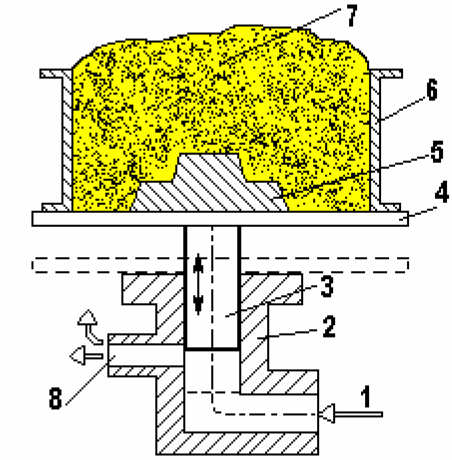


Fig. 42 Compacting of sand mix by shaking

There are other ways of pressing of a moulding mix (top pressing, with multiplunger head, with an elastic diaphragm).

Compacting by shaking

Compressed air 1 lifts piston 3 together with table 4 on which there is pattern 5 in flask 6 (Fig. 42). When exhaust window 8 is open the space under the piston is depressurized and the piston goes down quickly under the weight of flask so that table impacts the butt end of cylinder 2. So mix 7 is compacted under the influence of inertial forces. The impact frequency of blows is not over 200 per minute. Sometimes prepressing is used for more uniform compacting.

Compacting by sand-throwing machine

The throwing head of the device consists of rotor 4 with ladle 2, placed into jacket 1 (Fig. 43). During rotation of the rotor the ladle grasps the moulding mix, which is supplied using conveyor 3, and throws mix portions out with force through jacket window 5 onto the surface of pattern 8 inside flask 7. Compacting occurs under the influence of kinetic energy of mix portions 6. Speed of throwing is in the range 30–50 m/s. The head moves over the flask, which is motionless. This approach is applied for manufacturing large moulds.

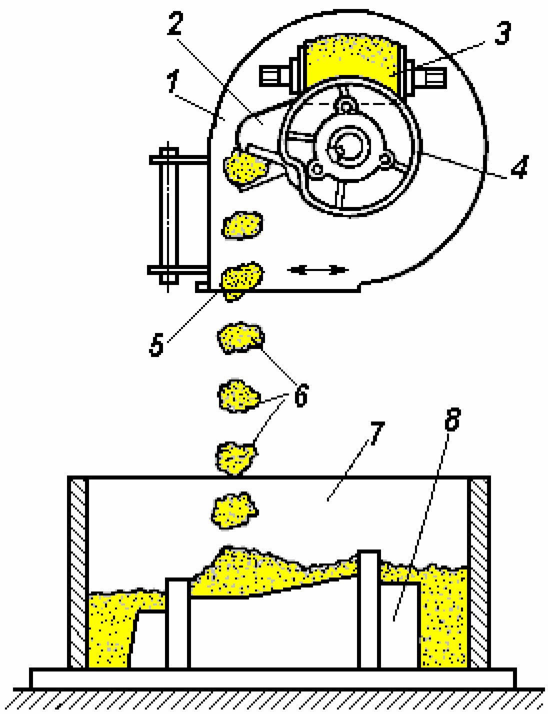


Fig. 43 Compacting of sand mix by sand-throwing machine

Fabrication of cores

Core boxes are filled with a mix by blowing machines or core shooters. For mix compacting compressed air is used. The blowing machine gradually blows a mix into a core box; core shooter shoots a portion of a mix. Then cores are finished, dried, and painted.

Cores are more often than moulds, manufactured of special mixes: mixes hardening in heated up equipment, liquid self-hardening mixes, cold setting mixes, soluble silicate mixes (Fig. 44).

Assemblage of moulds, pouring, knock-out and machining of castings

The bottom half-mould is placed onto a pouring table. Cores are set into it, then it is covered with top half-mould and flasks are fastened. For large moulds sometimes it is necessary to put weight on the top half-mould to prevent the metal from flowing out in the split.

Before pouring metal is overheated at above the melting temperature. The overheat value is 100º for steel, 200º for cast iron, 150º for nonferrous alloys. It is necessary to increase the running quality. However, the overheating enhances absorption of gases by molten metal, it is oxidised easily and gives a big shrinkage. Therefore, it is necessary to choose suitable temperature of pouring.

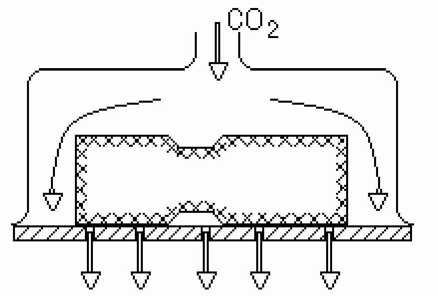


Fig. 44 Hardening of a core made of soluble silicate mix in carbon dioxide atmosphere

Metal is let out from the furnace into a pouring ladle or in an automatic device for pouring.

Sandy moulds filled with metal are cooled for several hours or several weeks (multi-ton casting). To accelerate the cooling, moulds may be blown with the cold air, or cooled by water passing throw the coils laid inside the mould. For massive casting it is necessary to provide uniform cooling across its total volume thusly improving the quality of castings.

Knocking-out castings is the destruction of the casting mould and removal of the finished casting. It is carried out on knockout grates (Fig. 45). The clod of the mix with casting 1 is pushed out from the flask by pressure squeeze board and falls on grate 2. Under vibration created by connecting rod gear 3 and springs 4 the mix falls down.

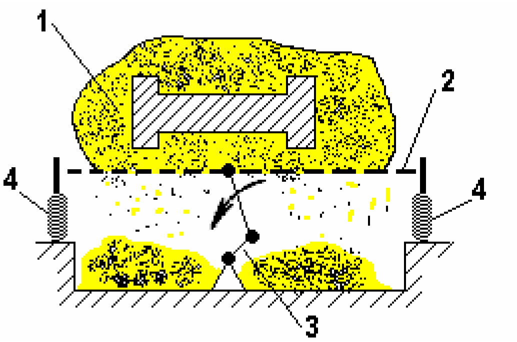


Fig. 45 Knock-out of casting on vibration grate

Cores are beaten out of the casting holes by pneumatic vibrating devices similar to a jackhammer, or washed away by water stream in hydraulic chambers.

Fettling of castings is the removal of pouring gates, loss heads, vent pipes, films (a film is a portion of metal which has flown to a split of the mould). Nonferrous castings are machined with ribbon or disk saws, steel ones – by gas or plasma cutting, from pig-iron pieces loss heads are beaten off with hammers.

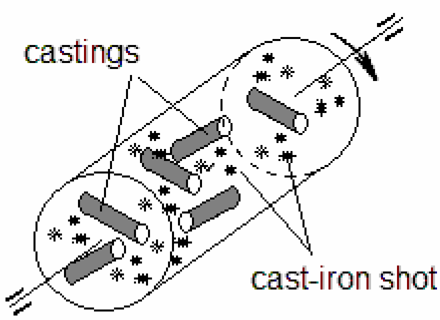


Fig. 46 Cleaning of casting in tumbling dram

Cleaning is the operation of removal of the pouring channel rests, small films, etc. It is carried out by grinding wheels, pneumatic chisels, gas-flame processing, etc.

Sand blowing or *steel grit blasting* of castings allows removing scale and the rests of a sand mix both from external and internal surfaces. It is carried out in tumbling drums (Fig. 46), in grit blasting and sand-water cleaning chambers, and also by chemical and electrochemical methods (in solutions and fusions of alkalis).

Thermal processing is necessary for refining grain, decreasing hardness, removing internal stresses. Castings are heated up in the furnace and then cooled slowly.

Special methods of casting

Sand casting does not always give the necessary accuracy of the sizes and smoothness of the surface. Therefore, the considerable quantity of other moulding methods has been developed. All of them are called *special methods*.

Shell casting (Fig. 47)

Moulding mix 3 consists of quartz sand and thermosetting resin. The dry mix is in bunker 2. The pattern plate 1 with the half of the pattern fixed on it and heated up to 250°C (Fig. 47, *a*) is mounted on the bunker. Then the bunker is flipped so that, the mix covers the pattern surface (Fig. 47, *b*). During heating the resin in the layer adjoining to pattern melts and binds the sand grains thus forming a shell 4 over the pattern. Shell thickness is about 20 mm.

Then the bunker is flipped back in a starting position (Fig. 47, *c*) and plate with the shell is removed and placed to the furnace heated to 350°C for curing. Thus irreversible hardening of a mix occurs.

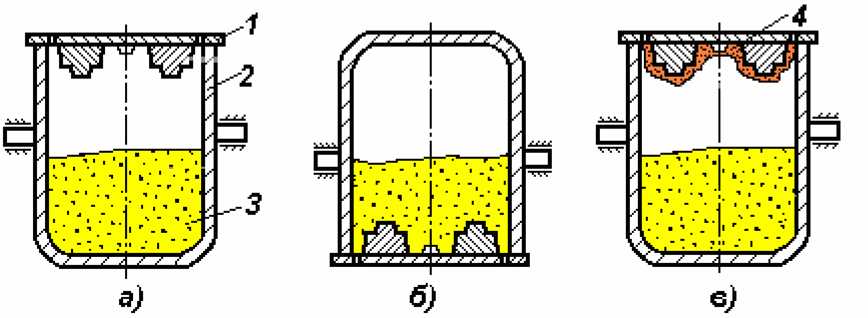


Fig. 47 Manufacture of shell mould

In the same way the second half-mould is made, after which halves are assembled and fastened one to each other by clamps or glue. To prevent the shell from prematurely fracturing, the moulds are placed in a container and filled in with dry sand. During pouring the molten metal, the resin starts to burn out, the shell disintegrates gradually, but metal has already solidified.

Advantages of this process are the pinpoint accuracy of the sizes (allowances make the tithes of millimeter) and smoothness of the surface, high gas permeability of moulds. The expenses for moulding materials makes only 5 % from the expenses for green-sand casting. The method may be applied to any alloys.

The *limitation* of this method is that resin is expensive material, besides toxic gases are emitted during casting. The weight of castings is limited by 100 kg approximately because mould cannot hold the big weight of the liquid metal.

Investment casting (Fig. 48)

Pattern of the casting shown in Fig. 48, *a*, is made of a mix of fusible substances (for example, 50 % paraffin and 50 % stearine). The mix melts at 80°C and is softened at 60°C.

The warmed-up pattern substance is filled or pressured into a metal mould (Fig. 48, *b*). After cooling (Fig. 48, *c*) patterns are removed from compression moulds and assembled in blocks with one gating system for many patterns, with a junction being heated up with a soldering iron (Fig. 48, *d*). The block may include up to a hundred patterns. It is possible to reinforce the pouring gate with a wire.

The assembled block of patterns is immersed into ceramic suspension of quartz sand and hydrolyzed ethylsilicate solution in ethyl alcogol; then it is sprinkled with dry sand and dried. In so doing, ceramic coating is formed on the pattern surface. Operation is repeated 3–4 times, until obtaining a shell or crust about 8 mm in thickness (Fig. 48, *e*) appears.

Then the pattern substance is melted out of the shell using hot water or steam; collected, recycled and used again. The shell is calcinated at 850°C, being previously placed into a flask and filled with sand. The shell becomes strong.

Molten metal is poured into the flask. During removal of casting, the crust is destroyed, but for full cleaning of the surface alkalis are applied.

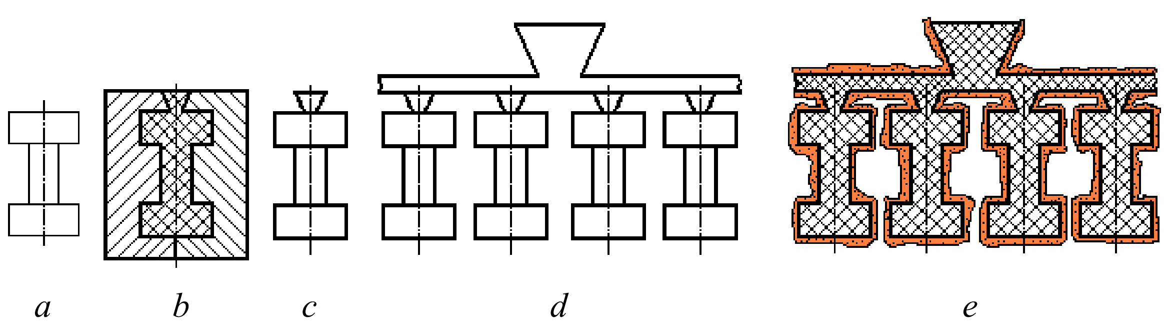


Fig. 48 Manufacture of casting mould by the investment pattern method

The advantages of this way are high accuracy of the sizes with allowances in the order of 1/100-th parts of mm, which is achieved owing to the absence of the split of the mould and cores. Castings do not demand machining, except grinding of working surfaces.

The limitation is high labour input of manufacturing and high costs of castings approximately 10 times higher than in sand casting.

Investment pattern casting is applied for small complex shape items, especially made of expensive alloyed steels and alloys, for example, heat resistant steels or tool alloys. It allows saving metal (the general gating system for a set of castings) and obtaining precise castings from hard-processing materials.

Cavityless casting, Chill casting

These methods are described in methodical instructions for laboratory work “Special methods of casting”. Study individually!

Pressure casting

It is a mode of chill casting (in metal moulds) with which filling of the mould with the molten metal as well as casting crystallization occurs under pressure.

Die-casting machines have a complex design. It is possible to subdivide them into three groups:

1) *Machines with cold horizontal compression box* (Fig. 49)

The portion of metal is filled inside compression box 1, then molten metal fills pressure casting die 3 under the pressure of plunger 2. After solidification of casting the mould is opened and casting is pushed out by means of pushers 5. Mould halves are joined together again, and the cycle repeats. To make a cavity in casting metal core 4 is applied. Plunger pressure in liquid metal is about 200 MPa.

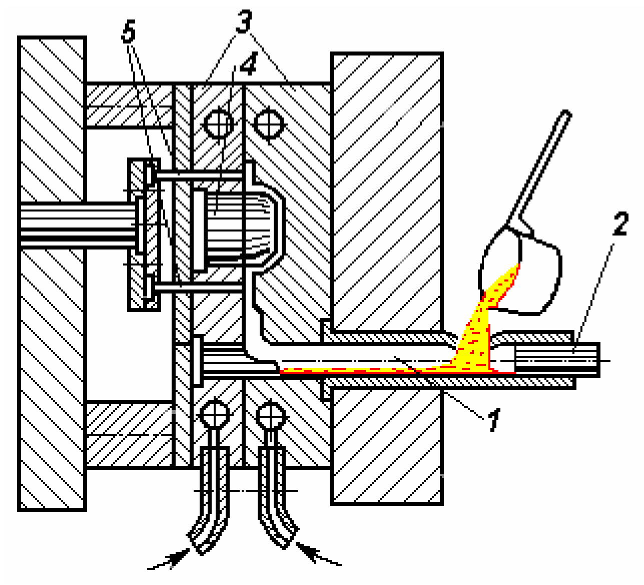


Fig. 49 Die-casting machine with cold horizontal compression box

2) *Machines with cold vertical compression box*

3) *Machines with hot vertical compression box* (Fig. 50)

Compression box 1 is located in a heated crucible and surrounded by the fused metal which gets to the chamber through holes 2 with plunger 3 moving upwards. Downward plunger movement forces fused metal to flow under pressure into pressure casting die 4.

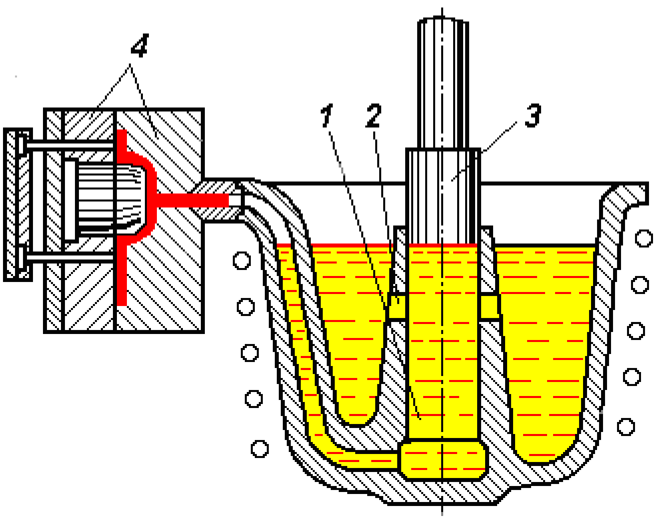


Fig. 50 Die-casting machine with hot vertical compression box

Advantages of pressure casting are as follows: it is high-precision method. It is possible to make thin-walled castings (the minimum wall thickness is 0.8 mm) even from alloys with bad fluidity. Die-casting machines work with high efficiency because they are completely automated. Good sanitary-and-hygienic working conditions in comparison with other ways of casting are inherent with this method.

