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**DEPARTMENT OF METAL TECHNOLOGY AND MATERIALS
SCIENCE NAMED AFTER O. M. PETRYCHENKO**



Technology of Construction Materials and Materials Science

Lecture Notes

Lectures 1–22

COURSE OF LECTURES

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Contents

Introduction	3
Topic 1. The crystalline structure of metals, alloys and their properties	4
Topic 2. Engineering properties of construction materials	11
Topic 3. Metallurgical production of ferrous metals	16
Topic 4. Prospects of steelmaking. Steel casting. Crystallization and structure of pig steel. Methods to improve steel quality. Carbon steel. Alloy-treated steel	30
Topic 5. Production of non-ferrous metals	39
Topic 6. General description of foundry engineering. Theoretical fundamentals of ingot production. Methods of ingot production	50
Topic 7. Shell mould casting	54
Topic 8. Metal forming	65
Topic 9. Forming rolls and roll mills	72
Topic 10. Factors influencing the properties of materials	77
Topic 11. Plastic deformation and recrystallization	83
Topic 12. Basics of alloy theory	87
Topic 13. State diagram iron-carbon (iron-cementite)	92
Topic 14. Steel classification	97
Topic 15. Thermal basics steel processing	102
Topic 16. Types of heat treatment. Hardenability and hardenability	117
Topic 17. Main types steel heat treatment	125
Topic 18. Hardenability and hardenability become	131
Topic 19. Surface methods hardening machine parts	136
Topic 20. Methods of surface hardening of machine parts	147
Topic 21. Basics of doping theory	152
Topic 22. Alloy steel classification	157
Literature	160

INTRODUCTION

The lecture course «Construction Materials Technology and Materials Science» is aimed at developing theoretical knowledge and practical skills in the field of materials science and construction materials technology. In today's world, the development of engineering solutions, the creation of new materials, and the improvement of existing technologies are integral parts of progress across many scientific and technical fields.

This course is intended for students studying engineering disciplines and professionals seeking to deepen their knowledge of the properties, structure, and practical applications of structural materials. Particular attention is paid to the basic concepts of materials science, modern manufacturing technologies, and their implementation in industries such as mechanical engineering, construction, and aerospace.

Delivering this course in English aligns with international educational and scientific standards, supporting student academic mobility and the mastery of professional terminology.

The lecture course is logically structured: each topic presents systematic theoretical material illustrated with real-world industrial examples, self-assessment questions, and practical tasks to reinforce learning. This approach enables students not only to master the fundamentals of materials science but also to apply their knowledge to real engineering problems.

The course «Construction Materials Technology and Materials Science» serves as a comprehensive educational resource for students, lecturers, and engineering professionals, preparing qualified specialists ready to tackle modern technological challenges.

TOPIC 1

THE CRYSTALLINE STRUCTURE OF METALS, ALLOYS AND THEIR PROPERTIES

The engineering of structural materials is a science that studies the structure and properties of metals and alloys as well as their interrelation, methods to recover metals from ores, methods to fabricate blanks and work pieces from them.

Sections to be considered:

1. The structure and properties of structural materials;
2. Methods to produce structural materials:
 - a) Ferrous metallurgy;
 - b) Non-ferrous metallurgy;
3. Foundry engineering;
4. Plastic metal working;
5. Machining.

All structural materials are grouped into:

1. Metals further subdivided into:
 - a) Metals;
 - b) Alloys;
 - c) Metal ceramics – materials obtained from powders of metal and their oxides by special methods (powder metallurgy).
2. Non-metals further subdivided into: plastic materials, rubber, glass, wood, leather, paper.

1.1 Classification of metals

Metals are crystal bodies where atoms are spaced apart at regular intervals, follow a certain pattern, and feature indicative metallic lustres, high heat conductivity, thermo-electric emission (ability to radiate electrons when heated) as well as high plastic deformation.

All metals can be divided into:

I. FERROUS METALS (steel, cast iron). Group I – distinguishing colour (grey), high melting point, high hardness, and plasticity.

II. NON-FERROUS METALS: light (Na, K, Ca, Mg, Al); heavy (Ni, Cu, Pb, Sn). Group II – lower melting point, lower hardness, higher plasticity – compared to Group I.

III. NOBLE (gold Au, silver – Ag). Group III features high corrosion-resistance.

IV. ALLOYING (Cr, Mo, W, N). Group IV – these elements are introduced into alloys to impart certain required qualities.

1.2 Crystalline structure of metals

In metals, all atoms are spaced in a strict geometric order and kept in their place by the forces of inter-coalescence. To describe the atomic crystalline structure, a notion of spatial, or crystalline lattice is used.

The crystalline lattice is an imaginary spatial grid with atoms (ions) that form a crystalline solid placed in its nodal points. The smallest crystal space that gives an idea on the atomic structure of the metal in any volume is called the elementary crystalline... The crystalline lattice is constructed from numerous elementary. Crystalline lattices where atoms are located only at vertices are known as simple ones. Crystalline lattices where atoms are located not only at vertices but in the mid-space as well as on their faces are known as composite ones. Most metals feature a composite highly symmetric closed-packed lattice.

SCC – space-centred cube.

FCC – face-centred cube.

HCP – hexagonal close packing.

1.2.1 SCC – space-centred cube (Fig. 1.1).

In lattices of this type, atoms are located in the angles of the cube and one is in the mid-space of the cube. The elementary has 9 atoms. The distance between atoms is called the lattice parameter and is measured in angstroms.

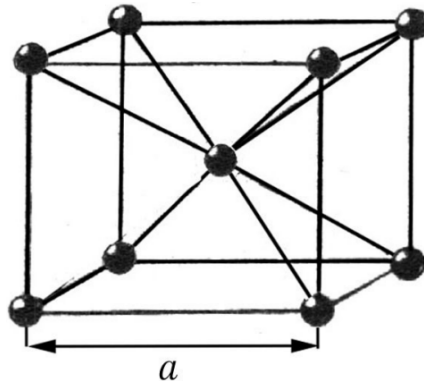


Figure 1.1 – The cubic space-centred lattice is typical for metals like α - Fe, W, Mo, R, V, Cr, Ba

1.2.2 FCC – face-centred cube (Fig. 1.2).

In cubic, face-centred lattices, atoms are located in the angles of the cube and centered on the middle of each face. The elementary has 14 atoms.

1.2.3 HCP – hexagonal close packing (Fig. 1.3).

In hexagonal close-packed lattices, atoms are located in the angles of the hexagon and in the center of the hexagon basis. Additionally, three atoms are situated in the middle plane of the prism.

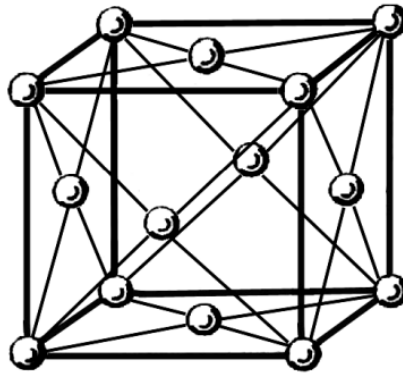


Figure 1.2 – The cubic face-centred lattice is typical for metals like Cu, Ni, Au, Pt, Al

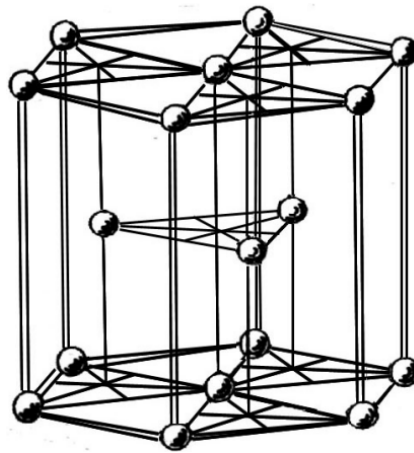


Figure 1.3 – The hexagonal close-packed lattice is typical for metals like Ti, Zn, Mn, Cd

Lattice parameters can vary when the temperature or pressure is changed. Crystalline lattices of some metals (in solid state) are different under different temperatures which always lead to changes in their mechanical-and-physical behaviour. The existence of the same metal in several crystalline forms is called polymorphism, or allotrope.

Crystalline lattice rearrangement at critical temperatures is known as polymorphic transformation (Fig. 1.4). To illustrate, let us consider the polymorphic transformation of IRON. IRON is a silvery-white metal. Its atomic number is 26 and its atomic weight is 55,85.

There are two known iron polymorphic modifications – α and γ . α -Fe exists at temperatures below 910°C, and above 3a 1392°C. Iron melting point is 1539°C.

For temperature range 1392-1539°C α -Fe is often designated as δ -Fe.

Up to 768°C iron has ferromagnetic properties. Above this point, the magnetic properties of iron are lost (Para magnetism). The critical point of 768°C that corresponds to magnetic transformation, i.e., the loss of magnetic properties, is called. Curie point and designated as A_{c2} (at heating) and A_{c1} (at cooling). The critical

point of α - γ transformation at 910°C is designated as A_{c3} (at heating) and A_{c4} (at cooling).

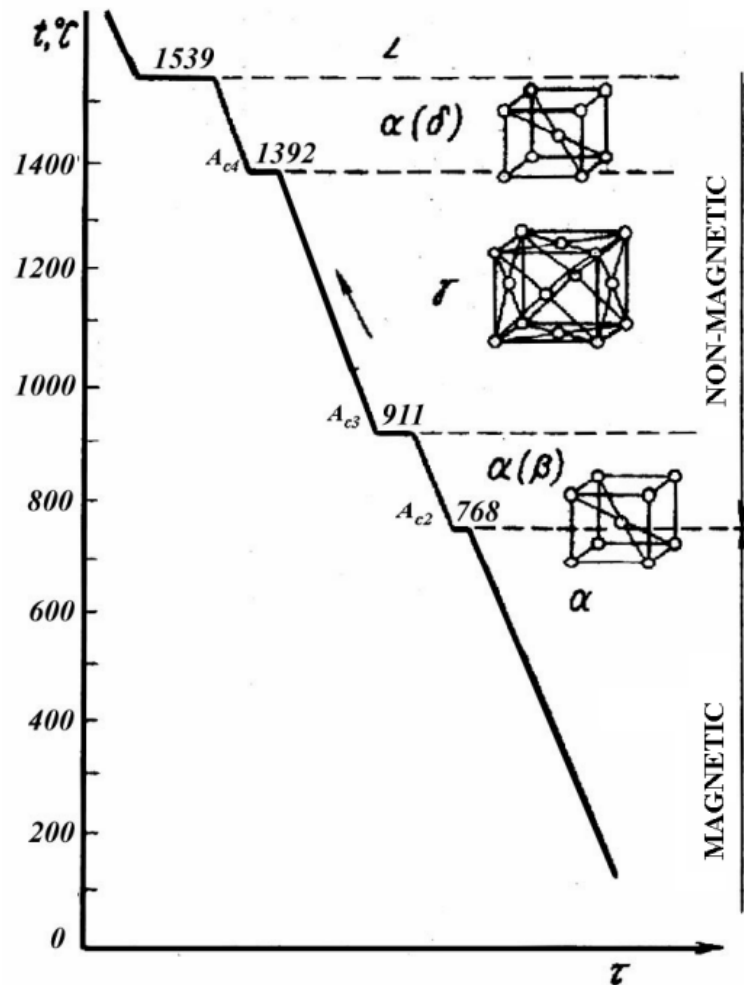


Figure 1.4 – The graph of polymorphic transformations that take place when iron is heated (cooled)

The critical point of α - γ transformation at 1392°C is designated as A_{c4} (at heating) and A_{c4} (at cooling). The whole process of all polymorphic transformations that take place when iron is heated is shown on the following graph.

1.3 Crystal structure of alloys

The alloy (or stop) is known as a substance made by alloying two or more elements. Both metals and non-metals can be elements of an alloy. These elements are called alloys components.

An alloy usually includes major components and additions. The latter are divided into additives – those improving the behaviour of alloys- and impurities – those impairing the behaviour of alloys.

The crystalline structure of alloys is more complex than that of pure metals and depends on the interaction of their crystallization components. When in solid

state, the components can make a solid solution, chemical compound and a mechanical mixture.

The solid solution – alloy components are mutually solvable. One of the components retains its crystalline lattice, the other component in separate atoms is distributed amidst the lattice.

Chemical compound – alloy components come into chemical interaction. Meanwhile, a new crystalline lattice is formed, and the components have mass relation.

Mechanical mixture – alloy components are absolutely mutually-insolvable and feature different crystalline lattices. The alloy will be made of a mixture of crystals which are its components. A mechanical mixture created during simultaneous melt crystallization is called autism.

1.4 Crystallization of metals

Crystallization of metals is the formation of the crystalline lattice in metals and alloys. Crystallization can be subdivided into primary crystallization and recrystallization.

Primary crystallization is a liquid-to-solid transition of a metal or alloy accompanied with the formation of a crystalline lattice.

Recrystallization is the re-production of crystals from a solid phase. It occurs in metals, which feature polymorphic transformations.

Crystallization occurs at transition of the system to a more thermodynamically steady state with less free energy F). Free energy (F), or thermodynamic potential, is the component of the full-of-energy substance that invisibly modifies its value when the point of the polymorphic transition and melting is changed. The higher the temperature, the less is the value of free energy. Free energy of liquid and solid state vs. temperature dependence can be described by the graph below.

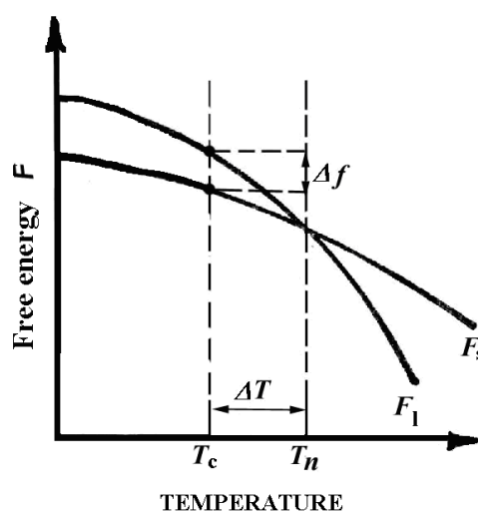


Figure 1.5 – Dependence of free energy on temperature for metal crystallisation

F_s – the value of free energy at solid state.

F_l – the value of free energy at liquid state.

T_n – the point corresponding to the equilibrium crystallization (or melting) temperature of the substance in question. At this point, both liquid and solid states can simultaneously exist. Crystallization does not start at this point.

Crystallizing starts when F_s is less than F_l . Therefore, crystallizing starts only when the metal is overcooled down to temperatures that are lower than the equilibrium crystallization point (T_n). The $T_n - T_c$ difference, which allows crystallizing, is called the level of overcooling and designated as ΔT .

$$\Delta T = T_n - T_c$$

D. K. Chernov proved that any crystallization goes through two stages:

1. Formation of crystallization nuclei.
2. Growth of crystals. As long as the growth of crystals is unrestricted, and they are few, they feature regular geometric shapes.

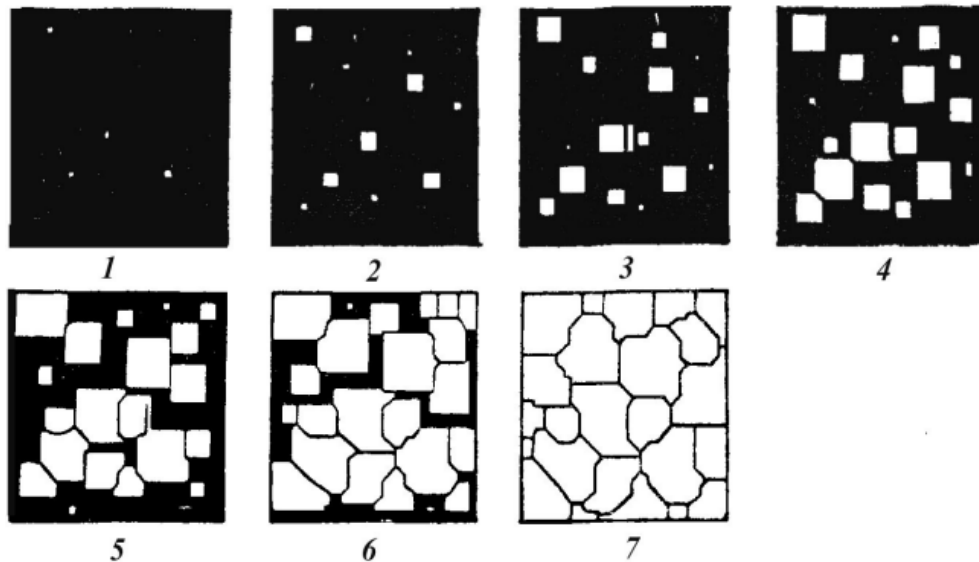


Figure 1.6 – The scheme of crystallizing for metals and alloys

When crystals are numerous, they collide and change their shapes into irregular ones. In this case they are called crystallites, or grains.

To evaluate crystallizing, 2 parameters were introduced:

1. The number of crystallization nuclei (NCN).
2. The rate of crystallization.

NCN is the number of centres (nuclei) formed in a unit of volume within a unit of time. Dimensionality [$\text{mm}^{-3}/\text{sec}^{-1}$] The rate of crystallization is the growth rate of crystal linear dimensions. Dimensionality [mm/sec] In order to make a qualitative metal or alloy, both parameters given above must be modified: the first – increased, the second – decreased.

In order to obtain fine grains, it is necessary:

- a) To boost the rate of cooling of a liquid metal;
- b) To introduce additional nuclei.

This process is called a modification, and the substances introduced are known as modifiers.

The number of crystallization nuclei and the crystallization rate depend on overcooling.

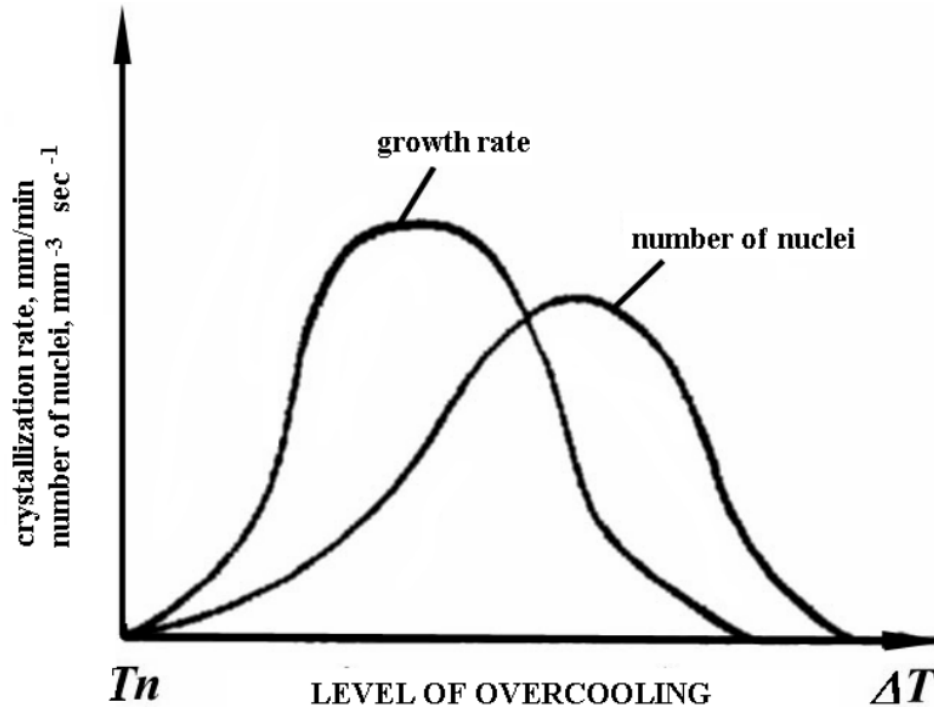


Figure 1.7 – Effect of supercooling on the crystallisation rate of metals

Crystals formed during crystallizing can vary in shape depending on the rate of cooling, nature and amount of additions. Most common are dendroidal crystals known as dendrites.

Due to unbalanced multioriented heat withdrawal, the crystal growth is oriented towards the heat withdrawal, which is faster and more massive than others.

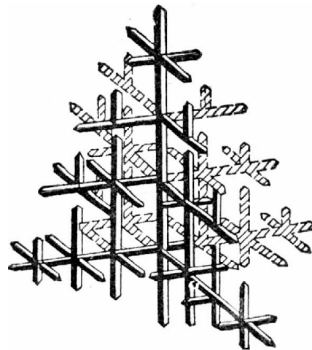


Figure 1.8 – Dendritic structure of the crystal

TOPIC 2

ENGINEERING PROPERTIES OF CONSTRUCTION MATERIALS

Construction materials (CM) are intended for making parts of machines and mechanisms. Therefore, they should feature certain properties:

1. Mechanical;
2. Physical;
3. Chemical;
4. Technological;
5. Special.

Major mechanical properties are:

1. Strength;
2. Ductility;
3. Viscosity;
4. Hardness;
5. Endurance.

Strength is the ability of a material not to fracture under external loads. External loads can be either static or dynamic. Strength under static loads is assessed by ultimate resistance σ_B and yield point σ_T :

σ_B – maximum metal breaking stress, $\sigma_B = P/F_0$ [MPa];

σ_T – metal yield flow stress point;

P – load value;

F_0 – reference area of the specimen under load.

To evaluate strength under static loads, specimen metals undergo tension, compression, bending and torsion tests. With this aim, special specimen metals are made (Fig. 2.1, a).

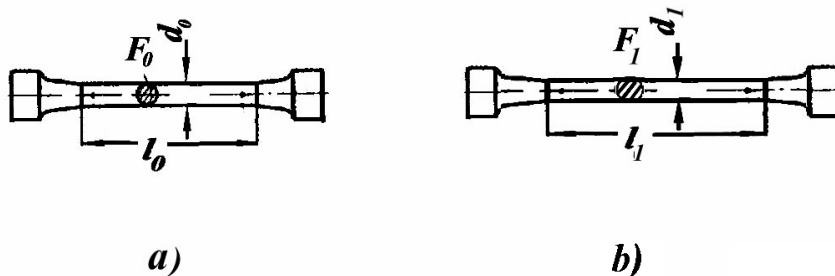


Figure 2.1 – Tensile test of a specimen before and after deformation

When loads increase up to a certain value, length varies in direct proportion to load, then fracturing starts. In this case σ_B – yield point.

Ductility is the capacity of a material to absorb mechanical energy without fracturing. The measure of viscosity is impact strength, which is determined as work done to fracture the specimen taken relative to the reference plane of specimen separation. This value is determined as KC [Joule/cm²]:

$$KC = A / F_0$$

Ductility is understood as relative reduction or elongation of the investigated specimen after fracturing at rupture.

Relative elongation: $\delta = (l_0 - l_1) \cdot 100\% / l_0$

Relative reduction: $\psi = (F_0 - F_1) \cdot 100\% / F_0$

where l_0 – the reference length;

l_1 – post-fracturing length of the specimen;

F_0 – reference surface area of the specimen;

F_1 – post-fracturing surface area of the specimen.

Viscosity is the capacity of a material to absorb mechanical energy without fracturing. The measure of viscosity is impact strength, which is determined as work done to fracture the specimen taken relative to the reference plane of specimen separation.

For most materials, value KC is found in notched specimen metals, which are stress concentrators (Fig. 2.2).

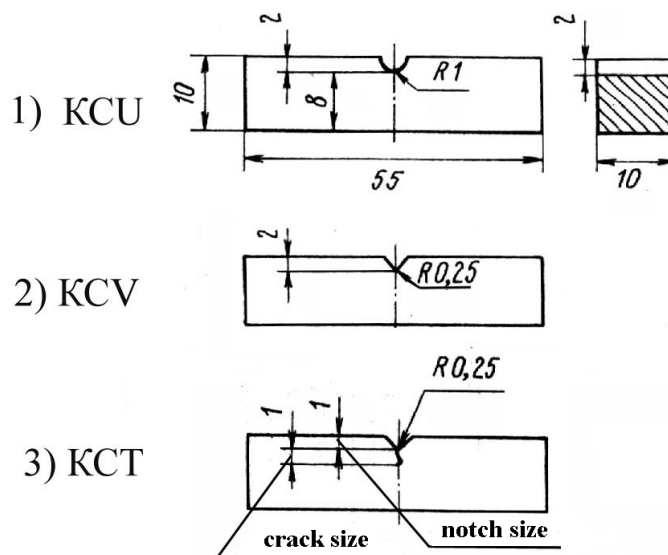


Figure 2.2 – Types of cuts for determining impact strength

Impact strength is found on smooth specimens only for brittle materials.

Depending upon notch geometry, impact strength is designated as:

1. KCU (U-notch),

2. KCV (V-notch),

3. KCT (stress concentrator in the form of cracks).

Impact strength KC is an integrated characteristic, which includes work of crack nucleation (KC_3) and work of crack spreading (KC_p):

$$KC = KC_3 / KC_p$$

Value of fracture KC_p determines structural resistance in the presence of cracks. The higher is KC_p , the less is the tendency to metal embrittlement.

If KC_3 (work of crack nucleation) is plotted as a function of temperature variations, then work of crack nucleation can be seen as being very low under low temperatures, but when passing through temperature T_{xp} it increases abruptly (Fig. 2.3).

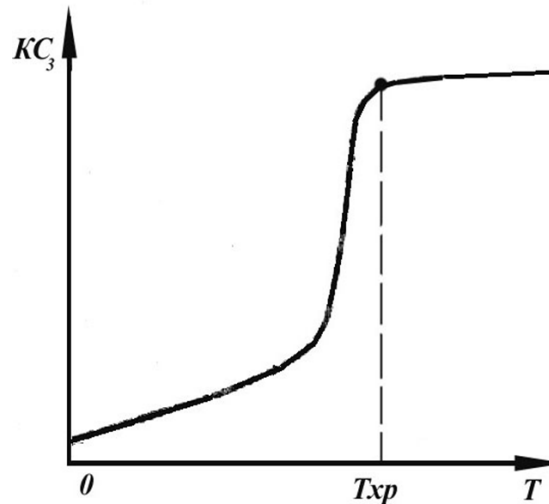


Figure 2.3 – Transition curve from viscous to brittle state

The phenomenon of disastrous dropping of impact viscosity at low temperatures is called cold brittleness, and brittle-to-viscous state jump temperature (T_{xp}) is known as cold-brittleness threshold.

Toughness reserve ΔT is the capacity of a material to withstand alternate load. (The stress vs. alternate load graph is supplied below). Stress depends on cycle numbers, and strength σ_B decreases as load cycle numbers go up. Toughness reserve is described by fatigue limit – σ_{-1} . σ_{-1} is the maximum stress when the material serves without failure in a certain cycle number. E.g., number of load cycles for steel (N_{st}) make 10^7 , for aluminum – $N_{Al} = 10^6$, for cuprum – $N_{Cu} = 10^9$.

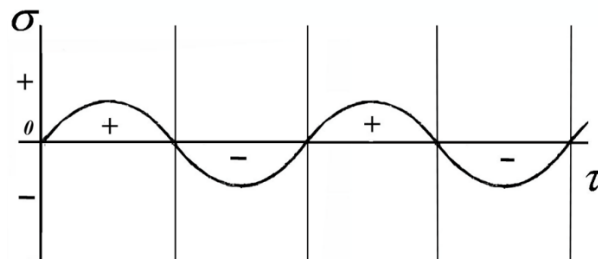


Figure 2.4 – Cyclic stresses in material fatigue

Hardness is the capacity of a material to resist the intrusion of another rigid body into it. There are 3 methods of hardness measurement:

- a) Scratching method;
- b) Pendulum method;
- c) Pressing-in method.

In its turn, the pressing-in method has 3 versions:

- a) Brinell's method;
- b) Rockwell's method;
- c) Vickers method.

Brinell's method is the most routine one when ball-like indenter with diameter D intrudes into probation object under action of force P (Fig. 2.5).

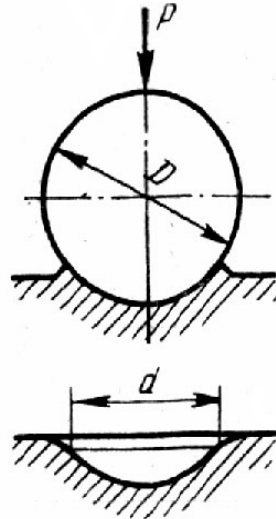


Figure 2.5 – Hardness measurement for Brinell's method

According to Brinell, hardness number HB is load P divided by the spherical surface indentation of diameter d .

Vicker's method. In this case, indenter is a diamond pyramid (Fig. 2.6).

Hardness is found by measuring the diagonal line of the pyramid indentation (d).

Rockwell's method. Indenture is a diamond cone or sometimes a small steel ball (Fig. 2.7).

The hardness number is a value regressive for bulge height (h). This method employs 3 scales – HRC, HRB and HRA. The first scale (HRC) is used in diamond cone tests under load $P = 150$ collages. The second scale (HRA) is used in diamond cone tests under load $P = 60$ collages. The third scale (HRB) is used for indentation steel ball load $P = 100$ collages.

Methods HB and HRB are used for soft materials, method HRC is employed for hard materials. Methods HRA and HV are used to measure hardness on thin coats (sheets).

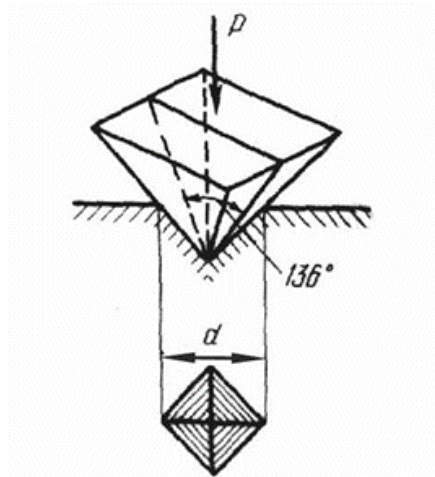


Figure 2.6 – Hardness measurement for Vicker's method

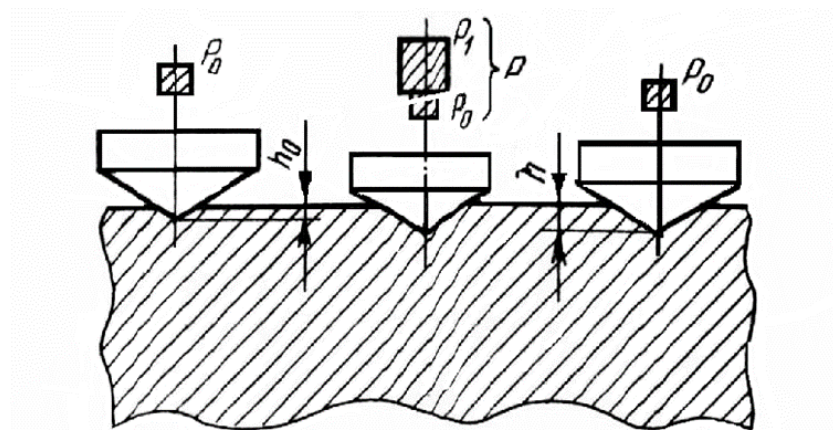


Figure 2.7 – Hardness measurement for Rockwell's method

Physical behaviour is determined by atomic (molecular) composition of a substance. Physical behaviour includes density, electrical conduction, heat resistance, melting temperature, magneto conductance. Chemical behaviour is the capacity of a material to interact with acids, alkali and environment. Processing behaviour is a complex of properties that determine production techniques for details. They include tempering capacity, malleability, weldability, casting characteristics.

2.1. Special properties

Scale resistance is the capacity of the material to retain its strength under high temperatures.

High-temperature strength is the capacity of the material not to interact with the environment under high temperatures.

Heat resistance is the capacity of the material to retain its behaviour when heated up to 600°C.

TOPIC 3

METALLURGICAL PRODUCTION OF FERROUS METALS

Metallurgy deals with the process of producing metal from ores.

3.1 Materials for metal and cast-iron production

3.1.1 Materials for metal production

To produce metal ores, flux metals, fuel, fire-resistant materials are used.

1. Ore minerals are rocks containing metals in an amount ensuring their cost-effective processing. Iron ores, for example, contain 30-60 % of metals. Content of non-ferrous metals from ores does not exceed 5 %, and it is a fraction of per cent in others (molybdenum is, for example, is less than 0.02 %).

Ore materials consist of minerals carrying metal in the form of oxides, sulphides, carbonates, and lean material (mainly silicon SiO_2 , aluminum oxide Al_2O_3 impurities of sulfur, phosphorus, arsenic etc.).

2. Flux metals or materials developed in the result of slug smelting – fusible mixture with lean material of ore, fuel ash and other non-metal impurities. Slag thickness is, as a rule, less than that of a smelted metal, thus slag conglomerates above it and can be fused during the process of smelting.

When smelting ferrous and some non-ferrous metals, quartz sand consisting mainly of SiO_2 and limestone CaCO_3 as well as other compounds of calcium and magnesium can be referred to as flux metals.

3. Coke, natural gas, blast-furnace gas or coke gas and black oil can serve as a Fuel in metallurgical processes.

Coke is obtained by destructive distillation of black coal without air penetration at 1000-1100°C. When coal is processed in this way, valuable co-products can be obtained, such as carbon oil and phenols. Besides, coke gas can be collected.

Natural gas consists mainly of methane CH_4 .

Blast-furnace gas is a co-product of smelting cast-iron in blast furnace; it contains a large amount of combustible ingredients (up to 32 % of CO , up to 4 % of H_2).

Black oil is a heavy residual of oil refining, it contains up to 90 % off C, 10-12 % of H_2O and a small amount of oxygen and sulphur.

4. Fire-resistant materials are materials capable of resisting high temperatures and staying undamaged under action of processes in blast furnace. They are used for the inner lining (lining-up) of blast furnaces and other equipment which is under the action of high temperatures, molten metals and slag.

Fire-resistant materials must possess the following properties:

1. High temperature of softening
2. High strength at normal and high temperatures
3. Not to fracture at sharp temperature changes;

4. Not to change their linear dimensions of temperature changes

By their chemical composition, fire-resistant materials can break up into acid, basic and neutral.

Acid is ganister, silica powder and other materials with high silica SiO_2 content; Basic are dolomite, magnesite and other materials with high basic oxides MgO , CaO content; Neutral materials are those consisting of oxides Al_2O_3 , Cr_2O_3 , MgO (grog, chrome magnesite), and carbon material.

Methods of metal extraction:

1. Pyrometallurgical method is one of the oldest methods of metal extraction based on the fact that heat required for metal smelting is provided by fuel combustion. This method is now the principal for production of iron and its alloys, copper and other metals.

2. Electrometallurgical method of metal extraction is carried out in electric arc furnaces, induction arc furnaces and other electric furnaces or by electrolysis from fused electrolytes and water solutions of chemical compounds (e.g., aluminum extraction from aluminum oxide Al_2O_3).

3. Hydrometallurgical method consists in leaching metals from ores with various solvents and their further extraction from the solution. Leaching can be accomplished both on the earth's surface and under it by means of wells. This method is widely used, for example, to mine copper and, lately, uranium and some other metals.

4. Chemicometallurgical method combines chemical and pyrometallurgical processes. Titanium, for example, is produced by restitution of tetrachloride TiCl_4 with magnesium and further smelting in electric arc furnaces.

Alongside with the above methods, powder metallurgy has been widely used lately to obtain engineering materials on the basis of these metals or their compounds as well as finished goods made from them.

3.1.2 Materials to produce cast iron

Cast iron is pyrometallurgically smelted from iron ores in blast furnaces using solid fuel (coke) and flux metals.

1. Iron ores contain iron in the form of oxides, hydroxides, carbons. In these ores quartzite or sandstone, and also clouks appear as lean material.

Basic iron ores are:

– Magnetic iron ore, which contains up to 65 % of iron in the form of magnetic oxide Fe_3O_4 (Sokoliv's'ke and Sorbait's'ke fields, Kursk Magnetic Anomaly etc.);

– Red iron ore contains up to 60 % of iron in the form of oxide Fe_2O_3 (Kryvoriz's'ke and Atasuis's'ke fields, Kursk Magnetic Anomaly etc.);

– Brown iron ore has up to 55 % of iron in the form of hydroxides $n\text{Fe}_2\text{O}_3 \times t\text{H}_2\text{O}$ (Kerchens's'ke, Lysakiv's'ke and other fields);

– White iron ore contains up to 40 % of iron in the form of carbonate FeCO_3 (Bakal's's'ke, Kryvoriz's'ke fields).

2. Fuel is not only the combust in the process of smelting, it also restitutes iron from ore. Coke meets these requirements to the best advantage.

3. Flux metals in cast-iron smelting in blast furnace are usually limestone CaCO_3 or dolomitic limestone consisting of CaCO_3 and MgCO_3 . Their function is to fuse together with lean material SiO_2 and Al_2O_3 and converse them into slag as well as to purify fuel and ore from sulphur impurities.

To increase the content of iron in the charge, improve its homogeneity according to the piece sizes and chemical composition, iron ore undergoes special treatment before smelting: dressing, agglomeration and burnishing.

Dressing means increasing the content of iron in the ore by various methods:

1. Ore washing that partially removes sandy and clay rock;
2. Ore division;
3. Magnetic separation (stone separation);
4. Dressed ore (concentrate) is worked out into lump materials or by burnishing.

Agglomeration is baking the ore (40-50 %), limestone (20-30 %) and coke at 1300-1500°C in a special machine. During this process, some impurities are removed from the ore, carbonates are dissolved and porous flux material – agglomerate – is formed. The use of fluxed agglomerate makes it possible to increase blast furnace productivity by 10-25 % and decrease coke consumption by 10-20 %.

Burnishing is lumping crushed concentrates. For this purpose, concentrate, fluxes and fuel are moistened and loaded into a revolving inclined cup (granulator) or into tubular drum where pellets (balls of 25-30 mm in diameter) are formed. These pellets are dried and singed at 1200-1300°C. Using both pellets and agglomerates enhances blast-furnace smelting, increases blast furnace efficiency, reduces fuel consumption.

3.2 Blast furnace schematic

Most of blast furnaces in operation have an active area of 1300-2300 m³ and height dimension up to 30 m. More than 2000 tons of cast iron is smelted in such blast furnaces. In 1986 the blast furnace of 5600 m³ came into operation in Cherepovets.

Blast furnace with auxiliary equipment is a rather complex engineering structure weighing about 200,000 tons. It is capable of 4-8-year continuous work.

To smelt cast iron, the charge, which is a mixture of a certain proportion of ore, fuel and flux metals, is loaded into a blast furnace. Single portions of the charge are called stocks.

Stocks from storage hoppers 1 (Fig. 3.1) are delivered on dillies 2 by assembly line 8 into a receiving cone 9 of furnace charging gear. When smaller bell 10 is lowered, the charge gets into a pot 11 and when the large bell 12 is lowered the charge gets into a mouth 13 and further into a furnace shaft 14.

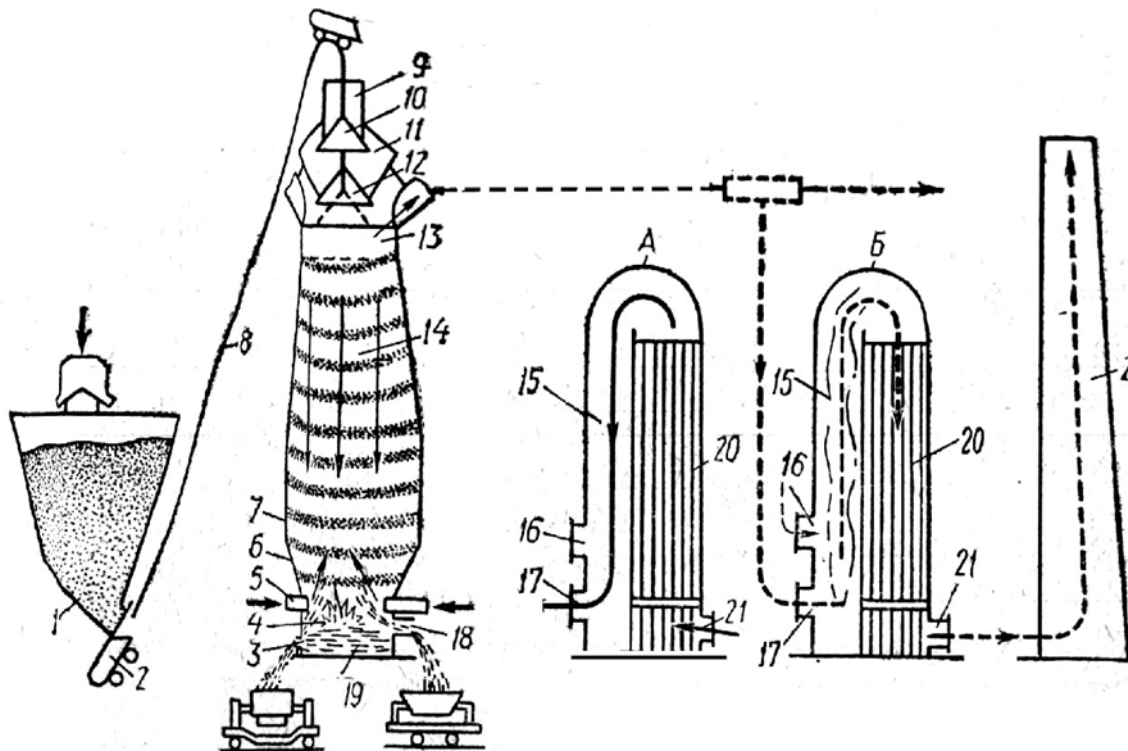


Figure 3.1 – Diagram of a blast furnace and its components

The biggest cylindrical part of the blast furnace is called furnace waist (7). Below it there are shoulders (6) in the form of a cut-down cone and chimneys (4) limited by hearth bottom (19). Tap holes for drawing cast iron (3) and slag (18) are located in the lower part of the chimney. To maintain fuel combustion, air under the pressure of 0.3 MPa is blown into a blast furnace through a number of jets (14-24) located along lance contours (5). Air consumption for smelting 1 ton of cast iron is up to 3,000 m³ per min in modern blast furnaces, and up to 7,000 in big ones.

To intensify smelting and for a lower fuel consumption, the air is heated up to 1,000-2,000°C in regenerative hot-blast stoves.

Hot blast stove is a steel cylinder of 6-8 meters in diameter and 30-40 meters high, coated with brick (Fig. 3.1, A), which has a combustion chamber 15 and a refractory-brick bushing 20. There are 3-4 hot blast stoves near each blast furnace.

Furnace top gas is delivered hot blast stove B through opening 17, and air necessary for gas combustion is delivered through opening 16. Combustion gases from chamber 15 go through vertical channels of bushing 20, heat it and escape through opening 21 into the chimney shaft 22.

When the hot blast stove bushing reaches the required temperature, gas feeding is stopped and air is delivered backward. It goes through the channels of cadent fitting on and is heated up to 1,000-1,200°C, and then it is blown into the blast furnace. While one of the hot blast stoves is getting hot, the other, which was previously heated, is in operation.

A great improvement of blast-furnace method is oxygen enrichment of blast air (up to 30 %) as well as partial replacement of coke natural gas.

3.2.1 Blast furnace method (physical and chemical processes)

The blast furnace works by counter flow principle: the charge moves downward, and the flow of hot gases – fuel combustion products – goes upward. During this process, the fuel burns, iron is renewed and enriched with carbon, other elements are regenerated and slag is formed. In the area of blower nozzles, coke carbon interacts with air blast oxygen and burns. As a result, carbon dioxide CO_2 ($\text{C} + \text{O}_2 \rightarrow \text{CO}_2$) is developed and the temperature in this part of blast furnace reaches 1,800-2,000°C. Under these conditions, carbon dioxide CO_2 reacts with coke carbon and forms white damp, or carbonic oxide ($\text{CO}_2 + \text{C}_k \rightarrow \text{CO(r)}$), which is the main regenerator of iron.

A bit above, in the furnace zone of 700-450°C, part of carbonic oxide dissolves producing soot carbon.

The charge gets hot when falling towards the hot gas flow, the moisture vaporizes them and volatile substances evolve. When the temperature is 750-900°C, iron is regenerated in the charge following the pattern:

1. $3\text{Fe}_2\text{O}_3 + \text{CO} = 2\text{Fe}_3\text{O}_4 + \text{CO}_2$;
2. $\text{Fe}_3\text{O}_4 + \text{CO} = 3\text{FeO} + \text{CO}_2$;
3. $\text{FeO} + \text{CO} = \text{Fe} + \text{CO}_2$.

Some part of oxide FeO goes downward to the furnace waist and shoulders and is regenerated by coke carbon, soot carbon Cc and hydrogen H_2 . As the result of these reactions hard sponge iron is produced. At 100-1100°C sponge iron is carbonated:

1. $3\text{Fe} + 2\text{CO} = \text{Fe}_3\text{C} + \text{CO}_2$.
2. $3\text{Fe} + \text{C} = \text{Fe}_3\text{C}$.

Carbon decreases the melting temperature of iron carbon alloys, so when coming down to the lower part of the hole the alloy begins melting, extra carbonated and saturated with other elements, that regenerate from ore, i.e., manganese, silicon, phosphorus and sulphur.

Manganese appears in ores mainly in the form of oxides and is partially regenerated by solid carbon. Silicon exists in lean material as silica SiO_2 and is also regenerated by hard carbon. Non-regenerated manganese oxide and silicon oxide run into slag. Phosphorus mainly exists in ores as a compound $\text{P}_2\text{O}_5 \times 3\text{CaO}$, it is regenerated by carbon oxide and hard carbon and almost completely runs into the alloy.

Sulphur comes into the blast furnace as a component of ore and coke as compounds FeS_2 , FeS , CaSO_2 , CaS .

A large part of sulphur evaporates in the form of volatile compounds (SO_2 , H_2S), the rest verges into the alloy (FeS), or slag (CaS).

Thus, in the result of regeneration of iron, manganese, silicon, phosphorus and sulphur, their dissipation in iron in the blast furnace chimney, cast iron is produced. Alongside with cast iron, slag – i.e., the alloy of lean material, flux metal, fuel chark and some part of non-regenerated oxides – is accumulated in the lower part of the

furnace. As cast iron and slag are produced and accumulated, they are drawn out of the blast furnace: cast iron along the tap-hole 3 in 3-4 hours, and slag – along the tap-hole 18 in 1-1.5 hours.

3.2.2 Blast furnace practice products

Basic products of blast furnace practice are cast iron and ferroalloys, co-products are slag and furnace top gas. Depending on their chemical composition, structure and intention, cast irons smelted in blast furnaces are divided into, convertible, foundry and specific.

1. Convertible cast irons are a basic form of cast iron for steel production. Their usual composition is: 3-4 % C; 0.3-1.3 % Si; 0.8-1.2 % Mn; up to 0.3 % P and 0.07 % S. The specific feature of convertible cast irons is that carbon is present in them in the form of compound Fe_3C – cement carbide. Such cast irons have white shade on fracture, so sometimes they are called white. They possess high index of hardness and are tough-to-machine. Therefore, they are rarely used as engineering materials. In foundry, they are used to produce malleable iron.

2. Foundry cast irons are meant for producing shaped castings, they feature high silicon content of up to 3.6 %. Most of carbon in them is present in free state – in the form of flaked graphite, therefore they are of grey shade on fracture. Such cast irons are called grey. Cast iron ingot bars weigh about 50 kg.

3. Specific cast irons (ferroalloys) are iron alloys with high concentration of Si, Mn, Cr, and other elements. Here belong: ferrosilicon (9-13 % Si), ferromanganese (70-75 % Mn), mirror iron (10-25 % Mn) and others. They are used for steel deoxidation and alloyage.

4. Slag is used to manufacture slag wool, slag stone and cement.

5. Gases (CO , CO_2 , H_2 , CH_4 , N_2) are produced in blast furnaces, go upward and escape from the furnace through the tubes in the mouth zone. These gases are called furnace top gases. They are used as a fuel to heat hot blast stove.

Blast furnace cost-performance ratio:

a) Coefficient of payload volume utilization – $CPVU$:

$$CPVU = V/P$$

where V is the blast furnace payload volume, m^3 ;

P is blast furnace daily average efficiency, tons.

b) Specific coke consumption:

$$K = A/P$$

where A is daily coke consumption, tons,

P is daily average blast furnace efficiency, tons.

The specific consumption is an essential index of blast furnace operation, because cost of coke makes about 50 % of cast iron cost.

Blast furnaces cost-performance ratio is advanced by improvements of their structure, better preparation of the charges, intensified smelting, and oxygen air enrichment. Construction and operation of big blast furnaces produce great economic impact. Therefore, blast furnaces of 5000 m³ are in common use now. Furnaces of such volume are capable of smelting over 10 thousand tons of cast iron daily. Labour productivity at cast iron smelting in such blast furnaces is 30 % higher and capital-output ratio is 12 % lower than in 2,700 m³ blast furnaces.

Alongside with increase in blast furnace volume, enhancement of mechanization and automation systems of cast iron smelting control is of great importance.

Steel differs from cast iron by less content of carbon, silicon, manganese, and sulphur and phosphorus impurities; i.e., processing cast iron into steel means decreasing carbon content in it.

3.3 Steel making

The core of the process: steel differs from cast iron by less content of carbon, silicon, manganese and sulphur and phosphorus impurities, i.e., processing cast iron into steel means decreasing carbon as well as other element's content in it and transform them into slag or gases during the smelting process (Table 3.1).

Table 3.1 – Comparison of chemical element's content in steel and cast iron, %

Alloy	Carbon (C)	Silica (Si)	Manganese (Mn)	Sulphur (S)	Phosphorus (P)
Cast Iron	3.5	0.5 – 1.5	1 – 1.5	0.3	0.3
Steel	0.5	0.3	0.4	0.03	0.02

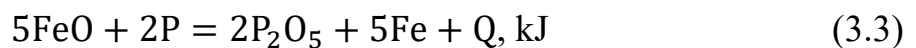
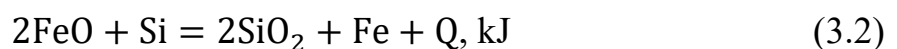
Impurities differ from each other by their physical and chemical properties, therefore, to remove each of them melting unit; special conditions are created on the basis of fundamental laws of physical chemistry.

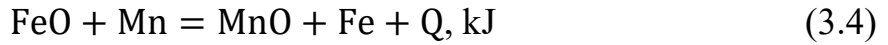
According to the law of mass action, the speed of chemical reaction is proportional to the concentration of reacting compounds.

Since cast iron contains more iron than iron, it oxidizes foremost when cast iron interacts with oxygen in steel furnace:



Oxide Fe fuses into Fe at high temperature, and oxygen oxidizes Si, P, Mn, and C:

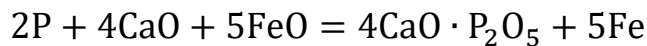




The more FeO molten metal contains, the more active is the process of oxidizing impurities.

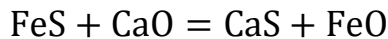
Using the above-mentioned laws, melting process undergoes several stages:

1) Melting the charge and heating the molten metal pool. At this stage the temperature of the metal is not high (reactions 1-4 are in the process). At this stage phosphorus (P) is to be extracted. To this effect smelting should be performed in the basic furnace where basic slag can be used (CaO).



2) The pool boiling begins as it is heated up to high temperatures. Oxide Fe reacts with carbon as in (5), and bubbles of carbon oxide CO disengage from molted metal and cause “boiling”.

This stage is useful because of sulphur removing (S). The higher the temperature, the higher is FeS solvency in slag, i.e., more sulphur passes from metal slag.



3) Stage is steel deoxidation. It means regeneration of iron oxides. During smelting, oxygen is required to oxidize impurities, and in finished steel oxygen is a harmless impurity, because it reduces mechanical properties, especially at high temperatures. There are methods of steel deoxidation – settling down and diffusion.

Settling down is adding deoxidizers with Mn, Si, Al. Oxides – MnO_2 , SiO_2 , Al_2O_3 – are produced and iron is regenerated.

Diffusion is slag deoxidizing. Decomposed FeMn, FeSi are loaded on the slag surface. Oxide Fe will pass into slag and regenerated iron will verge into steel.

The core of the process is in reducing the content of carbon and other elements in cast iron and their passing into slag or gases. Ingoing materials for steel are processed cast iron and scrap steel. Steel is mainly manufactured in basic oxygen furnaces, open-hearth furnaces (Martin furnaces) and electrical furnaces.

Steel making in basic oxygen furnaces. Oxygen – conversion process is molten cast iron lancing.

Basic oxygen furnace or converter (Fig. 3.2) is a pear-shaped bucket 1 made of a steel sheet, lined with refractory bricks 2. The furnace operates in vertical position. Oxygen is fed under pressure of 1-1.5 MPa by means of water-cooled lance 3, delivered to the converter through the furnace throat and placed 0.7-3 m above the hot metal level.

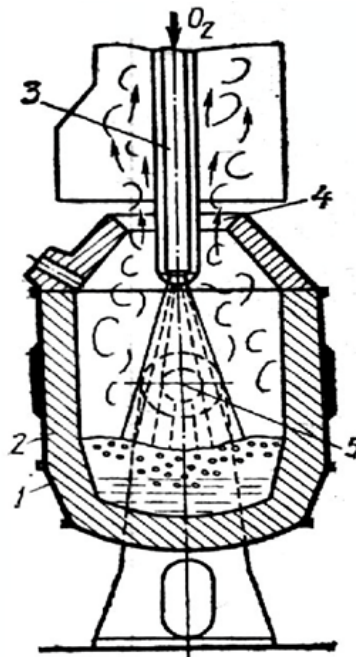


Figure 3.2 – Schematic diagram of the oxygen converter

Converters are made from 100-350 tons of hot cast iron. Total bulk oxygen consumption is 50-60 m³ per 1 ton of steel.

Ingoing materials for steelmaking are molten pig iron and scrap steel. To feed slag into the converter, up to 10 % of iron ore and lime are added; to decompose it – bauxite (Al (OH)₃) and fluor spar (CaF₂) are added.

Before the work begins, the converter is turned on journals 5 around the horizontal axle and with the help of golf device feed up to 30 % of scrap steel, then hot cast iron is poured at 1250-1400°C. After that converter is turned to its start vertical position, oxygen lance is set up, oxygen is fed and slag-makings are added.

Metal composition changes in the process of smelting can be shown in the diagrams below (Fig. 3.3).

During lancing, carbon and other impurities are oxidized directly with air-blast oxygen and iron oxide. At the same time, reactive slag CaO is formed contributing to the removal of sulphur and phosphorus with simultaneous creation of steady compounds 3CaO · P₂O₅ and CaS in slag.

After 15-16-minute lancing, lance is risen, converter is inclined, a sample of metal is taken to be analyzed and the most part of slag is rolled down.

After a snap on the steel composition having been made (it takes 7 to 8 minutes), the converter returns to vertical position, lance is turned on and lancing goes on within an hour depending on the analysis data and the specified steel grade.

To reduce oxygen content, steel discharged from converter is deoxidized; i.e., elements with more affinity for oxygen (silicon, manganese, aluminum) are added to it. Interacting with iron oxide FeO they produce infeasible oxides MnO, SiO₂, Al₂O₃, which die into slag.

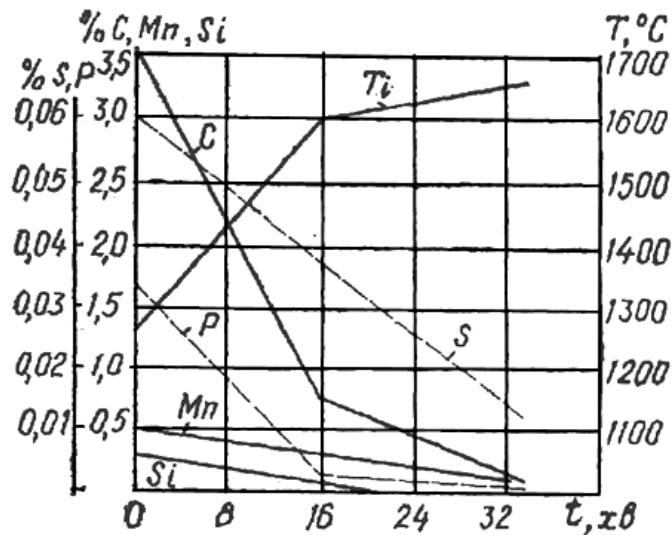


Figure 3.3 – Graph of oxidation of impurities in the process of cast iron processing

The capacity of a 300-ton basic oxygen furnace (converter) is 400-500 tons a year. Due to high productivity and low steel intensity, oxygen steelmaking becomes the most common method.

3.3.1 Steel making in open hearth furnaces (martin furnaces)

Open hearth furnace (Martin Furnace) (Fig. 3.4) is a regenerative flame furnace, where high temperature (750-1800°C) is obtained by gas combustion above the melting space. Gas and air entering the furnace, are heated in regenerators. To the left of the melting space 7 there are channels for gas 3 and air 4, linked to regenerators 1 and 2.

Same channels for gas 9 and air 8 are located to the right of melting space 7. They are relatively linked to regenerators 10 and 11. Each of the regenerators has a checkerwork of fire-resistant bricks laid in squares. The charge is fed through windows 5.

Gas and air get into the furnace through regenerators 10 and 11 heated to 1200-1250°C, get hot there and come into the melting space of the furnace.

Here, gas and air mix and burn, producing high temperature flame.

Through channels 3 and 4 combustion products enter regenerators 1 and 2, heat them, cooling themselves down to 500-600°C and escape through tube 13.

As regenerators 10 and 11 are cooled, air and gas direction in the furnace is changed into a backward one by valves 12 and 14. Then gas and air enter the melting space through channels 3 and 4, passing heated regenerators 1 and 2; the combustion products pass out through channels 8 and 9, heat regenerators checkworks 10 and 11 and escape through tube 13.

Thus, during the furnace operation gas and air go through the left and right regenerators in turns. The common volume of Martin furnaces is within 20 and 900 tons of melted steel. The hearth bottom area of these furnaces is their essential feature. In 900-ton furnace it is about 120 m².

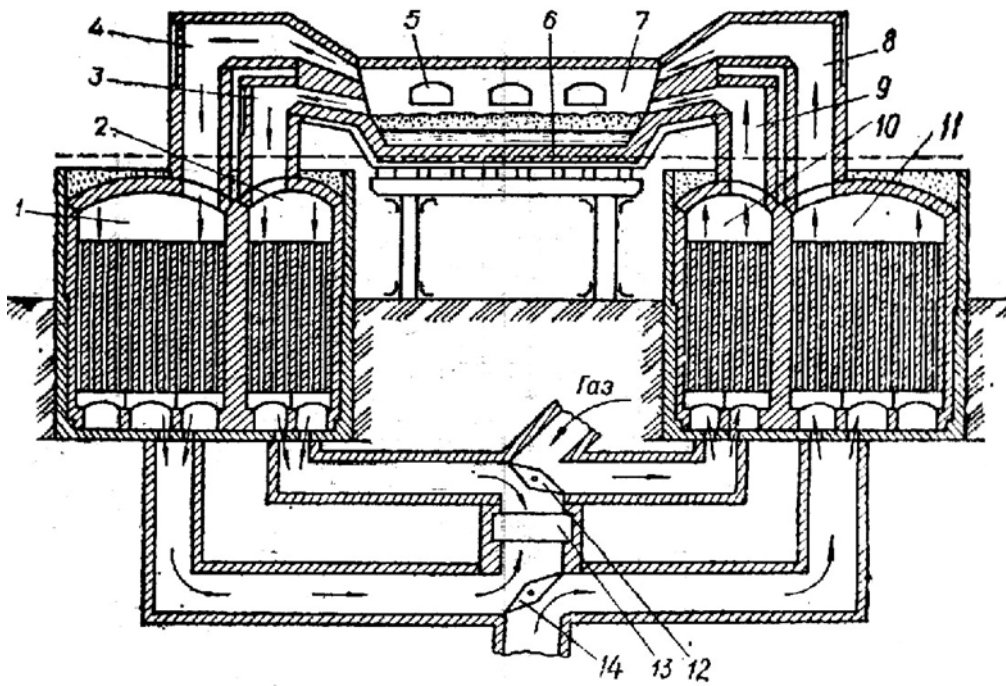


Figure 3.4 – Schematic diagram of an open-hearth furnace

3.3.2 Open hearth process

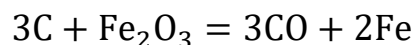
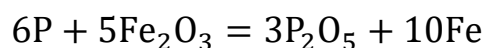
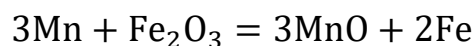
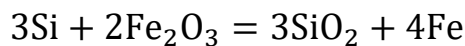
Metal scrap, liquid and hard cast iron, iron ore can be materials for steelmaking in open hearth furnaces. Depending on their proportion, two processes are distinguished:

Scrap-ore processing: the charge consists of liquid cast iron, 20-30 % of steel scrap and iron ore.

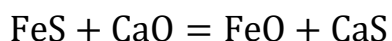
Scrap process: the charge's composition is steel scrap and 25-40 % of cold pig iron.

Flux material in both processes is limestone CaCO_3 (8-12 % of the metal mass). Scrap-ore process in open hearth furnaces has become more common in metallurgy. Furnace is loaded with iron ore and limestone which are heated, then steel scrap and liquid iron are added.

During the smelting, impurities in cast iron oxidize at the expense of iron oxide, ore and scrap:



Sulphur is removed from the result of ferrous sulphate – limestone interaction:



Oxides SiO_2 , MnO , P_2O_5 , CaO , and also sulfide CaS make slag, which is periodically discharged from the furnace into slag pans.

To intensify smelting and oxidizing impurities the tank is blasted with oxygen. The length of the process is 2-3-fold reduced.

After smelting the period of pool's boiling starts. Now carbon begins to oxidize actively in metal. When the content of carbon reaches the intended volume and the amount of sulphur and phosphorus reduces to minimum, boiling is ceased and steel deoxidation is started in the furnace with the help of ferromanganese, ferrosilicon and aluminum. Steel deoxidation is finished with aluminum and ferrosilicon in steel-teeming ladle when it is discharged from the furnace. The process lasts 6-10 hours. This method, unlike the converting enables obtaining high-grade carbon and alloy-treated steels.

Acid open-hearth process is the process of high-grade steel smelting. Here, the charge with low content of phosphorus and sulphur is used since basic slag can not be added to remove phosphorus and sulphur.

Steels smelted in acid open-hearth furnaces contain less hydrogen, oxygen and non-metal impregnations. Therefore, steel possesses higher metallic properties, namely impact viscosity and plasticity. It is used to manufacture crankshafts and turbine runners.

3.3.3 Steelmaking in electric furnaces

Compared to other melting facilities, electric furnaces have a number of advantages: ability of fast heating and maintaining the required temperature up to 2000°C ; ability to create oxidizing, regenerating or neutral atmosphere as well as vacuum. This allows smelting steels and other alloys with minimum amount of harmful impurities and optimum content of ingredients in electric furnaces.

Metallurgic electric furnaces are divided into arc furnaces and induction furnaces. Arc furnace (Fig. 3.5) is a steel cylinder 4 with slanting or spherical base, covered with fireproof bricks 1 inside. There is a window 7 and an opening with a changeable groove 2 on the body face. At its top, the furnace has a bump 5 with openings for graphitized electrodes 6. By means of mechanism 8 the furnace can incline so that steel and slag could be loaded and discharged. Electric arc emerging between the electrodes of 350-500 mm in diameter and charge 3 is a source of heat in such furnaces.

Electric current of 200-600 V and 1-10 kA is delivered to the electrodes. The furnace volume is 0.5-400 tons.

Steel is mostly smelted in electric furnaces with oxidizing and without oxidizing impurities. Smelting with oxidizing coincides with open hearth scrap process in many points. It is used to melt carbon steels. The charge for this includes steel scrappage, converting pig iron, coke for cementation and 2-3 % of limestone. Smelting includes 2 periods: oxidation and regeneration.

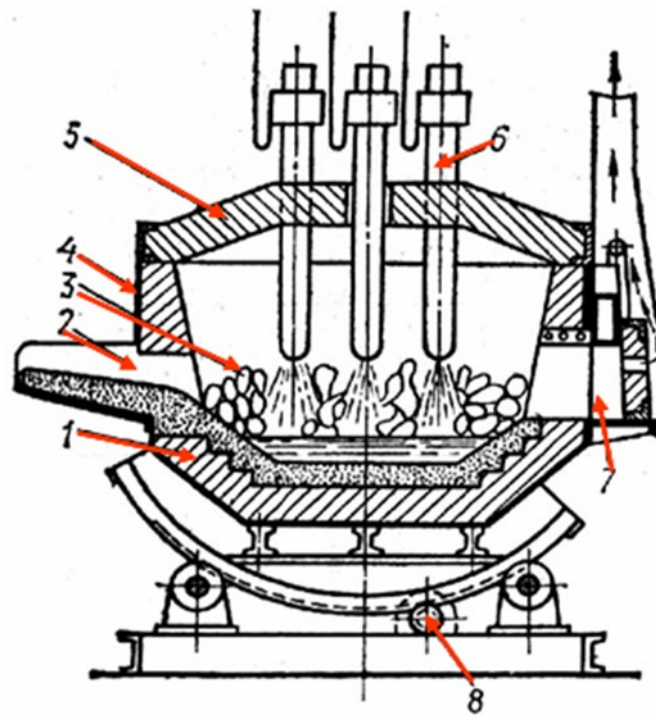


Figure 3.5 – Electric furnace design

The content of oxide in the slag reduces at that, and it starts diffusing from metal slag, where it regenerates right off. Regenerating takes place in slag and on the metal-line slag. Hence metal does not get fouled with non-metal impurities (SiO_2 , Mn, Al_2O_3), which happens when regular deoxidation is involved.

Due to a great proportion of CaO in slag, sulphur is also intensively removed from the metal. In ordinary electric steel smelting, sulphur content does not exceed 0.015 %, while in open hearth steel 0.02 % of sulphur is considered a low content.

Smelting without oxidation is used to obtain alloy-treated steel and scrap and also scrapings of corresponding composition. In this case manufacturing is reduced to the charge remelting.

Electric induction furnace (Fig. 3.6) consists of a capsule 5 with a cap 1 of water-cooled inductor 2 mounted in body 4. When alternative current of 500-2000 kHz goes along the inductor, magnetic flow develops powerful turbulent flows in metal the charge 3. These flows heat the charge up to its melting.

Furnace volume varies from 10 kg to 5 tons, in certain cases their capacity reaches 25-30 tons.

In induction furnaces, smelting is carried out by the method of remelting alloy-treated steels or sulphur – phosphorus clear carbon scrap and ferroalloys. After the charge melts, slag is fed onto the metal surface: in basic furnaces it is limestone and fluor spar, in acid furnaces it is crushed glass and other materials that are rich in SiO_2 . Slag protects metal from oxidizing, decreases heat losses and alloying elements burn-off. One-ton melting time is 45 minutes, power consumption is 600-700 kW a year for a 1 ton of steel.

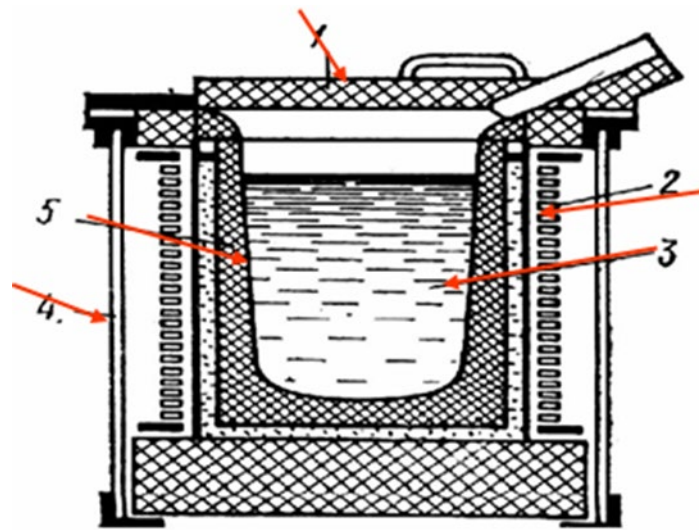


Figure 3.6 – Electric induction furnace design

TOPIC 4
PROSPECTS OF STEELMAKING. STEEL CASTING.
CRYSTALLIZATION AND STRUCTURE OF PIG STEEL.
METHODS TO IMPROVE STEEL QUALITY. CARBON STEEL.
ALLOY-TREATED STEEL

4.1 Prospects of steelmaking

The above technological peculiarities of steelmaking prove that the basic oxygen and electro smelting methods possess more advantages than all the rest of them. Therefore, they are gradually ousting the Martin process (Fig. 4.1).

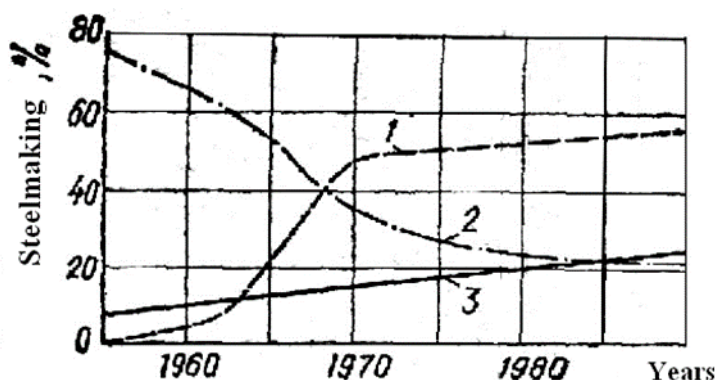


Figure 4.1 – The world steel making in oxygen converters (1), in Martin (2) and electric (3) furnaces

It is also necessary to draw your attention to the fact that all modern methods of steelmaking are based on two-stage treatment of iron ores: at first cast iron is smelted and then steel is produced from it. This method is complicated – it demands huge inputs of time, labour, energy and capital.

Besides, steel making is a source of environmental pollution. Without severe control, over 200,000 tons of dust, 50,000 tons of sulphur compounds, 250,000 tons of sulphur, 250,000 tons of carbon, nitric and other oxides will be released into the atmosphere every year by the metallurgical works with the annual productivity of 10 million tons of steel.

Some activities (installing gas and dust catchers, special filters etc.) have been recently introduced to protect the environment from the harmful discharge of metallurgy industry.

In a number of countries, iron is produced directly from ore by various manufacturing schemes. One of them is direct ore-reduction steel making process (Fig. 4.2).

The raw stock for iron production is a concentrate of 70 % Fe, which is delivered in the form of a pulp (mixture with water) 1 by the 27-km-long pipeline 2 from Lebedyn concentration plant.

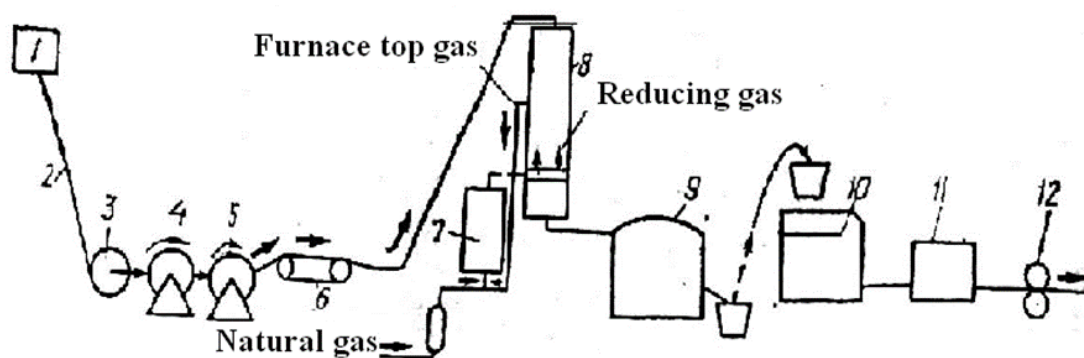
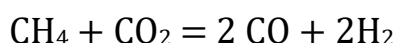


Figure 4.2 – Direct iron recovery process

After pulp having been deposited, the sludge of concentrate is dewatered with disk vacuum filters 3. Afterwards, it is mixed with the binder (bentonite) in mixing drums 4 and is subjected to palletizing inside the apparatus 5 – pellet is obtained. The pellet is scorched inside the furnace 6 and then delivered by the conveyor to the shaft furnace of iron direct reduction 8. Reducing gas is delivered from the bottom to the furnace at 1000°C and under the pressure of 0.15 Pascal. This gas is generated inside reformer 7 after interaction between the furnace top gas and natural gas by the following chemical reaction:



Following the reducing process, iron content in the pellet is raised up to 90-95 %. Then, the pellet is delivered to 150-ton electric furnace 9. The pellet is smelted, the metal is cleared of impurities, some necessary concentrates are added and alloy treated steel, which is cast in CCM, is finally obtained.

Pig steel is heated in the furnace (11) and rolled on the mill (12). The share of the steel smelted in by this method is about 2 % of the world output so far.

4.2 Steel casting

The steel smelted in the furnace is placed into the iron ladle and moved to the place of teeming by an overhead traveling crane. Ladle capacity is 50-480 tons. The steel is poured into moulds or crystals for continuous casting. Moulds are cast iron forms for producing big castings of different sections. Casting mass for rolling is 10-12 tons, and 350-400 tons for forging. Alloy-treated steel can be sometimes cast into pieces weighing hundreds of kilograms.

There are 2 ways of casting steel in moulds: atop and trumpet casting.

In a top casting, steel is poured out of the ladle 2 (Fig. 4.3, a) into each mould 1 separately. In this kind of casting the surface of moldings becomes soiled with oxide films (as a result of liquid metal splash falling on the walls of the mould). Atop casting is used for carbon steel.

In trumpet casting (Fig. 4.3, b) from 2 to 50 moulds placed on a bottom plate 5 are filled with steel simultaneously. Steel is poured into moulds through the central

funnel 3 and channels on the bottom plate. Meanwhile, steel is at the bottom of the mould, which ensures its gradual filling. Due to the fact that steel in adjutage 4 retains its liquid state, the hole capacity and molding wastes are reduced. Trumpet casting is used for alloy-treated steels.

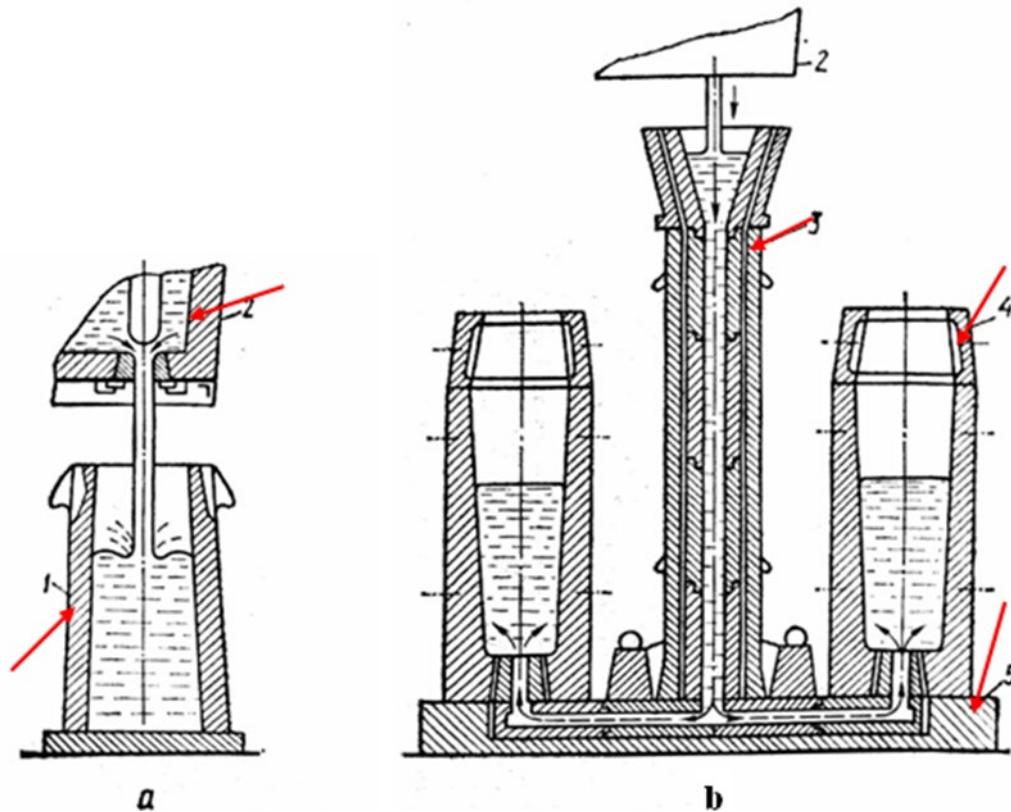


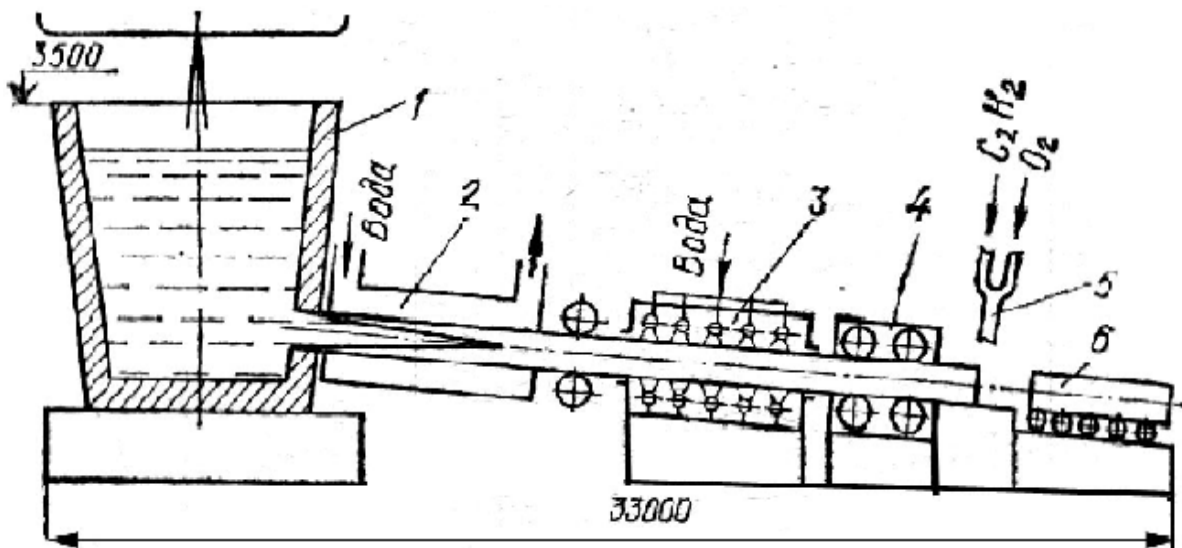
Figure 4.3 – Casting steel into ingot moulds atop (a) and trumpet casting (b)

Continuous steel casting is done on special continuous casting machine (CCM) (Fig. 4.4).