Limitations of the method are that porosity is possible in massive parts of castings because of high crystallization rate which interferes with free removal of the gases dissolved in metal. It is necessary to treat the melt under vacuum or apply other ways of degasification.

During filling the pressure casting dies intended for large pieces there is a hydraulic impact, as a result the die may open and splash out the molten metal through the split. Therefore, the weight of castings is limited.

Machines with a cold compression box are applied for copper and aluminium alloys, those with hot one are suitable with magnesium and zinc alloys.

Centrifugal casting

This method implies that both pouring of molten metal and casting formation are assisted by the centrifugal forces. Centrifugal casting machines may have either horizontal or vertical axis of rotation. Metal is poured into rotating moulds (metal, sand or shell). To simplify the casting removal, the mould should have a small taper, serving to forming a shrinkage gap after solidification. This gap makes the removal of the casting much easier.

By means of centrifugal forces the liquid metal is pushed aside to the mould walls so that holes in the casting may appear without application of cores.

Centrifugal casting machines with a vertical axis of rotation (Fig. 51, *a*) make it possible to obtain castings of height not over 500 mm as the gravity does not allow metal to rise higher. Thus the walls in the bottom part are thicker than in the top part of casting.

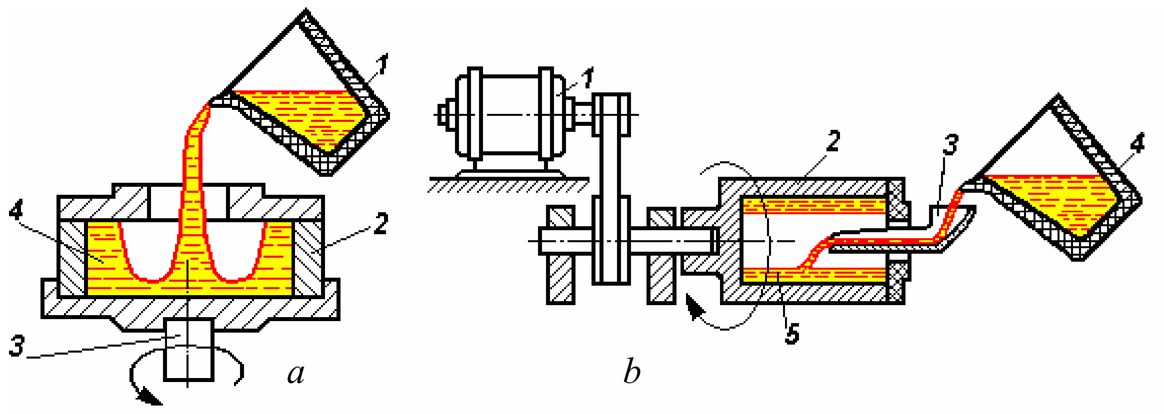


Fig. 51 Centrifugal casting:
a – with vertical axis of rotation (1 – ladle, 2 – mould, 3 – spindle, 4 – liquid ring layer of metal);
b – with horizontal axis of rotation (1 – electric motor, 2 – rotating mould, 3 – launder, 4 – ladle, 5 – hollow cylindrical casting)

Centrifugal casting machines with a horizontal axis of rotation (Fig. 51, *b*) produce 12 m length cast pipe. For cast iron pipes it is the unique way of manufacturing them.

Advantages of the method: castings turn out dense; it needs not use of cores for making holes and cavities; there is no metal waste for gating system. It is possible to obtain multilayered casting, consistently filling in portions of different alloys.

Limitations are stratification of some alloys by relative density (tin bronzes, for example) and slag crust formation inside castings.

The shape of castings made by this way is a rotation body. These are rings, bushings, barrels, pipes, sliding bearings.

Casting defects

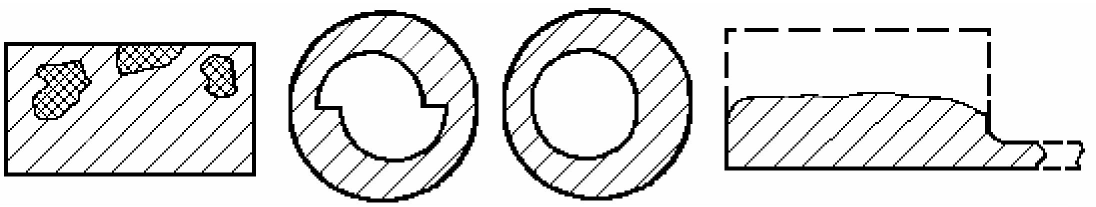
1) Shrinkage cavities and pores.
2) Hot cracks and cold cracks.
3) Distorting.
4) Gas porosity.

All these defects have already been described above. However, some other defects caused both by improper pouring or using bad mould assemblage technology are possible in casting manufacturing.

5) *Sandy bolls* are the cavities in the casting filled with a sand mix. They are formed because of the mould damaging by the melt stream resulting from improper pouring technology or insufficient sand mix compacting (Fig. 52, *a*).

6) *Misalignment* is the displacement of the top half-mould relative to the bottom one; the reason is negligent assemblage or worn centring pins (Fig. 52, *b*).

7) *Incomplete filling* of mould cavities with molten metal (Fig. 52, *c*).



a *b* *c*

Fig. 52 Some casting defects:
a – sandy bowls; *b* – misalignment; *c* – incomplete filling

Part IV Welding Fabrication

Welding is a process of permanent joint production by formation of interatomic bonds origination between the parts being joined.

Creation of these bonds between atoms on the surfaces of parts being joined demands energy consumption, which may be brought to a welding zone by two ways: heating or plastic deformation. Therefore, two groups of welding methods are distinguished: welding by fusion and welding by pressure.

During *welding by fusion* interatomic bonds between connected pieces result from melting of their edges adjoining to each other with formation of a liquid metal pool. While cooling this pool is solidified and joins two pieces into a single one.

During *welding by pressure* parts in a junction zone are subjected to common plastic deformation by compression. Thus, surfaces become cleared of polluting films, the microrelief smoothes out, and interatomic bonds appear. Pieces are heated before welding, but wrought metals (aluminium, copper) can be welded without extra heating.

The combined processes are possible when metal of work-pieces melts and welding zone is plastically deformed.

There are more than 70 different kinds of welding: it is possible to heat up with electric arc, with gas-oxygen flame, by laser, by direct current passage, etc. It is possible to protect differently the zone of welding from air oxygen or deform by different ways etc.

Welding is applied in all areas of engineering. Not only metals are welded, but also glass, plastic, ceramics, as well as dissimilar materials. Welding is carried out in space and under water. The basic fields of welding application include building, pipeline transport, mechanical engineering (especially shipbuilding and aircraft engineering).

Electric arc welding

It is a way most widely applied today.

In 1893 on the World's fair in the USA the Russian scientist Slavjanov has shown a 12-faced prism fabrication by welding using an electric arc. All its faces were plates from different metals and alloys, from nickel to pig-iron. Those times it seemed like a miracle. Today work of a welder in a mask and holding electrode in his hand is the routine picture at any building or in repair of various communications.

Welding arc

The welding arc is a powerful stable electric discharge (arc) burning between electrodes in the atmosphere of ionised gases and vaporised metals.

Usually the *arc of direct action* is used which strikes between an electrode and a piece (Fig. 53). Heating occurs by means of bombing the metal surface by electrically charged particles. The *indirect arc* strikes between two electrodes, and metal is heated for the account of arc radiation.

More often *consumable* metal electrodes are applied which form a welded seam. Infusible (coal, tungsten) electrodes are used rather seldom as they complicate welding technology so that the filler material is required.

Fig. 53 shows a scheme of *normal polarity* welding when electrode is connected to the negative pole of a power supply source.

The arcing is initiated when electrode strikes on the surface of the work-piece so that the short circuiting is formed. Microirregularities both on the electrode and piece surfaces heat up to the boiling temperature, and during electrode removal thermal electron emission begins. Also autoelectronic emission joins up, i. e. separation of electrons from atoms under the influence of high intensity electric field. In a gap between the electrode and base metal free electrons appear, they ionise metal vapors. The flux of the charged particles grows like an avalanche. Electrons and negatively charged ions travel to anode, while positive ions to cathode. The work-piece and electrode surfaces are heated up, and the arcing is established in 10^{-6} s. The temperature near the axis of the arc column is in the range 6,000–8,000 K. The arc is a low-temperature plasma.

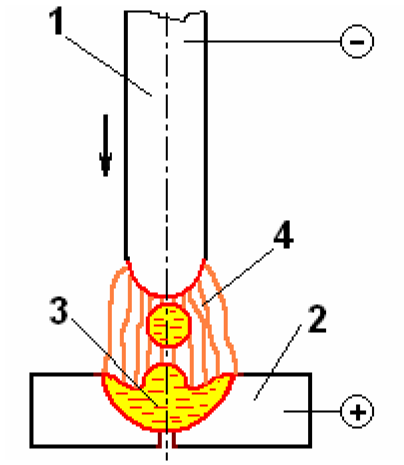


Fig. 53 Scheme of direct current welding arc: 1 – electrode; 2 – base metal; 3 – bath of liquid metal; 4 – arc column

The arc voltage-current dependence for constant arc length *l* is called *static volt-ampere characteristic* of the arc. It is nonlinear dependence with the curve showing three different curve portions such as: falling I, flat II and increasing III (Fig. 54, *a*).

The arc voltage is proportional to its length, i. e. for constant voltage retention it is necessary to support constant arc length.

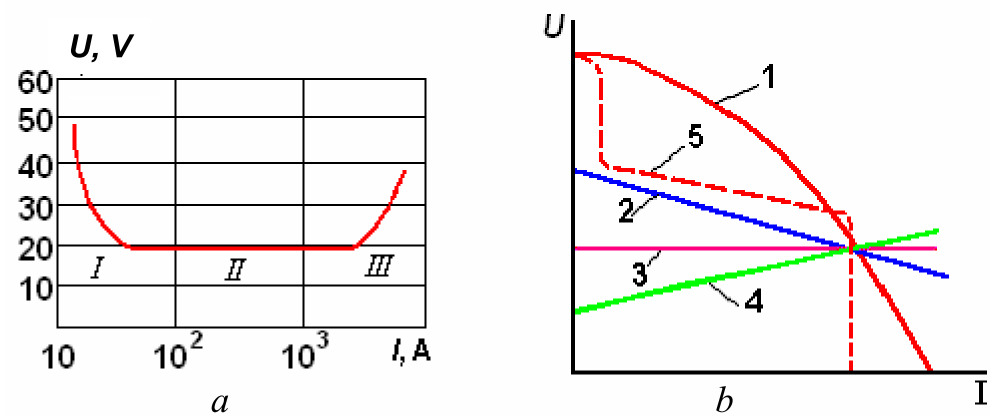


Fig. 54 Static volt-ampere arc characteristic *(a)*; external characteristics of current sources for welding*(b)*

Manual metal arc welding (MMAW) is carried out under condition corresponding to the falling portion of the volt-ampere characteristic with transition to the flat one, automatic submerged arc welding (SAW) utilizes the flat portion of the characteristic with transition to the increasing one, while gas metal arc welding (GMAW) the increasing portion of the characteristic.

When arcing is carried out using 50 Hz frequency alternating current (AC) both anode and cathode currents change 100 times per second and arc quenching events occur at the same frequency. Therefore, voltage of striking the arc on alternating current is within 50–70 V, whereas for direct current (DC) it is 40–60 V

.

Manual arc welding

1) Equipment for MMAW: arc power supply, or welder, flexible wires (cables), electrode holder, electrode (see Fig. 57, p. 53).

a) Power supply for an alternating current arc is a *welding transformer*, for a direct one – *welding rectifier* and *generator*. Modern *inverter sources* of current for welding allow obtaining both direct and alternating currents and a wide spectrum of volt-ampere characteristics. In the field conditions *welding units* applied are generators with a drive from an internal combustion engine.

External volt-ampere characteristic of power source is the dependence between terminal voltage of a source and current in a circuit at the steady run. Sources of current for welding can be of various types of characteristics (Fig. 54, *b*): 1 – high-angle falling, 2 – low-angle falling, 3 – flat, 4 – increasing. Idealised external characteristic 5 in the best way meets requirements to a source of welding current. Inverter power sources have precisely such characteristic.

The arc welding sources with high-angle falling characteristics are used only for manual arc welding. Why is it so important? The length of the arc during manual welding always fluctuates, but it is necessary to provide constant current *I* to keep the size of a welding pool and a seam section constant.

The magnitude of both current and voltage at the output of the source are equal to those of the arc, that means that the mode of stable arcing is defined by the point of intersection of a source and an arc characteristics (Fig. 55). There are two such points: point *A* and point *B*. But steady arcing is possible only by the mode of point *B*.

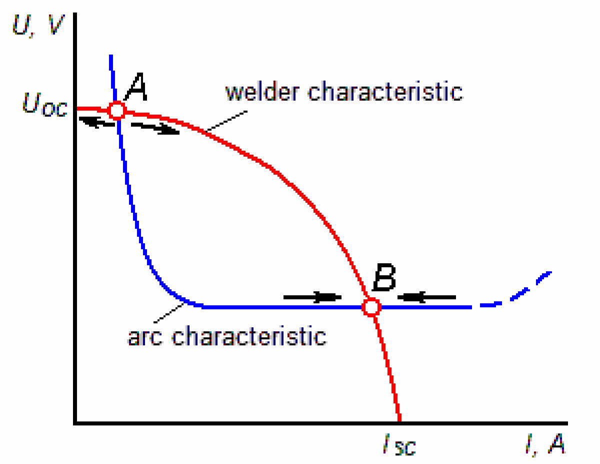


Fig. 55 Condition of stable arcing

If the arc current decreases casually, the source will give out more voltage than the arc consumes. Therefore, the current in a circuit will increase to value I_B, process will return to the parameters of point *B*.

If the arc current casually increases, voltage of an arc will exceed the at the output of the source. Therefore, the current in a circuit will decrease to value I_B, and process will also return to parameters of point *B*.

In point *B self-established balance* is observed, and in point *A* current deviation will result in arc extinction or in transition to point *B*.

From this it follows that at the high-angle falling characteristic of a source the current magnitude practically does not depend on arc length.

In MMAW current is regulated by changing of the external characteristic of the power supply. For this purpose a power supply design includes devices for step and smooth regulation, for example, a choke (an inductance coil).

b) Wires (cables). A welding cable has bigger cross-section than a primary one. The length of cables should not exceed 30–50 m as if cables are longer voltage drop in wires increases.

c) Electrode holder is a handle from insulator material with three metal rods (fork) on one end between which the bared end of an electrode is clamped. The cable passes inside the handle and is connected to the fork (Fig. 56). There are also other designs.

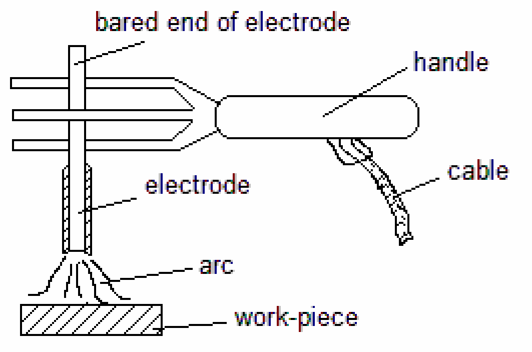


Fig. 56 Electrode holder

d) Welding electrode represents a core from a wire covered with a layer of a mix of powders with binding substance. The coating is deposited by moulding or by dipping, and then dried.

Two types of coatings are applied: *thin* (stabilizing) and *thick* (shielding and alloying). The composition of the coating includes the following substances intended for:

– ionising an arc space (arc stabilizers);
– slag-forming (for protection of a liquid metal bath and a seam);
– gas-forming (for gas shielding of a welding zone);
– deoxidizing (for removal of oxygen from molten metal);
– alloying (for increase of seam metal strength);
– binding (usually soluble silicate).

Deoxidizing and alloying components are present only in the thick coatings, ionising and slag-forming– in all of them.

Depending on the type of slag-forming substances electrode coatings are subdivided into four types: acid, basic, rutile TiO_2 and cellulose. Electrodes with rutile covering provide high mechanical characteristics of a seam and good technological properties; they are most widespread today.

Length of electrodes is 250–450 mm. Standard diameters are 2 to 6 mm, but also either bigger or smaller diameters may be fabricated for some special cases.