Steel from the ladle is poured into a water-cooled mould – crystallizer. A false bottom (inoculum) is inserted into the crystallizer before casting.

Liquid metal hardens when touches cold inoculum and walls of the crystallizer. The inoculum together with the hardened metal on it is then drawn out of the crystal and tows a ready-made molding. At that time, the molding may be still liquid inside, therefore it is intensively cooled by water jets.

The surface of such moldings is of very high quality, and the metal has a uniform structure. Then the stock material is cut into pieces of the predetermined length of 3-8 meters with a gas-oxygen torch. There are S-type continuous casters, curved and horizontal casters. The scheme of horizontal CCM is shown in the Fig. 4.4.



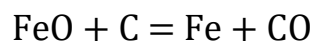
1 – lined hearth; 2 – crystallizer; 3 – secondary cooling zone; 4 – take-off assembly; 5 – torch; 6 – ingot

Figure 4.4 – The scheme of horizontal CCM

4.3 Crystallization and structure of steel ingots

The process of steel molding and crystal structure creation is determined by cooling conditions and the deoxidation rate. According to the deoxidation rate all types of steel are divided into unskilled (rimming), fully-killed (deoxidized) and semi-killed (balanced) steels.

Unskilled (rimming) steel is not fully deoxidated inside the furnace. Its deoxidation continues in moulds due to the carbon – ferrous oxide (FeO) interaction:



Carbon oxide is released from the steel fostering the removal of other gases (N_2 , H_2). This creates the impression of a liquid metal. Gas release continuous during the molding setting. Therefore, a great number of distributed gas bubbles are found inside a steel molding (Fig. 4.5, a).

Bubbles disappear during the hot rolling. Unskilled steel is the cheapest and very ductile, it contains no nonmetallic impurities.

Fully-killed steel is obtained when metal is fully deoxidated in the ladle (Fig. 4.5, b).

This kind of steel is set without any gas release. That is why a molding obtains a close structure, though the contraction cavity is concentrated in the upper part, which reduces the metal extraction by 15-20 %. This steel is extremely strong but less ductile than unskilled steel. It is also expensive, but its mechanical properties are better than those of unskilled steel.

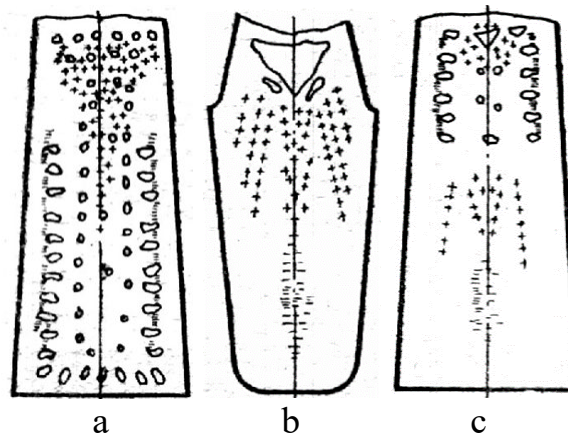


Figure 4.5 – The effect of deoxidation on the structure of steel castings

Semi-killed steel is obtained when metal is deoxidated by ferromanganese and when there is an undersupply of ferrosilicium or aluminium. In this case, a molding has no concentrated contraction cavity. The structure of its lower part is similar to the structure of the fully-killed steel, and the structure of its upper part is like the structure of unskilled steel (Fig. 4.5, c).

In terms of quality and value, this steel is intermediate between unskilled and fully-killed steel. The metallic extraction is 5-10 % as big as that of fully-killed steel.

4.4 Methods of steel quality improving

The properties of steel smelted in various melting units do not always meet the requirements of modern technology. Therefore, special technological processes of out-of-furnace refining and refining remelting have been developed. Vacuum refining and synthetic molten slag treatment are the most widely used methods of out-of-furnace steel refining.

Vacuum refining is used for reducing the content of dissolved gases O_2 , H_2 , N_2 in steel. Vacuum refining leads to three-fivefold reduction of gas content and two-threefold reduction of nonmetallic impurity content in steel, which contributes to increasing its strength and ductility.

The following methods of vacuum refining are the most widely-spread:

a) A ladle with metal is placed into a vacuum chamber with residual pressure of 250-650 Pa and is kept there for 10-15 min. For vacuum refining acceleration steel is moved by an inert gas;

b) When steel is poured out of the ladle or into a mould, a metal stream is treated with vacuum (degaussed);

c) Steel degaussing in batches.

For this, the vacuum chamber 3 is lowered or the ladle 1 is raised so that the connecting piece 2 dips into metal.

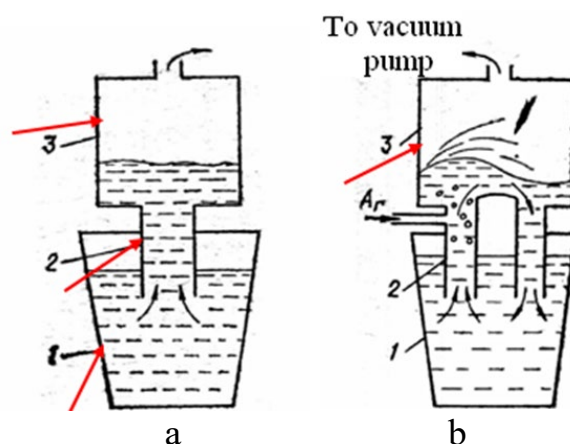


Figure 4.6 – A unit for steel dedassing in batches (a) and for circulation degassing (b)

Under the influence of vacuum, metal is drawn into a vacuum chamber, kept there for a period of time and then poured into the ladle again. This process is repeated several times.

d) Circulation degaussing is more effective.

Two connecting pieces of vacuum chamber 3 dip into metal and it is raised into the chamber. An inert gas (argon) is injected in one of the connecting pieces, as a result, metal is moved to the chamber through this piece and flows down into the ladle through the other piece. Thus, metal circulates in the unit.

4.5 Synthetic molten slag treatment of steel

At first molten slag (about 45 % CaO, 40 % Al_2O_3 , 10 % SiO_2 , 5 % MgO) is poured into a ladle. Its temperature is 1700°C . The quantity of slag equals 3-5 % of molten slag mass. Then smelted steel is released from a height in a strong stream. As a result of steel and slag rapid mixing, the surface of their interaction is increased by hundreds of times as compared to that inside the furnace.

Synthetic slag treated steel is noted for a small content of oxygen, sulphur and nonmetallic impurities, which ensures its high ductility and impact strength.

There exist the following types of refining remelting:

- Electroslog remelting,
- Vacuum-arc remelting,
- Plasma-arc remelting,
- Electron-beam remelting.

Now we will consider electroslog remelting (ESR). Steel for remelting moves into a unit in the form of an electrode 6. Molten slag 5 (a mixture of 60-65 % CaF, 25-30 % Al_2O_3 , CaO and other additives) is highly electrical-resistant, therefore electric current that flows in the slag creates enough heat energy to melt the electrode. Metal drops penetrate the layer of the slag and gather in the bath 4. Then they harden in the water-cooled mould 2 and form a molding 3.

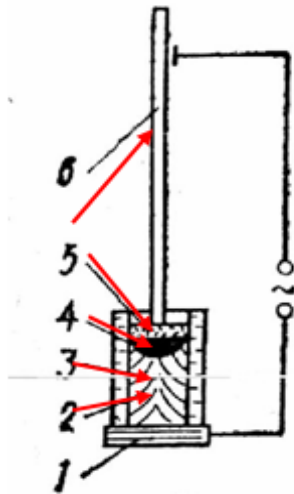
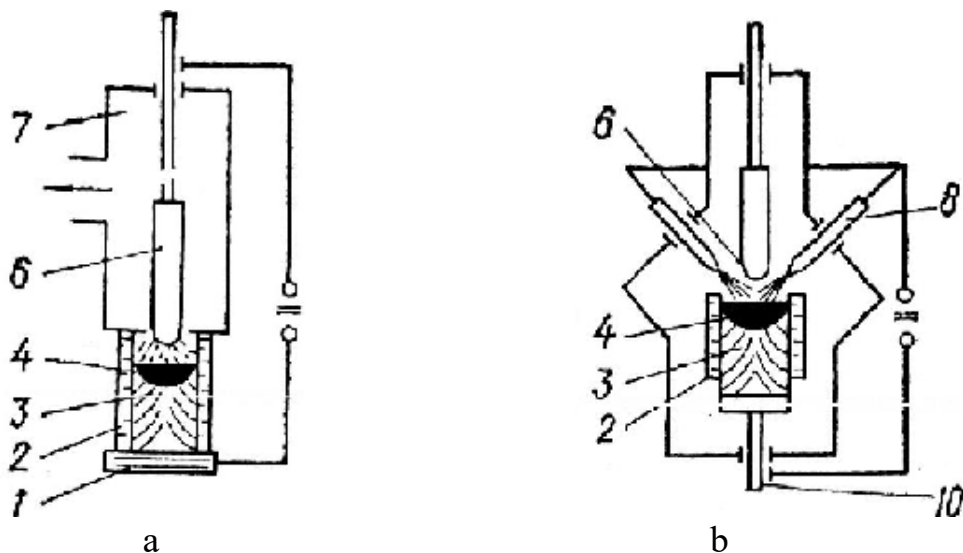


Figure 4.7 – An electroslag remelting unit schematic

Plasma-arc remelting is used for obtaining steel and alloys of very high purity. A source of heat energy in the unit is a plasma arc with the temperature of 10000-15000°C.

Vacuum-arc remelting is carried out in vacuum arc furnaces. The electrode is steel being remelted. Vacuum inside the furnace body is about 1.5 Pascal. The arc emerges between the electrode (cathode) and the starting bar (anode). Metal drops penetrate the electric arc zone and get degassed. Meanwhile, they create a solid structure without any cavities.

Vacuum-arc and plasma-arc remelting models are shown in the Fig. 4.8.



- 1 – water-cooled ingot mold stool; 2 – crystallizer, 3 – ingot, 4 – metal bath;
 5 – molten slag; 6 – billet (electrode) that is remelted; 7 – vacuum chamber;
 8 – plasmatron; 9 – electron gun; 10 – device for ingot withdrawal

Figure 4.8 – Refining remelting models: vacuum-arc (a) and plasma-arc remelting (b)

Zone melting (refining). This method is based on the difference between the solubility properties of impurity elements in liquid and hard phases.

4.6 Steel Classification

Different types of steel are classified according to the following characteristics:

1. According to the production method:
 - a) Type of melting unit (converter steel, Martin steel, electric steel);
 - b) Type of steelmaking practice (basic, acidic, vacuum- treated and molten-slag-treated steel).
2. According to the nature of setting in the mould: fully-killed, semi-killed, unskilled.
3. According to the chemical composition: carbon steel and alloy-treated:
 - a) Carbon steel: low-carbon steel (under 0.25 % C), medium-carbon steel (under 0.60 % C), high-carbon steel ($C \geq 0.60$ %);
 - b) Alloy-treated steel: low-alloy steel – (total alloy content is below 3.5 %); medium-alloy steel – (total alloy content is below 10 %); high-alloy steel – (total alloy content is over 10 %).
4. According to the quality: commercial-quality steel, refined steel, high-grade refined steel.

Refined steel is marked with the letter A, and high-grade refined one – with letter III at the end of the grade. They differ in the content of detrimental impurities (sulphur and phosphor), nonmetallic impurities, gases and nonferrous-metal impurities.

5. According to the properties and field of application:
 - a) Construction steel;
 - b) Instrumental steel;
 - c) Special quality steel;
 - d) Welding steel.

4.7 Carbon Steel

Carbon steels are divided into construction and instrumentation. Construction steel contains under 0.6 % C. They are further subdivided into commercial-quality and high-quality steels. Commercial-quality steel (government standard 380-88) are of the following grades: СтО, Ст1кп, Ст1пс, Ст1сп, Ст2кп, Ст2пс, Ст2сп..., Ст6пс, Ст6сп.

The higher the number is the strongest and the hardest but the least ductile the steel is.

High-quality steels (government standard 1050-88) contain less sulphur and phosphor (under 0.04 %) and less other elements and nonmetallic impurities. These steels are marked with the numbers that denote the hundredth parts of the carbon percentage (0.8; 10; 15; ...; 60). The steel deoxidation rate is also shown in grades – 10 кп; 10 пс; 10.

Instrumental, Martin and electrical steels are smelted and delivered in compliance with the government standard 1435-90 according to their chemical composition. They are divided into high-quality and refined steels.

High-quality steels are marked with the letter Y and the number denoting the tenth part of the carbon percentage, e.g.: Y8 (0.8 % C), Y12 (1.2 % C). Refined steel has also lettered A at the end of the grade (Y8A, Y12A).

For cutting tools that work without impacting (files, screw taps), harder steels – Y10, Y12 – are employed. Tools that are imposed to impact load (chisels, hammers) must possess certain viscosity. Steels Y7, Y8 are used to produce such tools.

4.8 Alloy-Treated Steel

Some alloy content (chrome, nickel) was added to the steel that is called alloy-treated.

Construction alloy-treated steels are used for producing machine parts, cushions and springs, ball bearings and roller bearings.

Instrumental steels are aimed for producing cutting, stamping and measuring tools. They are alloyed mostly with carbide-forming elements – Cr, W, V, Mn.

TOPIC 5

PRODUCTION OF NON-FERROUS METALS

Production of copper (Cu), copper alloys. Production of aluminium (Al), aluminum alloys. Production of magnesium (Mg). Production of titanium (Ti)

5.1 Production of copper (Cu)

The content of Cu in Earth crust is 0.01 %.

Copper ores contain 1-5 % of Cu. They contain copper in the form of chalcocite, Cu_2S , CuFeS_2 , CuO , Cu_2O , $\text{Cu}_2\text{S} \times n\text{H}_2\text{O}$ (copper pyrite), CuCO_3 – malachite. Along with Cu these ores also contain nickel, zinc, lead, Argentum, Aurum.

Production of Cu includes the following processing steps:

1. Ore recovery;
2. Ore reduction;
3. Ore concentration;
4. Ore blasting;
5. Half-finished material (matte) smelting;
6. Production of Bessemer copper;
7. Refining (flame, electrolytic).

We will consider the production of Cu starting with the process of concentration.

Concentration is carried out on a basis of floatation.

This method is based on a different watering rate of copper compounds and lean material. Reduced ore, water and flotation reagents (for example, spruce oil) form a fine pulp in a flotation machine. Flotation elements are adsorbed on ore parts in the form of a hydrophobic film. During pulping blowing, air bubbles concentrate on the surface of these elements and lift them up, creating a layer of foam, while watered lean material deposit onto the bottom of the bath. A 15-35 % Cu concentrate is obtained after filtration and drying of the collected foam.

5.2 Concentrate smelting

Smelting is carried out in the air atmosphere at the temperature of 750-850°C for oxidation of sulphides and desulphuration ($\text{S} + \text{O}_2 = \text{SO}_2\uparrow$; $2\text{Fe} + \text{O}_2 = 2\text{FeO}$).

Smelting in a “boiling” sphere is an advanced method. Reduced material is loaded into the furnace through a window 3 (Fig. 5.1). Air enters the furnace from below through the channel 2 and openings in the tray 1.

Air pressure value is selected so that concentrate particles remained in unchanging (“boiling”) state. Smelted concentrate “flows” over sill 5 in the underfired form. Escaping sulfur trioxides is purified in cyclones 4 and then used in sulphuric-acid industry.

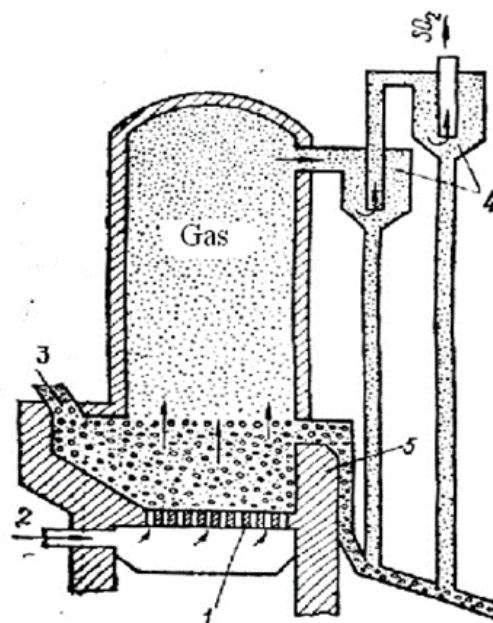
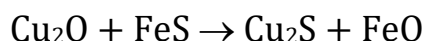
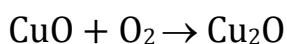
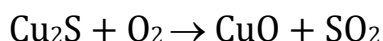


Figure 5.1 – The scheme of the furnace for smelting the concentrate in a boiling sphere

Matte is smelted out of concentrate in fire buttonhole heaters.

The heater is scorched with black oil fuel, black dust or gas. Maximum temperature in the heater is 1550°C, and 1250°C-1300°C in the tailpiece.

Copper oxide (CuO) and ferrous oxide (FeO) are also recovered in the process of smelting:



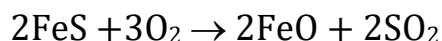
Copper and ferrous sulphides interfuse and form matte.

Matte – is an alloy of Cu₂S and FeS, containing 20-60 % of Cu, 10-60 % of iron, under 25 % of sulphur.

5.3 Production of Bessemer copper

Bessemer copper is obtained when smelted matte is aerated in the converter (Fig. 5.2).

Air blow is fed through pipes 3 and delivered to the center of the converter 2 through 40-50 lances 4 placed along its generatrix. The converter is rotated on rollers 5 for pouring the matte into the converter mouth 1 and for discharging the smelting products.



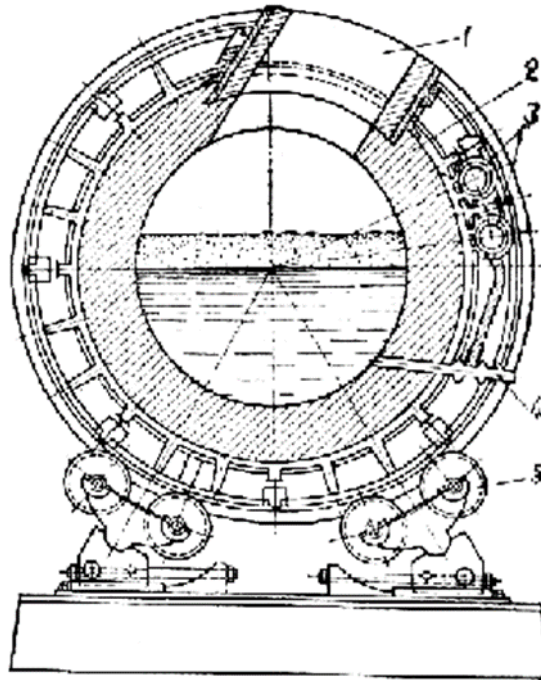
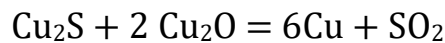
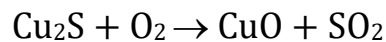


Figure 5.2 – Converter for Production of Bessemer copper

Ferrous oxide FeO is fixed with the fluxing agent – silica (SiO_2) and form a slag $2\text{FeO}_2 \times \text{SiO}_2$.

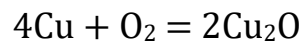
During the second step (2-3 hours), sulphides are oxidated:



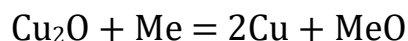
This copper is called Bessemer, or coarse copper, because it contains 1.5 % of impurities. For purification, coarse copper undergoes flame or electrolytic refining.

5.4 Flame refining

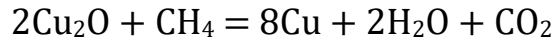
It is based on oxidation of impurities when Bessemer copper is blown. Meanwhile, oxygen from the air combines with the copper and form Cu_2O :



Then this oxide interacts with metallic impurities (Me) according to the chemical reaction:



After that copper is oxidated when it is stirred with wooden barlings – Cu_2O is recovered. Active water-gas and carbohydrate evolution facilitates outgassing and copper recovery:



After flame refining the copper purity can reach 99-99.5 %.

5.5 Electrolytic refining

Electrolytic refining is used to obtain copper with the 99.5 % purity. Electrolysis is done in special baths. Anodes are 50 mm thick 1×1 slabs of Bessemer copper, cathodes – 0.5 mm thick sheets of pure copper, electrolyte – sulphuric acid and copper sulfate-water solution (Fig. 5.3).

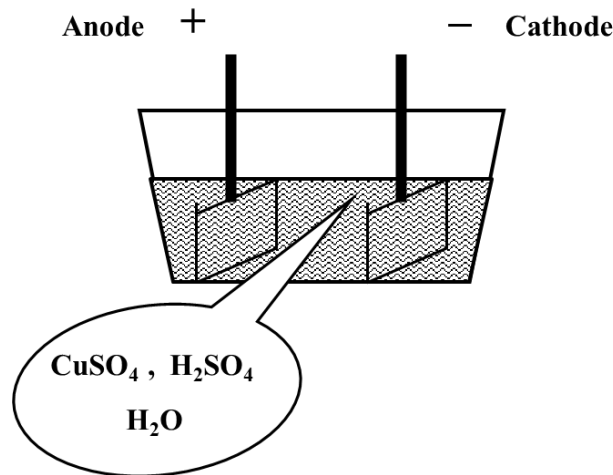


Figure 5.3 – Schematic diagram of electrolytic copper refining

A node is dissolved when the voltage of current electricity is 2-3 V and its ampere density is 100-400 A/m², copper goes into solution in the form of cations Cu^{2+} , which are discharged on cathode and settle in a layer of pure copper. Meanwhile, impurities deposit onto the bottom of the bath in the form of slime. The slime sometimes contains up to 35 % of Ag, 6 % of Se, 3 % of Fe, 1 % of Au and other precious elements. Therefore, slimes are processed in order to recover these elements.

5.6 Copper alloys

In this renewed state, the strength of copper is $\sigma_B = 250$ MPa, hardness is HB 45, ductility is $\delta = 45$ %. Copper is seldom used as a construction material in mechanical engineering. More often it is used for obtaining alloys – brass and bronze.

Brass is an alloy of copper and zinc. Zinc (under 39 %) is mixed with copper to form a solid solution α , the so called α -brass. If the content of zinc is higher, the second phase β -solid solution is formed in alloys. Two-phase brass is called $(\alpha + \beta)$ -brass. The presence of stronger and harder a β -phase in the structure raises the strength of brass, though ductility is considerably lowered. Therefore, one-phase brass is used for pressure shaping, and two-phase – basically for cutting work and casting. Alloys, which contain more than 45 % are brittle, so they are rarely used.

Ni, Pb, Sn, Si and other elements are added into brass for strengthening and increasing its corrosion-resistance, as well as for improving some processing characteristics. Such brass is called complicated.

Pressure shaped brass is marked with the letter Л and figures indicating the content of copper in the alloy, e.g., brass grade Л80 denotes the brass containing 80 % of Cu, the rest is Zn.

In compound brass grades (like in grades of other non-ferrous alloys), components are marked with initial letters of their names: А – aluminum, О – tin, Мг – manganese, etc. The first two figures following letters denote the average content of copper, and next figures – the content of other elements (the rest is Zn). For example: grade ЛЖС 58-1-1 denotes the brass containing 58 % of Cu, 1 % of Fe and 1 % of Pb, the rest is Zn.

Grades of cast brass differ from those mentioned above. Thus, grade ЛЦ40МЦ3Ж denotes the brass containing 40 % of Zn, 3 % of Mn, 1 % of Fe, the rest being Cu.

Bronze is an alloy of copper, tin, aluminium, beryllium and other elements, except for zinc as a basic element. Unlike zinc, these elements either have a changeable solubility in copper depending on temperature, or form solid solutions, which undergo eutectoid transformation when cooled. Therefore, bronzes are divided into wrought and cast bronze according their processing characteristics. Besides, bronzes with considerable solubility of components or eutectoid transformation can undergo strengthening high-temperature processing.

Bronze, as well as brass, can be either simple or complicated. Grades of wrought bronze begin with the letters Бр (бронза) followed by letters that denote alloying elements, and then by figures denoting the content of these elements in the same order (the rest – Cu). For example, bronze-grade БрОЦС-4-4-4 contains 4 % of Sn, Zn and Pb, the rest being Cu.

In cast bronze grades the content of the elements is depicted immediately after their symbol. For example, Бр08Н4Ц2 (8 % of Sn, 4 % of Ni, 2 % of Zn, the rest is Cu).

Bronzes are divided into tin bronzes and tinless ones according to their chemical composition. Among all bronzes, beryllium bronze with the content of Be about 2 % holds a special place. After being hardened at 780°C and thermally aged at 300°C, their strength is $\sigma_B = 1300$ MPa, hardness is HB 370, they have great ductility and high corrosion-resistance. This allows their use for making such products as springs, membranes, bench work tools etc.

5.7 Production of aluminium

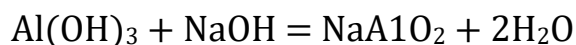
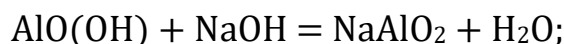
Aluminium is the most widely spread metal in the Earth crust. Its content equals 8.8 %. Bauxites, nephelines, apatites and alunites belong to aluminium ores. They contain aluminium in the form of aluminum oxide Al_2O_3 or aluminum hydroxides $Al(OH)_3$ and $AlO(OH)$.

Production of aluminium includes two processing steps:

a) Extracting aluminium oxide from ore

b) Electrolysis of aluminium oxide

1. Alkali production process is used to obtain aluminium oxide. Reduced bauxite undergoes leaching – chemical decomposition by means of strong caustic NaOH:



Meanwhile, well-soluted sodium aluminate NaAlO_2 goes into solution, and impurities (ferrous oxide, titanium oxide, etc) sedate. Then sodium aluminate NaAlO_2 is decomposed and aluminum hydroxide $\text{Al}(\text{OH})_3$ is obtained. After aluminum hydroxide having been fried, aluminium oxide is obtained:



2. Electrolysis of aluminium oxide. The aluminium oxide obtained is soluted in cryolite – aluminium-sodium fluoride Na_3AlF_6 – and undergoes electrolysis in electrolytic furnaces (Fig. 5.4), which consist of a steel jacket 4 lined inside with carbon blocks, cathodic rails 5 and carbonic anodes 1 suspended on rails 2.

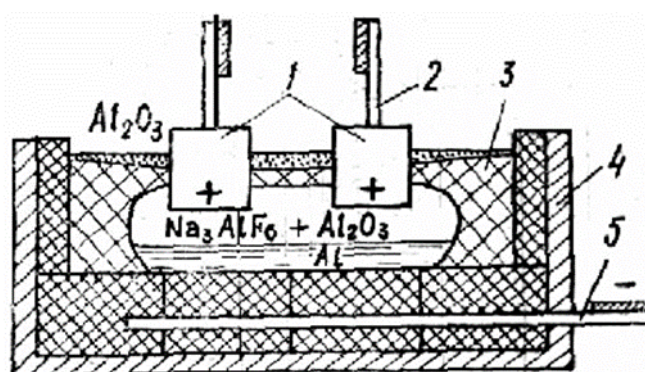
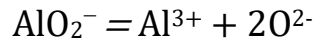


Figure 5.4 – The scheme of the electrolytic furnace for aluminium production

While operating, the lower part of anodes 1 is submerged into electrolyte. Under current electricity (4.0-4.5 V, 75-150 kA), the electrolyte is heated up to 950°C, and some electrolyte in the form of navvy pick 3 sedates on the walls of the electrolytic furnace and round anodes. Next portion of aluminium oxide is bulked on it at regular intervals.

Dissociation of cryolite and aluminium oxide follows chemical reactions:





The cation Al^{3+} uncharges on the cathode (the bottom of the bath) and forms liquid aluminium, and anion 2O^{2-} does the same on the anode. Meanwhile, carbon of the anode oxidizes to CO and CO_2 . Liquid aluminium is poured out through a siphon or a vacuum ladle once or twice a day. Productivity of the electrolytic furnace is about 350 kg of aluminium a day. In order to obtain 1 ton of aluminium 15,000-17,000 kWh of electric power is used.

3. Refining of aluminium means blowing the liquid metal with chlorine for 10-15 min. Meanwhile, steamy aluminium chloride AlCl_3 is formed. It is adsorbed on the surface of non-metallic impurities and they emerge in the form of a slag. Chlorine also facilitates solute gases (O_2 , CO_2) disposal.

Having been refined and settled for 30-45 min, the aluminium purity can reach 99.5-99.85 %. If the aluminium purity requirements are higher, aluminium additionally undergoes electrolytic refining. The purity of such aluminium is 99.99 %.

5.8 Aluminum alloys

The annealed aluminium feature $\sigma_B = 80\text{-}100$ MPa, HB 25-30, high ductility ($\delta = 35\text{-}40$ %), corrosion-resistance, electrical and thermal conductivities.

Cu, Si, Mg, Ni and other elements are used for aluminium alloying. Iron is a detrimental impurity in most of aluminium alloys.

The higher is the temperature, the more soluble most alloying elements are. Eutectics occurs in the alloy if there is a certain balance of elements.

According to their processing behavior, aluminium alloys that solidify when a solid solution is being made belong to wrought alloys, while eutectic alloys go to cast alloys.

1. Wrought aluminium alloys are divided into unstrengthened and strengthened by heat treatment. This division is based on the miscibility gap of alloying elements at room temperature. AM Π - and AM Γ -type alloys belong to alloys that are not strengthened by heat treatment. Alloys AM Π contain under 1.5 % of Mn, and AM Γ – about 7 % of Mg and 0.8 % of Mn.

They also add 2 % of V, 0.1 % of Ti, 0.005 % of Be for strengthening the alloy.

These alloys are very ductile, well-welded, corrosion-resistant, their strength is $\sigma_B = 200\text{-}300$ MPa. Pressed and welding articles (containers, tanks, etc) are made of them.

Duralumins belong to heat-treated alloys. They contain 2-5 % of Cu, under 1.5 % of Mg, 1 % of Mn. Duralumins are marked with the letter Д and an identification number, e.g., Д1, Д6.

Duralumin heat treatment consists in its hardening under temperatures over 500°C and subsequent natural ageing at room temperature within 5-7 days, or false ageing at $100\text{-}150^\circ\text{C}$. After such treatment, characteristics of duralumin can reach: $\sigma_B = 420\text{-}470$ MPa, HB 90-100, $\delta = 18\text{-}20$ %.

Alloys intended for malleating or stamping – AK2, AK4, AK6 (aluminium, malleable, alloy number) also belong to duralumin-type alloys. Unlike duralumin, they are additionally alloyed with nickel or titanium.

2. Cast aluminium alloys contain an increased amount of silicon, copper, magnesium, zinc. Of these alloys, silumins – aluminium alloys containing 8-14% of Si and a small amount of other elements – is most commonly used.

Aluminium alloys containing 4-11 % of Cu, 8-11 % of Mg, 10-14 % of Zn and 6-8 % of Si are used as cast alloys as well.

Cast alloys are marked with letters AJI (aluminium, cast) and an identification number, e.g., AJI4, AJI9.

5.9 Production of magnesium

The content of magnesium in Earth crust is 2.4 %. Carnallite $\text{MgCl}_2 \times \text{KCl} \times 6\text{H}_2\text{O}$, magnesite MgCO_2 , dolomite $\text{MgCO}_3 \times \text{CaCO}_3$ and bischofite $\text{MgCl}_2 \times 6\text{H}_2\text{O}$ belong to magnesium ores.

Electrolytic method of magnesium production is the most common. It includes two processes: obtaining magnesium chloride MgCl_2 and its electrolysis.

1. The basic raw material for production of magnesium is carnallite. With the aim of its concentration, reduced carnallite is treated with hot water. At this stage, chlorides MgCl_2 and KCl go into solution. It is cooled then, and artifactual carnallite crystals are obtained.

Artifactual carnallite is roasted in swiveling or fluid bed furnaces for moisture removal. Afterwards, anhydrous carnallite is smelted in chlorators for MgO component reduction. Magnesite and dolomite are smelted and then chlorated in the presence of carbon. Thus, magnesium chloride MgCl_2 is obtained.

2. Magnesium chloride electrolysis is carried out in fireclay-coated electrolytic furnaces that consist of a number of chambers with carbon anode 4 and two cathodes in the form of steel plates 2 (Fig. 5.5).

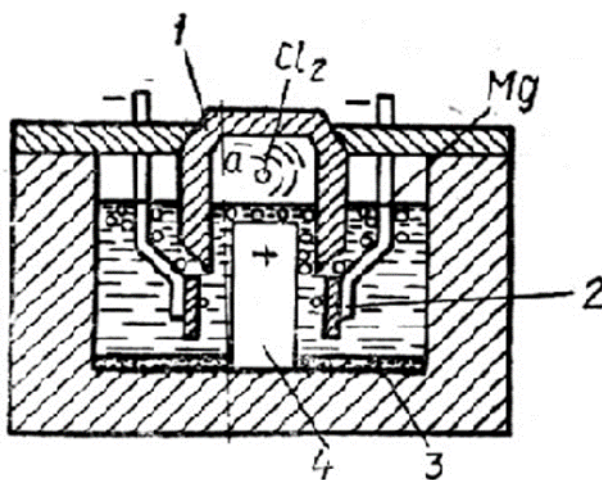


Figure 5.5 – The scheme of the electrolytic furnace for magnesium production

In the upper hermetically-sealed part of the chamber the anode space is separated from the cathode one by a fireclay baffle 1 for collection and removal of chlorine.

Molten salts MgCl_2 , CaCl_2 , NaCl , KCl with NaF and KF act as an electrolyte for production of magnesium.

Electrolysis is carried out at 720°C , electric voltage is 3 V and electric current intensity is 30-50 kA. Power consumption for production of one ton of magnesium is as high as 15-17 kWh.

Magnesium ions created during electrolysis are discharged on the cathodic plates 2. Liquid magnesium is regularly removed with a vacuum ladle. Chlorine ions are discharged on the anode. Then they appear on the surface under the baffle 1 and are pumped out. The slag 3 is formed on the bottom of the bath.

3. Magnesium refining. Crude magnesium contains up to 2-5 % of various impurities. Therefore, commonly it is refined i.e. remelted with fluxing agents that contain magnesium, barium, potassium, sodium and other chlorides. Remelting is done in electric furnaces at 720°C for 0.5-1 hour. Stirring the fused electrolyte facilitates dissolution of impurities in the fluxing agent, their floating-up and changing into slag. The purity of refined magnesium reaches 99.9 %. An advanced purification of magnesium can be ensured by vacuum sublimation.

5.10 Production of titanium

Titanium is the fourth element after aluminium, iron and magnesium by the content in the Earth crust (0.61 %). About 60 titanium minerals are known. Ilmenite $\text{FeO} \times \text{TiO}_2$, rutile TiO_2 and sphene (titanite) $\text{CaO} \times \text{TiO}_2 \times \text{SiO}_2$ are the most commercially valuable of them.

The important raw material for ilmenite is titanomagnetite iron ore, which is a mixture of ilmenite and magnetite Fe_3O_4 and a part of hematite Fe_2O_3 . After gravity dressing and magnetic concentration of this ore, a concentrate containing under 40 % of TiO_2 , 50 % of iron oxides and 8-10 % of other oxides is obtained.

1. Titanium recovery. Several methods of titanium recovery are known. The most common method is carbothermic reduction according to the scheme shown in the coming slide (Fig. 5.6).

According to this scheme, the concentrate is reclaimed with charred coal, briqueted and smelted in the electric furnace. As a result of smelting, iron oxides are reduced and cast iron containing 2.5-3.0 % of C and 0.4-0.9 % of Si and Mn is obtained.

Titanium and silicon oxides form a slag containing 65-85 % of TiO_2 , 10-15 % of SiO_2 and other oxides. This slag undergoes chlorination, i.e., molten chloride treatment in the chlorator (with MgCl_2 , KCl , NaCl). Chlorine comes to the chlorator through a number of lances.