The electrode material forms a weld therefore the chemical composition of electrode wires should correspond to the composition of the welded joint. *Grades of electrode wires* are designated by the carbon content in wt% and letters indicating alloying elements (chrome, manganese, silicon).

Electrodes for welding of carbon and alloyed constructional steels are classified by mechanical characteristics of the weld metal which they provide. The *elec-*

trode type is designated as E38 … E150, where numbers are guaranteed tensile strength of a seam in kg/mm^2.

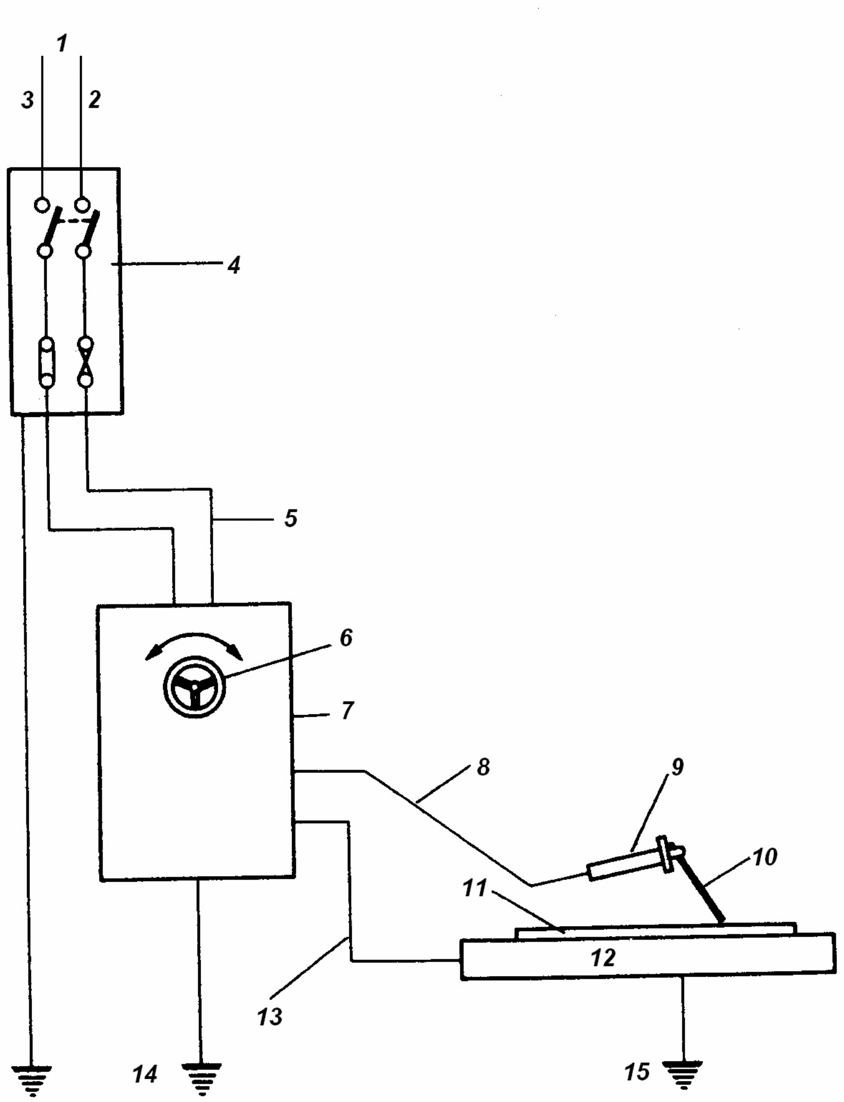


Fig. 57 Manual metal-arc welding circuit diagram:
1 – A.C. mains supply; 2 – neutral; 3 – live; 4 – fused switch; 5 – primary cables; 6 – current control; 7 – welding set; 8 – welding cable; 9 – electrode holder; 10 – electrode; 11 – work-piece; 12 – work support; 13 – return current cable; 14 and 15 – earth

Electrode mark is a code name given by the designer; it does not contain information of weld metal characteristics.

It is necessary to note that in manual arc welding the electrode consumption for waste, spattering, cinders (the electrode rest in the holder) is high enough and can make up to 25 % of electrodes weight.

2) Scheme of welding process by a covered electrode is represented in Fig. 58. Here 1 is welded metal, 2 – electrode core, 3 – electrode coating, 4 – arc, 5 – droplets of the fused electrode metal, 6 – welding pool; 7 – droplets of melting coating, 8 – layer of liquid slag formed from coating, 9 – gas shield atmosphere

(produced by a coating), 10 – welded seam, 11 – slag crust which is cleaned off subsequently.

3) Welding mode includes parameters of process as follows: diameter of electrode, welding current strength, voltage of arc and arc length.

Diameter of electrode d is chosen depending on welded metal thickness:

$d = \frac{s}{2} + 1$, where s is the thickness of welded metal, mm.

Current strength I is specified in the passport of an electrode or it is calculated by formula $I = k \cdot d$ where coefficient k depends on steel grade of an electrode wire. For carbon steels k = 35–60 A/mm.

Arc voltage for the majority of electrodes' marks and coatings is equal to 20–28 V.

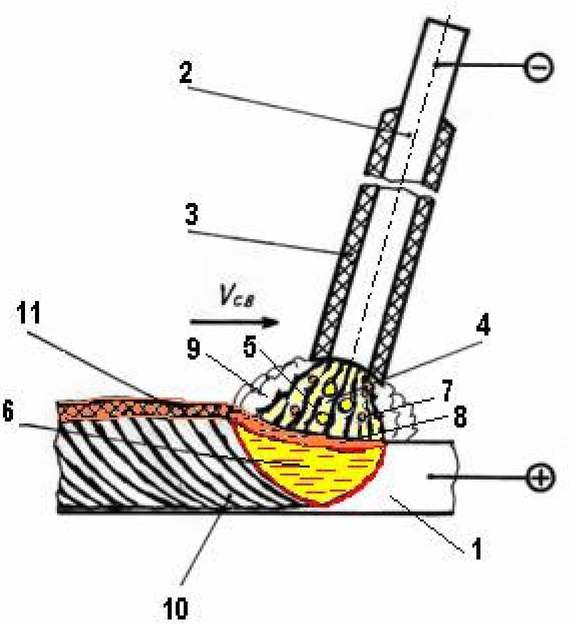


Fig. 58 Scheme of welding by coated electrode

Arc length is supported by the welder within 4–6 mm. It is possible to consider that the length of an arc makes approximately l = (0.5–1.1) d.

4) Classes of welding joints are shown in Fig. 59.

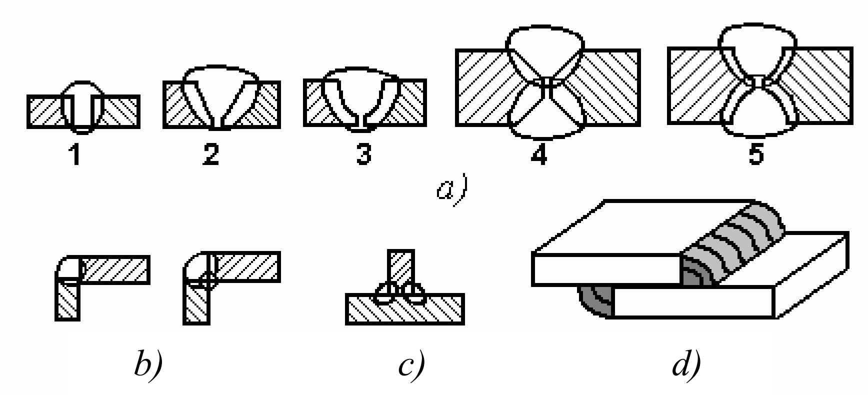


Fig. 59 Welding joints: *a)* butt welds (1 – without welding groove, 2 – *single Vee groove*, 3 – *single U groove*, 4 – *double Vee groove*, 5 – *double U groove*); *b)* corner welds; *c)* fillet weld; *d)* lap weld

Making a welded joint is possible in various positions: *flat position* (Fig. 60, *a*), *horizontal position* (Fig. 60, *b*), *vertical* position (Fig. 60, *c*) and *overhead position* (Fig. 60, *d*).

For manual arc welding the depth of the arc penetration for one pass is not more than 8 mm. Sheets more than 8 mm in thickness can be welded for several passes, the seam turns out to be multilayered. Metal sheets less than 6 mm in thickness are welded without forming a welding groove.

The process of manual electric arc welding, the power supply and safety regulations are described in methodical instructions to laboratory work “Equipment and technology of manual arc and electro contact welding”. Study individually!

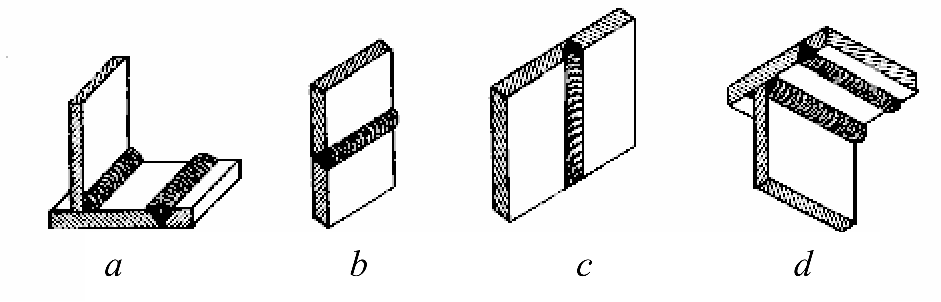


Fig. 60 Weld location in space

Automatic submerged arc welding (SAW)

Welding is conducted under a layer of a flux, with a bare wire. A joint place before welding is filled with a flux (a layer 30–50 mm in thickness), and the arc burns under this layer.

The scheme of SAW process is shown in Fig. 61. The feeder 2 provides feeding the welding wire 3 into arc zone 10. The wire is connected to a current source with sliding conductor 1. The arc is closed by layer of a flux 5. During fusion of basic metal 8 and a wire pool of liquid metal 9 appears, and the fusing flux makes pool of liquid slag 4. Welded seam 7 is formed upon crystallization of the fused metal, from above it is covered with solidified slag crust 6.

Equipment: *automatic arc welder*. This device serves for mechanized arc starting and maintaining, moving it along the seam line and feeding it with the consumable welding material. There are various designs of welding automatic machines, but all of them contain components as follows:

1) device for fastening a wire coil,
2) feeder of a wire,
3) mouthpiece (sliding contact) for supply of welding current,
4) mechanism of arc moving along a seam line.

Also *hose semiautomatic devices* are applied. They mechanise only wire feeding into the pool. Semiautomatic devices allow combining flexibility of manual arc welding with the depth of penetration and high efficiency of SAW.

Materials: welding wire and *fluxes*, fused or ceramic (sintered). Fluxes

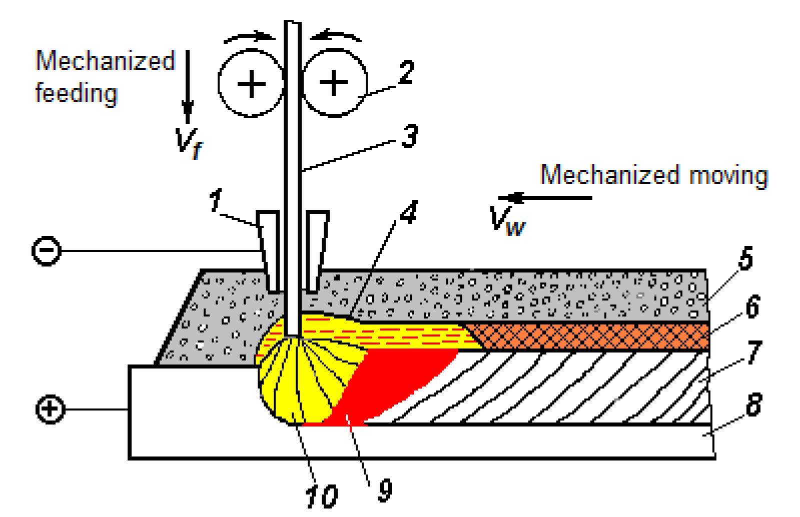


Fig. 61 Scheme of automatic submerged arc welding

carry out the same functions as electrode coating in MMAW:

1) shielde a welding pool against air,

2) provide steady arcing,

3) give the necessary structure and properties to welded metal.

Advantages: it is the most productive way of welding. At the account of the high current (up to 2 kA) and continuity of process, the productivity of SAW is 5–20 times higher than that of manual welding.

High quality of a seam is provided by reliable shielding against surrounding atmosphere, deoxidizing and alloying of seam metal by flux components, slow cooling of a seam, constancy of the welding pool sizes. The production cost of 1 m of seam is lower since metal is not splattered; there is almost no waste of electrodes. The high current allows welding metal up to 20 mm thickness for one pass without cutting of edges.

Application: in serial and mass production, such as manufacturing of boilers, tanks, ship hulls, bridge beams, welded pipes with a direct and a spiral seam, wheels.

Automatic flux-cored arc welding (FCAW)

Flux-cored wire is a 0.1 mm thickness tape rolled up into a tube and filled with a mix of powders of the same ratio as used for electrode coating but without binding. With such wire it is possible to conduct both automatic and semi-automatic welding.

Advantages: both welding pool and seam are visible unlike in SAW. The wire is consumed at a rate less than that of electrodes thus increasing the depth of penetration.

Lecture 10

Automatic gas metal arc welding (GMAW)

This method involves the seam protection by a stream of pressurized gas fed into a welding zone through a torch. For this purpose heavier than air gases like argon or carbonic gas are suitable which do not oxidize the fused metals.

The scheme of welding in carbonic gas is shown in Fig. 62. Here 1 – wire coil, 2 – feeder, 3 – wire (consumable electrode), 4 – current supply conductor, 5 – torch case, 6 – nozzle, 7 – atmosphere of shielding gas, 8 – arc, 9 – pool of liquid metal, 10 – welded metal, 11 – welded seam.

Carbonic gas is 1.5 times heavier than air. It efficiently protects the welding zone against air and its transparency serves for the seam visibility. Welding is conducted using the *reverse polarity* when electrode is connected to the positive pole of a source and the work-piece to the negative one.

Welding in argon atmosphere (it is 1.4 times heavier than air) is carried out according to the same

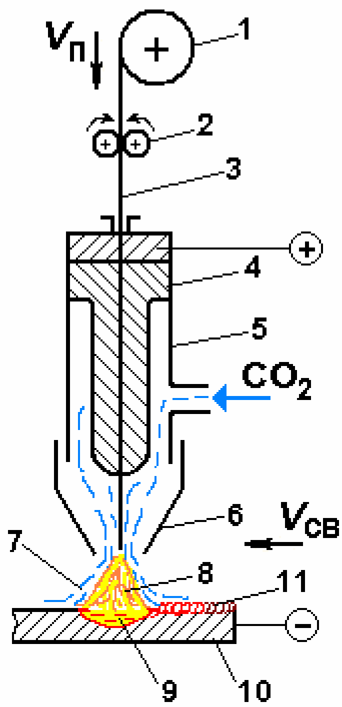


Fig. 62 Scheme of welding in carbonic gas

scheme, but instead of welding wire the non-consumable tungsten electrode is used while the wire is fed into a welding zone separately. Polarity is normal. This method is called *gas tungsten arc welding (GTAW).*

Advantages: good protection of a weld. Welding is possible in all spatial positions. Productivity is higher than that of manual welding. The seam is visible, so it is possible to supervise process visually. Welding in argon does not give slag at all; welding in carbonic gas gives a little of slag. Welding in CO_2 atmosphere is a low cost process.

Application: structures made of carbon and low-alloyed steels are welded in carbonic gas (gas and oil pipelines, ship hulls). Argon welding is used for the alloyed steels, aluminium, copper, magnesium alloys, refractory metals.

Gas welding

In Fig. 63 the scheme of *gas welding* is shown. Basic metal 1 and filler material 2 are melted using the high-temperature gas flame 4. Combustible gas (acetylene C_2H_2, propane C_3H_8, etc.) is mixed with oxygen at the outlet of the flame torch 3 and burns being ignited thus giving high temperature flame. Combustible gases are stored and supplied in gas bottles from which they are fed to the welding zone through rubber hoses and reducers which serve to reduce the high pressure of stored gases. For weld formation the filler rods made of an alloy of the necessary composition are used.