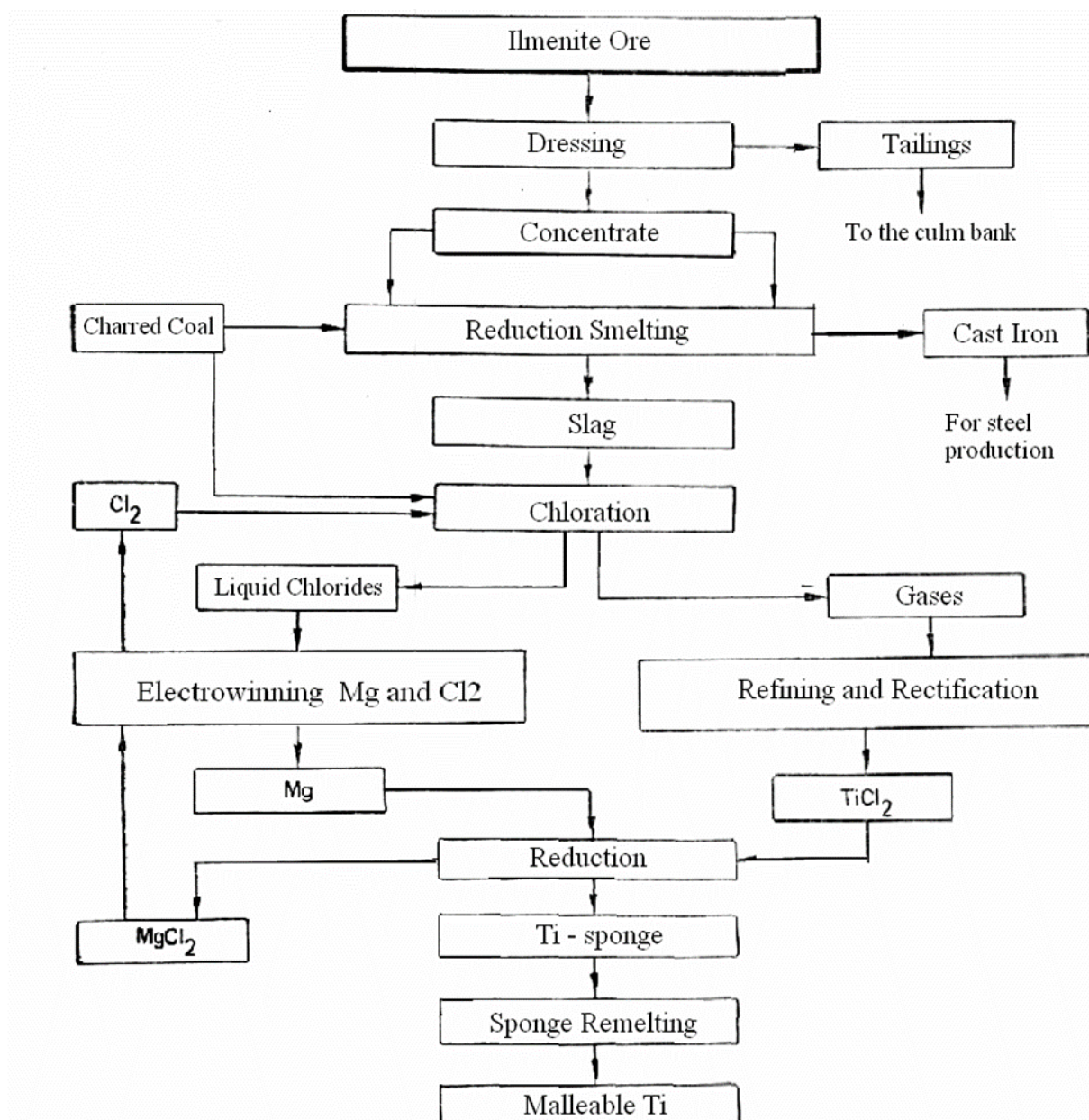
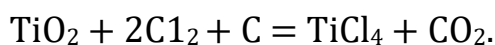


Figure 5.6 – Titanium production scheme

In the presence of charred coal, chloration of TiO_2 is done at 600°C :

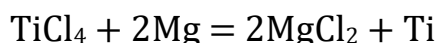


Together with titanium chloride, chlorides of some impurities (SiCl_2 , FeCl_3 , MgCl_2 and others) are also formed. Chloride TiCl_4 melts at -23°C and boils at $+136^\circ\text{C}$. Therefore, it is evocated in the chlorator in the form of vapour co-opting volatile silicium and iron oxides. Less volatile magnesium and calcium oxides, and oxides of some other metals compose a liquid.

A vapour-gas mixture from the chlorator is sent to a sophisticated system of condensing plants. There it is cooled stage-by-stage and refined due to the different condensation temperatures of chloride impurities and titanium. After condensation,

TiCl₄ is settled from the hard phase, and then it undergoes a long and elaborate process of refining, which is called rectification. Metallic titanium is obtained when TiCl₄ is reduced with the help of magnesium in steel hermetic retorts 0.9-1.5 m wide and 1.8-3.0 m high. A retort is set vertically in the electric resistance furnace. It is closed with a lid having tubes for injecting magnesium and TiCl₄, air disposal and argon injection.

After air disposal, the retort is filled with argon and heated to 750-800°C. Liquid magnesium is poured, and liquid titanium chloride is injected gradually. Reduction follows the reaction:



Titanium in the retort takes the form of sponge, and magnesium chloride is regularly poured out through the tube in the bottom of the retort. When the reaction is completed, heating starts. The retort is kept for one more hour at 1000-1100°C. After that the retort is taken out of the furnace and cooled to 20-40°C. The whole reduction process takes 30-35 hours when done at an industrial plant. After one operation up to 1.5 ton of titanium is produced.

Titanium sponge contains 35-45 % of magnesium and magnesium chlorides as well as some other impurities. Therefore, it is refined by vacuum distillation method – it is kept in vacuum for several tens of hours under residual pressure about 0.1 Pa at 900°C. Within the process, some impurities are disposed in the form of molten metal, others are evaporated and then condensated.

Titanium sponge is smelted in vacuum electric arc furnaces with a water-cooled copper melting crucible. One of the electrodes is a pressed titanium sponge rod, the other is a molten metal. While arcing, the rod melts and titanium drops flow down, harden into castings. Vacuum prevents metal oxidation and aids its clearing from solute gases.

The sponge-titanium purity is 99.6-99.7 %. Titanium with fewer impurities can be obtained by the iodide refining method based on thermal dissociation of titanium chloride TiCl₄ on the surface of titanium wire electrically heated up to 1300-1400°C. The evocating titanium deposits on the bottom and forms a bar. This refining method is efficient but not productive. That is why iodide titanium is expensive.

TOPIC 6
GENERAL DESCRIPTION OF FOUNDRY ENGINEERING.
THEORETICAL FUNDAMENTALS OF INGOT PRODUCTION.
METHODS OF INGOT PRODUCTION

6.1 Foundry Engineering

Foundry engineering has been known for many centuries. Due to its omnitude, it is very important for mechanical engineering (where the mass of ingots is up to 60 %) and for machine-tool industry (where up to 80 % of all machines and tools is cast). This fact is explained by the ability to produce components of both the simplest and the most sophisticated shapes that can weigh from several grams to hundreds of tons. Unlimited number of identical ingots can be cast. Foundry engineering is used in aircraft and rocket industries, in shipbuilding. Demand for ingots is increasing due to the development of chemical machine-building, as many components made of heat- and corrosion-resistant alloys can be produced only by casting.

This technology is almost wasteless.

The main point in foundry engineering is that a shaped component, or a blank part, is produced by pouring liquid metal into a mould, whose cavity corresponds to the size and configuration of the component. Such components are called ingots.

Foundry includes the following bays: pattern-making, earth preparing, Rodding, molding, furnace, shakeout, degating and surface cleaning.

Cast iron, carbon and alloy-treated steel, Al-, Cu-, Mg-, Ti-, Mo-base alloys are used to produce ingots. In order to produce quality ingots, casting alloys should feature not only certain mechanical, physical and chemical behaviour but also casting technological characteristics. They are as follows:

Flowability – ability of a liquid metal to fill slots molded into cavities very quickly.

Shrinkage – reduction of volume and linear dimensions of an ingot during its crystallization and cooling in solid state. Therefore, shrinkage is of two types: volumetrical and linear ones. The volumetrical contraction results in a porous contraction cavity in the ingot heavy section.

Liquation – nonuniformity of the ingot chemical composition through the section. Liquation negatively impacts the mechanical behaviour of an ingot because the structure of its metal is different in different sections. In order to reduce liquation, the cooling rate is raised.

Gas absorption – ability of liquid metal alloys (during overheating) to solute oxygen, nitrogen and hydrogen that evolve in the casting mold during cooling and can cause gas cavities in the ingot.

That is why foundry molding sand and core sand mixture must be gas-permeable. Thus, technological casting alloys must possess high flowability, low shrinkage and must not create liquation.

6.2 Methods of ingot production

The following methods to produce ingots are used in modern mechanical engineering:

- Manual or mechanical sand casting;
- Permanent mould casting;
- Pressure die casting;
- Investment casting;
- Shell casting;
- Centrifugal casting;
- Electrical slag casting;
- Others.

The use of these methods is determined by a number of factors: type of production (single, mass, large-scale); mass, accuracy and surface cleanliness; and cost value.

All casting moulds are categorized according to:

- Service life (disposable, reusable);
- State before casting (dry, semi dry, moist, chemically-hardening, self-hardening);
- Manufacturing technique (manual- or machine-shaping).

6.3 Production of moulds in disposable moulds

The technique includes the following operations:

- Production of gated patterns;
- Foundry molding sand and core sand mixture making;
- Formation of moulds and foundry cores;
- Drying cores, and sometimes moulds;
- Mould folding;
- Liquid metal preparation;
- Dislodging ingot from the mould and dislodging cores from the ingot;
- Chipping of castings and ingot refining;
- Ingot thermal treatment;
- Control and ingot defect elimination.

6.4 Molded and rod mixtures

Molded and core sand-clay mixtures must have the following properties: refractoriness, plasticity, gas permeability, malleability, strength, and non-stickiness.

Resistance to melting – the ability of the mixture not to melt or soften under the action of molten metal.

Plasticity – the ability of the mixture to take on the shape given to it without destruction and to produce accurate impressions of the model or core box.

Gas permeability – the property of a mixture to allow gases formed in the mold and released by the metal during cooling to pass through at a certain rate.

Plasticity is the property of a mixture not to resist metal shrinkage significantly when the casting cools in the mold (this is especially important for core mixtures).

Strength is the ability of a compacted mixture not to be washed away by the liquid metal that fills the mold.

Non-adhesiveness is the ability of a mixture not to chemically interact with metal and not to stick to the surface of the casting.

Mold and core mixtures differ in composition. Mold and core mixtures consist of sand, clay, water, and special additives.

Sand adds refractoriness and gas permeability to the mixture; clay adds plasticity and hardness, but reduces gas permeability and ductility. Therefore, various organic and inorganic substances are added to the core mixture instead of clay: resins, liquid glass, rosin.

The production of castings in disposable sand-clay molds on machines and especially in manual molding has significant disadvantages:

- low accuracy and insufficient surface cleanliness of castings;
- the need to leave significant allowances for mechanical processing;
- the formation of a coarse-grained structure.

To eliminate these shortcomings, special casting methods are used:

- into metal molds (sand casting);
- under pressure;
- using lost wax models;
- into shell molds;
- centrifugal and others.

6.5 Manufacturing castings in molds

1. The essence of the method lies in the fact that instead of a disposable sand mold, a reusable metal mold (cokil) is used. To form internal cavities or holes in the casting, the cores are often also made of metal. Cokils are used to produce castings from non-ferrous alloys, cast iron, and, rarely, steel.

Compared to sand molds, coquille molds have a number of advantages: no need for molding compounds and pattern and core equipment; increased accuracy and cleanliness of the casting surface; high-quality and density of the cast metal; reduced dust; significantly increased productivity. The dense metal and fine-grained structure of the casting are formed due to the significant cooling and crystallization rate of the alloy, which is dozens of times higher than in a sand mold. For the same reason, gases dissolved in the metal do not have time to be completely released, remain in a dissolved state, and have a less harmful effect on the density of castings.

Disadvantages: high cost of molds, which explains their use only in serial and mass production; inflexibility of molds, which increases the risk of cracks in castings; cast iron castings made in molds will have a bleached surface, which requires annealing of cast iron castings.

2. Depending on their design, molds can have a vertical or horizontal joint and be non-separable. A separable mold (Fig. 6.1) consists of two halves, 1 and 2, which

contain a cavity 5 with a core 3. The sprue bowl 6, riser 7, feeder 4, and ejector 8 are located in the plane of the joint. The mold is opened and the finished casting is ejected manually or mechanically.

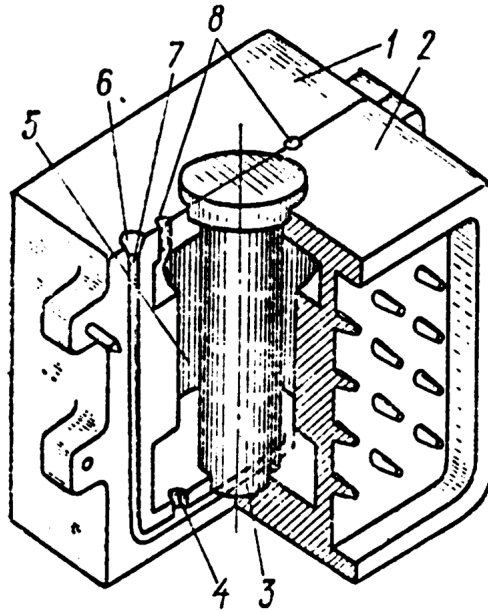


Figure 6.1 – Die casting mold components

3. The peculiarities of the technology for manufacturing castings in molds consist in the fact that before pouring, the inner surface of the mold is coated with refractory paint to insulate the mold from contact with liquid metal in order to increase its service life or reduce the cooling rate of the casting. The whitening of cast iron castings in molds is prevented by selecting the chemical composition of the cast iron, heating the mold to 250-300°C before pouring, and minimizing the time the casting is held in the mold. When manufacturing silumin castings in a mold, there is no need to modify it with sodium salts, since rapid cooling crushes silicon in the eutectic.

Casting copper alloys into molds requires coating the mold with greasy paint to form a gas layer between the metal and the mold, which eliminates the possibility of burning and promotes the formation of a smooth casting surface.

6.6 Manufacturing castings by centrifugal casting

The idea is that the me is poured into a coil that rotates at a certain speed. Filling of the ladle and crystallization of the me occurs under the influence of centrifugal forces, which ensures the integrity of the me, because gases and non-metallic impurities are not forced into the internal cavity of the casting and then removed during machining. The method is common in the manufacture of castings having the shape of a body of revolution in the production of cast iron pipes.

TOPIC 7

SHELL MOULD CASTING

1. The main point of the method lies in the usage of thermoreactive resin with technical aminoform in forming mixture, which melts under the influence of insignificant temperatures, and polymerizes and non-convertibly solidifies when further heated. As for the dimensional accuracy and surface roughness, shell mould castings surpass sand- and plaster-cast ones. This method is used in large-scale and mass manufacturing of small and middle-size ingots from any alloys. The components weigh 5-10 Kg.

2. Production of shell moulds starts from heating of metal plates in electric furnace up to 220-280°C (Fig. 7.1, a). Heated modeling board 1 (Fig. 7.1, b) is fixed to the model underneath above the storage hopper 2 with forming mixture 3, which consists of sand and additive compound of 4-6 % powdered resin.

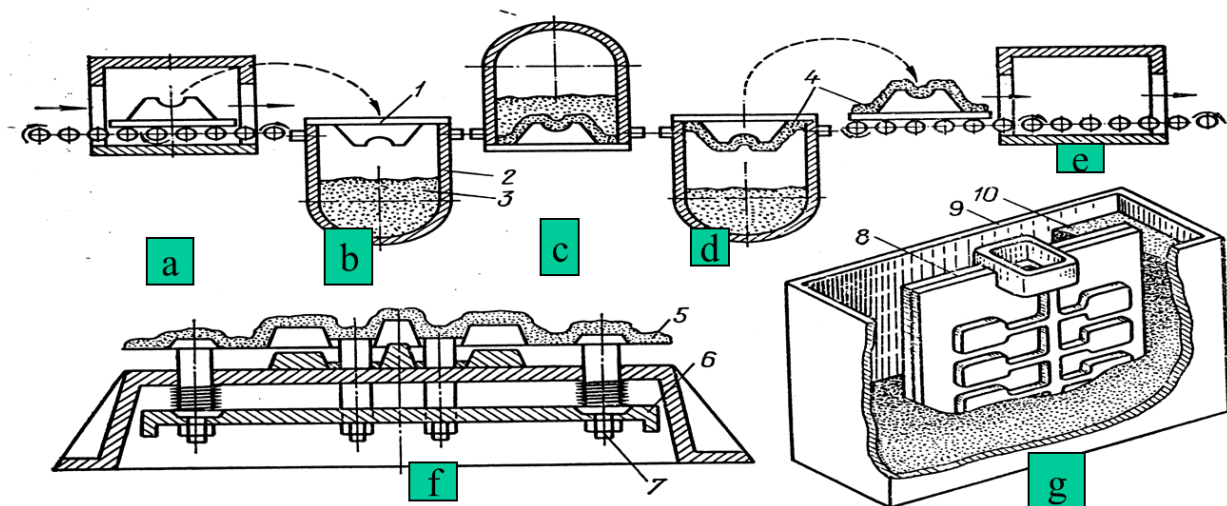


Figure 7.1 – The scheme of shell mould casting

The storage hopper with modeling plate turn round (Fig. 7.1, c) and the forming mixture falls on the modeling board. The resin of the mixture is melted and interconnecting sand grains into semi-solid skin. Then the storage hopper resets, the forming mixture that didn't react falls at the bottom of storage hopper and semi-solid jacket 4 6-8 mm thick stays at the modeling board (Fig. 7.1, d). Then the modeling board is brought to the furnace for the final hardening of the shell under the temperature of about 350-500°C (Fig. 7.1, e). Ready solid skin is taken off the model board 5 with the help of ejector 7 (Fig. 7.1, f). Both parts of shell mould are made in such way. The mould cores are also made from this mixture in metal core boxes following the same technology. The concluding action is shell mould making from half-molds. The half-molds 8 (Fig. 7.1, g) are fastened by buckles, mold clamps or are agglutinated at the connector area. The joint form is taken to the metal box 9,

covered with coarse sand 10 (or descaling grit) and filled up with the metal. Under the influence of high temperature, the resin from the forming and mould core mixtures gradually burns down, the shell loses its strength and is easily broken when the bar is beaten out.

Disadvantages: the great amount of toxic substances, which contain phenol; distorting of big forms; expensive model equipment.

7.1 Investment casting

The main point of the method lies in the fact that liquid metal is filled into thin-walled ceramic mold made with the help of low-melting models.

Low-melting models are made from modeling mass, which consist of low-melting materials (paraffin, stearin, wax, colophony).

1. According to the drawing, the standard sample is made which is the copy of the ingot-to be.

2. According to the standard sample the metal plate is made, the pocket of which gives the exact imprint and exact dimensions of future bar.

3. Low-melting mass is filled into the molding machine. Paraffin and strain mixture are often used. This mixture has good flow characteristics, that's why it reproduces an internal surface of molding machine. The models of a standpipe and feeding gates are also made of modeling mass.

4. Low-melting models (several things or several tens) are brazed to the general standpipe 1 and the block of models is made 2 (Fig. 7.2).

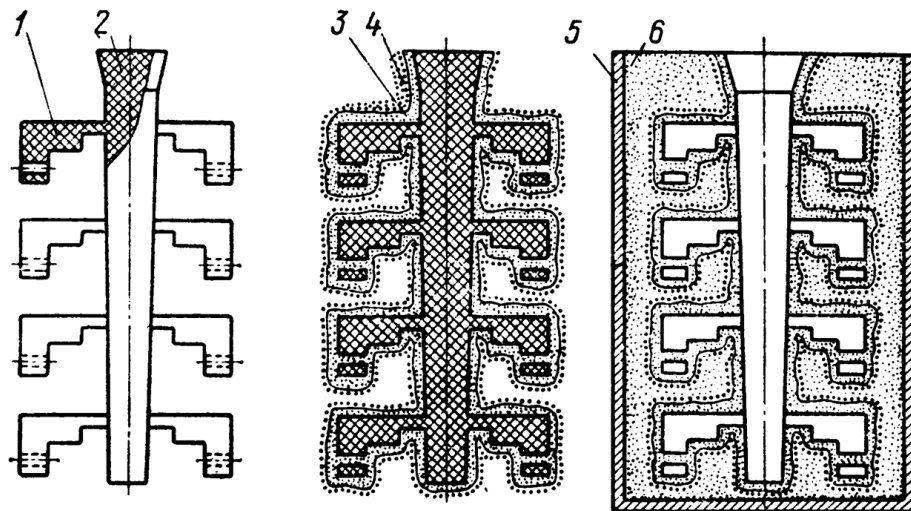


Figure 7.2 – The scheme of investment casting

5. Then refractory coating is applied at the model block. For this reason, the block model is steeped into the mixture of 60-70 % marshalite and 30-40 % hydrolyzed ethyl silicate. The thin layer of refractory mixture 3 is formed at the models. To strengthen this layer, the block is powdered with quartz sand 4 and dried up; the steeping into refractory coating is repeated from three to five times with drying up every time after steeping.

6. The next step is the liquitation of low-melting models from fire-proof form. The block of models with the shell is steeped into hot water (90°C) or placed into the drying box. Models and elements of molding system are liquated and flow out of form.

7. As the shell is not strong enough, it is formed in metal boxes 5 with dry sand and placed into a heat-treatment furnace, where the process of liquation takes place under the temperature of about 800-900°C.

8. The liquid metal is flushed into hot molding box immediately after shell liquation, which makes it possible to make thin-section casting. Ingots are shaken out of molding forms and separated from molding system with the help of vibration machines. Fire-proof mass is rather difficult to remove, therefore the final step is alkaline washing shell remnants at 120°C in the pool with alkaline cleaner and further washing the ingots in water.

This method of getting ingots is labour-intensive and expensive, but the advantage is that ingots need no mechanical treatment. Filling up hot forms allows to get complex 1-3 mm thick shaped ingots.

7.2 Centrifugal casting

The main point of this method lies in the fact that metal is filled foundry mold, which circulates with certain speed. Foundry mold filling up and metal crystallization takes place under the influence of centered forces, which provides a significant hardness of metal, because gases and additive compounds are pressed out to internal bar cavity by high-density metal and then they are removed during mechanical operations. The advantage of centrifugal casting is a high output of available bars (90 %) due to zero metal consumption for foundry system and additives.

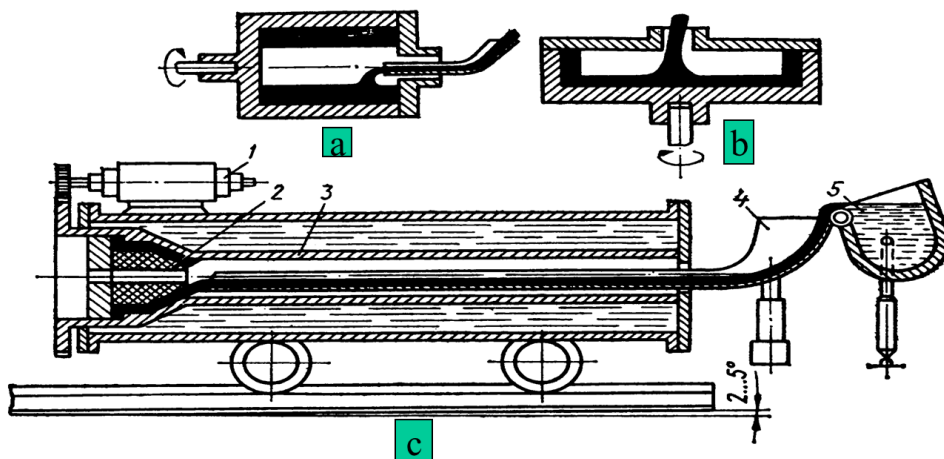


Figure 7.3 – The scheme of centrifugal casting

7.3 Pressure die casting

1. The main point of this method lies in the fact that the metal fills in the metal compression mold under the pressure. This prevents possible shrink cavity formation. Thus, it is possible to refuse from additive compounds. Due to the

pressure, the dissolved gases stay in aperture, which decreases gas unsoundness and increases bar density and hardness. This method does not require mechanical treatment for ingots. Pressure die casting is suitable for getting ingots with deep cavities, port holes of small diameter (up to 2 mm), ready-made thread, thin-walled (about 0.5 mm). The advantage of this method is high labor productivity and ready components interchangeability.

Metal compression molds are rather sophisticated and expensive, therefore pressure die casting is used only in mass production of small thin-section bars from nonferrous alloys, the melting temperature of which is not high.

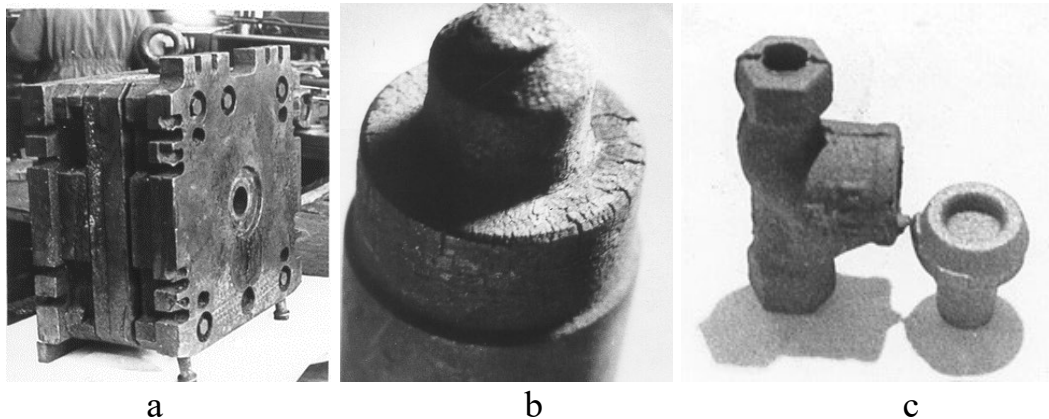


Figure 7.4 – Compression mold (a); Compression mold components (b); Castings/Ingots (c)

2. Piston hydraulic engine for pressure die casting with hot high-pressure chamber is commonly used for obtaining castings alloys with low melting points for those based on zinc, plumbum and stannum; with cold pressure chamber for obtaining castings from other nonferrous alloys.

Cold pressure chamber 5 (Fig. 7.5, a, b, c) is separated from the pool with fluid metal. Metal 4 is flushed into the cave with a ladle. Upper piston 1, while running down, presses the metal; Simultaneously lower piston 10 goes downward and opens foundry port way 3. The metal fills in the compression mold 2 (Fig. 7.5), which consists of movable hemi-section 6 (movable die) and immovable hemi-section 7 (negative die). On hardening the metal, the movable die evades (Fig. 7.5), the bar 9 together with the foundry mold 12 is shaken out with ejector 8. Metal surplus 11 is surfaced with lower piston 10.

Hot pressure chamber 15 (Fig. 7.5, d) is placed directly in pool 13 with fluid metal 14, and so it works in difficult conditions. The metal comes to compression mold cavity 18 through port way 17. Such design of the pressure chamber doesn't allow the ingot production from alloys with melting points above 500°C, because piston 16 wears out quickly.

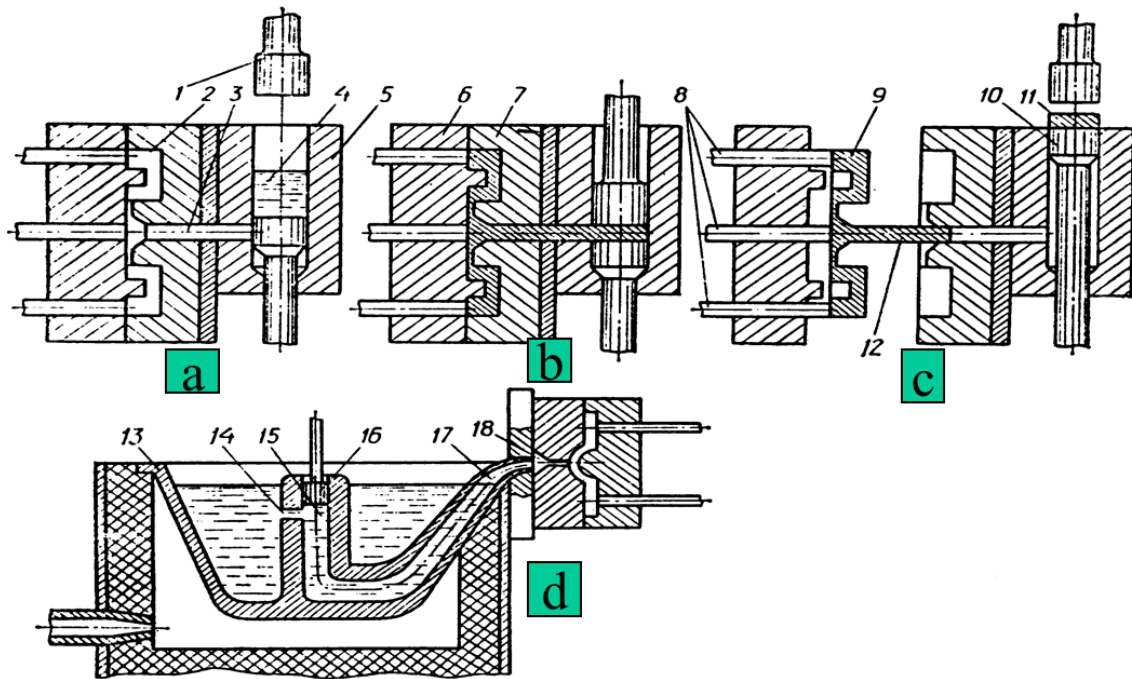


Figure 7.5 – Types of injection molding machines

7.4 Electrical slag casting

The main point of electrical slag casting (ESC) lies in the usage of electroslag remelting process technology, as a result of which high-test metal is obtained. During ESF, the process of metal melting, pouring into the mold and ingot hardening take place permanently and simultaneously. During standard casting processes these operations are separated, which worsens the quality of metal ingot.

When ESC, the casting mold performs two functions: it is a melting unit and it forms the bar. This process happens under the layer of fluid sillage, which is the source of heat, clears the metal from sulfur and phosphorus, protects it from oxygen and nitrogen of air, performs the roles of thermal additive during metal crystallization, which removes shrinkage cavities and necessity of additives. The advantages of ESC: high quality of large bars; irrelevance of melting unit, top-pour ladle, modeling mixture, foundry system and additives; metal savings are 2.3 tonnes at every tonne of final bars.

ESC is used in power engineering industry (nuclear reactor vessels, high pressure steam pipelines, steam generators, etc.); shipbuilding (crankshaft); metallurgical engineering (forming rolls, pipe-and-tube mill calibers, press forgings, pipe molds for centered foundry).

7.5 Casting alloys

Casting alloys are alloys obtained by smelting two or more metals. The alloys can be ferrous (steel, cast iron), and non-ferrous.

To get high-quality castings, alloys should comply with the following requirements:

- Good viscosity;

- Minimal shrinkage capacity;
- Minimal liquation;
- Low melting point;
- Not to solute oxygen, nitrogen, hydrogen, air.

Let's recall that when in liquid state, alloying components make homogeneous solution.

In solid state components can make:

1. Mechanical mixture: components don't make chemical bonds and compose individual crystal latitudes.

2. Solid solution: atoms of one of the components create a crystal latitude, and atoms of another component decompose into the latitude of the first one.

3. Chemical compound: atoms of components chemically interact and make chemical compound.

Steel and cast iron are casting alloys. Steel is an alloy of iron and carbon with carbon content under 2.14 %.

Solid solution of carbon α -Fe is called ferrite magnet. Under 427°C it contains 0.03 % of carbon, under 20°C it contains 0.006 % C.

Solid solution of carbon in γ -Fe is called austenite. Under 1147°C it contains 2.14 % of carbon and under 727°C it contains 0.8 % C.

Chemical compound is cement carbide (6.67 %). Mechanical mixture is pearlite (ferrite magnet + cemented carbide).

7.6 Ingot production from cast iron

Cast iron is an alloy of iron, carbon (over 2.14 %) and other elements (Si, Mn, P, S). Carbon in cast iron can be fixed in the form of cemented carbide (Fe_3C) and in a form of that with carbon spots. Depending on the quantity of fixed carbon, cast iron is divided into white and gray. The proportion of fixed carbon in gray cast iron is less than 0.8 %, in white cast iron almost all carbon is in the form of cement carbide. Formation of white and gray cast iron microstructure is influenced by the chemical composition and the bar cooling speed.

Carbon and silicium foster the process of graphitization or greying (formation of gray cast iron); sulfur and manganese foster the process of emitting cemented carbide (whitening of cast iron).

Higher casting chilling rate facilitates the formation of cemented carbide and lower speed contributes to graphite formation. Therefore, castings with different wall thickness show different chilling rate and will have different structure with the same chemical compound. So, in the ingot zone, where the metal is cooled with higher speed (i.e., near the surface) fine grain is formed and fine graphite is emitted and as the result of its higher mechanical behavior. In the middle zone, where chilling is less intensive, coarse grain and rough graphite spots occur.

Combined influence of carbon, silicium and chilling rate (wall-thickness, mm) on the structure of cast iron casting is depicted in the diagram. The diagram is divided into five zones (Fig. 7.6):

- I – white cast iron (cemented carbide);
- II – molted iron (perlite, ledeburite, graphite);
- III – gray cast iron (perlite, graphite);
- IV – gray cast iron (perlite, ferrite magnet, graphite);
- V – gray cast iron (ferrite magnet, graphite).

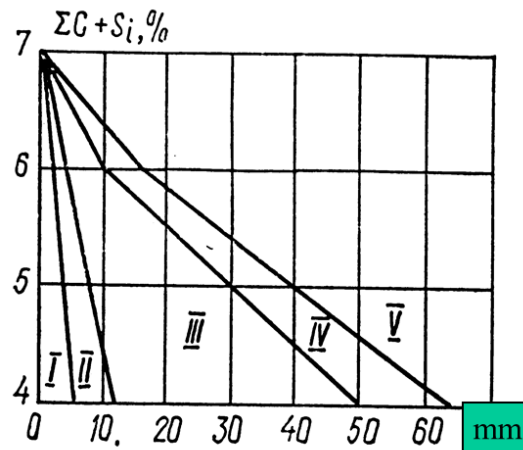


Figure 7.6 – The diagram of combined carbon – silicon total content influence, and ingot wall thickness vs. cast iron microstructure

This diagram is of considerable practical use. It shows that in castings with different wall thickness various cast iron microstructures are formed (thin-walled one can form the structure of white cast iron; thick-walled one can form the structure of gray cast iron).

1. Gray cast iron is the cheapest of casting alloys and is widely used for ingot casting because of its casting properties: good viscosity, minimal linear shrinkage (1 %), comparatively low melting point. Usual gray cast iron contains: 2.9-3.6 % C; 1.5-3.5 % Si; 0.4-1.0 % Mn; 0.2-0.6 % P; 0.03-0.12 % S.

Carbon provides good viscosity, in particular it reduces linear shrinkage at the expense of graphite finishing in the process of crystallization. The low bottom of carbon content (2.9 %) is applicable for thick-walled ingots, The high band (3.6 %) is for thin-walled ingots.

Silicium adds to the viscosity, facilitates the graphitization, which considerably decreases cast iron shrinkage and is one of the important elements in cast iron, which improves its casting properties.

Manganese poaches cast iron, promotes shrinkage, but when developing MnS compound, it neutralizes hazardous influence of sulfur, therefore its content in cast iron should be 5-7 times as high as sulfur content. Sulfur worsens casting properties of cast iron, decreasing viscosity and accelerating shrinkage; it contributes to the formation of gas cavities and ruptures in bars. Therefore, safe amount of sulfur in cast iron should not exceed 0.12 %.

Mechanical characteristics of gray cast iron considerably depend on quantity and the shape of graphitic spots. In standard gray cast iron, graphitic spots are wafer-shaped (Fig. 7.7, a), which disjoin metal base and act as inner fractures. Therefore, standard gray cast iron ingots with flaked graphite are soft (or cut easily), but brittle. Gray cast iron ingots irradiate vibrational oscillations, and for this reason it is widely used for production of machine-tools bed frames.

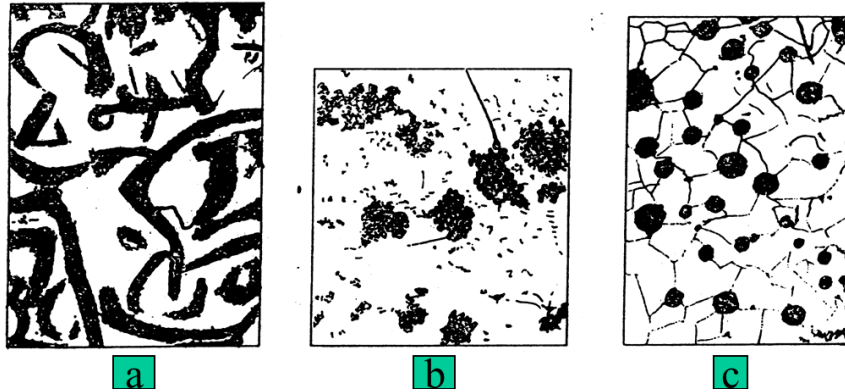


Figure 7.7 – Microstructure of standard gray (a), malleable (b) and high-duty (c) cast irons

2. Malleable cast iron is the iron obtained by method of long-term annealing the ingot, which have a microstructure of white cast iron. When ingots are annealed at 950-1000°C, cemented carbide disintegrates into ferrite matrix and temper carbon (temper graphite) of flake – shape (Fig. 7.7, b), not plate-shape (as in standard grey cast iron). Such graphite shape provides cast iron ingots with higher strength, ductility and impact resistance. Thus, malleable cast iron ingots mediate between standard gray cast iron and steel.

To obtain ingots with the structure of white cast iron, initial cast iron composition is limited to element content: 2.4-2.8 % C; 0.8-1.4 % Si; $Mn \leq 1.0 \%$; $S \leq 0.1 \%$; $P \leq 0.2 \%$.

Malleable cast iron ingots are much more expensive than standard gray one, which is explained with continuous expensive annealing that can last as long as 70-80 hours. There exist methods of short-term anneal (10-15 h.) of malleable cast iron.

When producing ingots from malleable cast iron, it is necessary to overheat the metal up to 1400-1450°C before pouring into molds. The process requires forming and core sand mixture with increased flame resistance. Considerable volumetric shrinkage of white cast iron (5 %) requires supplements or cooling houses near increased local ingot thickness, while higher linear shrinkage calls for malleable mixtures.

It has high wear resistance, good antifriction properties. It is used for production of brackets and supports, differential compensating cases, pipe fittings, T-joints for pipe connections.

3. To produce ingots of steel and malleable cast iron is more difficult and less profitable than from gray cast iron. However, this gray cast iron features poor mechanical behavior. Modification of overheat liquid grey cast iron magnesium with ferrosilicium or cerium before pouring into molds make it possible to extract round shape graphite in the structure (Fig. 7.7, c). This type is called high-strength cast iron. As for the strength, such cast iron approximates steel and surpasses gray and malleable cast iron strength; its plasticity is 5-15 times as high as that of cast iron and approximates; and ingots are 25-30 % cheaper than those made of steel.

There is no difference in molding technologies for ingots from high-strength and gray cast iron.

They sustain high static and dynamic loads. Nowadays, it has substituted steel the production of crankshafts. It is used in production of components for diesel engines, steam, gas and hydraulic turbines.

4. Cast iron melting. Initial materials used for liquid cast iron melting are called charging material or the charge. The metal part of the charge includes 30-40 % of pig iron, 40-60 % of own production turn and cast-iron scrap, 0-20 % of scrap steel and 0-10 % of ferroalloys. Fluxing agents, used for cast iron melting, flux coke ash, forming and core sand mixtures, burnt before turning, and oxides of different elements of metal part of the charge stocks, which burn out. Lime carbonate, magnesium, lime and open-hearth slag are fluxing agents.

Cupola furnace is widespread cast iron melting apparatus in foundries. It is of unsophisticated design and can be easily serviced, fuel consumption and iron cinder are comparatively low.

Cupola furnace (Fig. 7.8) – is cylindrical shaft furnace. Stack casing 6 is welded from plate steel and lined with refractory brick 7 inside. Stack is based upon workframe 2, fixed on four vertical towers 1. Through the window opening (which is married and closed with cover plate 3 during the work of cupola furnace) the bottom is filled with the forming mixture. The cupola furnace is topped with the pipe 10 and spark extinguisher 11, which is situated above and catches incandescent particles of fuel and carries them out together with exhaust flows. Stack is filled through the window 9. To protect refractory lining from the charge, the stack is lined with cast iron bricks 8 at the charging door level. Liquid iron and slag flow down through the mouth 12 to forehearth 13, where they are gathered and settled. Cast iron is let out through hot-metal taphole 15, and slag goes through cinder notch 14. Receiver cupola is used to produce cast iron of required consistency with the lowest proportion of sulfur and carbon. If there is no forehearth the liquid cast iron is gathered in cupola crucible and is in contact with overheat slag for a long time, saturating sulfur and carbon.

The air for fuel combustion is supplied to cupola furnace from bustle pipe 5 through lances 4. Modern cupola furnaces have three rows of lances: lower (basic) 1; two uppers (supplementary) (the figure above shows one row of lances). Useful height of cupola furnace is the distance from basic row of lances to charging door bottom edge. This is the area where hot gases interact with the charge.

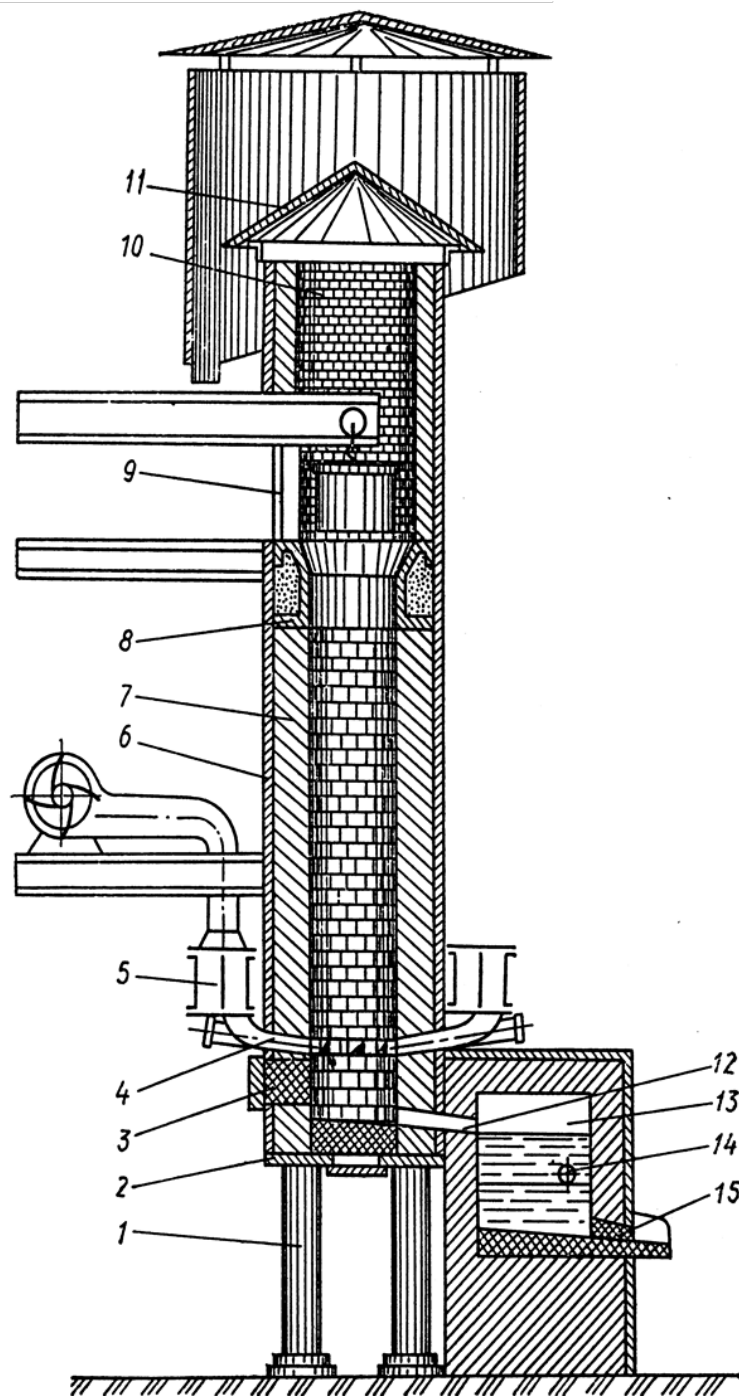


Figure 7.8 – Receiver cupola

Before melting starts, the cupola furnace should be prepared for work, which is: to clean the stack from slag remnants, to repair refractory lining, to cover the bottom, to fill in cupola furnace and forehearth bottom and to place and fire fuel wood there, then, through the charging door, to charge the bed coke 700-800 mm above the basic row of lances, where maximum temperatures are obtained. The bed charge heats the cupola furnace and supports the sprue.

The bed coke is loaded with iron charge, then with working fuel bed and after that with fluxing agent. In this way the cupola furnace is loaded layer by layer

through all its height up to the charging door. When being melted, charging materials gradually sink, and new portions of the charge are loaded through the charging door.

Gases, evolved as a result of carbon combustion, rise towards the sinking charge and release their heat to melt the charge.

Nowadays cupola furnaces with shell cooling, oxygen-rich drafting and electric cupola furnaces are used.

7.7 Peculiarities of steel ingot production

1. Steel has poor casting characteristics. The more admixtures are added, the worse are its properties.

2. Steel has a high melting point of about 1490-1580°C.

3. With a view to this fact, requirements for forming and core sand mixtures are higher. Investment compounds are added to chrome iron powder, carbonate of magnesium, and new moulds are coloured marshalite-based paints.

4. Steel ingots have high shrinkage capacity; thus, they should be filled with additives.

5. Steel tends to liquefy. Heat treatment prevents liquation.

Steel ingots are labor-intensive; therefore, they are used for increased strength and plasticity.

Finished steel casting is used when it is necessary to raise strength and plasticity of components and when structural complexity and sizes make hammering or stamping impossible.

TOPIC 8 METAL FORMING

1. The subject and features of metal forming
2. Fabrication and hot work.
3. Heating before metal forming.
4. Main types of metal forming.

Metal forming is based on the use of one of the main characteristics of metal: on its plasticity.

The matter of forming is that the metal has the property to deform without forming fractures.

Deformation is called irreversible when the object changes its form and size under the influence of external force and without disordering its integrity with the structure and the mechanical behavior of this metal having changed. Deformation can be flexible and plastic.

Flexible deformation – is the deformation, which influence on the object form, structure and properties discontinues as soon external forces disappear. If the load exceeds a certain value, the deformation becomes irreversible.

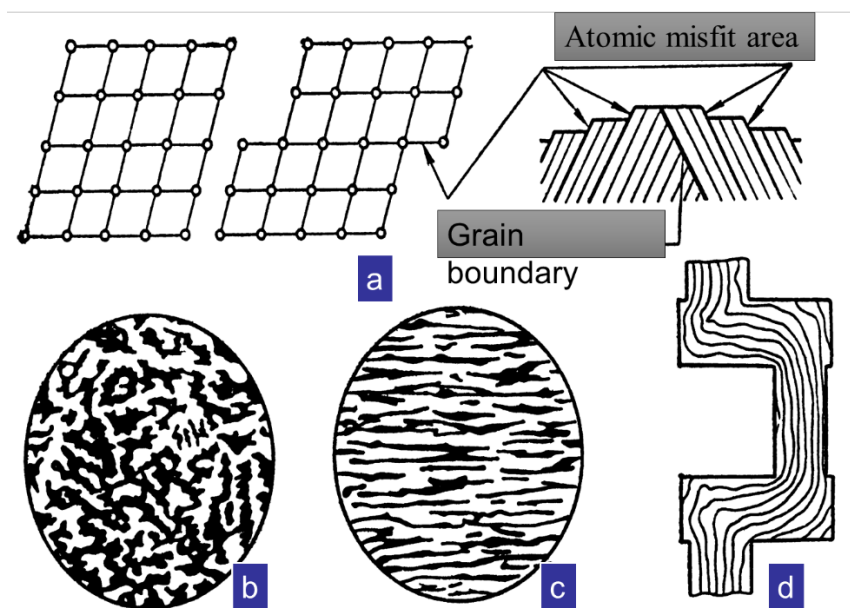


Figure 8.1 – The scheme of sliding (a) and metal macrostructure changes under deformation (b, c, d)

During relieving only, the flexible constituent of the deformation disappears. The deformation portion left is called plastic deformation.

At plastic deformation, the structure and the characteristics of the metal irreversibly change.

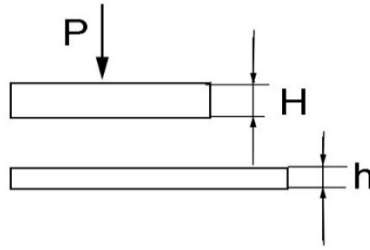


Figure 8.2 – Schematic representation of metal deformation during rolling

Deformation is characterized by its extent ε :

$$\varepsilon = (H - h) \times 100\% / H$$

σ_B – maximum load that the metal can bear without destruction

σ_T – the load when first plastic deformation features appear after its relieving.

When we graph the tension σ vs ε we will see that if $P < \sigma_T$ then deformation is plastic, $P > \sigma_T$ then it is flexible.

Plastic deformation is due to sliding and doubling. Plastic deformation lies in moving some atoms relative to others on distances which are longer than inter-atomic ones in a crystallographic plane. When atoms move within the distances between crystallographic planes of an alloy, the atomic interaction doesn't disappear, the deformation takes place at the expense of sliding one crystal part relative to the other. The atomic misfit occurs without object crippling. This misfit does not take place when there is simultaneous atomic displacement, but during gradual hunting dislocation along the slide area. When the crystal parts move simultaneously, it is necessary to raise the tension hundredfold compared to those observed during metal deformation.

At metal forming, components are produced at the expense of partial metal plastic displacement. Metal forming is an efficient process as the size and shape of the half-finished material change by making a single external effort. Such treatment is applied for about 90 % of steel and over 50 % of non-ferrous metals.

8.1 Fabrication and hot metal working

At metal deformation, both the defect density of crystal structure and the metal resistant to replacement increase.

If the deformation degree increases, then the ultimate stress limit σ_B , σ_T , HB grows but the plasticity δ , KC – decreases, i.e., the metal strengthening occurs. Metal strengthening while plastic deformation is called cold work hardening.

While strengthening the metal transit into a thermodynamically unstable state with advanced level of internal energy. Therefore, it strives to transit into a more stable state by itself.

While heating the strengthened state to the temperature $0.2-0.3 T_{\text{melting}}$, the crystal lattice and internal stress are somewhat less deformed, and the structure and behavior of the deformed metal do not essentially change.

While heating the deformed metal to more than $0.4 T_{\text{melting}}$, new equilibrium granules are formed, and the metallic behavior renovates to its reference pre-deformation value.

The formation process of new crystallization nuclei and new equilibrium grains in the deformed metal, which is accompanied by decreasing strength and increasing ductility is called recrystallization.

The minimum temperature when both recrystallization and metal weakening start is known as recrystallization temperature, i.e., the temperature at which the strength and ductility of the deformed metal change sharply.

Micro structural anisotropy is the difference in crosswise and longwise properties.

The recrystallization temperature depends on the metal nature and its purity.

Cold work hardening is a widespread way to increase the strength of components (cold plastic deformation).

8.2 Hot Plastic Deformation (HPD)

This is the deformation, which takes place when temperatures exceed the recrystallization temperature.

In the process of recrystallization, the metal strengthening takes place as well. HPD consists of four technological steps.

1. Metal heating
2. Soaking
3. HPD itself
4. Cooling

Let's consider metal heating.

To increase the metal ductility and its resistance to deformation, the metal is heated to a certain temperature before metal forming begins. There is a certain temperature interval for every metal.

When steel is heated to over 700°C , the upper layer is oxidized, and scale, which consists of (Fe_2O_3 , Fe_3O_4 , FeO), is formed. Metal consumption for scale (burn-off) during one heating in an open fire furnace is as much as 1.5-2.5 %; during electrical heating this figure makes 0.4-0.7 %. The scale hardness is high; therefore, it increases the deformed component wearability. When the temperature is high, decarburization of the surface layer occurs due to carbon burning. The depth of this decarburized layer is 0.2-0.5 mm, sometimes 1.5-2 mm. To decrease oxidation, electrical heating of the workpiece or its heating in a protective environment is practiced.

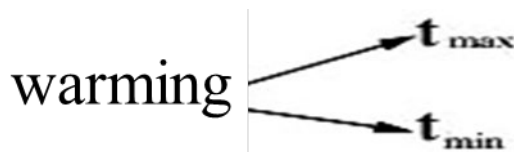


Figure 8.3

At temperatures above this heating is not recommended because spoilage of two types – overheating and burning – can occur.

Grains are grown intensively at high temperatures. This phenomenon is called overheating. This spoilage can be corrected by one more heating at a lower temperature.

When the steel is heated to T_{melting} , intense oxygen diffusion takes place. Fractures appear. This phenomenon is called burning. Such spoilage is irreversible.

8.3 Soaking

Soaking length depends on heating rate, dimensions and thermal conductance.

The metal should be heated in such a way that no cracks could occur (fast). On the other hand, if the heating process is slow, the oxidation will happen. Therefore, the best rate should be chosen.

$$\tau = \alpha \cdot \kappa \cdot (D)^{3/2}$$

τ – soaking time

α – thermal-conductivity coefficient ($\alpha = 1$ – for carbonic, $\alpha = 2$ – for mid-alloyed, $\alpha = 3$ – for heavy-alloyed);

κ – packing density

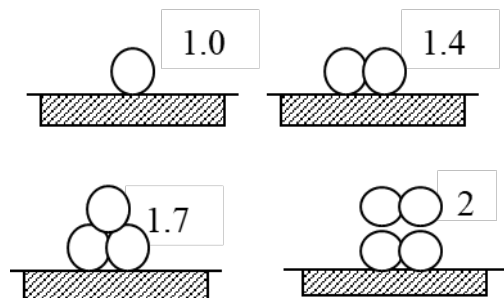


Figure 8.4 – Heating diagrams for metal blanks in a furnace

D – the diameter of a cross-section or square work piece

Soaking time:

$$\tau_{\text{warming}} = (1/3 \div 1/4) \cdot \tau_{\text{equalizing}}$$

8.4 Cold Work Hardening

Cooling should be as slowly as possible to avoid cracks. After HPD, the cold work hardening is held in special pits.

8.5 Heaters

Metal is heated in open flame furnaces or in electric furnaces. Open flame furnaces are used for bigger work pieces, and electric furnaces are used for midsize ones.

According to their operating principles, furnaces are divided into box furnaces and continuous furnaces.

Box furnace can be portable (for heating work pieces with diameter up to 150 mm) and stationary.

The working space of the furnace (smelting chamber), 3 (Fig. 8.5, a), lined with refractory bricks, is heated while the fuel is burned by means of two burners (sprayers) 2 1 and has the same temperature. Work pieces 1, which are placed on the furnace bottom, are loaded and unloaded through the window 5. Combustion products are released through the chimney 4 and are used to heat the incoming air up to 200-300°C to raise the efficiency of the furnace. Furnaces for large work pieces are equipped with different appliances to make the process of loading and unloading easier. There are push-type furnaces, rotary hearth furnaces, conveyor furnace, and sliding hearth furnaces.

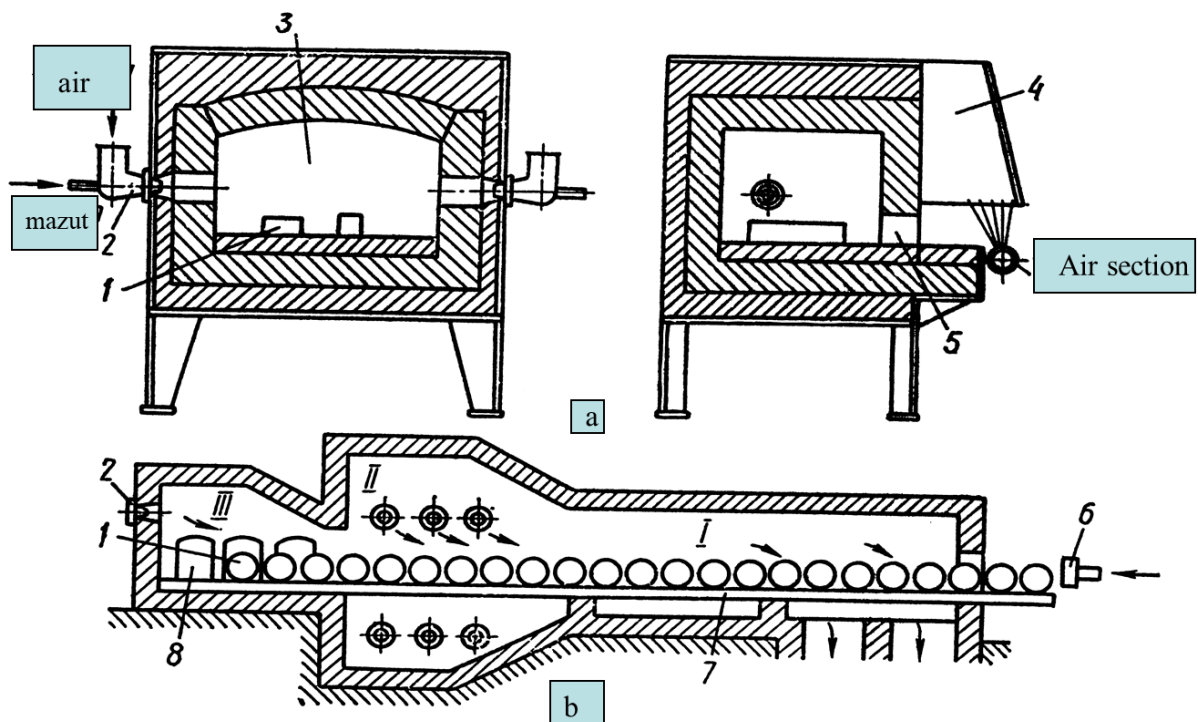


Figure 8.5 – Open fire furnace for heating work pieces

A kind of chamber furnaces pit-type furnaces used for heating big-sized ingots for milling and forging. These ingots are arranged vertically and loaded from above by means of a crane.

Continuous furnaces are meant for heating big-sized work pieces for milling and forging in large-scale production. These furnaces are notable for their significant length (8-22 m) and three available zones with different temperatures. Work pieces 1

(Fig. 8.5), gradually moving towards hot gases along the furnace goes through zones of heating I (600-800°C), maximum heating II (1350°C), where the main fuel burning takes place by means of burners 2, and the zone of soaking III (1200-1300°C), where the temperatures equalize along the cut off pieces. Products of combustion with the temperature of 700°C leads to recuperators to heat the air. With the help of pushers 6 the pieces are pushed through cooling conductor pipes 7 through the furnace and are unloaded through the window 8.

Furnaces for heating work pieces with diameters of up to 120 mm have two zones of heating (600-700°C and 1250-1300°C) and are called semi-continuous.

Electrical heaters. Inductive heating is based on alternating currents occurrence in work pieces placed in an alternating electromagnetic field. As a result of surface effect (skin effect), the depth of the surface layer where alternating current is induced and which is heated decrease as current frequency grows higher. Therefore, the frequencies of 500-8000 Hz are used for heating workpieces of up to 150 mm in diameter, 50 Hz frequency is used for bigger pieces. Inductor in the form of a multilayer solenoid along the diameter of a piece is made of a water-cooled copper pipe.

Electrocontact heating based on heat release at the time while current passes through the work piece (Joule-Lentz law) is used for heating steel ingots of up to 75 mm in diameter. In this case the voltage is 5-15 V, current intensity is up to 5000 A. The work piece tails clipped between copper current contacts are heated up to 200-300°C above its middle part. Thus, this method is expedient for heating steel work pieces of uniform section and significant length.

Electric heating speed is 8-10 times higher and the intensity scale emerging is 4-5 times lower compared to heating a furnace. Other advantages of this method are better sanitary conditions of labor and possible automation of the process. Among the limiting factors we can mention high prices on high-frequency generators and the necessity to change the inductor for inductive heating every time sizes and shapes of work pieces vary, low resistance (under 1000 cycles) of current contacts at electrocontact heating.

8.6 Main Types of Metal Forming

1. Rolling is the process of pressing metals with working rolls. As a result, products of cross section shape (sticks, cables, battens, sheets), which is identical in length, or of shape, which varies its length on a regular basis, are obtained (Fig. 8.6, a).

2. Pressing is forcing the heated metal out of a closed cavity through the hole in matrix (Fig. 8.6, b).

3. Drawing is pulling a heated work piece through the hole in the wire drawing matrix (draw). As a result, fine wires, caliber bars, thin-wall pipes are produced (Fig. 8.6, c).

4. Forging is the process of deforming a heated workpiece between hammers or presses (Fig. 8.6, d).

5. Die and plate stamping. Die stamping is simultaneous deforming all pieces into a special one. In this case, stamp is the instrument. The shape and size of inner die cavity determine the size and configuration of the pieces. Plate forming is meant for production of flat and three-dimensional cavitated components from sheets or strips by means of stamps on cold stamping presses.

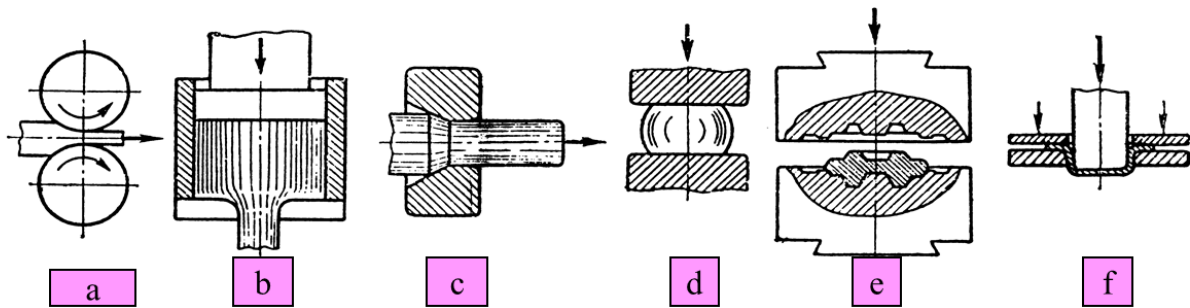


Figure 8.6 – Main Types of Metal Forming

TOPIC 9

FORMING ROLLS AND ROLL MILLS

1. Forming rolls are basic work tools for rolling. They can be smooth, standardized with hills and special.

Smooth rolls are used for production of plates, straps etc. Grooved rolls are used for rolling all types of merchant bars.

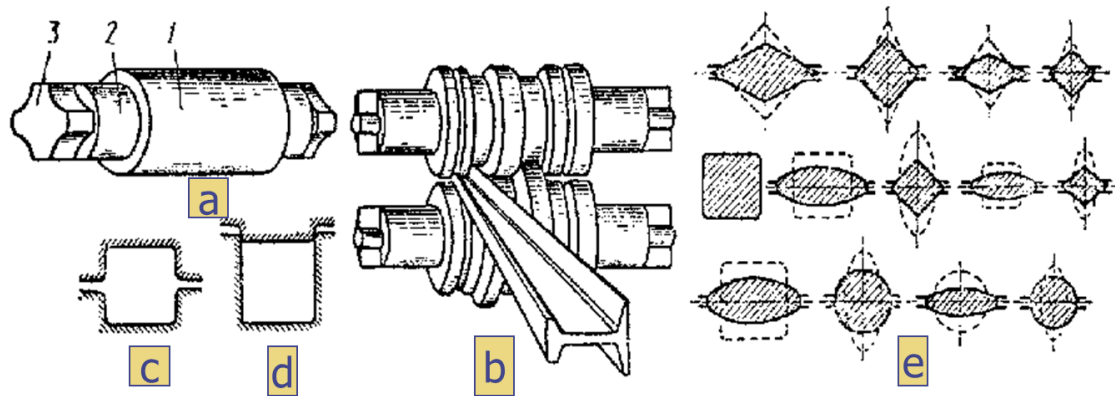


Figure 9.1 – Forming rolls and calibrating flow chart

2. Roll grooving is rolling project and positioning grooves that ensure required sections during the least number of passes. By their use, grooves are divided into pressing (stretching), roughing and finishing (curing).

Pressing grooves are employed only for drafting semi-finished products. Usually, they have right-angled, square, rhomb- or oval shaped.

Roughing grooves diminish the surface area of work pieces, change their drafting shapes and gradually approaching to finished products. The difference between finishing grooves from required profiles is that they allow for in linear expansion coefficients and tolerances.

3. Rolling mill structure. Rolling mill consists of one or several rolls stands and a drive, which includes engine and communicators.

The roll stand consists (Fig. 9.2) of bed frame 1, where rollers are assembled into bearing parts 2. To change the clearance between them, the upper roll and the bearings move along bed frame gutters with the help of pressing device 3. The motion from electric motor 8 to rolls passes through reducing gear 7, pinion stand 6 and wobblie spindles 5, which are connected with rolls by coupling boxes 4.

4. Rolling mill classification. By their use, rolling mills are categorized into rolling mills semi-finished products (blooming mills, slabbing mills, bar mills) and finished items (section-, sheet-, push-bench-, beam-, pipe-and-tube types, and mills for special rolling).

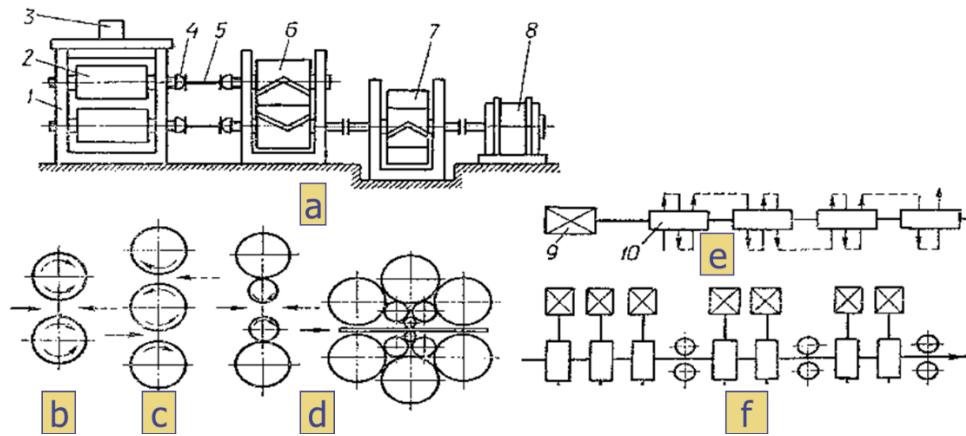


Figure 9.2 – Rolling mill scheme, rolls and rollstand arrangement

9.1 Production of basic types of rolling

1. Blooming, slabbing, bar iron and sheet rolling.

Technological process of bar iron and sheet production from bloom and slab lies in sequential operations like trimming the ends, cutting into parts, cooling and peeling-off the semi-finished products, heating them in continuous furnaces, rolling section and sheet mills, cooling and arrangement of finished rolls.

2. Plug rolling (Fig. 9.3).

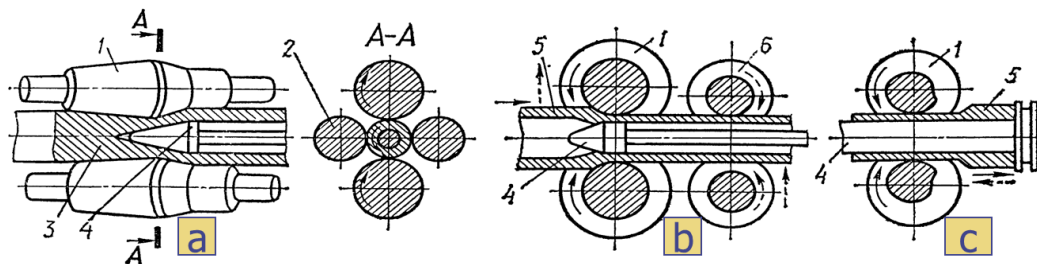


Figure 9.3 – Plug rolling

3. Welded pipe production (Fig. 9.4).

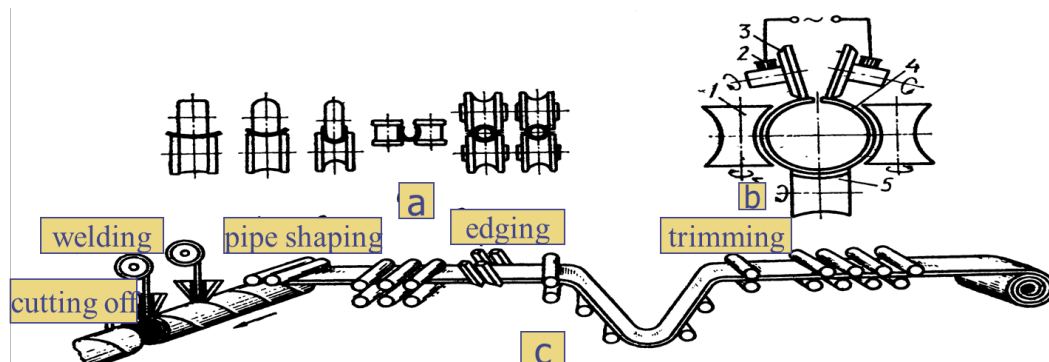


Figure 9.4 – Flow chart of welded pipe production

9.2 Production of special types of rolling

Production of components like wheels, belt lines, hoops. Semimanufactured articles for such components are ingots or round rolled products, which are sliced on washers. The technological process of their production consists of forging and rolling. Settling and broaching of workpieces are performed on pressing machines; hubs, disc plates and railroad wheel rims are formed by special wheel rolling mill.

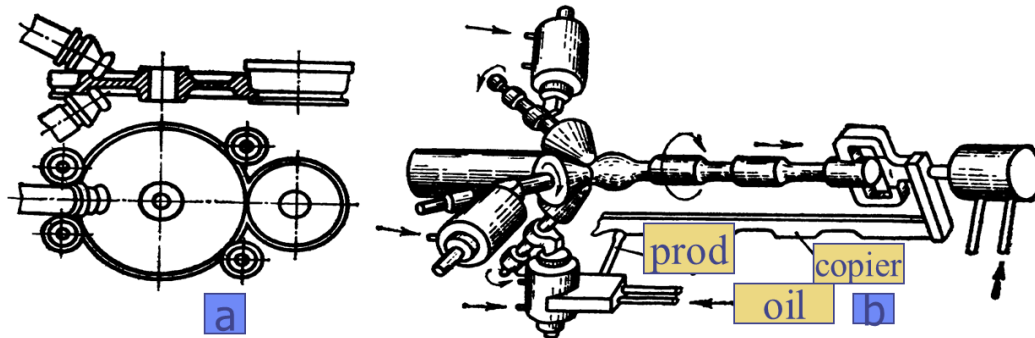


Figure 9.5 – Production schemes for some special types of rolling

9.3 Key points and technological steps in forging

1. Description of the process. Forging is the process of deforming heated ingots between upper and lower heads of the hammer or press with the help of multi-purpose tools. A type of forging is blacksmithing on club hammer. It is used mainly in insignificant repairs. Forged pieces for further treatment are called forgings, their weight varies from 0.1 kg to 300 t. Big forgings (more than 1.5 t) are produced by forging only. Smaller ones can also be produced by stamping. However, stamping is used only in mass and large-scale manufacturing due to sophisticated tools. To produce high-precision small-sized forgings (up to 150 kg) on hammers and pressing machines in large-scale manufacturing (lots of 50-250 pieces), self-guiding dies are often used. Small and middle-sized forgings are made from merchant bars or blooms.

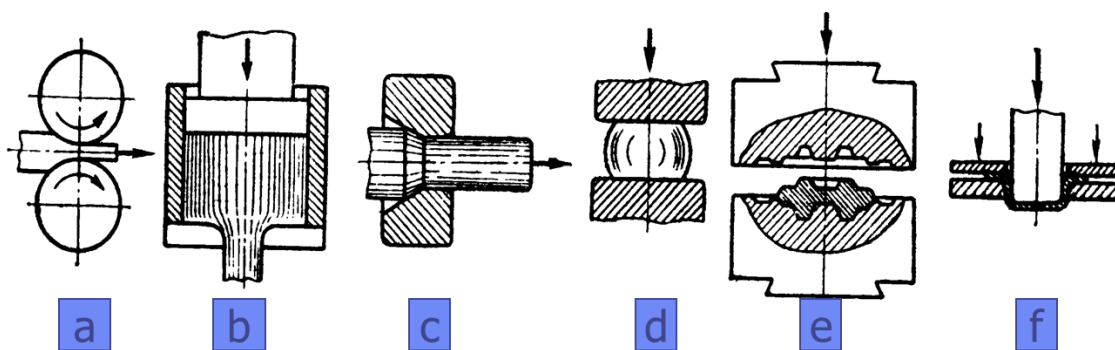


Figure 9.6 – Schemes for main types of metal forming

2. Tips and tools of forging. The most difficult forging can be performed following these operations: broaching, settling, piercing, flexing, curling and cutting.

Broaching is used for stretching out work pieces and reducing their cross-sections. It can be performed with flat and shaped heads. Shaped forging prevents fracturing while deforming low-ductility steels and alloys. Deformation ratio is described by initial-final cross-section ratio, which is called forging reduction ratio. The higher has the forging reduction ratio, the better been both metal structure and its mechanical behaviour. Types of broaching: billet spread, broaching of empty cylinder on die ring; hammering out of rings on cylinder die ring to expand the diameter.

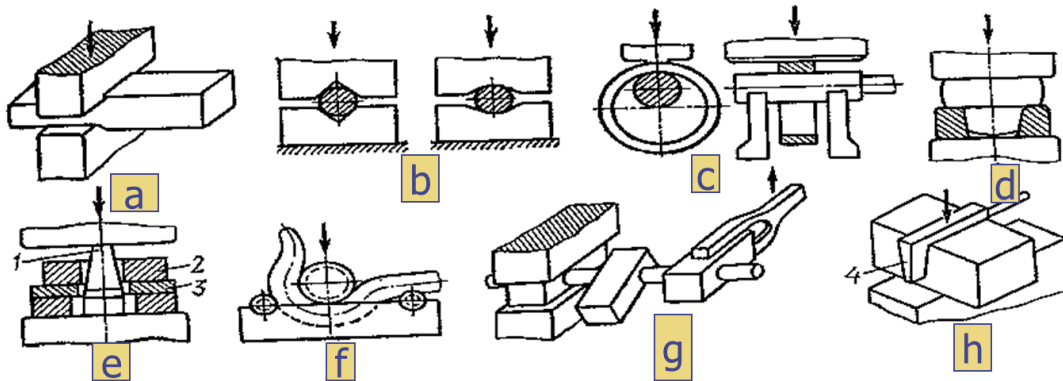


Figure 9.7 – Main technological operations of forging

Settling is an expansion of the initial cross-sections of workpieces by reducing their heights. During settling the height of initial work pieces should not exceed three diameters and their sides should be equal and parallel. A local boss of a workpiece is called an upsetting.

Piercing is making through-holes or niches in work pieces. To perform this operation, one-piece hollow piercers (of 400-900 mm in diameter) 1 are used. Through-hole piercing in thin forgings 2 is performed with foisted rings 3. For thicker pieces, niches (approximately $\frac{3}{4}$ of their depth) are first of all pierced, then the same piercer continues on the other side.

Folding is used for making gagers, shafts, clamps etc. Special dies 1 can be used for folding.

Curling is turning one part of a workpiece in reference to the other one at a certain angle. It is used for making crankshafts, drills etc. For this operation, curling winches, fork plates, shackles and crabs are used.

Chipping is used for dividing work pieces into parts, separating surplus metal and making engaging steps (notches) in forgings. Smith's flat and figurative chisels and clinks 4 are used.

9.4 Forging equipment

1. Forge hammers. Hammers create dynamic tool impact (of a raising hammer) on work pieces. Deformation length during forging is approximately 10-30 sec., and deformation speed is 6-6.5 m/sec. The most widespread hammers are air-and-steam and power-operated hammers.

2. Hydraulic presses. They differ from hammers in effecting the article statically. Deformation is about 10 seconds long and 0.3-0.5 m/sec. speed.

9.5 The technological development of forging

Forging drawings are based on drawings of finished components with forging tolerances, allowances for machining and laps.

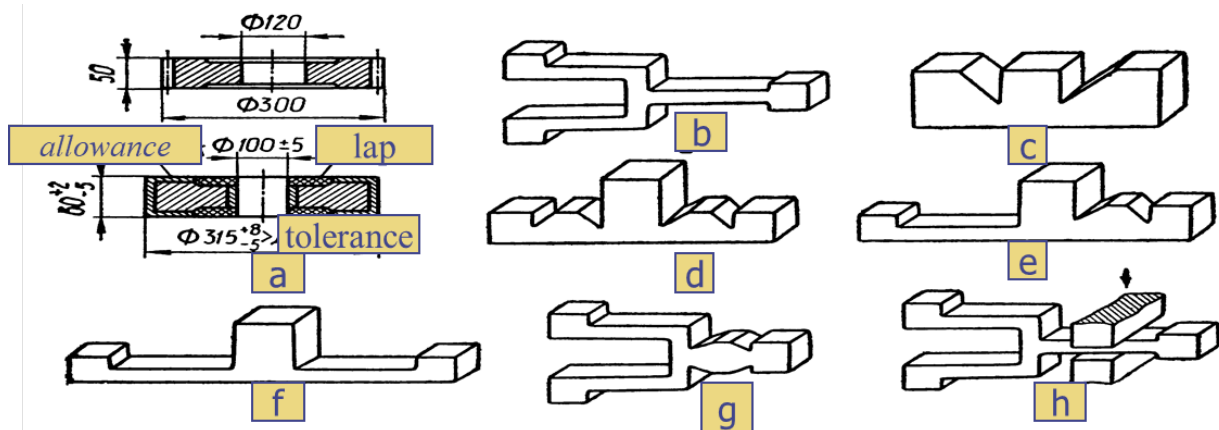


Figure 9.8 – The drawing of a gear forging and technological scheme of forging a forked end lever

Tolerance is a forging metal layer removed by cutting to a required size. It depends on the dimensions and configuration of the forging.

Allowance is a permitted deviation from sizes of a forging shown on its drawing.

Lap – is volume added more tolerance to a forging to simplify its shape. It is removed by cutting off.

Tolerances, allowances and laps are specified by GosStandart.