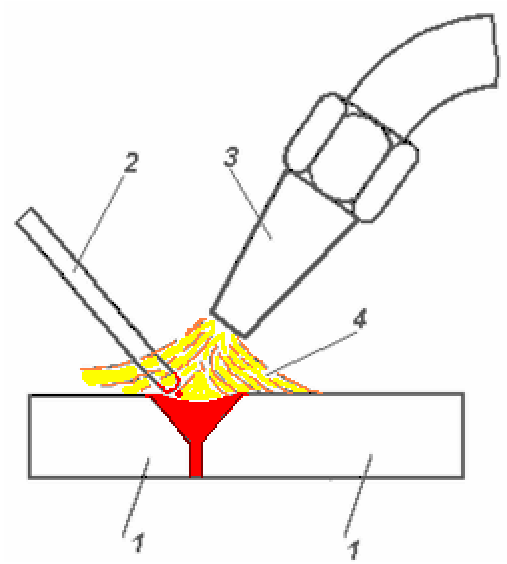


Fig. 63 Scheme of gas welding

Structure of oxygen-acetylene flame (Fig. 64): 1 – flame heart, 2 – welding zone, 3 – plume. The temperature in the welding zone is up to 3,200°C. This part of the flame serves to melt a metal. Brightly shining flame heart has temperature 300°C, and the plume – about 1,000 °C, it preliminary heats up welded metal.

Other combustible gases give flames of lower temperatures. Usually oxygen / acetylene ratio is as shown below

$$O_2 : C_2H_2 = 1.1.$$

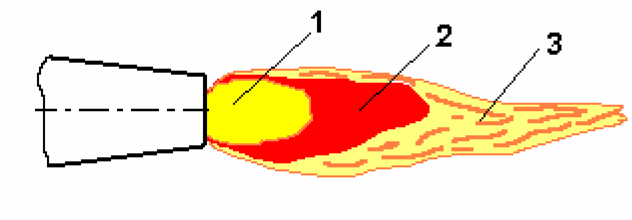


Fig. 64 Structure of welding flame

This is so-called *normal flame*. If there is more oxygen, the flame becomes *oxidizing*; this way it is used for welding the brass metal only. When there is more acetylene, the flame is *carbonizing*. It is used for welding high-carbon steels, cast irons, hard alloys.

Advantages: electricity is not necessary. Welding can be made in the field conditions away from electric power supply. Gas welding gives gradual heating that allows welding low 0.2–0.3 mm thickness metal sheets as well as low-melting metals and alloys. Gradual, soft heating is necessary for welding of cast irons and brass.

Gas welding is widely used for repair and elimination of castings defects.

Acetylene-oxygen flame is also applied for heating metal in process of gas-oxygen cutting.

There are also other ways of welding by fusion: *plasma*, *laser*, *electron beam*.

Resistance welding

The ways of welding considered above are carried out by means of fusion. But just melting the welded edges only is sometimes insufficient to make a high quality joint. Then combined ways are applied when the edges of welded parts are melted or heated up to become plasticized and then pressed against each other.

Electro-contact, or *resistance welding* is carried out by electric current heating the welded pieces and upsetting (squeezing) of heated billets. The heated, plasticized and pressed into each other edges form interatomic bonds along the join line in the process of plastic deformation and cooling. A strong joint is thusly formed.

The quantity of heat released from the current passage along a conductor is defined by the Joule's law as:

$$Q = k{\cdot}I^2{\cdot}R{\cdot}t,$$

where I is the current in a circuit, R is a conductor's resistance, t is the time of a current passage. The highest resistance is formed at the contact surfaces between the parts to be welded, therefore, the highest quantity of heat is given off there, and that allows to fuse steel billets.

Three kinds of resistance welding are distinguished by the type of joint formed.

Resistance butt welding

Butt welding is applied for billets having a rod-like shape. A joint is formed over the total surface contact area of billet ends. The welding scheme is shown in Fig. 65: 1 – current supply clips, 2 – billets, 3 – motionless plate; 4 – mobile plate, 5 – guide, 6 – welding transformer, 7 – flexible buses.

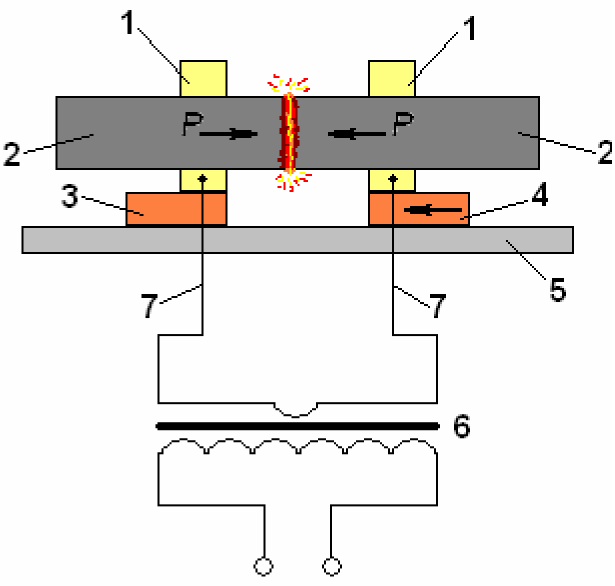


Fig. 65 Scheme of butt welding

There are two variants of butt welding:

1) *Upset welding (UW)*. Pressure is applied before heating is started and maintained throughout the heating pe-

riod. Billets are squeezed together, then the current is switched on, butt ends are become plasticized by the current generated heat, and then upsetting is made. Some thickening appears along the joint line.

Application: parts of small cross section (less than 20 mm in diameter).

Disadvantage: surfaces being joined should be smoothed out carefully (grinded) for the best contact.

2) *Flash welding (FW)*, Fig. 66. In the beginning the current is switched on, then billets butt ends start approaching each other. The microirregularities on the joined surfaces contact each other and then melted due to high current density (Fig. 66, *a*). Billets continue to approach being melted already over the entire surface area (Fig. 66, *b*), and then the mechanism of upsetting is actuated. A layer of fused metal together with oxides and other contaminations is squeezed out of the joint area thus forming a rough thickening, called *welding edge*, which is then removed using a lathe (Fig. 66, *c*).

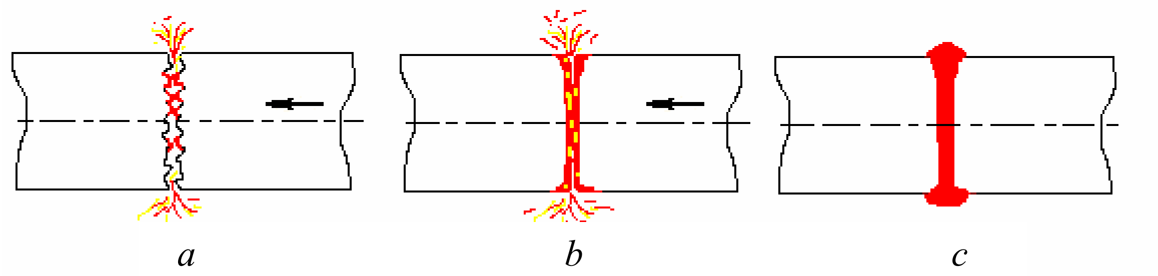
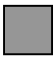
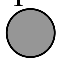


Fig. 66 Flash welding

Advantages: cleaning of surfaces is not necessary; it is possible to weld parts of a complex section and with the different shape of the section ( and ); dissimilar metals can be welded, too.

Application: welding of rings, wheels, the end tool (drills, mills, taps), rods, rails, reinforcement, pipes.

Resistance spot welding (RSW)

Metal sheets are joined in separate points. Sheets edges placed one on another thus forming a lap joint, clamped between copper electrodes, and current is switched on. Sheets are heated up to fusion in a contact place. Current is switched off, and pressure increases. Crystallization of a welded spot goes under pressure.

The welding scheme is shown in Fig. 67, *a*: 1 – electrodes, 2 – billets, 3 – welded spot, 4 – transformer. *The cyclogram* of the process is shown in Fig. 67, *b*: site 1 – compression of billets, site 2 – current passage and metal fusion, 3 – current switching off, 4 – forging force application, 5 – forging force removal.

Application: producing metal sheet constructions by stamping and welding from metal 0.5–6 mm in thickness. It is possible to weld structural steels, aluminium, copper and their alloys.

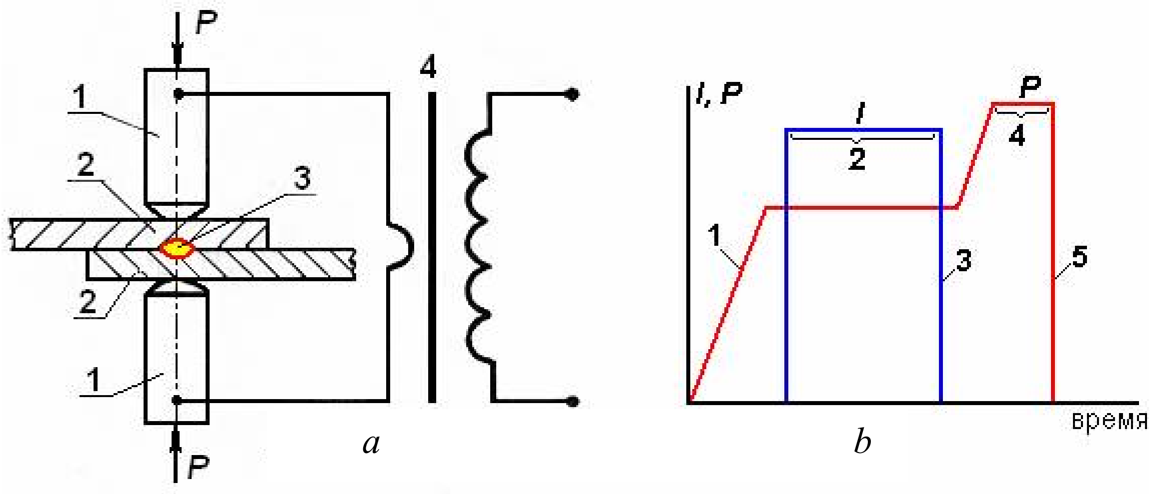


Fig. 67 Scheme of resistance spot welding *(a)*;
cyclogram of welding process *(b)*

Resistance seam welding (RSEW)

The resulting weld is a series of overlapping resistance spot welds made progressively along a joint by rotating electrodes. Sheets formed the lap joint clamped between copper roller electrodes and current is switched on. Rollers rotate, therefore welded spots are overlapped, forming a tight seam.

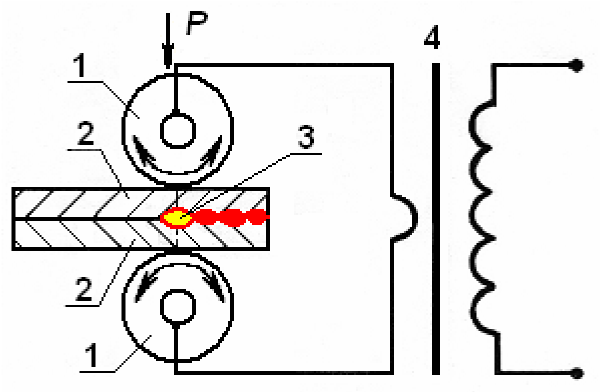


Fig. 68 Scheme of resistance seam welding

Positions in the scheme (Fig. 68): 1 – electrodes (copper rollers), 2 – billets, 3 – welded spot, 4 – transformer.

Application: manufacturing of various vessels and pipes, for water and other liquids and gases. The thickness of sheets is 0.3–3 mm. A high-efficiency method: speed of welding makes up to 10 m/min.

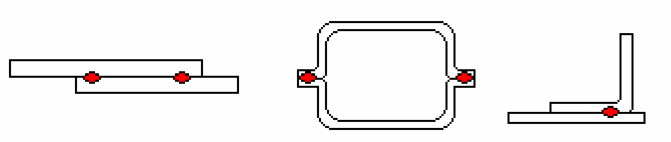


Fig. 69 Spot and seam welding joints

Technology of resistance welding is presented in methodical instructions to laboratory work "Equipment and technology of manual arc welding and resistance welding". Study individually!

Friction welding (FRW)

For this method both heating and pressure are applied too. Billets are heated up by heat resulted from friction of rotated billet against the motionless one, then axial compression is applied, and billets weld one to another. In the welding scheme (Fig. 70) positions are shown: 1 – motionless billet, 2 – rotating billet, 3 – clutch, 4 – welding edge.

Advantages: high quality of a joint. It is possible to weld dissimilar metals. Expenses for the electric power are 5–10 times less than during resistance butt welding.

Application: manufacturing of drills, taps and other cutting tools, welding of shaft, punches, pistons with rods, axes, pipes.

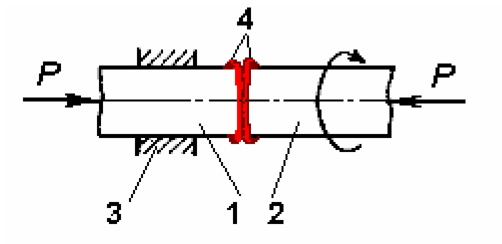


Fig. 70 Scheme of friction welding

Cold welding (CW)

It is welding by pressure in the pure state: it is carried out without any extra heating.

Welded surfaces approach each other until interatomic bonds are formed due to a considerable plastic deformation. Fatty and oxide films should be removed in advance.

The scheme of cold welding is presented in Fig. 71, *a*. During compression of billets 3 by force *P* projections 2 of punches are pressed into metal while punches 1 will not rest against the surfaces of billets. Projections are embedded into metal to 70–80 % of its thickness. In a welding zone there is a considerable plastic deformation of metal, oxide films and pollutions are squeezed out on the periphery, and interatomic bonds form between the pure surfaces of billets. So the welded joint is formed (Fig. 71, *b*). The shape of the welded spot corresponds to that of projection (Fig. 71, *c*).

By cold welding it is possible to obtain spot, butt and seam joints.

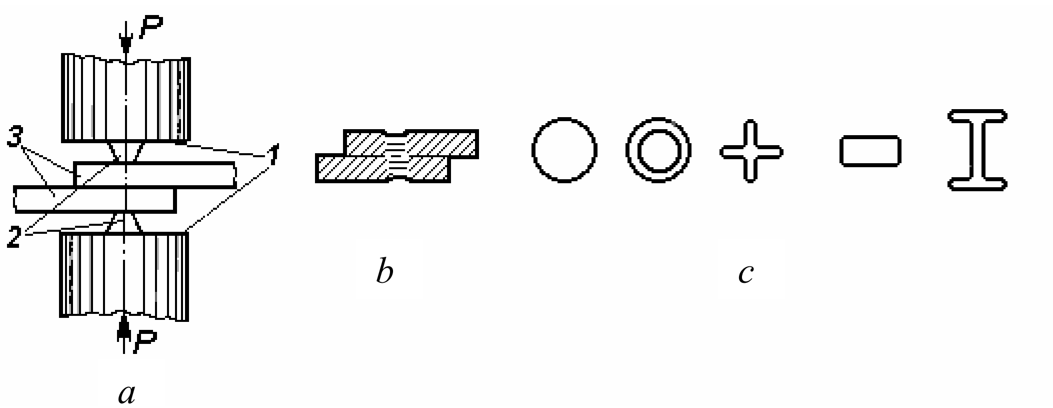


Fig. 71 Cold welding: *a)* scheme of spot welding;
b) welding joint; *c)* shapes of welded spots

Application: joining of billets of soft, ductile metals, such as aluminium, copper, nickel, lead, tin, zinc; welding of device cases, wires, buses, aluminium cable sheath.

Welding defects and quality inspection

All defects arising in welding can be divided into *external*, visible and *internal*, invisible, the latter are especially dangerous.

External defects, which can be detected by visual inspection, are defects of seam geometry: non-uniform section of a seam, deviation of the seam sizes from the established ones. Besides, *undercuts*, *leading-edge extensions*, *cracks* are external defects too (Fig. 72). During resistance butt welding displacement of rod axes is possible. During spot and seam welding metal splashing and indents take place.

Internal defects can be detected only by special methods of non-destructive testing. They are *lack of penetration*, *slag inclusions*, *pores* (Fig. 72). Occurrence of internal cracks and *overheat* (grain growth over acceptable values) are possible.

Methods of welding joints quality inspection

1) External visual inspection and measurements of seams.

2) Metallography analysis (allows to define depth of penetration and presence of internal defects, but it is a destructive quality testing).

3) Chemical analysis (allows to establish whether weld metal corresponds to the electrode certificate).

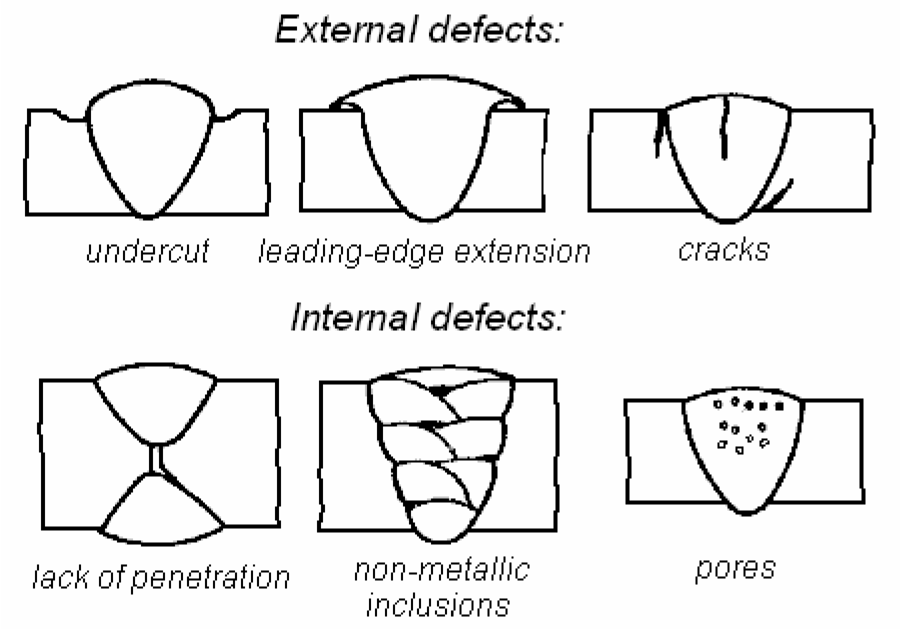


Fig. 72 Defects of welding joints

4) Mechanical tests define hardness and strength of a welded joint.

5) X-ray or gamma inspection are non-destructive methods, all internal defects are visible in a film.

6) Ultrasonic method allows to find defects due to the beam deviation on the oscillograph screen.

7) Magnetic methods fix defects for the account of magnetic stream dispersion.

8) Welded seams of vessels are tested for density by means of special penetrants (kerosene) or compressed air.

Soldering

Soldering is joining of metals and alloys in a solid condition by means of *solder* – an alloy with melting temperature lower than that of joined metals.

Solder should wet and dissolve metal of connected parts or to form chemical compounds with it. The major role in the soldering process is played by the capillary phenomena: they provide penetration of the liquid solder into a gap between the joined parts (Fig. 73).

For dissolution and removal of oxides from the surface of parts and also for improvement of metal wettability by solder *fluxes* are applied. They are rosin, hydrochloric acid, zinc chloride, borax, boric acid, liquid ammonia.

Solders are divided into *soft solders*, with low temperature of fusion (tin-lead solders) and *hard solders*, or *brazing alloys* with a high fusion temperature (alloys of copper with zinc, nickel, silver).

Advantages of soldering in comparison with welding: soldering is more economical, it does not change a chemical composition and mechanical properties of a metal, soldered joints deform less than welded ones.

Disadvantage: the strength of a soldered joint is lower than the strength of the base metal. Surfaces for soldering should be well prepared: smoothed out and degreased. The gap between the soldered parts should be minimal: the 1/100-th part of mm.

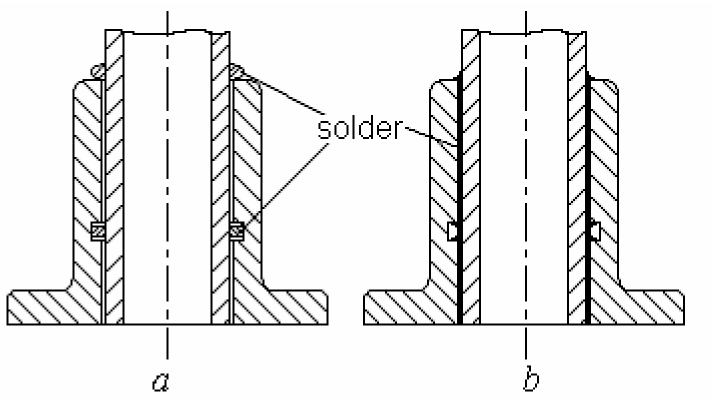


Fig. 73 Scheme of capillary soldering:
a – before soldering; *b* – after soldering

Appendix

Welding Process

Abstract:

The welding processes, in their official groupings. The letter designation assigned to the process can be used for identification on drawings, tables, etc. Allied and related processes include adhesive bonding, thermal spraying, and thermal cutting. Capillary attraction distinguishes the welding processes grouped under "Brazing" and "Soldering" from "Arc Welding", "Gas Welding", "Resistance Welding", "Solid State Welding", and "Other Processes."

The American Welding Society has made each welding process definition as complete as possible so that it will suffice without reference to another definition. They define a process as "a distinctive progressive action or series of actions involved in the course of producing a basic type of result".

The official listing of processes and their grouping is shown by Figure II.1, the AWS Master Chart of Welding and Allied Processes.

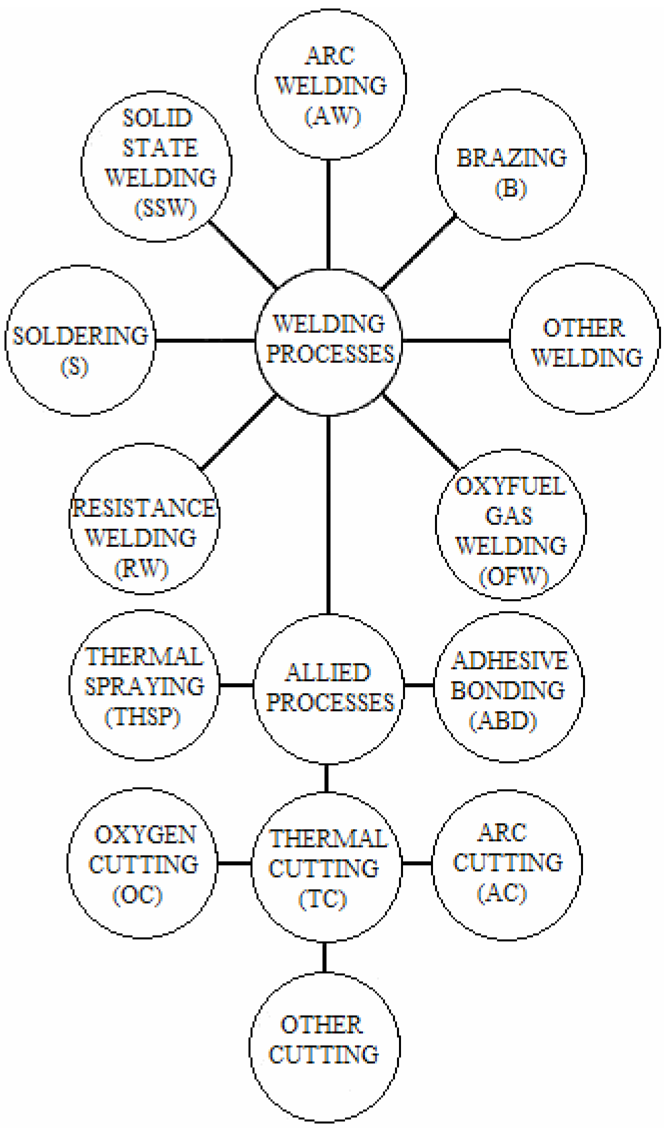


Figure 1 AWS master chart of welding and allied processes

The welding society formulated process definitions from the operational instead of the metallurgical point of view. Thus the definitions prescribe the significant elements of operation instead of the significant metallurgical characteristics.

The AWS definition for a welding process is "a materials joining process which produces coalescence of materials by heating them to suitable temperatures with or without the application of pressure or by the application of pressure alone and with or without the use of filler material".

AWS has grouped the processes together according to the "mode of energy transfer" as the primary consideration. A secondary factor is the "influence of capillary attraction in effecting distribution of filler metal" in the joint. Capillary attraction distinguishes the welding processes grouped under "Brazing" and "Soldering" from "Arc Welding", "Gas Welding", "Resistance Welding", "Solid State Welding", and "Other Processes".

The welding processes, in their official groupings, are shown by *Table 1.* This table also shows the letter designation for each process. The letter designation assigned to the process can be used for identification on drawings, tables, etc. Allied and related processes include adhesive bonding, thermal spraying, and thermal cutting.

Table 1 Welding processes and letter designation

Group	Welding Process	Letter Designation
Arc welding	Carbon Arc	CAW
	Flux Cored Arc	FCAW
	Gas Metal Arc	GMAW
	Gas Tungsten Arc	GTAW
	Plasma Arc	PAW
	Shielded Metal Arc	SMAW
	Stud Arc	SW
	Submerged Arc	SAW
Brazing	Diffusion Brazing	DFB
	Dip Brazing	DB
	Furnace Brazing	FB
	Induction Brazing	IB
	Infrared Brazing	IRB
	Resistance Brazing	RB
	Torch Brazing	TB
Oxyfuel Gas Welding	Oxyacetylene Welding	OAW
	Oxyhydrogen Welding	OHW
	Pressure Gas Welding	PGW

Resistance Welding	Flash Welding	FW
	High Frequency Resistance	HFRW
	Percussion Welding	PEW
	Projection Welding	RPW
	Resistance-Seam Welding	RSEW
	Resistance-Spot Welding	RSW
	Upset Welding	UW
Solid State Welding	Cold Welding	CW
	Diffusion Welding	DFW
	Explosion Welding	EXW
	Forge Welding	FOW
	Friction Welding	FRW
	Hot Pressure Welding	HPW
	Roll Welding	ROW
	Ultrasonic Welding	USW
Soldering	Dip Soldering	DS
	Furnace Soldering	FS
	Induction Soldering	IS
	Infrared Soldering	IRS
	Iron Soldering	INS
	Resistance Soldering	RS
	Torch Soldering	TS
	Wave Soldering	WS
Other Welding Processes	Electron Beam	EBW
	Electroslag	ESW
	Induction	IW
	Laser Beam	LBW
	Thermit	TW

Arc Welding

The arc welding group includes eight specific processes, each separate and different from the others but in many respects similar.

The **carbon arc welding** (CAW) process is the oldest of all the arc welding processes and is considered to be the beginning of arc welding. The Welding Society defines carbon arc welding as “an arc welding process which produces coalescence of metals by heating them with an arc between a carbon electrode and the work-piece. No shielding is used. Pressure and filler metal may or may not be used." It has limited applications today, but a variation or twin carbon arc welding is more popular. Another variation uses compressed air for cutting.

The development of the metal arc welding process soon followed the carbon arc. This developed into the currently popular **shielded metal arc welding** (SMAW) process defined as "an arc welding process which produces coalescence of metals by heating them with an arc between a covered metal electrode and the work-piece. Shielding is obtained from decomposition of the electrode covering. Pressure is not used and filler metal is obtained from the electrode."

Automatic welding utilizing bare electrode wires was used in the 1920s, but it was the **submerged arc welding** (SAW) process that made automatic welding popular. Submerged arc welding is defined as "an arc welding process which produces coalescence of metals by heating them with an arc or arcs between a bare metal electrode or electrodes and the work piece. Pressure is not used and filler metal is obtained from the electrode and sometimes from a supplementary welding rod." It is normally limited to the flat or horizontal position.

The need to weld nonferrous metals, particularly magnesium and aluminum, challenged the industry. A solution was found called **gas tungsten arc welding** (GTAW) and was defined as "an arc welding process which produces coalescence of metals by heating them with an arc between a tungsten (non-consumable) electrode and the work piece. Shielding is obtained from a gas or gas mixture."

Plasma arc welding (PAW) is defined as "an arc welding process which produces a coalescence of metals by heating them with a constricted arc between an electrode and the work piece (transferred arc) or the electrode and the constricting nozzle (non-transferred arc). Shielding is obtained from the hot ionized gas issuing from the orifice which may be supplemented by an auxiliary source of shielding gas." Shielding gas may be an inert gas or a mixture of gases. Plasma welding has been used for joining some of the thinner materials.

Another welding process also related to gas tungsten arc welding is known as **gas metal arc welding** (GMAW). It was developed in the late 1940s for welding aluminum and has become extremely popular. It is defined as "an arc welding process which produces coalescence of metals by heating them with an arc between a continuous filler metal (consumable) electrode and the work piece. Shielding is obtained entirely from an externally supplied gas or gas mixture." The electrode wire for GMAW is continuously fed into the arc and deposited as weld metal. This process has many variations depending on the type of shielding gas, the type of metal transfer, and the type of metal welded.

A variation of gas metal arc welding has become a distinct welding process and is known as **flux-cored arc welding** (FCAW). It is defined as "an arc welding process which produces coalescence of metals by heating them with an arc between a continuous filler metal (consumable) electrode and the work piece. Shielding is provided by a flux contained within the tubular electrode." Additional shielding may or may not be obtained from an externally supplied gas or gas mixture.

The final process within the arc welding group of processes is known as **stud arc welding** (SW). This process is defined as "an arc welding process which produces coalescence of metals by heating them with an arc between a metal stud or similar part and the work piece". When the surfaces to be joined are properly heated they are brought together under pressure. Partial shielding may be obtained by the use of ceramic ferrule surrounding the stud.

Brazing (B)

Brazing is "a group of welding processes which produces coalescence of materials by heating them to a suitable temperature and by using a filler metal, having a liquidus above 450°C and below the solidus of the base materials. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction."

A braze is a very special form of weld, the base metal is theoretically not melted. There are seven popular different processes within the brazing group. The source of heat differs among the processes. Braze welding relates to welding processes using brass or bronze filler metal, where the filler metal is not distributed by capillary action.

Oxy Fuel Gas Welding (OFW)

Oxy fuel gas welding is "a group of welding processes which produces coalescence by heating materials with an oxy fuel gas flame or flames with or without the application of pressure and with or without the use of filler metal."

There are four distinct processes within this group and in the case of two of them, **oxyacetylene welding** and **oxyhydrogen welding**, the classification is based on the fuel gas used. The heat of the flame is created by the chemical reaction or the burning of the gases. In the third process, **air acetylene welding**, air is used instead of oxygen, and in the fourth category, **pressure gas welding**, pressure is applied in addition to the heat from the burning of the gases. This welding process normally utilizes acetylene as the fuel gas. The oxygen thermal cutting processes have much in common with these welding processes.

Resistance Welding (RW)

Resistance welding is "a group of welding processes which produces coalescence of metals with the heat obtained from resistance of the work to electric current in a circuit of which the work is a part, and by the application of pressure". In general, the difference among the resistance welding processes has to do with the design of the weld and the type of machine necessary to produce the weld. In almost all cases the processes are applied automatically since the welding machines incorporate both electrical and mechanical functions.

Other Welding Processes

This group of processes includes those, which are not best defined under the other groupings. It consists of the following processes: **electron beam welding, laser beam welding, thermit welding, and other miscellaneous welding** processes in addition to **electroslag welding** which was mentioned previously.

Soldering (S)

Soldering is "a group of joining processes which produces coalescence of materials by heating them to a suitable temperature and by using a filler metal having a liquidus not exceeding 450 ^oC (840 ^oF) and below the solidus of the base materials. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction." There are a number of different soldering processes and methods.

Solid State Welding (SSW)

Solid state welding is "a group of welding processes which produces coalescence at temperatures essentially below the melting point of the base materials being joined without the addition of a brazing filler metal. Pressure may or may not be used."

The oldest of all welding processes **forge welding** belongs to this group. Others include **cold welding, diffusion welding, explosion welding, friction welding, hot pressure welding,** and **ultrasonic welding**. These processes are all different and utilize different forms of energy for making welds.

The Welding Processes: Resistance Welding

Abstract:
Resistance welding is a group of welding processes in which coalescence is produced by the heat obtained from resistance of the work piece to electric current in a circuit of which the work piece is a part and by the application of pressure. There are at least seven important resistance-welding processes.

Resistance welding is a group of welding processes in which coalescence is produced by the heat obtained from resistance of the work piece to electric current in a circuit of which the work piece is a part and by the application of pressure. There are at least seven important resistance-welding processes. These are flash welding, high-frequency resistance welding, percussion welding, projection welding, resistance seam welding, resistance spot welding, and upset welding. They are alike in many respects but are sufficiently different.

Resistance spot welding (RSW) is a resistance welding process which produces coalescence at the faying surfaces in one spot by the heat obtained from resistance to electric current through the work parts held together under pressure by electrodes.

The size and shape of the individually formed welds are limited primarily by the size and contour of the electrodes. The equipment for resistance spot welding can be relatively simple and inexpensive up through extremely large multiple spot welding machines. The stationary single spot welding machines are of two general types: the *horn or rocker arm* type and the *press* type.