Forgings are selected according to their mass calculated as follows:

$$M_{\text{article}} = M_{\text{forging}} + M_{\text{additives}} + M_{\text{burn-off loss}} + M_{\text{cutting off}} + M_{\text{forging reduction ratio}}$$

TOPIC 10

FACTORS INFLUENCING THE PROPERTIES OF MATERIALS

There are four groups of factors affecting the mechanical properties of materials: chemical composition; macrostructure; microstructure; atomic crystalline.

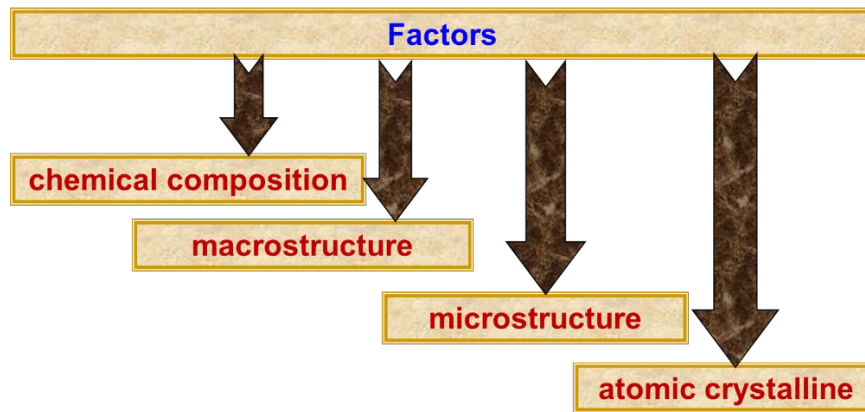


Figure 10.1 – Factors influencing the properties of materials

10.1 Chemical composition

There are four groups of factors: chemical composition; macrostructure; microstructure; atomic crystalline structure.

Chemical composition: pure metals – ductile, alloys – durable. In mechanical engineering, the main structural material is metal alloys.

Material	$\sigma_{0.2}$, MPa
Pure iron	25
Fe + 0,005 % C	147
Fe + 0,01 % C	245

Minor impurities increase the strength and hardness of the alloys.

10.2 Macrostructure

A macrostructure is the structure of a material that is studied with the naked eye, or with a magnifier at small magnifications (up to 30 times).

When studying the macrostructure, they study the shape and size of grains in cast metal, deformed fiber (forgings, stampings), casting and welding defects, segregation of harmful impurities (sulfur and phosphorus), and the depth of the hardened layer after surface thermal and chemical-thermal treatment of products.

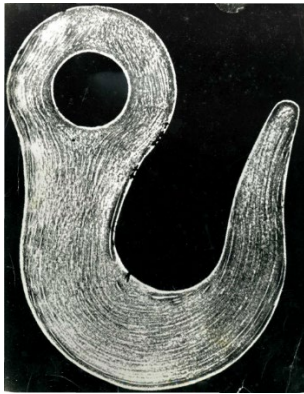


Figure 10.2 – Hook fiber strukture

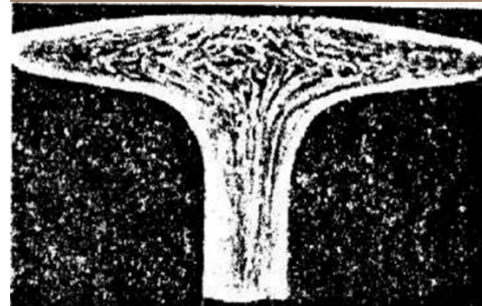


Figure 10.3 – Stamped valve macrostructure

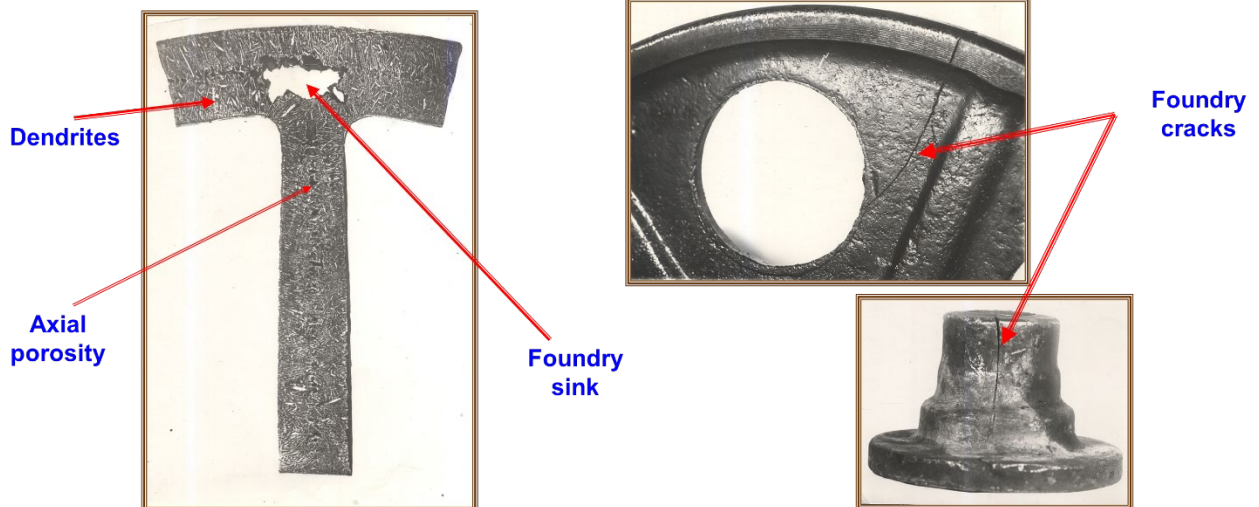


Figure 10.4 – Defects and macrostructure of cast products

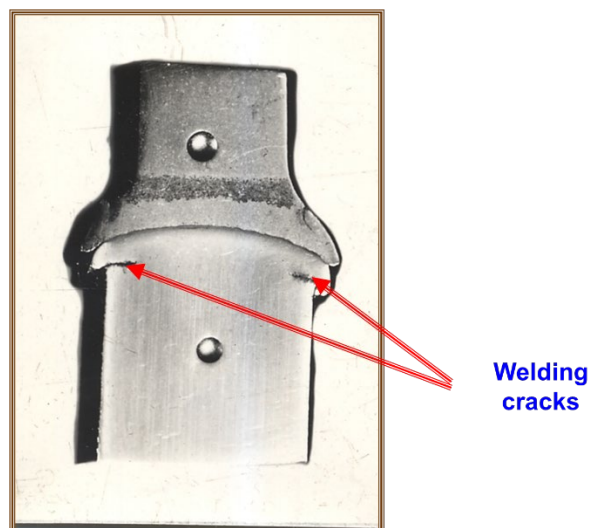


Figure 10.5 – Friction welding

10.3 Microstructure

The microstructure is the internal structure of the material, which is studied at significant magnifications using optical devices – microscopes.

Real metal consists of a large number of grains. The interface between the grains is the grain boundary. The grains are misoriented to large angles $> 12-150^\circ$. The boundaries between the grains are called high-angles.

Each metal grain consists of subgrains, which form the so-called substructure - the subgrain of misorientation at angles $2-120^\circ$. The boundaries between subgrains are called medium-angles. Each grain consists of mosaic blocks. The misorientation angle between blocks is $\leq 20^\circ$. Blocks are separated by small angle boundaries.

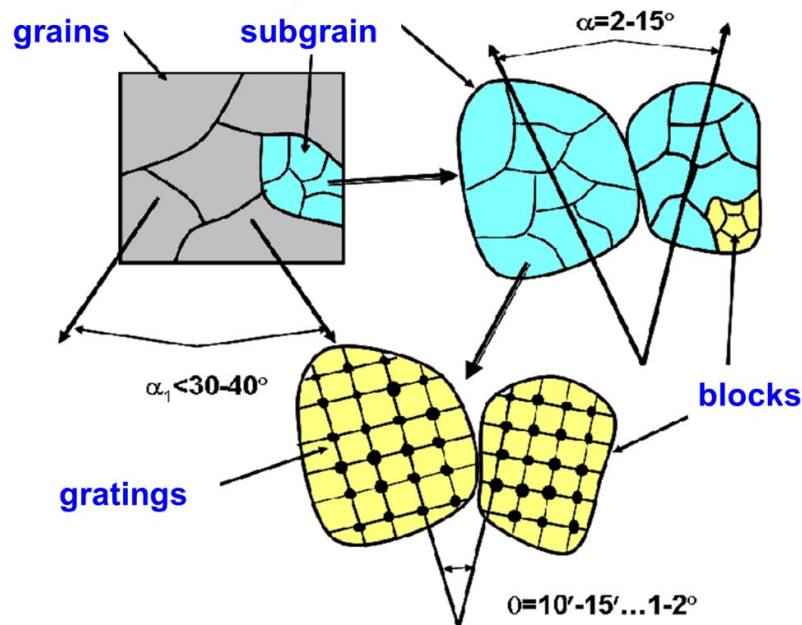
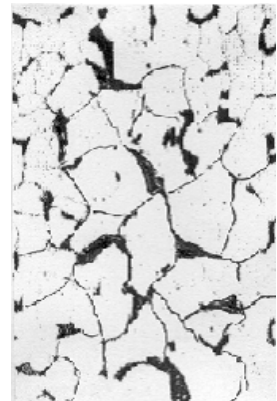


Figure 10.6 – Microstructure

The finer the grain, the more grain boundaries, the more obstacles in the path of the crack and the greater efforts must be made to spread it.

Grinding grain leads to an increase in ductility (Ψ and especially δ), a decrease in T_{xp} . If, by special processing methods, the grain is reduced to ultrafine (0.1 mkm), then the strength is significantly increased.

By grinding grain, a combination of high values of indicators, strength, ductility, and crack resistance can be achieved.



10.4 Atomic crystal structure

The atomic-crystalline structure is understood as the mutual arrangement of atoms in a crystal. In a real crystal, there are always defects in the crystal structure.

According to geometric characteristics, they are divided into point, linear, and surface. Point defects include vacancies and embedded atoms.

In pure metals, point defects have a significant effect on physical properties, and in alloys on physical and mechanical properties.

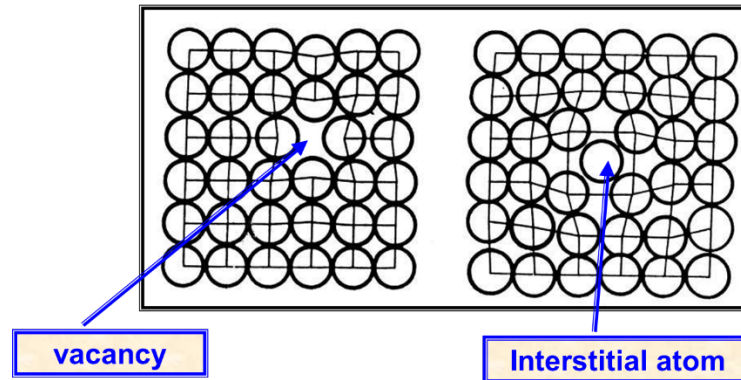


Figure 10.7 – Point defects

Linear defects are dislocations. They are small in two dimensions and of considerable length in the third.

The dislocation appears when the correct structure of the crystal lattice is violated due to the appearance of an extra half plane which is called extra planar bone, or displacement of the planes relative to each other.

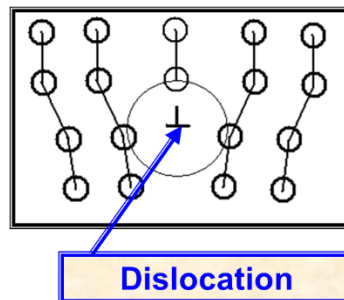


Figure 10.8 – Dislocation in a crystal lattice

Quantity or density ρ dislocations characterize their saturation of the crystal lattice.

Dislocation density is the total length of all dislocation lines per unit volume. The effect of dislocations on the strength of crystals is especially great. With an increase in the density of dislocations, the strength increases.

$$\rho = \frac{\sum l}{V} [\text{sm}^{-2}]$$

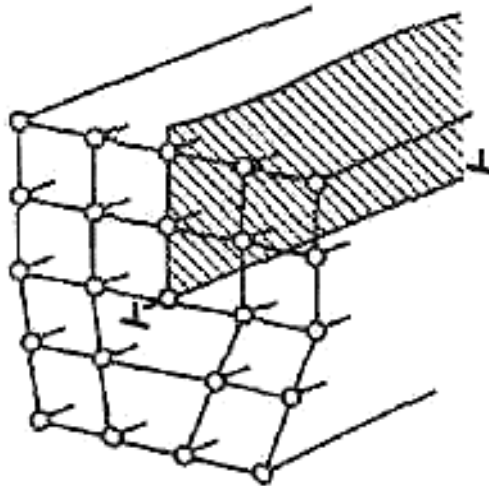


Figure 10.9 – Schemes of edge dislocation

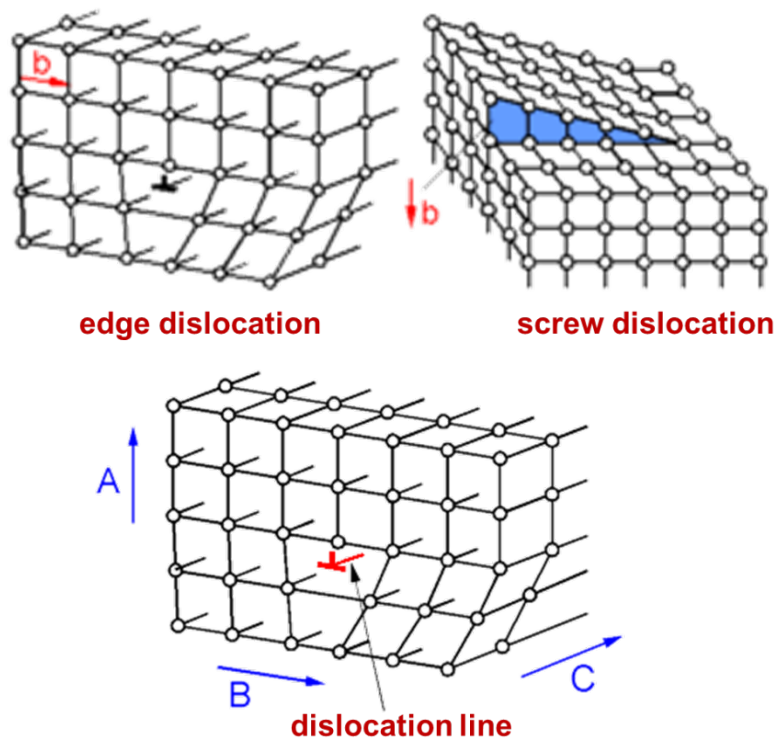


Figure 10.10 – Schemes of edge and screw dislocations

Surface defects – the boundaries of grains, subgrains, blocks.

10.4.1. Influence of density of dislocations on strength

The dependence of strength on the density of dislocations is quite complex. The metal will have theoretical strength (maximum) if there are no dislocations in it.

1. In a single crystal – 10^3 - 10^6 ;
2. In annealed metal – 10^6 - 10^9 ;
3. In deformed metal – 10^{10} - 10^{12} .

Polycrystalline metals have the lowest strength.

The greatest value is theoretical strength.

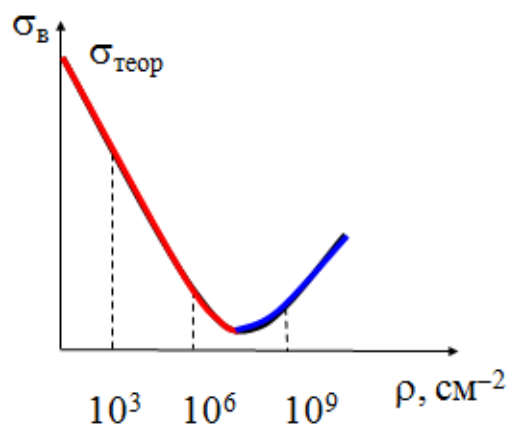


Figure 10.11 – Oding Curve

TOPIC 11

PLASTIC DEFORMATION AND RECRYSTALLIZATION

11.1 Plastic deformation

Deformation is a change in the size and shape of a solid under the influence of external forces or as a result of various physical and mechanical processes that occur in the body itself. Distinguish between elastic and plastic deformation.

Elastic deformation disappears after unloading and does not cause noticeable residual changes in the structure and properties of the metal.

Plastic deformation after unloading remains and leads to changes in the structure of the metal, and therefore, its properties.

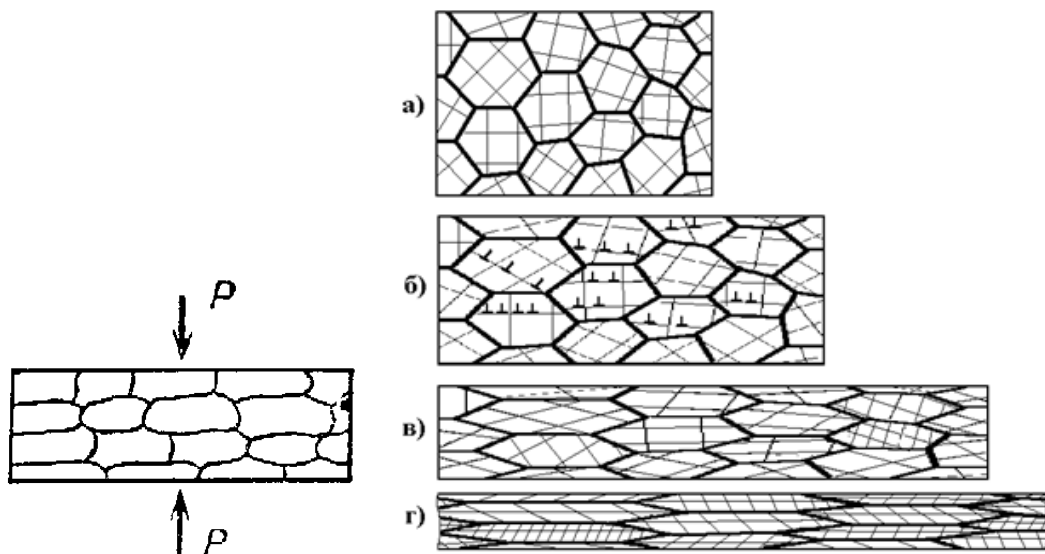


Figure 11.1 – Plastic deformation

11.1.1 Mechanism of plastic deformation

In real metals and alloys, plastic deformation is carried out by successive movement of linear defects – dislocations. Under the influence of the acting voltage, the dislocation easily glides from one atomic plane to another. Under the influence of the acting voltage, the dislocation easily glides from one atomic plane to another, until it comes to the surface of the crystal and, as a result, the upper part of the crystal moves relative to the lower one interatomic distance, i.e., plastic deformation will occur.

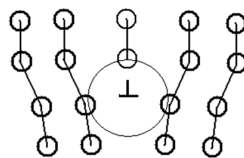


Figure 11.2 – Arrangement of atoms in a crystal with an extra-plane

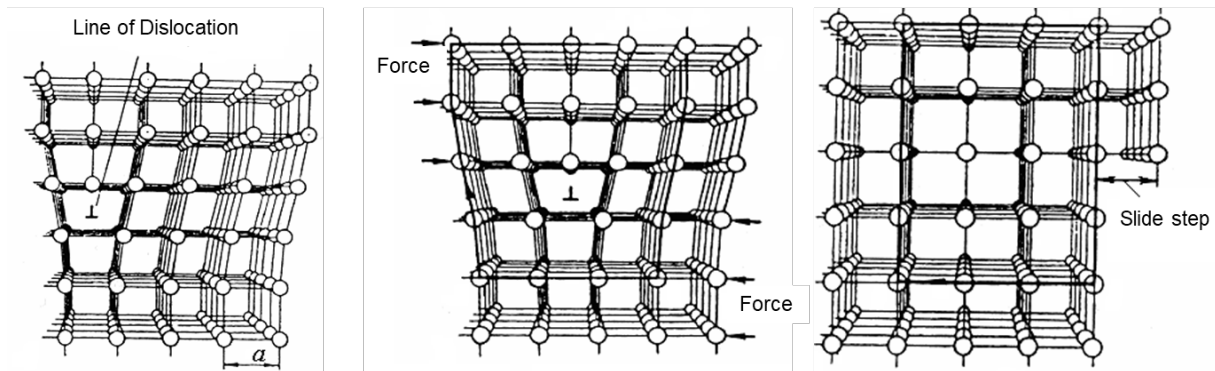


Figure 11.3 – Scheme of plastic deformation by sequential dislocation movement in a simple cubic lattice

Depending on the temperature, the plastic deformation is divided into cold ($CPD < T_r$) and hot ($GPD > T_r$), where there is the crystallization rate.

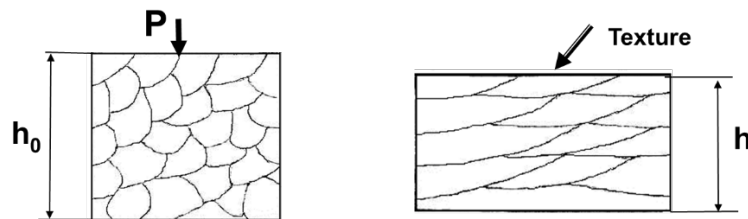


Figure 11.4 – The degree of plastic deformation

$$\varepsilon = \frac{h_0 - h}{h_0} 100\%$$

The recrystallization temperature T_p is the temperature corresponding to the onset of recrystallization processes.

It is related to the melting point $T_{пл}$

$$T_p = a \cdot T_{пл}$$

where T_p is the absolute temperature of recrystallization, K;

$T_{пл}$ – absolute melting point, K.

Coefficient a depends on the purity of metals: for pure metals it is 0.2, for most technical alloys – 0.4, for complex alloys in terms of chemical composition and structure – 0.6–0.8.

11.2 Cold plastic deformation

Cold plastic deformation is accompanied:

- The formation of texture;
- An increase in the density of dislocations.

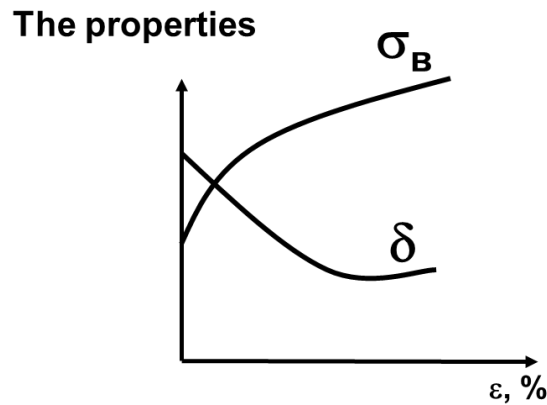


Figure 11.5 – Change in the properties of metals depending on the degree of deformation

This leads to hardening (increase in strength and hardness and a decrease in ductility) – the emergence of hardening. With an increase in the degree of deformation, strength and hardness increase, while ductility and viscosity decrease.

To remove hardening, a heat treatment is carried out, which is called recrystallization annealing. When heated in a metal, processes occur that lead to the improvement of the structure and restoration of properties.

When heated to temperatures below 0.2-0.3 T_m , the return process begins – reduction in the concentration of point defects and the redistribution of dislocations. In this case, the mechanical properties and structure do not change, and the physical ones – resistance – do change.

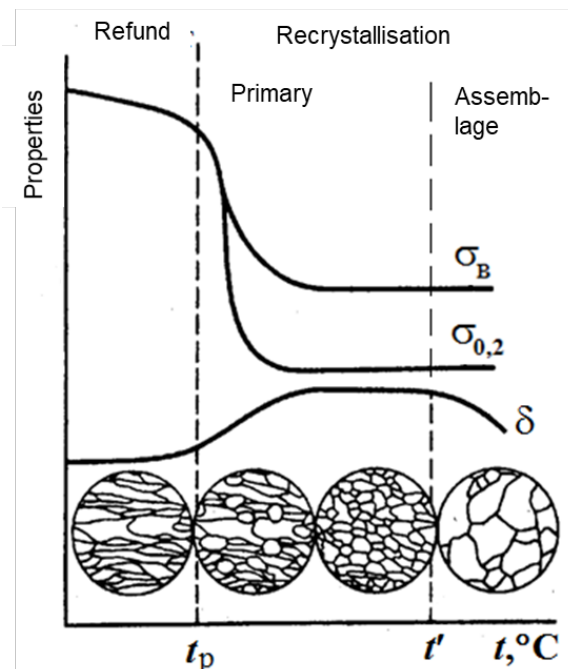


Figure 11.6 – Effect of heating on mechanical properties and structure changes of strain-hardened metal

With further heating, primary recrystallization takes place.

Primary recrystallization is the formation and growth of new small equiaxed grains inside the grains of the deformed metal decrease in dislocation density with $\rho = 10^{11}\text{--}10^{12} \text{ sm}^{-2}$ before $\rho = 10^6\text{--}10^9 \text{ sm}^{-2}$. At the same time, strength is reduced, and ductility is increased.

With a further increase in temperature, there is an increase in small recrystallization of grains, absorption of some grains of others and their unification into larger ones.

The process of enlargement of recrystallized grains is the so-called collective recrystallization.

An increase in grain size leads to a decrease in both strength and ductility. The higher the temperature, the larger the grain.

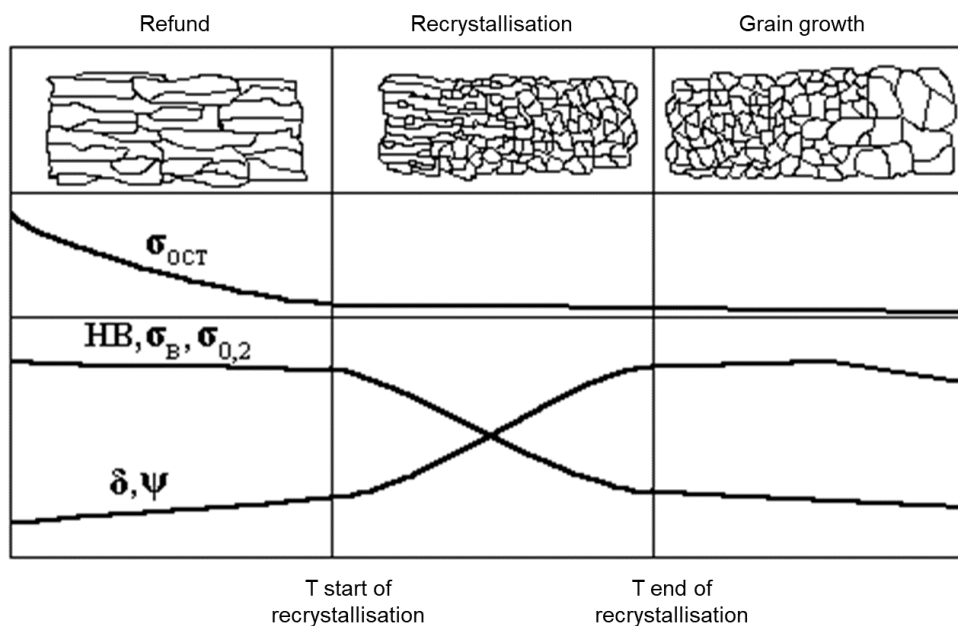


Figure 11.7 – Changes in the texture and properties of deformed metals during heating

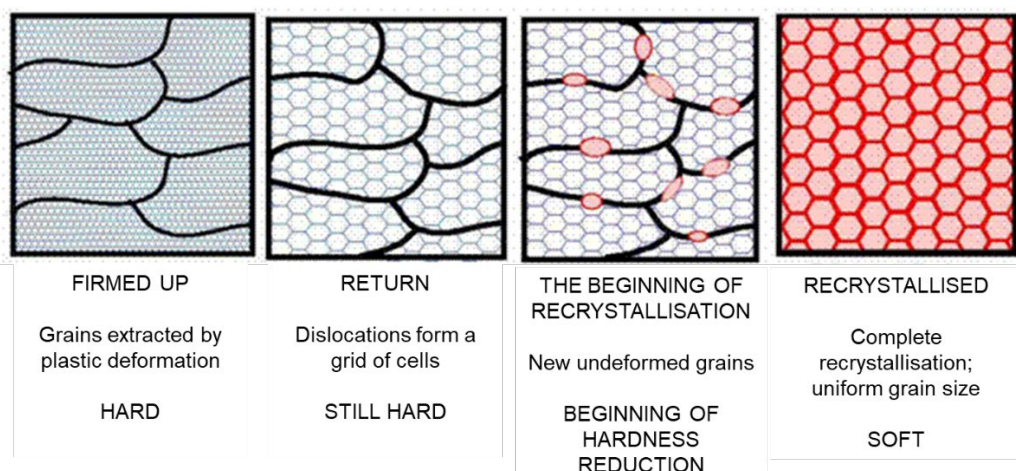


Figure 11.8 – Quenching, reflow and recrystallisation

TOPIC 12

BASICS OF ALLOY THEORY

An alloy is a substance obtained by fusing two or more components. In the theory of alloys, the following concepts are accepted: component, phase, structural component, alloy system.

Components are the substances that make up the alloy. The component may be a chemical element or a chemical compound.

A phase is a homogeneous part of an alloy separated from other parts by an interface, upon transition through which properties change abruptly.

The structural component is the part of the alloy that is detected by microscopic examination by shape, etchability or color. In some cases, the phase and the structural component coincide, but often the structural component contains several phases.

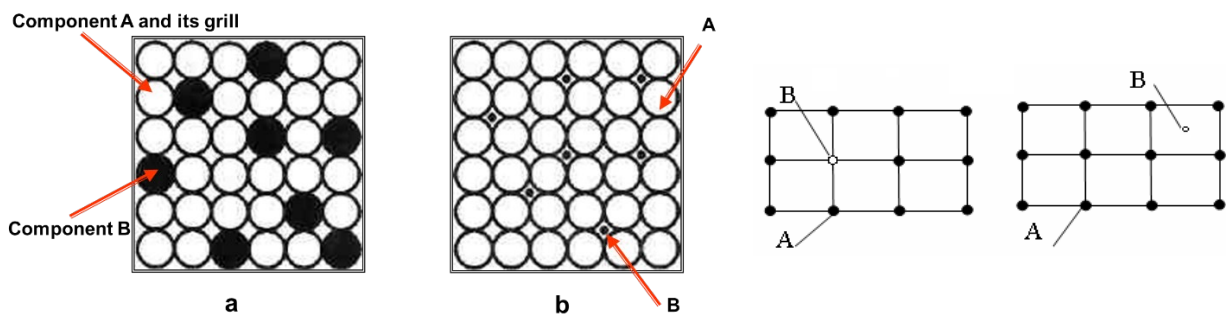
Depending on the physicochemical interaction of the components in the solid state, the following phases may form: solid solutions, chemical compounds, pure components.

A solid solution is a phase during the formation of which all components mutually dissolve into each other in a solid state, and the atoms of one of them are located in a certain way in the crystal lattice of the other. The component that is the basis of the solid solution and retains its crystal lattice is called a solvent.

Depending on the arrangement of the atoms of the dissolved substance in the solvent lattice, two main types of solid solutions are distinguished: substitution and incorporation.

A chemical compound is a phase that is formed during the chemical interaction of atoms, forming a new type of crystal lattice. Each chemical compound has a specific chemical formula. The chemical compound is characterized by high hardness and brittleness. If the alloy components in the solid state do not dissolve one in another and do not interact, an alloy with the structure of the mechanical mixture is formed.

Each component retains its crystal lattice.



a – solid substitution solution; b – solid solution introduction

Figure 12.1 – Atomic-crystalline structure of a solid solution (scheme)

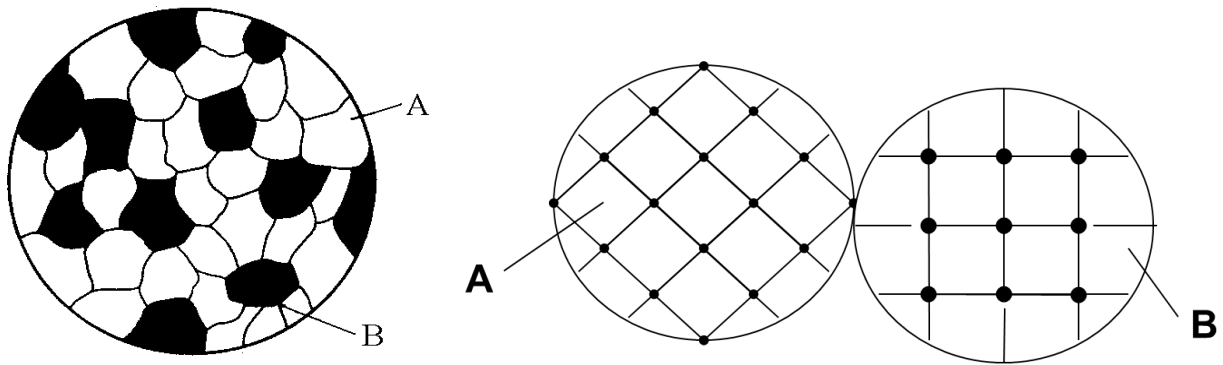


Figure 12.2 – Mechanical mixture. A and B are alloy components

12.1 Status Diagram

A state diagram is a graphical representation of the state of an alloy system in equilibrium depending on temperature and component concentration. To build a diagram using the method of thermal analysis. For this, cooling curves are constructed, from which critical points are determined.

Critical points are the temperatures of the transition of the alloy from one phase state to another. Critical points are determined from kinks or temperature stops on cooling curves.

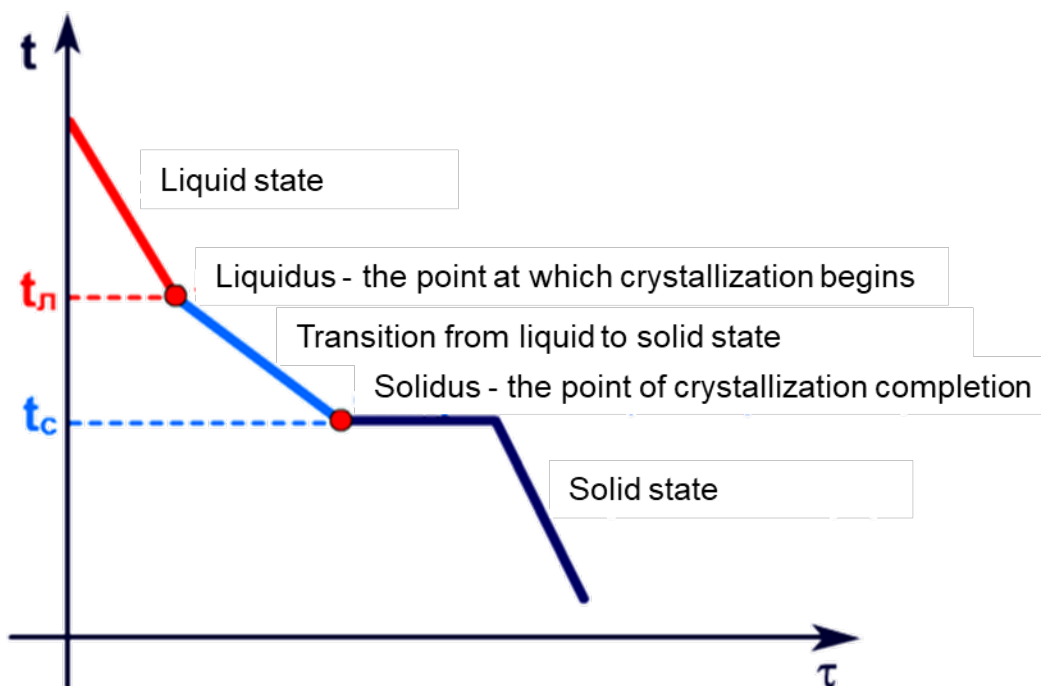
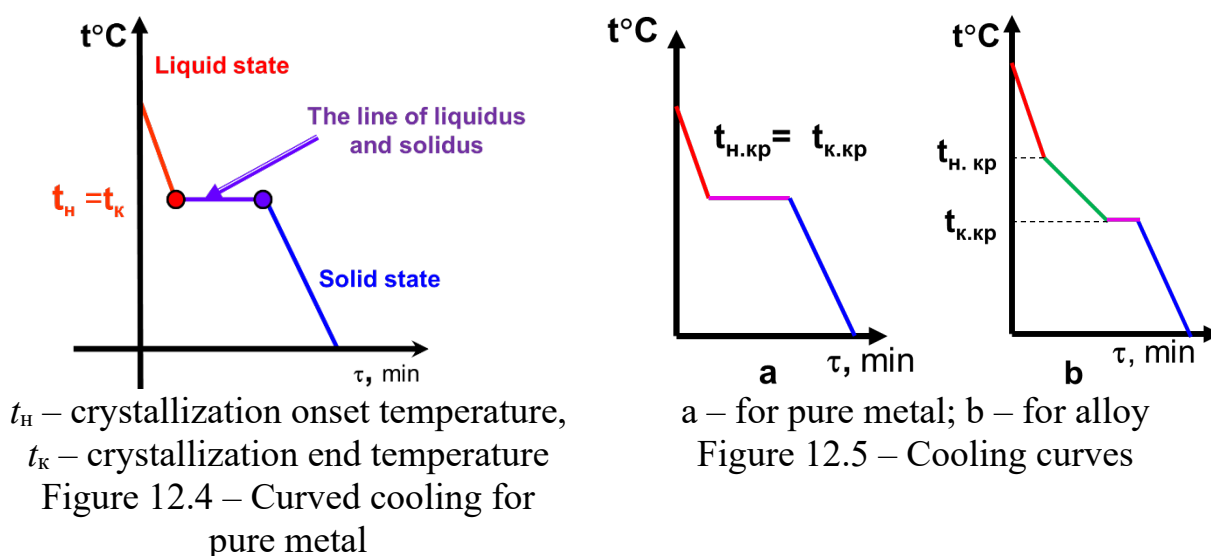
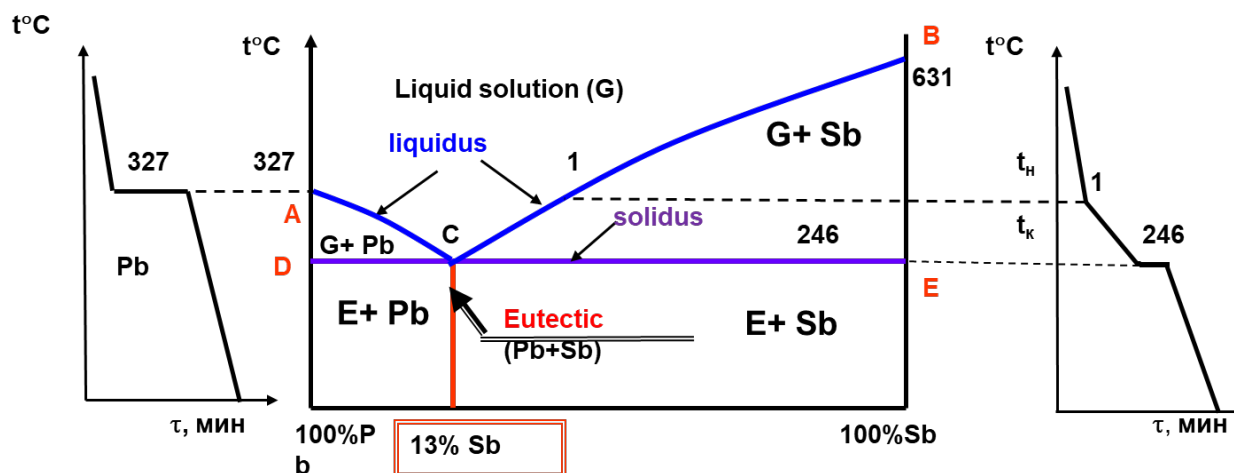


Figure 12.3 – Cooling curve for an alloy whose components form a mechanical mixture



12.2 Diagram of state for alloys whose components form mechanical mixtures

Components A and B are unlimitedly soluble in the liquid state, and when crystallised form a mechanical mixture of crystals of both components, which is called a eutectic. The following alloys crystallise according to this diagram: lead-antimony.