The horn type machines have a pivoted or rocking upper electrode arm, which is actuated by pneumatic power or by the operator`s physical power. They can be used for a wide range of work but are restricted to 50 kVA and are used for thinner gauges. For larger machines normally over 50 kVA, the press type machine is used. In these machines, the upper electrode moves in a slide. The pressure and motion are provided on the upper electrode by hydraulic or pneumatic pressure, or are motor operated.

For high-volume production work, such as in the automotive industry, multiple spot welding machines are used. These are in the form of a press on which individual guns carrying electrode tips are mounted. Welds are made in a sequential order so that all electrodes are not carrying current at the same time.

Projection welding (RPW) is a resistance welding process which produces coalescence of metals with the heat obtained from resistance to electrical current through the work parts held together under pressure by electrodes.

The resulting welds are localized at predetermined points by projections, embossments, or intersections. Localization of heating is obtained by a projection or embossment on one or both of the parts being welded. There are several types of projections: (1) the button or dome type, usually round, (2) elongated projections, (3) ring projections, (4) shoulder projections, (5) cross wire welding, and (6) radius projection.

The major advantage of projection welding is that electrode life is increased because larger contact surfaces are used. A very common use of projection welding is the use of special nuts that have projections on the portion of the part to be welded to the assembly.

Resistance seam welding (RSEW) is a resistance welding process which produces coalescence at the faying surfaces the heat obtained from resistance to electric current through the work parts held together under pressure by electrodes.

The resulting weld is a series of overlapping resistance spot welds made progressively along a joint rotating the electrodes. When the spots are not overlapped enough to produce gaslight welds it is a variation known as roll **resistance spot welding**. This process differs from spot welding since the electrodes are wheels. Both the upper and lower electrode wheels are powered. Pressure is applied in the same manner as a press type welder. The wheels can be either in line with the throat of the machine or transverse. If they are in line it is normally called a longitudinal seam welding machine. Welding current is transferred through the bearing of the roller electrode wheels. Water cooling is not provided internally and therefore the weld area is flooded with cooling water to keep the electrode wheels cool.

In seam welding a rather complex control system is required. This involves the travel speed as well as the sequence of current flow to provide for overlapping welds. The welding speed, the spots per inch, and the timing schedule are dependent on each other. Welding schedules provide the pressure, the current, the speed, and the size of the electrode wheels.

This process is quite common for making flange welds, for making watertight joints for tanks, etc. Another variation is the so-called **mash seam welding** where the lap is fairly narrow and the electrode wheel is at least twice as wide as used for standard seam welding. The pressure is increased to approximately 300 times normal pressure. The final weld mash seam thickness is only 25% greater than the original single sheet.

Flash Welding (FW) is a resistance welding process which produces coalescence simultaneously over the entire area of abutting surfaces, by the heat obtained from resistance to electric current between the two surfaces, and by the application of pressure after heating is substantially completed.

Flashing and upsetting are accompanied by expulsion of metal from the joint. During the welding operation there is an intense flashing arc and heating of the metal on the surface abutting each other. After a predetermined time the two pieces are forced together and coalescence occurs at the interface, current flow is possible because of the light contact between the two parts being flash welded.

The heat is generated by the flashing and is localized in the area between the two parts. The surfaces are brought to the melting point and expelled through the abutting area. As soon as this material is flashed away another small arc is formed which continues until the entire abutting surfaces are at the melting temperature. Pressure is then applied and the arcs are extinguished and upsetting occurs.

Upset welding (UW) is a resistance welding process which produces coalescence simultaneously over the entire area of abutting surfaces or progressively along a joint, by the heat obtained from resistance to electric current through the area where those surfaces are in contact.

Pressure is applied before heating is started and is maintained throughout the heating period. The equipment used for upset welding is very similar to that used for flash welding. It can be used only if the parts to be welded are equal in cross-sectional area. The abutting surfaces must be very carefully prepared to provide for proper heating.

The difference from flash welding is that the parts are clamped in the welding machine and force is applied bringing them tightly together. High-amperage current is then passed through the joint, which heats the abutting surfaces. When they have been heated to a suitable forging temperature an upsetting force is applied and the current is stopped. The high temperature of the work at the abutting surfaces plus the high pressure causes coalescence to take place. After cooling, the force is released and the weld is completed.

Percussion welding (PEW) is a resistance welding process which produces coalescence of the abutting members using heat from an arc produced by a rapid discharge of electrical energy.

Pressure is applied progressively during or immediately following the electrical discharge. This process is quite similar to flash welding and upset welding, but is limited to parts of the same geometry and cross section. It is more complex than the other two processes in that heat is obtained from an arc produced at the abutting surfaces by the very rapid discharge of stored electrical energy across a rapidly decreasing air gap. This is immediately followed by application of pressure to provide an impact bringing the two parts together in a progressive percussive manner. The advantage of the process is that there is an extremely shallow depth of heating and time cycle is very short. It is used only for parts with fairly small cross-sectional areas.

High frequency resistance welding (HFRW) is a resistance welding process which produces coalescence of metals with the heat generated from the resistance of the work pieces to a high-frequency alternating current in the 10,000 to 500,000 hertz range and the rapid application of an upsetting force after heating is substantially completed. The path of the current in the work piece is controlled by the proximity effect.

This process is ideally suited for making pipe, tubing, and structural shapes. It is used for other manufactured items made from continuous strips of material. In this process the high frequency welding current is introduced into the metal at the surfaces to be welded but prior to their contact with each other.

Current is introduced by means of sliding contacts at the edge of the joint. The high-frequency welding current flows along one edge of the seam to the welding point between the pressure rolls and back along the opposite edge to the other sliding contact.

The current is of such high frequency that it flows along the metal surface to a depth of several thousandths of an inch. Each edge of the joint is the conductor of the current and the heating is concentrated on the surface of these edges. At the area between the closing rolls the material is at the plastic temperature, and with the pressure applied, coalescence occurs.

Welding Procedures and the Fundamentals of Welding

Abstract:
As welding becomes a modern engineering technology it requires that the various elements involved be identified in a standardized way. This is accomplished by writing a procedure which is simply a "manner of doing" or "the detailed elements (with prescribed values or range of values) of a process or method used to produce a specific result."

Welding procedures take on added significance based on the quality requirements that can be involved. When exact reproducibility and perfect quality are required, the procedures will become much more technical with added requirements, particularly in testing. Tests will become more complex to determine that the weld joint has the necessary properties to withstand the service for which the weld is designed.

Welding Procedures

As welding becomes a modern engineering technology it requires that the various elements involved be identified in a standardized way. This is accomplished by writing a procedure which is simply a "manner of doing" or "the detailed elements (with prescribed values or range of values) of a process or method used to produce a specific result." The AWS definition for a welding procedure is "the detailed methods and practices including all joint welding procedures involved in the production of a weldment." The joint welding procedure mentioned includes "the materials, detailed methods and practices employed in the welding of a particular joint.

A welding procedure is used to make a record of all of the different elements, variables, and factors that are involved in producing a specific weld or weldment. Welding procedures should be written whenever it is necessary to:

- Maintain dimensions by controlling distortion
- Reduce residual or locked up stresses
- Minimize detrimental metallurgical changes
- Consistently build a weldment the same way
- Comply with certain specifications and codes.

Welding procedures must be tested or qualified and they must be communicated to those who need to know. This includes the designer, the welding inspector, the welding supervisor, and last but not least, the welder.

When welding codes or high-quality work is involved this can become a *welding procedure specification*, which lists in detail the various factors or variables involved. Different codes and specifications have somewhat different requirements for a welding procedure, but in general a welding procedure consists of three parts as follows:

- A detailed written explanation of how the weld is to be made
- A drawing or sketch showing the weld joint design and the conditions for making each pass or bead
- A record of the test results of the resulting weld.

If the weld meets the requirements of the code or specification and if the written procedure is properly executed and signed it becomes a *qualified welding procedure*.

The variables involved in most specifications are considered to be essential variables. In some codes the term nonessential variables may also be used. Essential variables are those factors which must be recorded and if they are changed in any way, the procedure must be retested and requalified. Nonessential variables are usually of less importance and may be changed within prescribed limits and the procedure need not be requalified.

Essential variables involved in the procedure usually include the following:

- The welding process and its variation
- The method of applying the process
- The base metal type, specification, or composition
- The base metal geometry, normally thickness
- The base metal need for preheat or postheat
- The welding position
- The filler metal and other materials consumed in making the weld
- The weld joint, that is, the joint type and the weld
- Electrical or operational parameters involved
- Welding technique.

Some specifications also include nonessential variables and these are usually the following:

- The travel progression (uphill or downhill)
- The size of the electrode or filler wire

- Certain details of the weld joint design
- The use and type of weld backing
- The polarity of the welding current.

The procedure write-up must include each of the listed variables and describe in detail how it is to be done. The second portion of the welding procedure is the joint detail sketch and table or schedule of welding conditions.

Tests are performed to determine if the weld made to the procedure specification meets certain standards as established by the code or specification. If the destructive tests meet the minimum requirements the procedure then becomes *a qualified procedure specification*. The writing, testing, and qualifying procedures become quite involved and are different for different specifications and will be covered in detail in a later chapter.

In certain codes, welding procedures are prequalified. By using data provided in the code individual qualified procedure specifications are not required, for the standard joints on common base materials using the shielded metal arc welding process.

The factors included in a procedure should be considered in approaching any new welding job. By means of knowledge and experience establish the optimum factors or variables in order to make the best and most economical weld on the material to be welded and in the position that must be welded.

Welding procedures take on added significance based on the quality requirements that can be involved. When exact reproducibility and perfect quality are required, the procedures will become much more technical with added requirements, particularly in testing. Tests will become more complex to determine that the weld joint has the necessary properties to withstand the service for which the weld is designed.

Procedures are written to produce the highest-quality weld required for the service involved, but at the least possible cost and to provide weld consistency. It may be necessary to try different processes, different joint details, and so on, to arrive at the lowest-cost weld which will satisfy the service requirements of the weldment.

The Physics and Chemistry of Welding

Welding follows all of the physical laws of nature and a good understanding of physics and chemistry will help you better understand how welds are made.

The science of sound is important to welding since one welding process and one weld nondestructive examination technique is based on the use of sound. Sound is transmitted through most materials: metals, gases, liquids, etc., but it will not pass through a vacuum. Sound is an alternating type of energy based on vibrations, which are regions of compaction and rarification.

The science of light also involves welding. The laser beam welding process utilizes light energy at very high concentrations to create heat sufficient to cause melting, which can be used for welding or cutting. Light is a by-product of the arc welding processes. Light is given off by the arc and by heated electrodes and base metals.

The science of friction also involves welding. Here we are interested in dynamic friction, better known as sliding friction. This is the force between two moving bodies and if sufficient force is available heat will be generated. This is the basis for the friction-welding process.

Several chemical definitions relate to welding. One is known as burning or oxidation. This takes place when any substance combines with oxygen usually at high temperatures. An example of this is the combining of acetylene with oxygen. This produces carbon dioxide plus water plus a large amount of heat. We use the heat produced by the burning of acetylene in the flame of the oxyacetylene torch to make welds. In all oxidation reactions heat is given off. Oxidation can occur very slowly as in the case of rusting. If iron is exposed to oxygen at high temperature rapid oxidation or burning will occur with the liberation of more heat. Rapid oxidation or burning does not occur until the kindling temperature of the material is reached. In the case of a liquid this term is called the flash point. Oxidation is very important in welding operations since oxygen of the air is usually present as well as heat.

Beam Welding and Thermit Welding

Abstract:

Electron beam welding (EBW) is a welding process which produces coalescence of metals with the heat obtained from a concentrated beam composed primarily of high-velocity electrons impinging upon the surfaces to be joined.

Laser beam welding (LBW) is a welding process which produces coalescence of materials with the heat obtained from the application of a concentrated coherent light beam impinging upon the surfaces to be joined.

Thermit welding (TW) is a welding process which produces coalescence of metals by heating them with superheated liquid metal from a chemical reaction between a metal oxide and aluminum with or without the application of pressure.

Electron Beam Welding

Electron beam welding (EBW) is a welding process which produces coalescence of metals with the heat obtained from a concentrated beam composed primarily of high-velocity electrons impinging upon the surfaces to be joined. Heat is generated in the work-piece as it is bombarded by a dense stream of high-velocity electrons. Virtually all of the kinetic energy - the energy of motion - of the electrons is transformed into heat upon impact.

The electron beam welding process had its inception in the 1950s in the nuclear field. There were many requirements to weld refractory and reactive metals. These metals, because of their affinity for oxygen and nitrogen of the air, are very difficult to weld.

The original work was done in a high vacuum. The process utilized an electron gun similar to that used in an X-ray tube. In an X-ray tube the beam of electrons is focused on a target of either tungsten or molybdenum which gives off X-rays. The target becomes extremely hot and must be water-cooled. In welding, the target is the base metal which absorbs the heat to bring it to the molten stage. In electron beam welding, X-rays may be produced if the electrical potential is sufficiently high.

As developments continued, two basic designs evolved: (1) the low-voltage electron beam system, which uses accelerating voltages in 30,000 volts or (30 kV) to 60,000-volt (60 kV) range and (2) the high-voltage system with accelerating voltages in the 100,000-volt (100 kV) range. The higher voltage system emits more X-rays than the lower voltage system.

In both systems, the electron gun and the work piece are housed in a vacuum chamber. There are three basic components in an electron beam-welding machine. These are (1) the electron beam gun, (2) the power supply with controls, and (3) a vacuum work chamber with work-handling equipment. The electron beam gun emits electrons, accelerates the beam of electrons, and focuses it on the work piece.

Recent advances in equipment allow the work chamber to operate at a medium vacuum or pressure. In this system, the vacuum in the work chamber is not as high. It is sometimes called a "soft" vacuum. This vacuum range allowed the same contamination that would be obtained in atmosphere of 99.995% argon. Mechanical pumps can produce vacuums to the medium pressure level.

One of the major advantages of electron beam welding is its tremendous penetration. This occurs when the highly accelerated electron hits the base metal. It will penetrate slightly below the surface and at that point release the bulk of its kinetic energy which turns to heat energy. The addition of the heat brings about a substantial temperature increase at the point of impact. The succession of electrons striking the same place causes melting and then evaporation of the base metal. This creates metal vapors but the electron beam travels through the vapor much easier than solid metal. This causes the beam to penetrate deeper into the base metal. The width of the penetration pattern is extremely narrow. The depth-to-width can exceed a ratio of 20 to 1. As the power density is increased penetration is increased.

The heat input of electron beam welding is controlled by four variables: (1) the number of electrons per second hitting the work piece or beam current, (2) the electron speed at the moment of impact, the accelerating potential, (3) the diameter of the beam at or within the work-piece, the beam spot size, and (4) the speed of travel or the welding speed. The first two variables, beam current and accelerating potential, are used in establishing welding parameters. The third factor, the beam spot size, is related to the focus of the beam, and the fourth factor is also part of the procedure.

Since the electron beam has tremendous penetrating characteristics, with the lower heat input, the heat-affected zone is much smaller than that of any arc welding process. In addition, because of the almost parallel sides of the weld nugget, distortion is greatly minimized. The cooling rate is much higher and for many metals this is advantageous; however, for high-carbon steel this is a disadvantage and cracking may occur.

The weld joint details for electron beam welding must be selected with care. In high vacuum chamber welding special techniques must be used to properly align the electron beam with the joint. Welds are extremely narrow and therefore preparation for welding must be extremely accurate.

Filler metal is not used in electron beam welding; however, when welding mild steel highly deoxidized filler metal is sometimes used. This helps deoxidize the molten metal and produce dense welds.

Almost all metals can be welded with the electron beam welding process. The metals that are most often welded are the super alloys, the refractory metals, the reactive metals, and the stainless steels. Many combinations of dissimilar metals can also be welded.

One of the disadvantages of the electron beam process is its high capital cost. The price of the equipment is very high and it is expensive to operate due to the need for vacuum pumps. In addition, fit up must be precise and locating the parts with respect to the beam must be perfect.

Laser Beam Welding

Laser beam welding (LBW) is a welding process which produces coalescence of materials with the heat obtained from the application of a concentrated coherent light beam impinging upon the surfaces to be joined.

The focused laser beam has the highest energy concentration of any known source of energy. The laser beam is a source of electromagnetic energy or light that can be projected without diverging and can be concentrated to a precise spot. The beam is coherent and of a single frequency.

Producing a laser beam is extremely complex. The early laser utilized a solid-state transparent single crystal of ruby made into a rod approximately an inch in diameter and several inches long. The end surfaces of the ruby rod were ground flat and parallel and were polished to extreme smoothness.

The laser can be compared to solar light beam for welding. The laser can be used in air. The laser beam can be focused and directed by special optical lenses and mirrors. The laser can operate at considerable distance from the work piece.

When using the laser beam for welding the electromagnetic radiation impinges on the surface of the base metal with such a concentration of energy that the temperature of the surface is melted and volatilized. The beam penetrates through the metal vapor and melts the metal below. One of the original questions concerning the use of the laser was the possibility of reflectivity of the metal so that the beam would be reflected rather than heat the base metal. It was found, however, that once the metal is raised to its melting temperature the surface conditions have little or no effect.

The welding characteristics of the laser and of the electron beam are similar. The concentration of energy by both beams is similar, with the laser having a power density in the order of 106 watts per square centimeter. The power density of the electron beam is only slightly greater. This is compared to a current density of only 104 watts per square centimeter for arc welding.

Laser beam welding has a tremendous temperature differential between the molten metal and the base metal immediately adjacent to the weld. Heating and cooling rates are much higher in laser beam welding than in arc welding, and the heat-affected zones are much smaller. Rapid cooling rates can create problems such as cracking in high carbon steels.

The laser beam has been used to weld carbon steels, high strength low alloy steels, aluminum, stainless steel and titanium. Laser welds made in these materials are similar in quality to welds made in the same materials by electron beam process.

Thermit Welding

Thermit welding (TW) is a welding process which produces coalescence of metals by heating them with superheated liquid metal from a chemical reaction between a metal oxide and aluminum with or without the application of pressure.

Filler metal is obtained from an exothermic reaction between iron oxide and aluminum. The temperature resulting from this reaction is approximately 2500 °C. The superheated steel is contained in a crucible located immediately above the weld joint. The superheated steel runs into a mold which is built around the parts to be welded. Since it is almost twice as hot as the melting temperature of the base metal melting occurs at the edges of the joint and alloys with the molten steel from the crucible. Normal heat losses cause the mass of molten metal to solidify, coalescence occurs, and the weld is completed.

The thermit welding process is applied only in the automatic mode. Once the reaction is started it continues until full completion.

Lecture 11

Part V Metal cutting

Metal cutting, or ***machining***, is a process of cutting off a layer of metal from a work-piece surface in the form of chips by the cutting tool in order to obtain the necessary geometry, size accuracy, and surface finish of a part.

To cut off a metal layer from a work-piece relative movements are given to the cutting tool and the work-piece. For this purpose the tool and the work-piece are fixed in working parts of machine tools – in a spindle, on a table, in a turret. These units of machine tools provide necessary movements of the tool and the work-piece.

Basic notions

Movements in metal-cutting machine tools

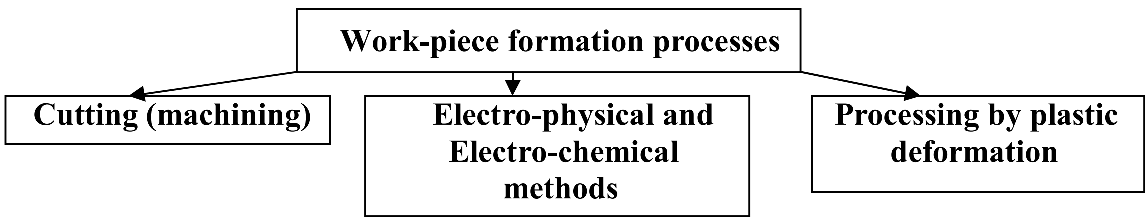
Motions of working parts of machine tools are subdivided into primary motions, adjusting motions and secondary motions.

Movements which provide removal of a layer of metal from a work-piece are called ***primary motions***. They are principal, or cutting, movement D_r and feed movement Ds. *Principal movement* defines the deformation rate and removal of chips, while *feed movement* provides continuous fitting the tool cutting edge to a work-piece material. These movements can be continuous and discontinuous, rotary and translation. Speed of the principal cutting movement is designated as V, speed of feed movement as Vs. The cutting movement is a single action for each machine tool; but there are usually several feed movements.

The movements providing mutual position of the tool and a work-piece for cutting off a set layer of material are called ***adjusting motions***.

both work-piece and tool fastening, fast movements of working parts of machine tool, and transportation of a billet comprise ***secondary movements***.

Metal cutting classification



There are also the combined ways including, for example, processing by cutting and electro-physical processes.

A share of processing by cutting in different branches of mechanical engineering is 80 to 95 % of all processed parts. The major advantages of processing by cutting in comparison with other ways are *mobility* (equipment change-over for processing of new products does not demand considerable expenses and time), possibility of parts fabrication *with any accuracy*, from *any metals and alloys*.

Kinds of machining are subdivided into edging and abrasive methods. In all *edging* methods the tool with one or several cutting edges is used. Edge geometry defines accuracy of the sizes and surface finish. These are turning, drilling, planing, milling, broaching. Grinding, polishing, lapped finishing, honing and other kinds of processing in which the tool is made of very hard abrasive particles joint by a binder or separated, are called *abrasive* methods. Abrasive methods are used mainly for finish machining.

Schemes of machining

Any process of cutting can be represented schematically: a work-piece, its placing and fastening on the machine tool, tool position and fastening, and also primary motions should be shown (Fig. 75). The finished surface is matched with colour or thickness of a line. The designation of feeds: S_l is a longitudinal feed, S_c is a cross feed, S_v is a vertical feed, S_{cr} is a circular feed etc.

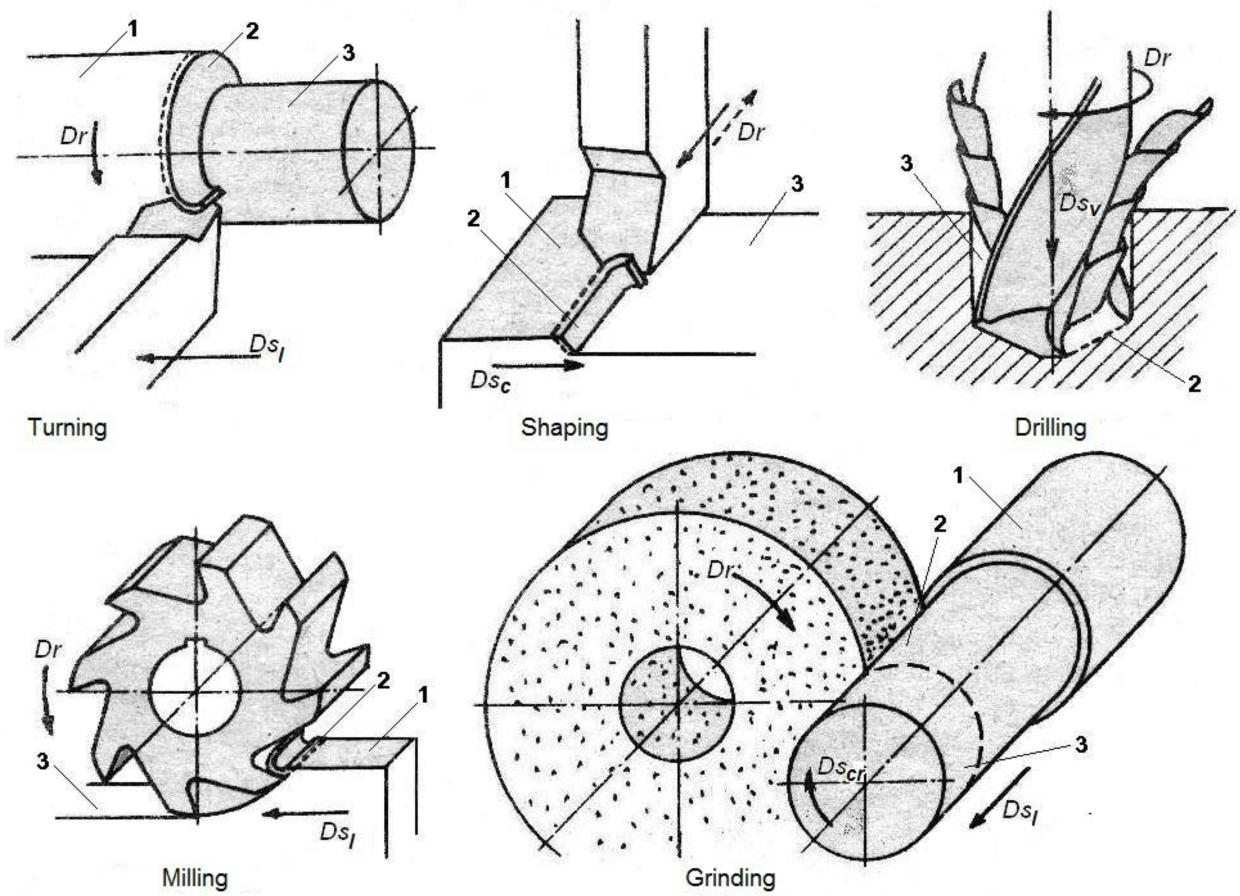


Fig. 75 Schemes of machining:
1 – processed surface, 2 – cutting surface, 3 – finished surface

Cutting mode and ***tool geometry*** are described in methodical instructions to laboratory work "Metal working by cutting". Study individually!

Physical phenomena in the cutting process

Metal cutting is a complicated process of interaction between the cutting tool and a work-piece which is accompanied by a number of physical phenomena.

1) Deformation of a cut off layer and kinds of chips

In a cut-off layer of metal, first elastic and then plastic deformations appear. In the zone adjoining to a cutter shear strain is developed, crystallites are deformed and fractured, grinded, elongated. The cut-off layer of metal is deformed additionally because of chip friction against the rake surface of the tool. Shear strain leads to chopping off elementary volume of metal, then the process is repeated and another element of a chip is formed (Fig. 76). Up to 90 % of cutting work is spent for plastic deformation of metal.

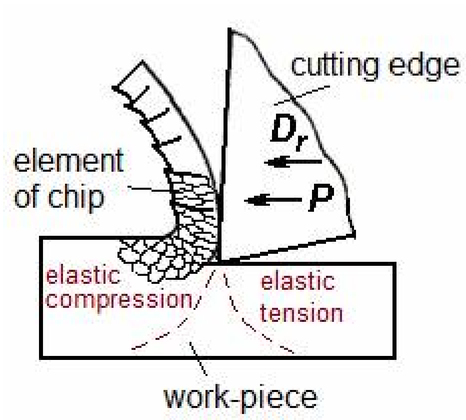
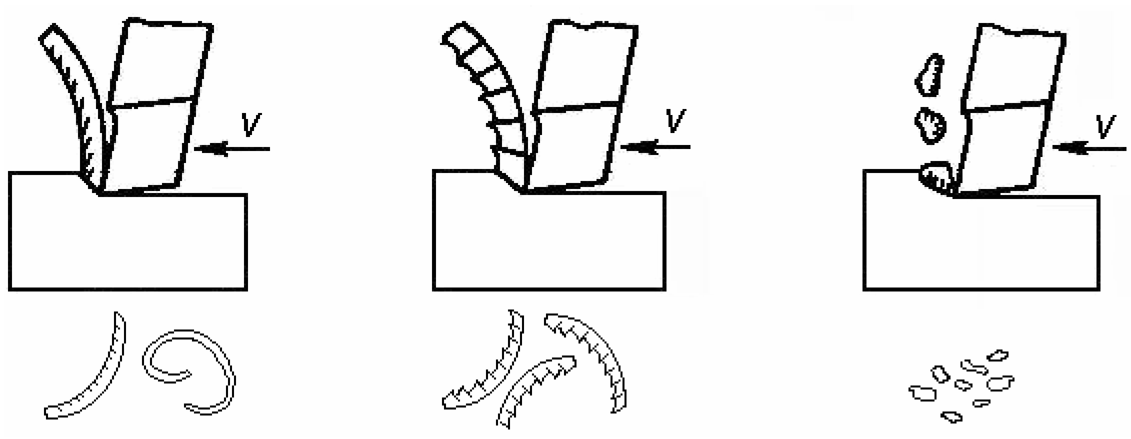


Fig. 76 Formation of chips

Types of chips:

continuous	*articulate*	*segmental*, or *discontinuous*
solid ribbon with smooth side adjoining to the cutter and small hacks on external surface	(*chips of chopping off*) with deep hacks on external surface	(*chips of break*) separate elements, not connected together



a *b* *c*

Fig. 77 Types of chips:
a – continuous chips (plastic metals); *b* – chips of chopping off (metals having medium hardness); *c* – element (brittle metals)

Cutting work is maximal in formation of the articulating chips and it is minimal for discontinuous chips. Continuous chips removal from a cutting zone is the most difficult since they wind up onto a cutter and a part, and then start fling at high speed. In order to make chips smaller, cutters of a special design are applied with chip braking ledges; vibrating cutting is used (fluctuations break shaving). Special steels are created for the mass production parts processed on automatic machines. These steels contain non-metallic inclusions; therefore, during their processing the element chips are formed.

2) Thermal phenomena in the cutting process

In the course of cutting the total amount of heat generated includes the heat generated by: 1) shaving friction against the rake surface of the tool, 2) friction of tool clearance surfaces against a work-piece, 3) metal deformation (Fig. 78). From a cutting zone heat is removed with chips (25–85 %), absorbed by the work-piece (10–50 %) and the tool (2–8 %), and also is radiated to environment (Fig. 78).

The equation of the thermal balance of a cutting process is given below:

$$Q_1 + Q_2 + Q_3 = Q_{ch} + Q_{tool} + Q_{w\text{-}p} + Q_{rad}.$$

Heat generation has detrimental effect on the tool since it may lose its cutting properties, its geometry changes resulting in deviations of the sizes and the shape of the processed surface from the set parameters. Heating of a work-piece leads to the change of its sizes and shape.

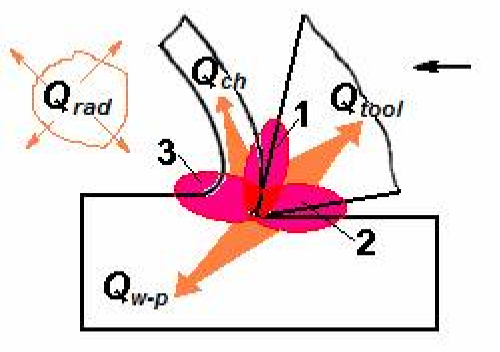


Fig. 78 Sources of heat generation and heat distribution upon cutting

To reduce the heat influence upon processing, the quality *lubricant-coolant liquids* are applied. These are water solutions of salts, emulsions, mineral oils, oils with additives of phosphorus, sulphur, chlorine, kerosene etc.

Liquids reduce friction between shaving and tool as well as friction of tool against the work-piece; they reduce quantity of released heat and take it away to environment. Greasing action of liquids interferes with metal sticking to the tool, as a result quality of processing is improved.

During rough operations intense cooling is necessary, therefore emulsions are applied. During finish processing when it is required to obtain high quality of the processed surface, various oils are used.

Liquid is usually fed under pressure through a narrow nozzle onto a rake surface of the tool; sometimes it is sprayed in the form of a fog.

3) Friction, wearing and durability of the tool

Wearing of the tool is caused basically by friction between chips and a rake edge surface, and also between the major flank of the tool and a work-piece. Wearing has an *abrasive* character; i. e. the tool is worn out along the face and flanks (Fig. 79).

On the rake surface of a cutter *a hollow* arises with width *b*, and on the major flank – a *ribbon* with width *h*. The flank wear is of the main importance since it decreases the depth of cutting (a cutter overhang from tool post). The finished surface turns out to be conical.

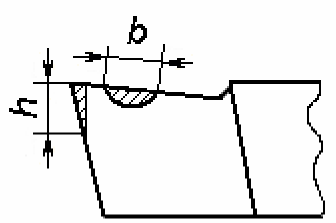


Fig. 79 Cutter wearing

The accepted *criterion of wear* is the greatest admissible value of ribbon width *h*. The criterion of wearing is:

for high-speed steel h = 1.5–2 mm,
for hard alloy h = 0.8–1 mm,
for mineral cyramics h = 0.5–0.8 mm.

Certain durability of the tool corresponds to the admissible wear. *Tool durability T* is a total time of its work between resharpenings on a certain cutting mode.

Durability is measured in minutes. Usual durability of turning cutters makes 30–90 min, durability of mills – tens of hours. Most strongly durability is affected by the cutting speed:

$$V \cdot T^m = \text{const, or } V = c/T^m,$$

where c is the constant, m is the indicator of relative durability (for cutters m = 0.1–0.3). Since m is of low value, durability sharply falls even for insignificant increase of cutting speed.

Therefore, it is necessary to carry out machining using optimized speed.

Processing of work-pieces by turning, milling, shaping machines is described in methodical instructions to laboratory work "Metal working by cutting". Study individually!