12.3 Diagram of the state for alloys the components of which form solid solutions

Components A and B are unlimitedly soluble in each other liquid and solid state. According to this diagram, the following alloys crystallize: bismuth-antimony, copper-nickel, iron-nickel, iron-chromium, etc.

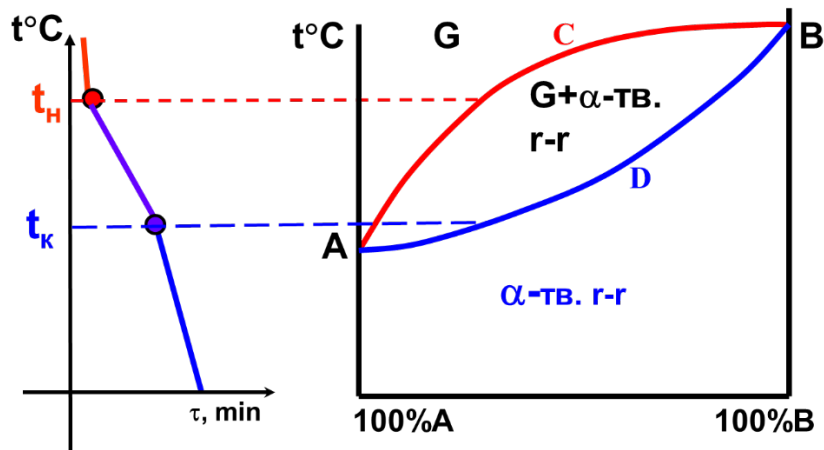


Figure 12.7 – Diagram of the state of alloys with unlimited solubility of components in the solid state

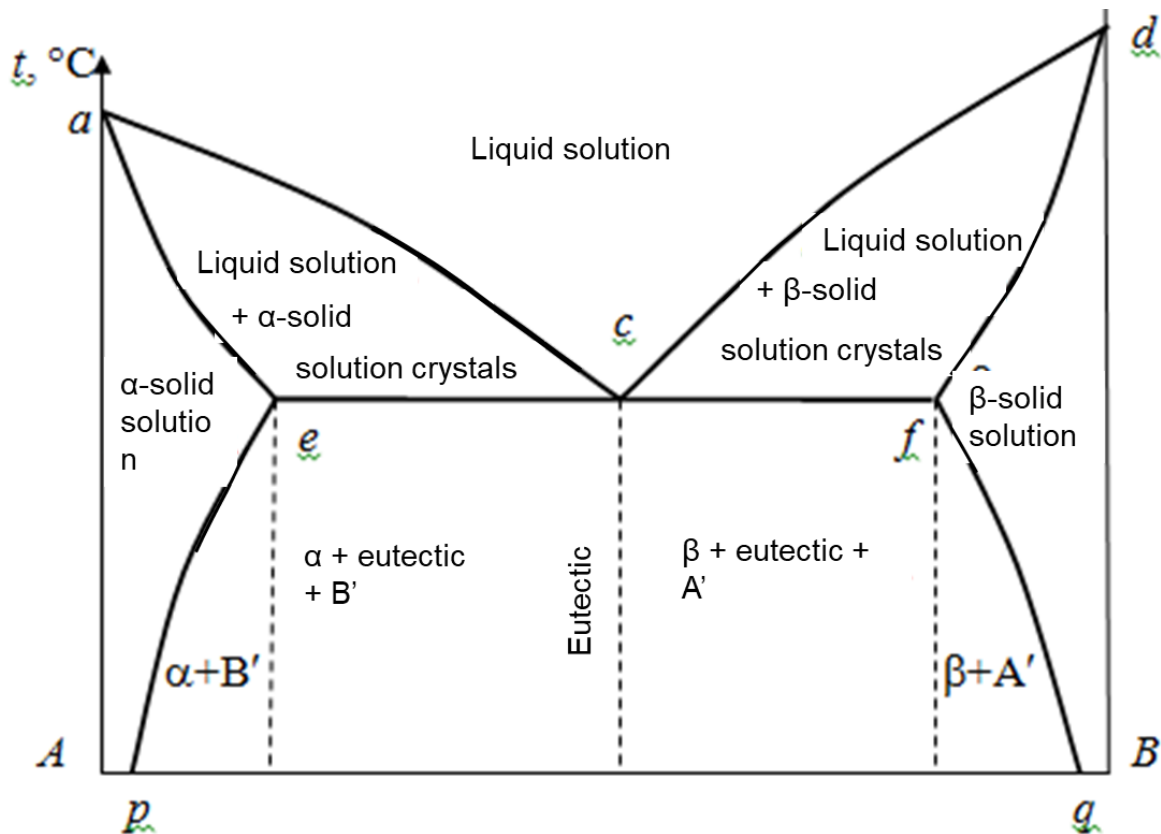


Figure 12.8 – Diagram of the state of eutectic alloys

12.4 Properties of alloys and the type of their status diagrams (by N. S. Kurnakov)

Analysis of state diagrams allows us to study the dependence of the properties of the alloy on their structure. The method of joint construction of state diagrams – properties of alloys was developed N. S. Kurnakov, who established a definite relationship between the properties of alloys and their state diagrams.

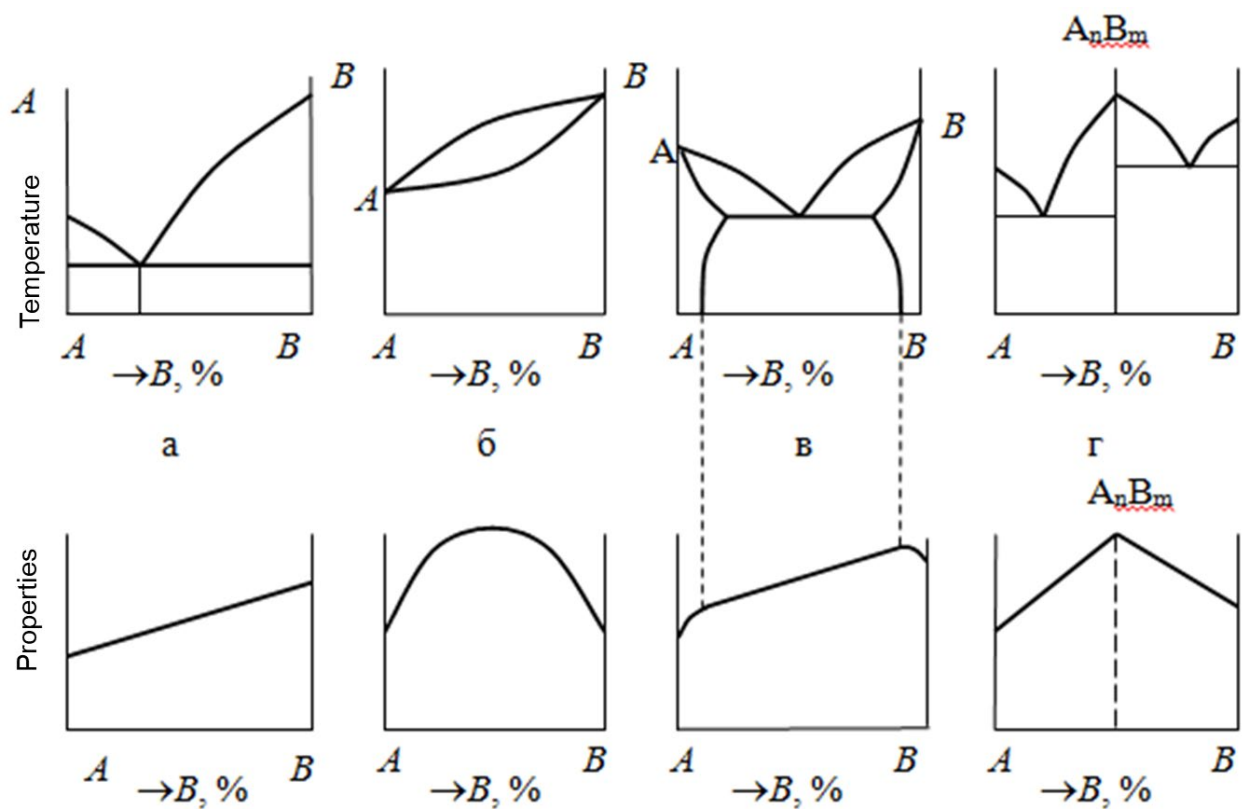
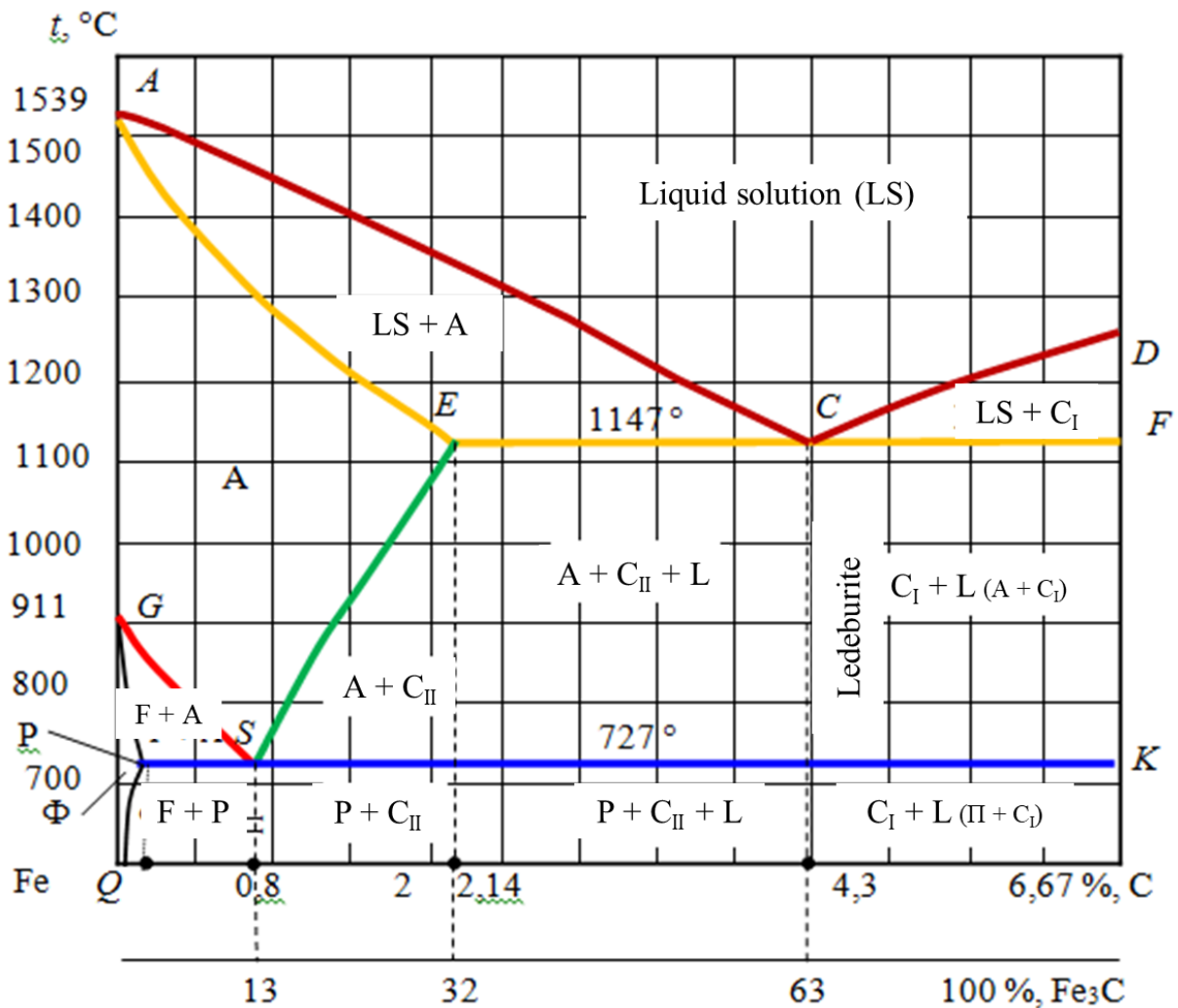


Figure 12.9 – Properties of alloys and the type of their status diagrams by
N. S. Kurnakov

TOPIC 13

STATE DIAGRAM IRON-CARBON (IRON-CEMENTITE)

13.1 Diagram of the state of Fe-C (Fe-Fe₃C)



LS – liquid solution; A – austenite; C – cementite; F – ferrite; P – pearlite;
L – ledeburite

Figure 13.1 – Diagram of the state of Fe-C (Fe-Fe₃C)

Iron-carbon alloys are the most common in modern industry. Iron is characterized by polymorphic transformation. Solid state transformations occurring iron-carbon alloys. Not only due to the polymorphism of iron, but also a change in solubility in the solid state, the release of excess phases.

Fig. 13.1: point A – melting point of pure Fe; point D – melting cementite; point C – eutectic point, eutectic crystallizes here; point G – 911°C – polymorphic transformation; line ACD – liquidus line (the beginning of crystallization); line AE CF – solidus line (end of crystallization).

On the AC line, austenite begins to crystallize from the liquid solution, and on the CD line – cementite, which is called primary (CI). The ACD line is the liquid line (critical temperature). The crystallization process ends on the AECF line; therefore, the AECF line is called the solidus line. This is the process of primary crystallization. Point C is an eutectic point. It corresponds to a carbon concentration of 4.3 %. ECF line (1147°C) – eutectic horizontal (critical temperature). Alloys with $"C" \geq 2.14\%$ undergo crystallization with the formation of a eutectic – a mechanical mixture of austenite and primary cementite. Such a mechanical mixture is called ledeburite.

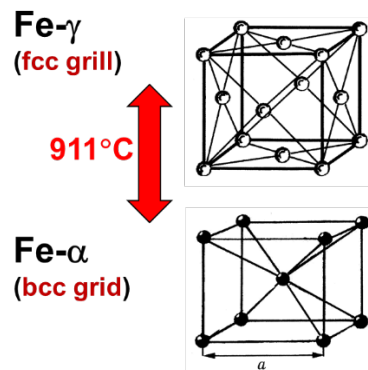


Figure 13.2 – The crystal structure of iron and its polymorphic transformations

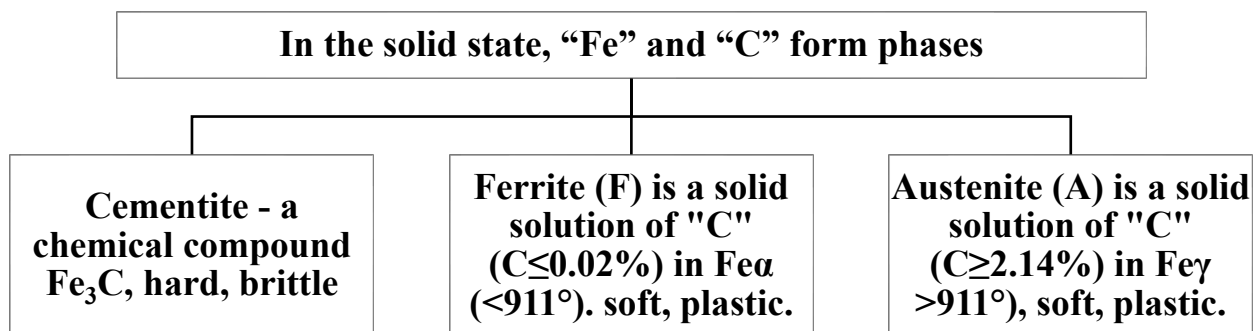


Figure 13.3 – Phase components of iron-carbon alloys

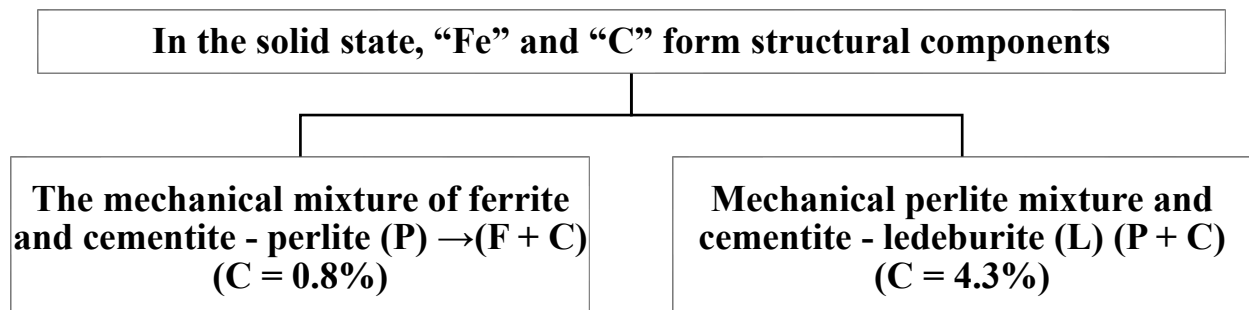


Figure 13.4 – Phases formed in the iron-carbon system in the solid state

The structure of alloys with a carbon concentration of up to 2.14 % below AE consists of austenite, from 2.14 % to 4.3 % below the ECF line consists of austenite, secondary cementite and ledeburite, with 4.3 % – ledeburite (austenite + cementite), with a carbon concentration of more than 4.3 % – ledeburite and primary cementite. The phase composition of these alloys below the eutectic horizontal is austenite and cementite.

Further cooling of the iron-carbon alloys leads to phase transformations due to both the polymorphic transformation $\text{Fe} \rightarrow \text{Fe}\alpha$ (secondary crystallization), and changes in the solubility of carbon in austenite and ferrite. Point G (911°C) – temperature of polymorphic $\gamma \leftrightarrow \alpha$ transformation of iron. Due to a decrease in the solubility of carbon in austenite from 2.14 % (point E) to 0.8 % (point S), carbon is released from austenite along the ES line. ES is the line of limited solubility of carbon in austenite. Excess carbon is released in the form of cementite, which is called secondary (C_{II}).

At a temperature of 727°C (PSK line), austenite turns into a homogeneous mechanical mixture of ferrite and secondary cementite, which is called perlite. Perlite is formed not from a liquid, but from a solid solution and is called a eutectoid. The PSK line along which perlite is formed is called the eutectoid transformation line (eutectoid horizontal). For all iron-carbon alloys, austenite is converted to perlite along this line (temperature 727°C). The structural components of iron-carbon alloys below a temperature of 727°C are different, and the phases are the same: ferrite and cementite.

Point P indicates the maximum solubility of carbon in ferrite. Point Q corresponds to the minimum solubility of carbon in ferrite at room temperature. In the field of GPQ, pure ferrite exists. The PQ line is called the line of limited solubility of carbon in $\text{Fe}\alpha$. Below the eutectoid horizontal, various structural components are formed depending on the carbon content. Alloys with a carbon concentration of less than 0.8 % have ferrite and perlite. With a carbon content of 0.8 % – perlite. If carbon is more than 0.8 %, then the structure consists of perlite and secondary cementite.

Alloys with carbon contents between 2.14 % and 4.3 % below the PSK line have a structure of pearlite, ledeburite and secondary cementite. If the carbon content is 4.3 %, the structure is ledeburite, at carbon content more than 4.3 % the structure is ledeburite and primary cementite. Above a temperature of 727°C, ledeburite is a mixture of austenite and primary cementite, and below 727°C it is a mixture of perlite and primary cementite.

13.2 Iron-Carbon Alloys

Steel is an alloy of iron with carbon in an amount $C \leq 2,14 \%$, cast iron is $C > 2,14 \%$. Pre-eutectoid steels contain carbon $C < 0,8 \%$. Eutectoid steels contain carbon $C > 0,8 \%$. Eutectoid steel contains 0.8 % carbon.

13.3.1 Phases and structural components in steel (Fig. 13.5).

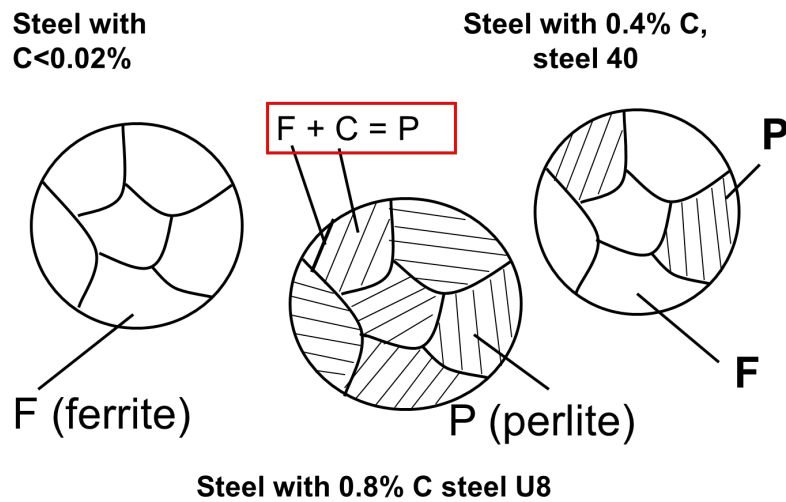


Figure 13.5 – Phases and structural components of the iron-carbon system in the solid state

13.3.2 Structure of steels (Fig. 13.6).

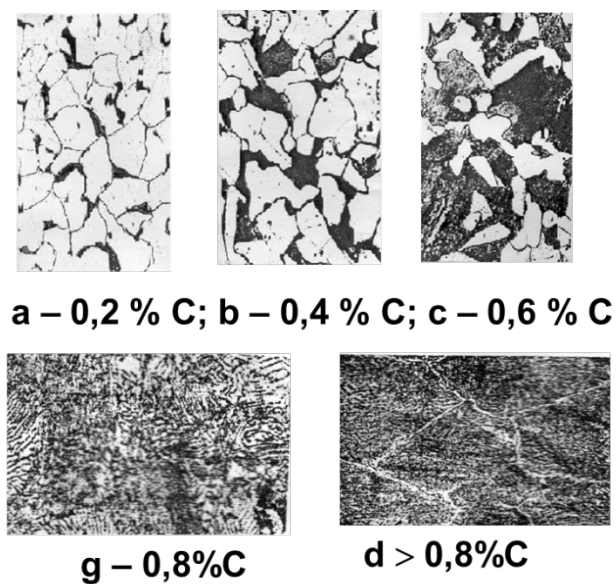


Figure 13.6 – Microstructures of steels of different compositions

The structure of the hypereutectoid steel at room temperature is ferrite and perlite. Moreover, the more carbon in steel, the more perlite.

Microstructure tour of pre-eutectoid steels (Fig. 13.6): a – 0.2 % C; b – 0.4 % C; c – 0.6 % C. The structure of eutectoid steel (g) is polite. The structure of hypereutectoid steel (d) is polite and cementite along the grain boundaries.

Due to the increase in the amount of hard cementite with increasing carbon content, the hardness and strength of steel increase, but the ductility and toughness

decrease. Hypereutectoid steels have a fairly high ductility, but a relatively low hardness.

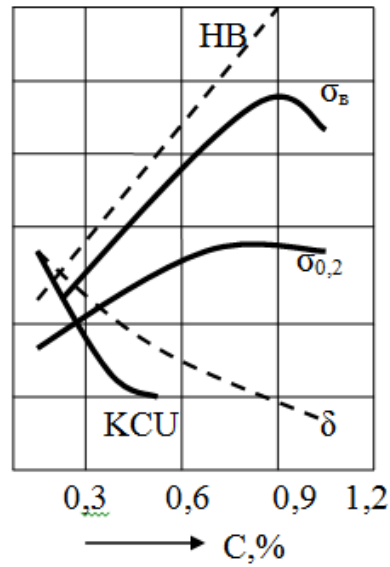
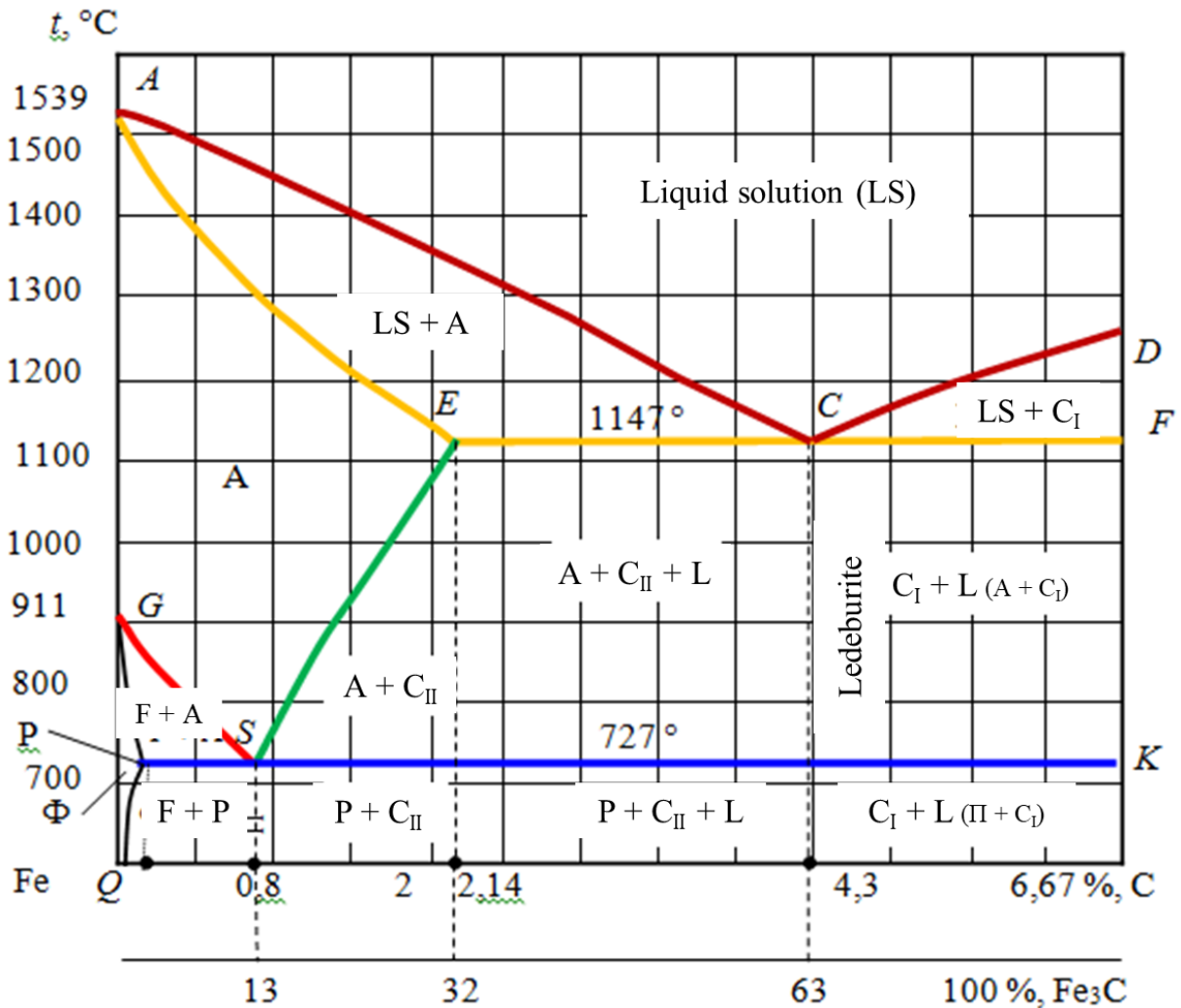


Figure 13.7 – The effect of the quantity of carbon on the properties of steel

Such steels are used for the manufacture of machine parts where a combination of high ductility and toughness with relatively high strength is required. Hypereutectoid steels are characterized by high hardness and not high ductility, so they are used for tools.

TOPIC 14 STEEL CLASSIFICATION

14.1 State diagram Fe-C (Fe-Fe₃C)



LS – liquid solution; A – austenite; C – cementite; F – ferrite; P – pearlite;
L – ledeburite

Figure 14.1 – Diagram of the state of Fe-C (Fe-Fe₃C)

14.2 Carbon content classification of steels and cast irons

Steel is an alloy of iron and carbon in the amount of $C \leq 2.14\%$, cast iron – $C > 2.14\%$. Pre-eutectoid steels contain carbon $C < 0.8\%$. Hypereutectoid steels contain carbon $C > 0.8\%$. Eutectoid steel contains 0.8% carbon.

14.2.1 Cast Iron Classification

There are white and graphitized cast irons. In white cast irons, all carbon is bound in the form of cementite. In graphitized cast irons, part of the carbon is in the

free state in the form of graphite. The Fe-Fe₃C diagram shows white cast irons. C < 4.3 % – pre-eutectic cast irons, C = 4.3 % – eutectic cast iron, C > 4.3 % – hypereutectic cast irons.

14.3 The effect of constant impurities on the properties of steels

In addition to carbon, there are still constant impurities in steel – manganese, silicon, sulfur, phosphorus, and gases. With an increase in the amount of carbon, strength increases and ductility decreases. Si and Mn are useful impurities; they dissolve well in ferrite and increase σ_b and $\sigma_{0.2}$. At the same time, Mn does not reduce ductility, and Si – with an increase in the amount of embrittlement of steel.

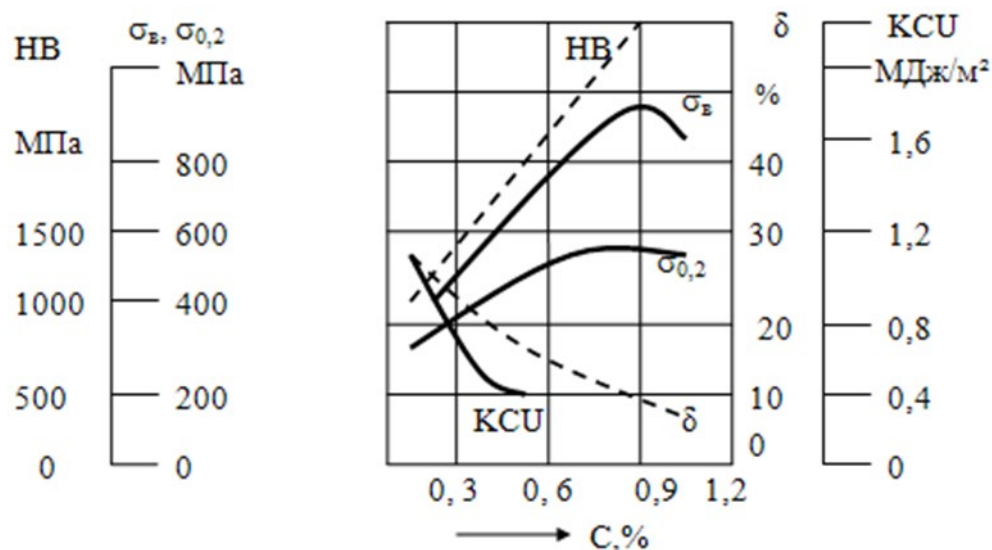
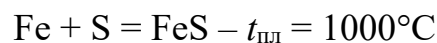


Figure 14.2 – The effect of carbon content on the mechanical properties of steel

Sulfur and phosphorus are harmful impurities. They embrittle the steel, reduce toughness and increase T_{khr} . Sulfur embrittles steel at high temperatures and causes a red bone. Sulfur is contained in the form of ferrous iron FeS, which forms a eutectic with iron located along the grain boundaries.



$$t_{OMI} = 1300^{\circ}C$$



$$S \uparrow \rightarrow \delta \downarrow \psi \downarrow KCU \downarrow, \text{property anisotropy}$$

$$S \leq 0,06 \%$$

At 988°C, this eutectic melt, which disrupts the connection between the grains and, when deformed, causes cracking. This phenomenon is called red breaking. Depending on the quality of the steel, the amount of sulfur should not exceed 0.06 %.

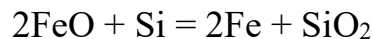
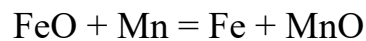
The harmful effect of phosphorus is manifested in a sharp increase in the brittleness of the steel at ordinary and low temperatures. This phenomenon is called cold brittleness of steel. Phosphorus increases the cold brittleness threshold of steel and reduces the crack propagation work. Phosphorus increases the cold brittleness threshold of steel and reduces the crack propagation work.



$$P \leq 0,06 \%$$

Therefore, the phosphorus content should not exceed 0.06 %.

Silicon and manganese are useful impurities in steel. Si and Mn are converted to steel during the deoxidation process. Si and Mn, combining with iron oxide FeO, in the form of oxides pass into the slag. These deoxidation processes improve the properties of steel. Silicon, degaussing the metal, increases the density of the ingot.



Silicon dissolves in ferrite and increases T_m , which reduces the ability of steel to cold stamping. Manganese increases strength, practically without reducing ductility.

Depending on the degree of deoxidation, they are distinguished. Boiling steel – deoxidized with manganese $FeO + Mn = Fe + MnO$. Quiet steel – deoxidized with manganese $FeO + Mn = Fe + MnO$, and silicon $2FeO + Si = 2Fe + SiO_2$.

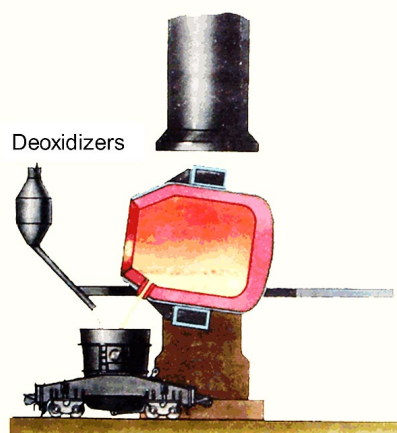
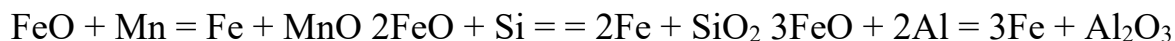


Figure 14.3 – Scheme of steel deoxidation in ladles

Depending on the degree of deoxidation, they are distinguished. Calm steel is deoxidized with manganese, silicon and aluminum.



Manganese neutralizes the harmful effects of sulfur. The manganese content in steels is 0.5-0.8 %, silicon content is 0.3-0.5 %.

Gases (O, N, H) degrade the properties of steel. Oxygen and nitrogen, forming brittle non-metallic inclusions (oxides, nitrides), increase the brittleness of the steel and the cold brittleness threshold. Hydrogen, dissolving in steel, increases its fragility. The solubility of hydrogen decreases upon cooling of the steel. The released hydrogen accumulates in micropores, which leads to the formation of flocken (tears) (Fig. 14.4).

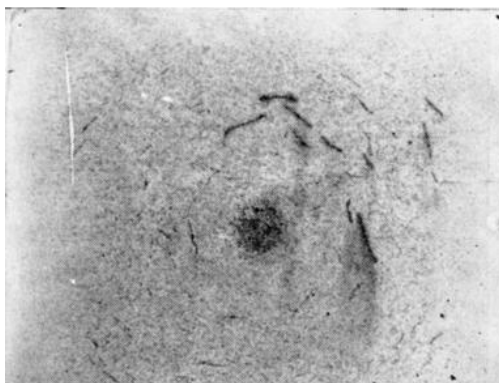
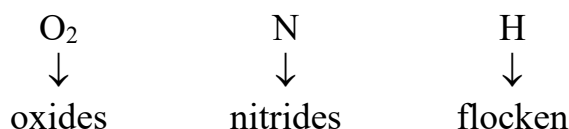


Figure 14.4 – Flocken

Electric steel is the purest, but it also contains impurities that can be removed by evacuation and the use of special slags. Such processing of steel leads to an increase in toughness and a decrease in T_{khr} . The remaining characteristics are practically not affected.



14.4 Classification of steels for their intended purpose. Classification of structural steels by quality

According to the purpose, the steel (carbon) is divided into: structural – instrumental. Structural steels are subdivided in quality into: steel-ordinary quality DSTU 2651-94; quality steels DSTU 7809:2015; Structural steel with increased and high machinability by cutting (automatic).

14.4.1 Classification of structural steels by quality

Steel of ordinary quality – in the production of these steels there are no high demands on the charge, the processes of melting and casting. As a result of this, steels contain a large amount of harmful impurities – sulfur and phosphorus – up to 0.06 %. Steel is marked with letters and numbers: St0, St1, St2, St3, St4, St5, St6. The letters "St" indicate steel, and the numbers indicate the serial number of steel St2kp – boiling steel (deoxidized by Mn), St4ps – semi-quiet steel (deoxidized by Mn and Si), the cn index is not indicated.

$$\begin{array}{c} \text{S and P} \leq 0,06 \% \\ \text{St0, St1 St6} \\ \hline \longrightarrow \\ \% \text{ C, } \sigma_B \end{array}$$

Quality steels are smelted in compliance with more stringent conditions with respect to the composition of the charge and the conduct of melting and casting. They are subject to higher requirements for chemical composition: (S and P) $\leq$ 0.03-0.035 %, fewer non-metallic inclusions. Quality steels are marked with the word "steel" and numbers 08kp, 10, 15, 20 ... 85. The numbers on the brand indicate the average carbon content in hundredths of a percent. For example, steel 45 (0.45 % C), steel 60 (0.6 % C). Quality steels are used for the manufacture of critical machine parts. They have a higher level of mechanical properties than ordinary quality steels.

Structural steels of increased and high machinability by cutting (automatic) – have good machinability by cutting (element chips or break chips are formed). Cheap steels with a high content of sulfur and phosphorus (up to 0.3 % S, up to 0.15 % P): A12 (0.12 % C), A20 (0.2 % C), A40Г (0.4 % C and high manganese content – 1.2-1.55 % Mn) are used for the manufacture of fasteners – AC20 steel – 0.2 % C, $\leq$ 0.3 lead, A40E – 0.4 % C, $\leq$ 0.15 % selenium. Automatic steel is used for the manufacture of non-critical parts (for example, fasteners), which are processed on machine tools with the formation of easily breaking chips.

14.5 Carbon Tool Steels

Carbon tool steels are divided into two groups:

- High-quality steels U7, U8 ... U13 (S and P 0.035 %) (carbon amount 0.7...1.3 %, respectively).