Lecture 12

Machining by drilling machines

Drilling is a technique used for making holes in a continuous material, and also processing of holes to increase their sizes and accuracy as well as reduce roughness.

The principal cutting movement is rotary motion of the tool round the axis; vertical feed is translation of the tool along the axis. A work-piece is fixed motionlessly (see Fig. 75).

Tool working conditions during drilling are more difficult than for turning, milling, planning: removal of chips and supply of a cooling liquid to the cutting zone is complicated. Chips wear out the surface of drill flutes, and the drill rubs against the surface of a hole.

Cutting speed for drilling is defined by the formula

$$V = \pi \cdot D \cdot n \cdot 10^{-3}, \text{ m/min},$$

where D is external diameter of a drill, mm,

n is frequency of drill rotation, rpm.

Feed S_v, mm is an axial moving of a drill for one turn.

Depth of cutting $t = D_{drill}/2$, for counter boring $t = (D - d)/2$, where d is diameter of a hole before processing.

The tool for drilling is usually the *twist drill* (Fig. 80) but there is a set of drills of other designs.

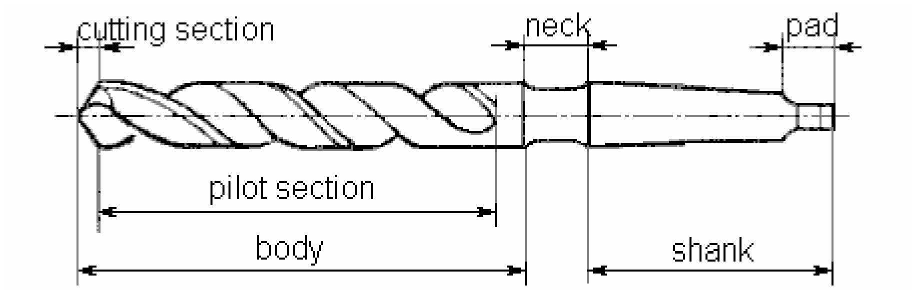


Fig. 80 Twist drill

A shank serves for drill fastening on the machine tool; a pad protects the shank at knocking-off a drill from a machine tool spindle. A body consists of cutting and pilot sections with helical flutes. The cutting section of a drill has two major cutting edges, the chisel cutting edge rumpling material of a work-piece before penetration of the major edges, and two minor cutting edges. Along helical flutes two narrow margins are located; they provide the direction of a drill in the process of cutting.

For processing of work-pieces on drilling machines core drills, reamers, taps are also applied. *Core drills are* used for roughness reduction and increase of accuracy of a hole. Unlike common drills, the core drills are provided with three or four major cutting edges and have no chisel cutting edge. Therefore, they are capable of processing only holes made preliminarily by casting, forging or cutting. *Reamer* is a multiple-point tool for finishing holes. A reamer has 6–12 major cutting edges and removes an allowance to the depth of cutting in the order of 100-th parts of mm. *Tap* cuts a thread in a hole. A tap is a screw interfaced to the cut thread with longitudinal shaving flutes and a conic lead-in section.

Machining by grinding machines

Grinding is processing of work-pieces by means of *a grinding wheel*, a tool having the shape of a body of revolution and consisting of abrasive grains and a binder.

During wheel rotation grains remove thin shavings, almost motes, by their sharp edges. But the amount of shavings produced is up to 100 million (10^8) per minute, therefore grinding is a highly productive treatment.

Speed of cutting for grinding is defined by the formula

$$V = \pi \cdot D_w \cdot n \,/\, (10^3 \cdot 60), \text{ m/s},$$

where D_w – external diameter of a wheel, mm; n – frequency of wheel rotation in rpm. When grinding speed is changed within the range 30–100 m/s, the temperature in a cutting zone reaches 1,500°C, therefore, you may see flying sparks of burning chips. Usually grinding is carried out with plentiful feed of a coolant.

Hardness of abrasive materials exceeds hardness of any metal, therefore it is possible to

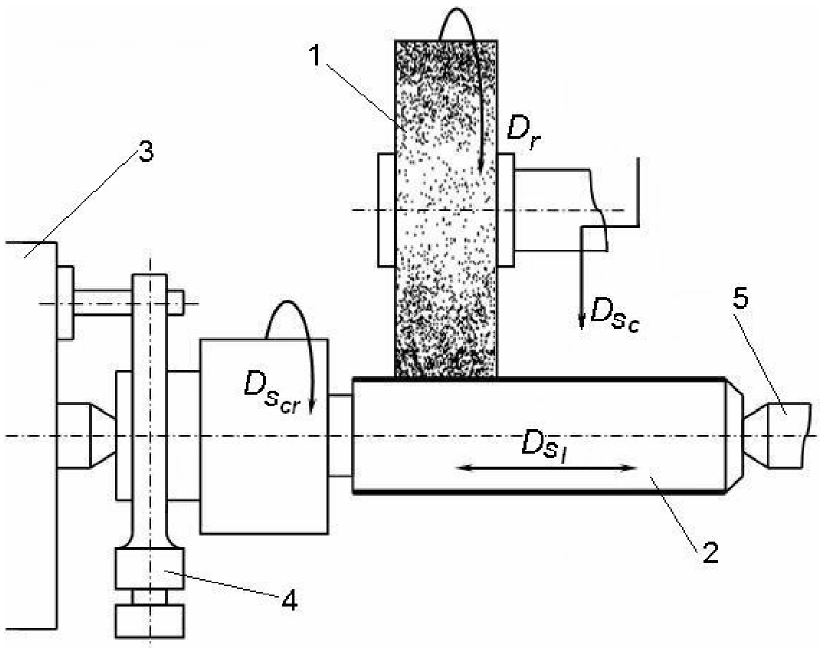


Fig. 81 Circular grinding:
1 – grinding wheel; 2 – work-piece; 3 – driver chuck; 4 – carrier; 5 – tail centre

grind the tempered steels, hard alloys, white cast irons, etc.

Accuracy of processing corresponds to 7–6 ISO accuracy degree, and surface roughness – to 0.4 μm.

Abrasive wheels possess the *self-sharpening* ability: blunted abrasive grains fracture because of the high friction force and form new sharp edges. However, wheel pores are gradually clogged up with wastes, and surface wearing becomes non-uniform. This phenomenon is called *glazing*, or loading of grinding wheel. Cutting properties are restored by *dressing*: a diamond tool removes the 0.01–0.03 mm thickness layer thus restoring the geometrical shape of the wheel.

The scheme of circular grinding is shown in Fig. 81.

Design of the circular grinding machine tool is similar to the lathe one. A work-piece is fixed in the centres, rotation (circular feed Ds_{cr}) is transferred to the work-piece from a driver chuck through a finger and a carrier fixed on it. The principal cutting movement is rotation of a grinding wheel, besides, the work-piece together with a table moves back and forth by longitudinal feed Ds_l. The grinding wheel at the end of a stroke together with the grinding head can make movement of cross feed Ds_c.

On plain grinders the work-piece fixed on a magnetic plate is processed along a plane by a lateral surface of the grinding wheel.

Finishing by cutting

Finishing processing raises accuracy of the sizes, reduces roughness of the surface, produces a special relief on the surface, and improves the reliability of machines work. The share of finishing methods in metal cutting is continuously growing.

Finishing by turning tools and grinding wheels

Fine turning and *boring* are carried out with high cutting speed but small cutting depth and feed using cutters with wide cutting edges parallel to the work-piece axis.

Fine grinding is carried out with very small depth with plentiful feed of coolant using soft high-porous fine-grained wheels.

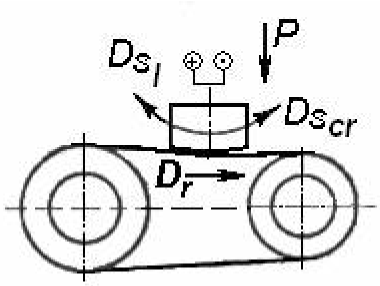


Fig. 82 Polishing with endless belt

Polishing

Polishing does not only reduce the roughness but also gives mirror shine that is necessary to decrease friction and improve the decorative appearance. Polishing pastes are applied, i.e. abrasive grains with lubricant substance. The tool is wheels made of felt or skin, brushes, endless abrasive belts (Fig. 82). It is necessary to notice that polishing does not correct shape errors as the flexible tool is used.

Honing

Honing serves not only for accuracy and small roughness but also creates a surface microprofile – a grid for the grease retention in a friction unit.

A work-piece is fixed motionlessly, the tool – *a honing head (hone)* – has fine-grained abrasive sticks and makes simultaneous rotary as well as backward and forthward motion; their speeds V_1 and V_2 are not equal (Fig. 83). The combination of these movements gives a grid of microscopic screw scratches which are traces of abrasive grains. Imposing of trajectories is excluded. Abrasive sticks are spring-loaded; therefore, their contact with the surface of a hole is continuous. A plentiful cooling by kerosene is necessary.

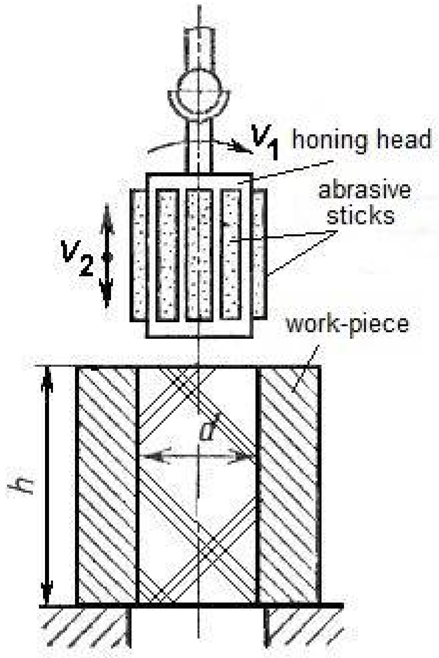


Fig. 83 Honing

Honing corrects the shape errors obtained during making of the hole.

A similar way of finishing abrasive processing is applied for external surfaces *(superfinish)*.

Accuracy of the sizes given by finishing methods corresponds to 5 ISO accuracy degree, and roughness (profile irregularity height R_z) is the 1/100-th part of micron.

Finishing by plastic deformation

Processing of surfaces without shaving removal, in particular by plastic deformation, allows to obtain the necessary accuracy and small roughness too. Plastic deformation is applied for processing the surfaces conjugate to surfaces of other parts only (shafts and holes, see Fig. 84, *a* and *b*). These ways are easier than finishing by cutting, besides they are waste-free.

The work-piece volume does not vary. Under the influence of the deforming tool only elementary volumes of metal undergo movement. There is smoothing of the profile irregularity due to crumbling of microirregularities and filling of microvalleys by deformation products (Fig. 84, *c*). The temperature during processing does not rise; therefore, the metal structure does not change.

Plastic deformation strengthens the metal surface, smoothes down scratches and micro cracks. Reliability of a product under service conditions thus increases (wear resistance, fatigue strength, corrosion resistance depend on surface quality).

It is possible to carry out finishing by plastic deformation; for this purpose ordinary metal-cutting machine tools are used with the special tool and adaptations. Cooling is not required, but kerosene, spindle oil, mineral oils with additives are applied for greasing.

Processing by plastic deformation is suitable for all ductile metals but the best effect is achieved on soft materials ($HB \leq 280$).

Important versions of this method are *thread rolling*, *spline shafts rolling* and *cogwheels rolling*. The profile of thread, etc. is formed due to tool indentation into a work-piece material. Roughing and finishing processing are thus combined.

It is a more productive and cheap method than machining by cutting. Quality of a surface is rather high, and structure favourable for mechanical loading is formed.

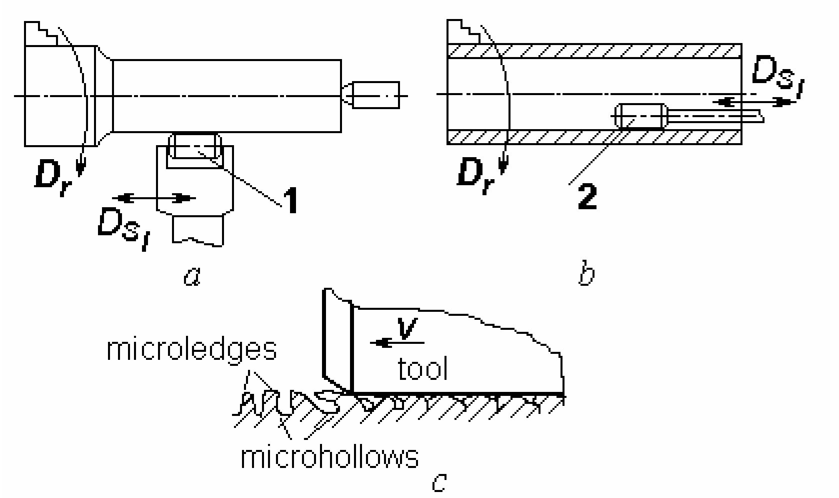


Fig. 84 Finishing by plastic deformation:
rolling of external *(a)* and internal *(b)* surface; smoothing of profile irregularity *(c)*;
tools 1 and 2 are hardened steel rolls

Electro-physical and electro-chemical processing

These methods utilize electric, chemical, sound, or ray energy. They supplement cutting but sometimes can replace it.

Advantages:

1) absence of force action raises accuracy of processing;
2) the surface of a part is not strengthened;
3) it is easy to automate processes;
4) it is possible to process all necessary surfaces simultaneously;
5) processing goes continuously.

Electrical discharge machining

Electrical discharge machining (Fig. 85) is based on erosion (destruction) of electrodes by electric current discharges generated between them. When voltage between electrodes reaches the breakdown value, a spark discharge is generated and elementary volume of metal on the anode is melted and evaporated thus forming a micro crater. Pulled out parts of the metal may solidify in a dielectric liquid forming granules of a micron size. The distance between electrodes is supported automatically at 0.01–0.05 mm.

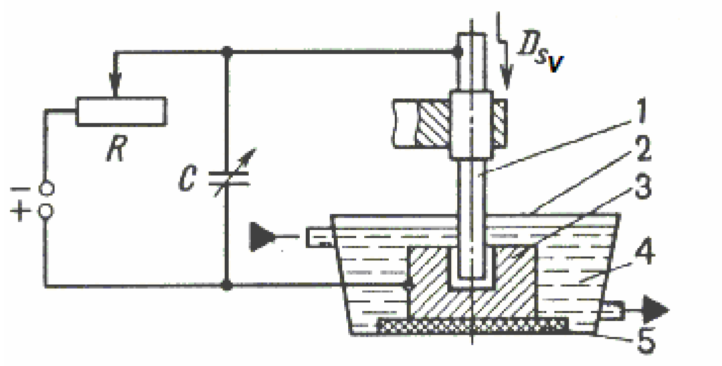


Fig. 85 Electrical discharge machining:
1 – tool (cathode); 2 – pool; 3 – work-piece (anode);
4 – dielectric fluid (kerosene); 5 – insulator

This method allows making holes and cavities, cut out work-pieces of a complicated shape.

It is applied for hard-processed metals and alloys, for example, tool alloys, heat resisting steels.

Electrochemical processing

Electrochemical processing (Fig. 86) is based on the phenomenon of anodic dissolution. Metal from the anode surface transfers into a chemical compound and dissolves; micro irregularities are dissolved first of all since current density is higher on them.

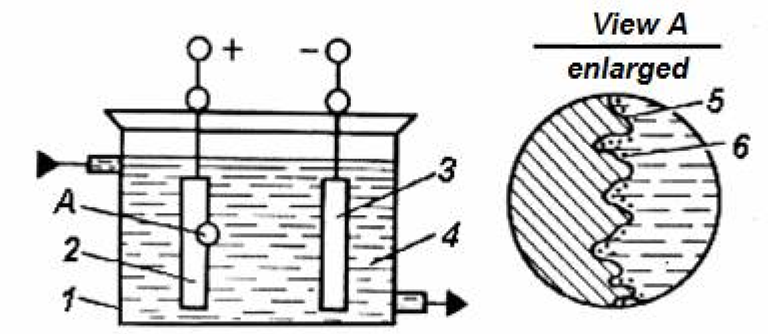


Fig. 86 Electrochemical polishing:
1 – pool; 2 – work-piece (anode); 3 – cathode;
4 – electrolyte; 5 – ledge; 6 – hollow

Electrochemical processing is applied for polishing and lapping of surfaces.

As a result of selective dissolution profile irregularity smoothes out and the finished surface gets metallic lustre.

It is possible to process simultaneously several work-pieces along their entire surface. This method is used for preparation of part surfaces before galvanic plating, for lapping of cutting tool working surfaces, for thin tapes and foil manufacture, for parts cleaning and decorative finishing.

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