- High-quality steels (S and P $\leq$ 0.02 %) – U7A ... U13A (the amount of carbon is 0.7...1.3 %, respectively).

Of steel U7, U8 makes percussion instruments – hammers, chisels. Small-size drills, hacksaw blades, dies, taps are made of U10-U13 steels.

TOPIC 15

THERMAL BASICS STEEL PROCESSING

15.1 The principal possibility of hardening heat treatment

Heat treatment gives a strengthening effect only when structural transformations occur in the alloy in the solid state. This information can be obtained from the state diagrams. In Fig. 15.1 shows a state diagram for a mechanical mixture.

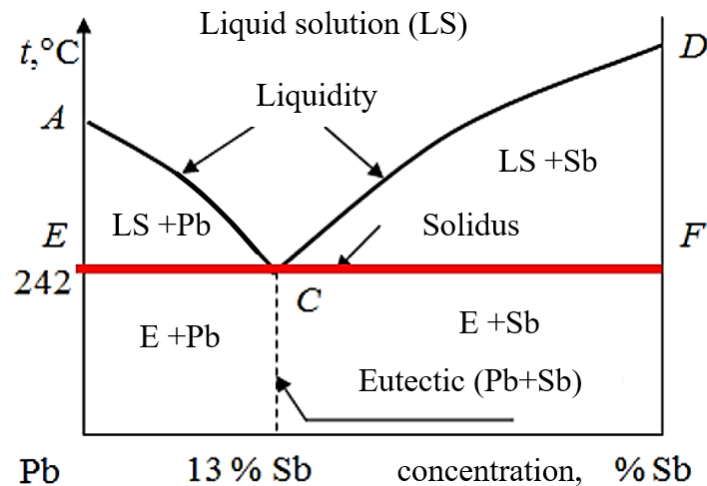


Figure 15.1 – Diagram of the state of the Lead-Antimony (Pb-Sb) system

Below the solidus line (horizontal) no structural transformations occur. Therefore, an alloy of this type is not subjected to hardening heat treatment.

The Fig. 15.2 shows a state diagram of alloys whose components form unlimited solid solutions.

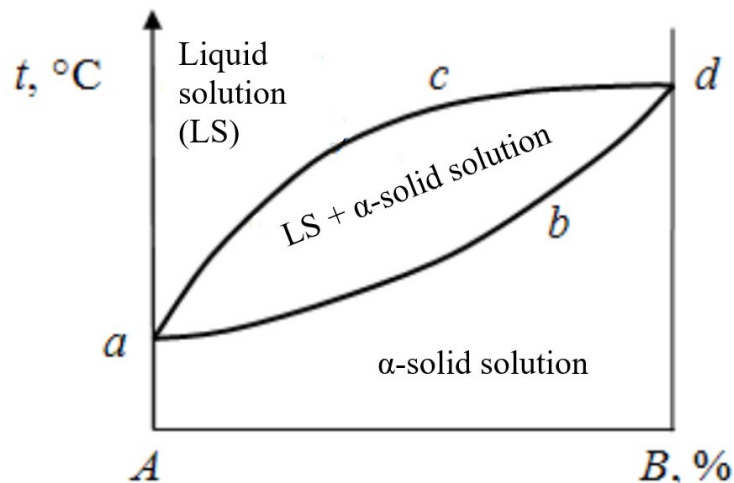


Figure 15.2 – Phase diagram of alloys with unlimited solubility in the solid state

On the liquid line *aced*, the formation of a α -solid solution begins. On the solidus line *abed*, the formation of a α -solid solution ends. Below the solidus line, no

more transformations occur. Therefore, an alloy of this type is also not subjected to hardening heat treatment.

The Fig. 15.3 shows a state diagram of alloys whose components form limited solid solutions.

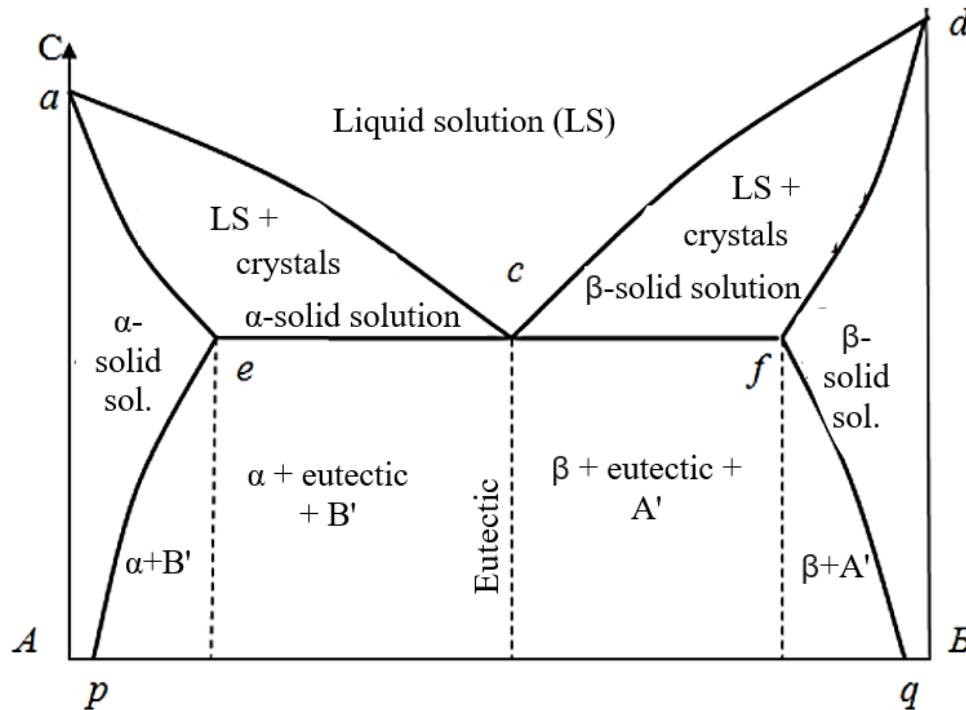


Figure 15.3 – Diagram of the state of alloys with limited solubility in the solid state and eutectic transformation

Below the solidus line, there are lines of limited solubility. Such an alloy undergoes hardening heat treatment at a certain ratio of components A and B.

For iron-carbon alloys, hardening heat treatment is possible, since phase transformations occur in the solid state.

15.2 Critical points

Heat treatment (T.O.) is heated above or below critical temperatures, holding at these temperatures and subsequent cooling at different speeds to obtain the desired properties. For competent execution T.O., it is necessary to know the critical points – the temperatures at which phase transformations occur.

In steel, critical points A_1 and A_3 are distinguished. When heated: A_{c1} – PSK line (727°C) – when heated, the formation of austenite begins. A_{c3} is the GSE line – upon heating, the formation of austenite ends; For the hypereutectoid A_{c3} steel, A_{cm} is designated. During cooling, critical points are denoted by A_{c1} , A_{c3} . A_2 is the temperature at which a change in the magnetic state occurs, so Curie – 768°C .

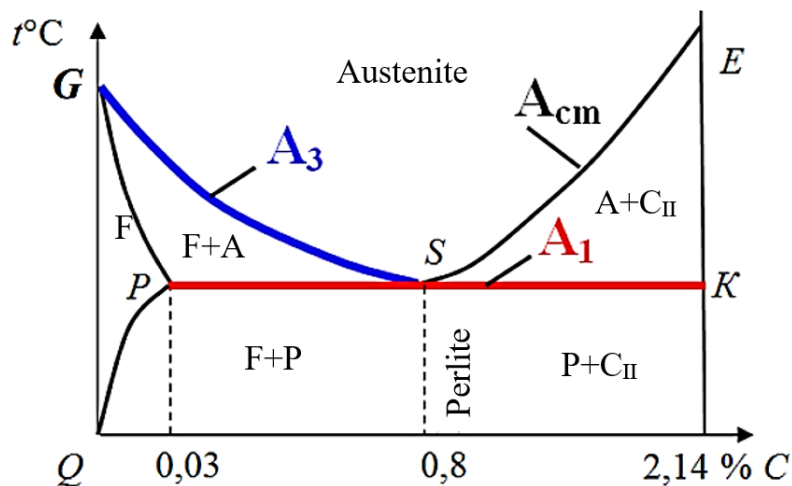


Figure 15.5 – Fragment of the Iron-Carbon phase diagram with critical points marked

15.2.1 Transformations during steel heating (austenitic transformation)

When heated, the formation of austenite begins at 727°C (point A_{c1}). This process takes place in two stages.

- 1) $\alpha \rightarrow \gamma$ transformation (Fig. 15.6) (the BCC lattice turns into FCC);
- 2) Dissolution of carbides in austenite and redistribution of carbon in solid solution.

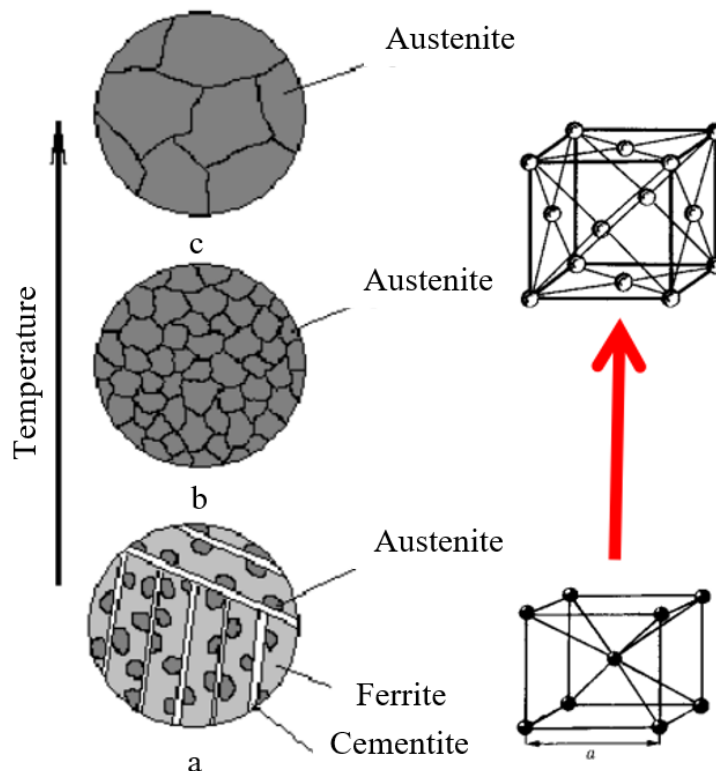


Figure 15.6 – Schematic representation of austenitic transformation in steel during heating

As the temperature rises to 1000-1200°C, austenite grains grow, which leads to brittleness of the metal. Grain growth is called overheating. This defect can be corrected by reheating to a temperature of ~ 50°C above A_{c3} . If steel is heated close to solidus, the grain boundaries are oxidized and melted. This type of marriage is called a burn and cannot be fixed.

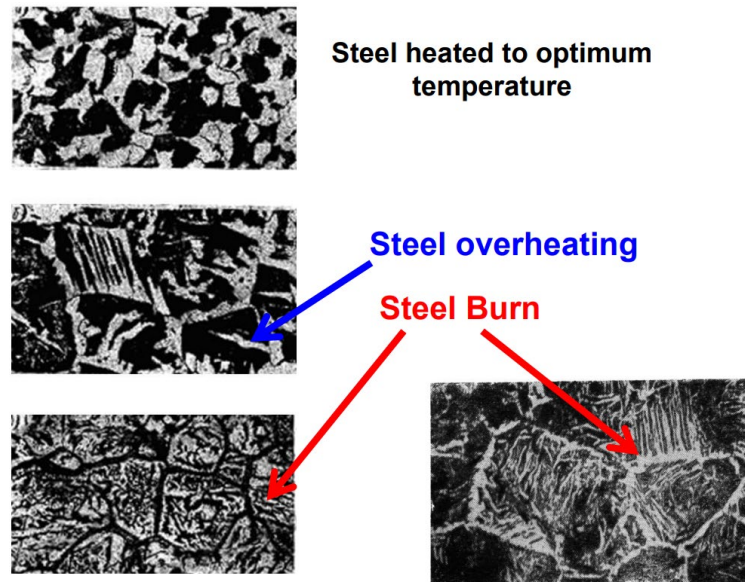


Figure 15.7 – Defects in the microstructure of steel due to overheating and overburning

Depending on the tendency of austenite grains to grow, they distinguish:

- 1) Hereditary coarse-grained steels;
- 2) Hereditary fine-grained steels.

The size of austenitic grain is affected by:

- 1) The chemical composition of steel;
- 2) Temperature and heating rate;
- 3) The duration of exposure at this temperature.

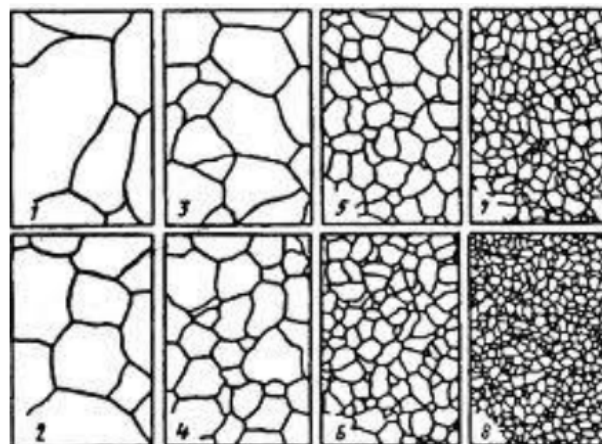


Figure 15.8 – Grain scale

Calm steels, additionally deoxidized Al, as well as steels containing Ti, V, Mo, Zr, are hereditarily fine-grained, since these elements form carbides (nitrides), which inhibit the growth of austenitic grains. Boiling steels are hereditarily coarse-grained.

15.3 Austenite isothermal decomposition diagram (C-shaped diagram)

At a temperature of 727°C, austenite, according to the Fe-Fe₃C diagram, decomposes into two phases – ferrite and cementite. Such a transformation occurs upon slow cooling. Under other cooling conditions, other structures are formed during the decomposition of austenite. The transformations that occur under isothermal decay (with constant T) are studied using diagrams of isothermal decomposition of austenite. Such a diagram is also called C-shaped.

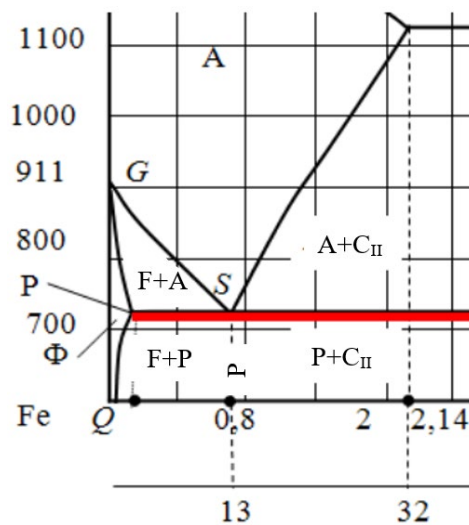


Figure 15.9 – Fragment of the iron-carbon phase diagram for steels

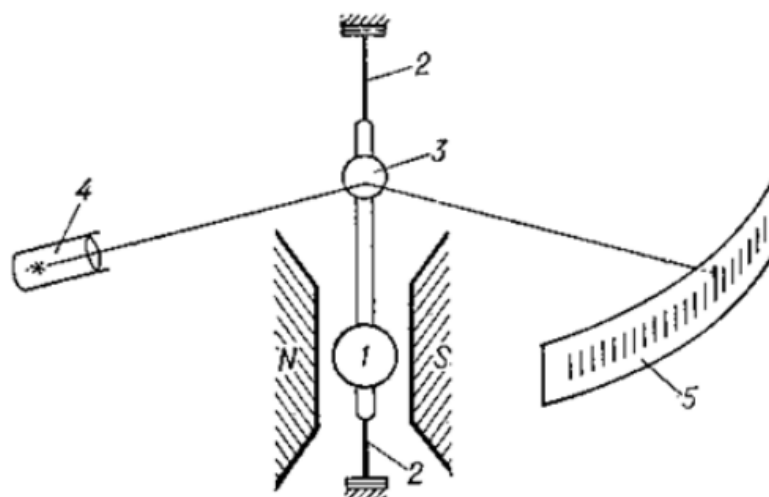
15.3.1 Anisometer Akulova

A C-shaped diagram is constructed using the Akulov anisometer, whose operation is based on the magnetic principle. Austenite is a paramagnetic component; its decay products are ferromagnets. In a magnetic field, the steel sample rotates through an angle proportional to the percentage of decayed austenite.

Appearance of Akulov's magnetic anisometer based on measurement of rotational moment (Fig. 15.11).

15.3.2 Kinetic curves of the decomposition of austenite

Based on the experimental data, kinetic curves of austenite decomposition are constructed at different isothermal holding temperatures in the temperature range 727-240°C. Most often, isothermal extracts are carried out at temperatures of 700, 600, 550, 400°C, etc. The figure shows the kinetic curves of the decomposition of austenite at temperatures of 550 and 700°C (Fig. 15.12).



1 – sample; 2 – elastic elements; 3 – mirror; 4 – light source; 5 – scale;
 N, S – magnet poles (the mass of the magnetic part of the device is 4.5 tons)
 Figure 15.10 – Diagram of a magnetic anisometer based on the measurement of
 rotational moment (design NIICHERMET)

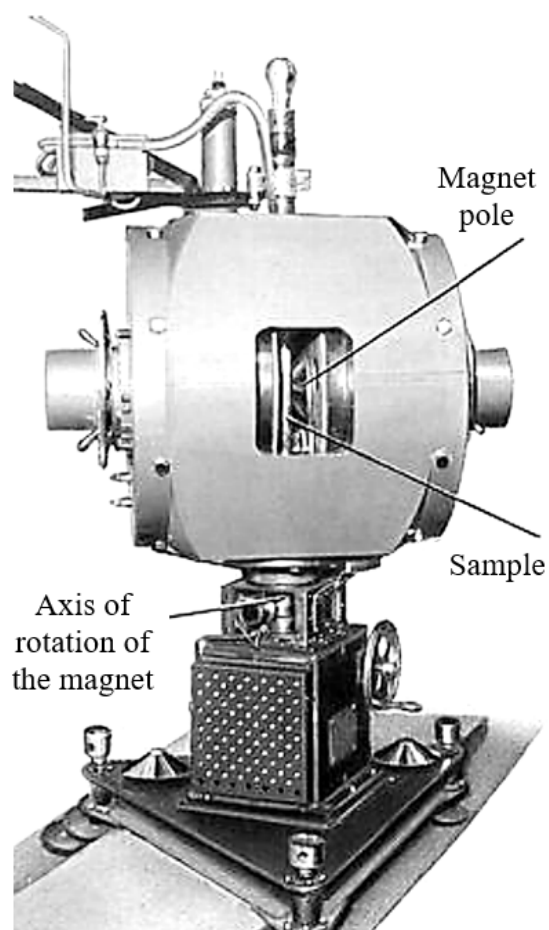


Figure 15.11 – Anisometer Akulova

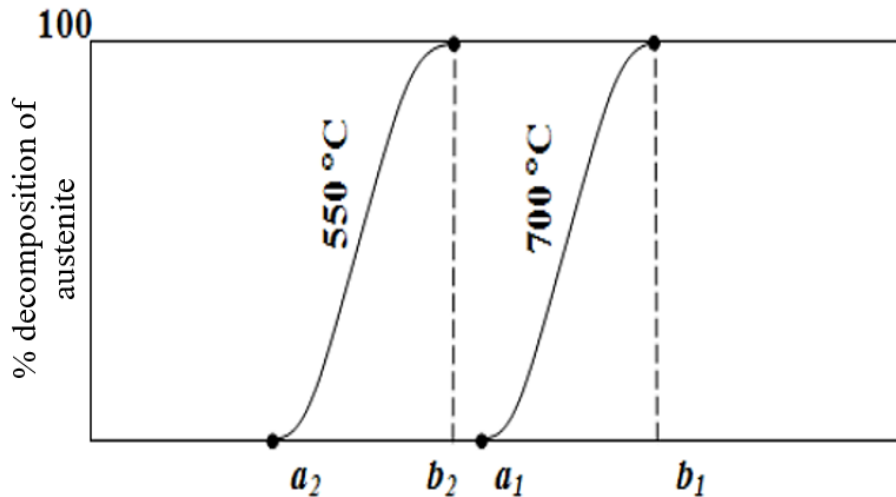


Figure 15.12 – Kinetic curves of isothermal decomposition of austenite

Points a_1 and a_2 are the time that passes before the start of the decomposition of austenite during isothermal aging (incubation period), b_1 and b_2 is the time that corresponds to the end of the decomposition of austenite.

15.3.3 Diagram of isothermal decomposition of austenite for eutectoid steel (0.8 % C)

Based on the kinetic curves of the decomposition of austenite, a diagram of the isothermal decomposition of austenite is constructed for eutectoid steel. Above A_1 , austenite is stable, and when cooled below A_1 in the temperature range 727-550°C, it decomposes into a ferrite-cementite mixture, which, depending on temperature, is dispersed (thickness of cementite particles + distance between them). Depending on their dispersion, they are called perlite, sorbitol and reed (Fig. 15.13).

Curve 1 characterizes the beginning of the decomposition of austenite into a ferrite-cementite mixture, curve 2 is the end. Pearlite, sorbitol and reed are called structures of the pearlite family.

Diagram of isothermal decomposition of austenite in coordinates temperature – lg time (Table 15.1). In eutectoid steel, the critical points A_1 and A_3 coincide.

During the formation of structures of the pearlite family, austenite, containing 0.8 % C, decomposes into two phases – ferrite, which practically does not contain carbon (no more than 0.03 at 727°C), and cementite with 6.67 % C. The processes that occur during the decomposition of austenite into a ferrite-cementite mixture in the temperature range 727-550°C:

- 1) Polymorphic transformation: $Fe\gamma \rightarrow Fe\alpha$ (HCC $\rightarrow$ BCC).
- 2) Diffusion redistribution of carbon: $A_{0,8} \rightarrow F^{0,03} + C^{6,67}$.

Such a transformation is called diffusion.

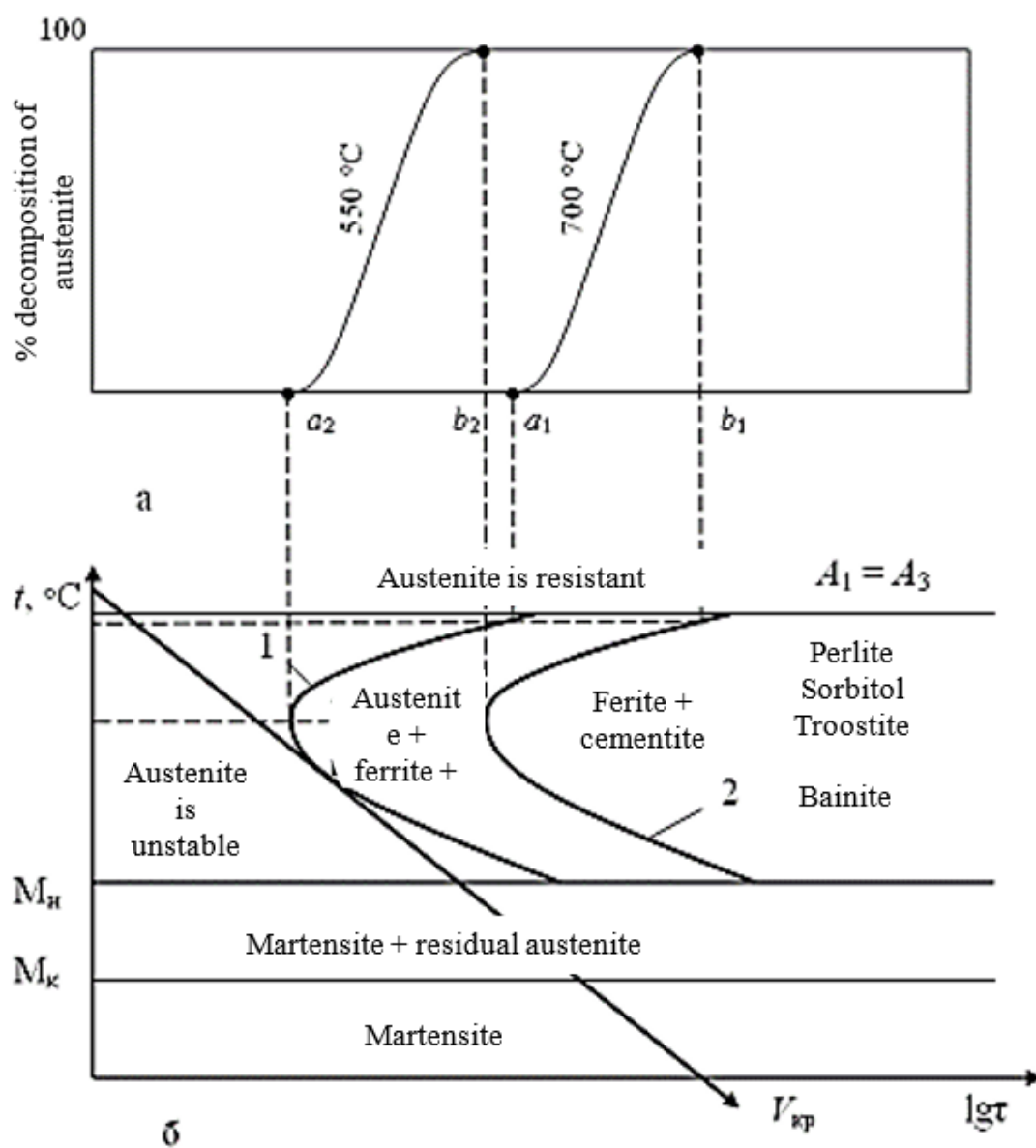


Figure 15.13 – Kinetic austenite decay curves

Table 15.1

Holding temperature at $t, ^\circ\text{C}$	Time of austenite decay onset τ , sec	$\lg \tau$	Time of complete decomposition of austenite τ , sec	$\lg \tau$
700	a1	1,78	b1	2,98
650	a2	0,48	b2	1,23
550	a3	0	b3	0,7
400	a4	1	b4	2,25
300	a5	2,25	b5	3,21

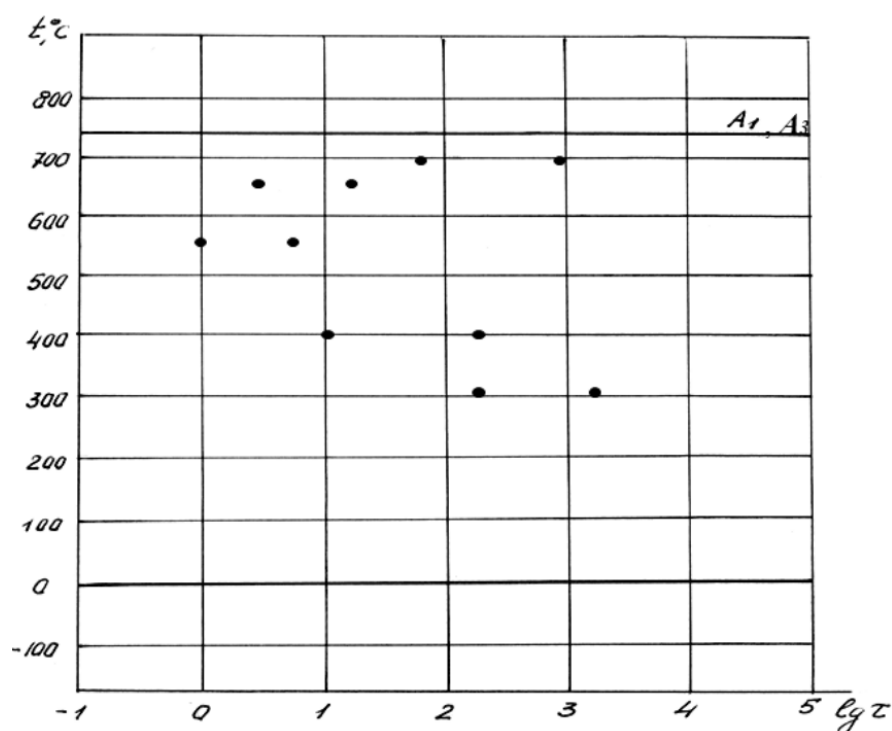


Figure 15.14 – Values of table 15.1

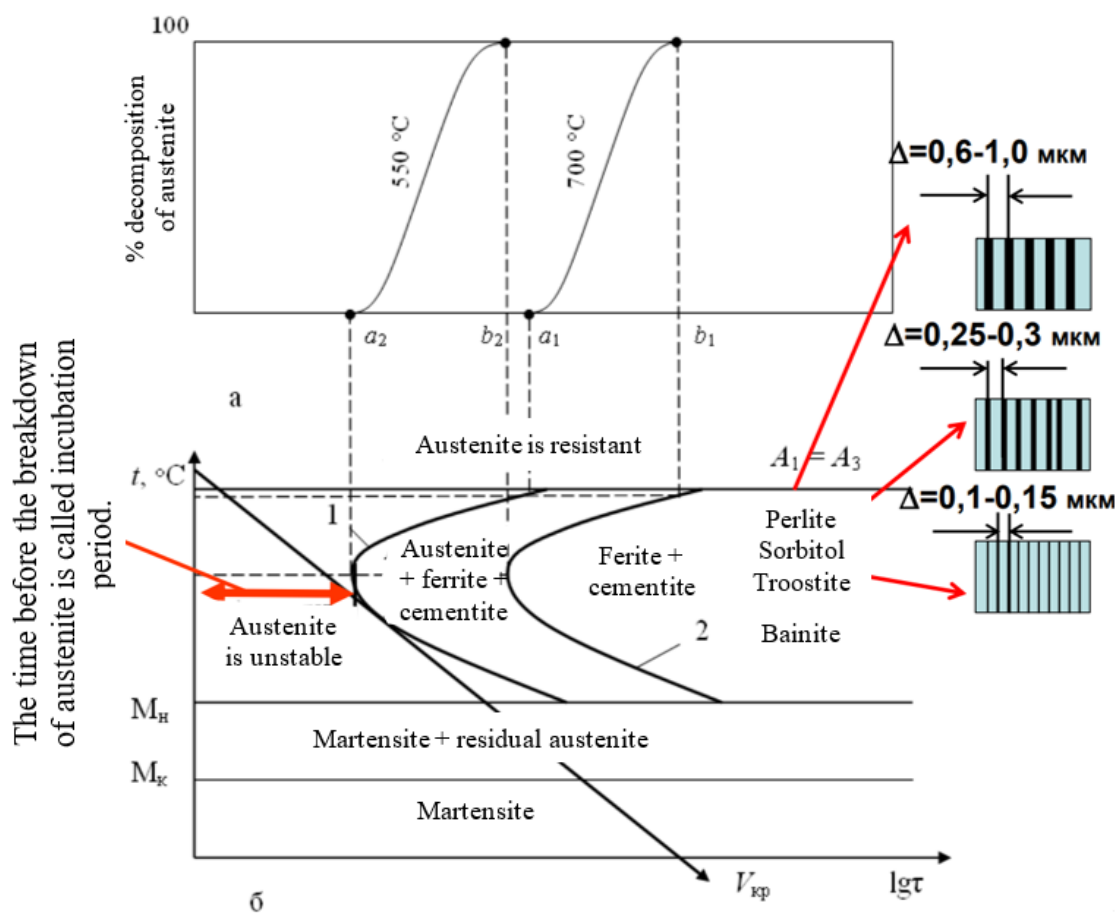


Figure 15.15 – Diagram of isothermal decomposition of austenite (C-shaped diagram) for eutectoid steel

15.3.4 Structures of the pearlite family resulting from the decomposition of austenite

Above the bend of the C-curves during the decomposition of austenite, pearlite family structures are formed that have a lamellar structure and are characterized by dispersity (the thickness of the cementite plates and the distance between them). The roughest structure is perlite, more dispersed – sorbitol and even more dispersed – reed. With an increase in the degree of dispersion of the structure, hardness and strength increase, while ductility and toughness decrease. During pearlite transformation, carbon redistribution occurs: ferrite plates containing 0.006 % carbon and cementite plates containing 6.67 % carbon are formed.

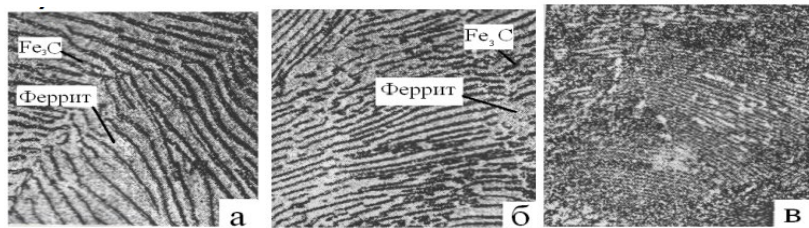


Figure 15.16 – Microstructures of perlite (a), sorbite (b), and troostite (c)

15.3.5 Features of martensitic transformation

When supercooling austenite to a temperature below M_n occurs martensitic transformation. Martensite (Fig. 15.17) – this is a supersaturated solid carbon solution in Fe_α , which has a needle standing.



Figure 15.17 – Martensite ($HCC \rightarrow BCC$): $A^{0,8} \rightarrow M^{0,8}$

With the formation of martensite occurs grid conversion $HCC \rightarrow BCC$, and carbon diffusion, due to low temperatures, is greatly slowed down. The carbon content in martensite is the same as in austenite. Such a transformation is called diffusionless.

Features of martensitic transformation:

- 1) Transformation occurs without an incubation period.
- 2) The transformation is not accompanied by diffusion of carbon atoms (low temperature).

3) The transformation does not occur isothermally. The transformation develops with decreasing temperature.

4) The size of the martensite plate depends on the size of the initial austenitic grain.

5) The martensitic transformation occurs by shear and is not accompanied by a change in the composition of the solid solution.

6) The specific volume of martensite is greater than austenite.

7) Temperatures M_n - M_k depend on the composition of the steel.

Martensite is a supersaturated solid solution of carbon in Fe_α . Carbon atoms strongly distort the BCC lattice. Martensite has a tetragonal lattice in which one lattice parameter h is greater than the other a . The ratio h/a is called the degree of tetragonality of the lattice. The greater the carbon content in martensite, the greater the degree of tetragonality of the lattice:

$$\frac{h}{a} = 1 + 0.046C$$

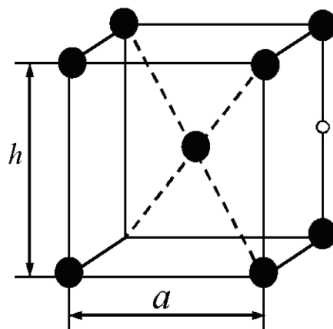


Figure 15.18 – Volume-centered tetragonal (VCT) lattice

Martensite is highly hard. Martensite crystals are in the form of plates.

Martensite can be obtained by cooling steel at a speed greater than critical. The critical speed is the lowest cooling rate at which a fully martensitic structure is formed.

The grain size of martensite is determined by the size of the original austenite grain (Fig. 15.20, a). A characteristic feature of martensite is its high hardness and strength, which increases with increasing amounts of carbon (Fig. 15.20, b).

With increasing carbon content, the height of the tetragonal prism $C(h)$ increases, and the dimensions of its base a decrease (Fig. 15.21, a). The martensitic transformation occurs by a shift, the external manifestation of which is a needle microrelief on the surface (Fig. 15.21, b).

Martensitic transformation does not proceed to the end. Therefore, in hardened steel having a point M_K below 20°C , namely in carbon steels containing $C > 0.4...0.5\%$, is present residual austenite (A_{ost}). With an increase in the amount of carbon, the temperatures of M_n and M_k shift in the region of lower temperatures. To reduce the number of A_{ost} and stabilize the size of the parts cold treatment.

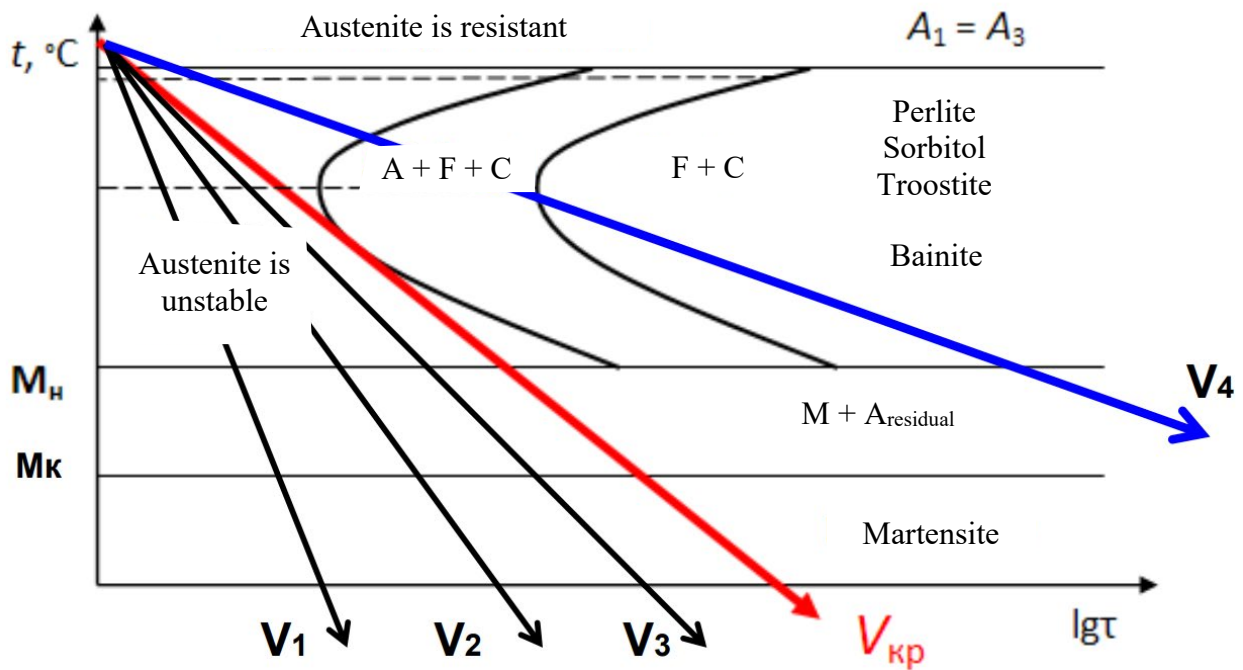
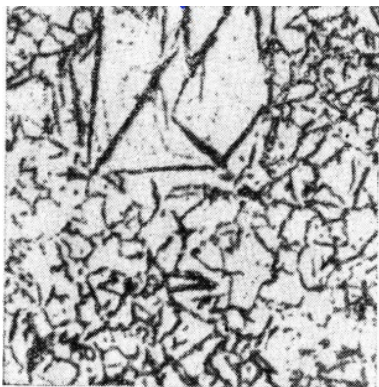
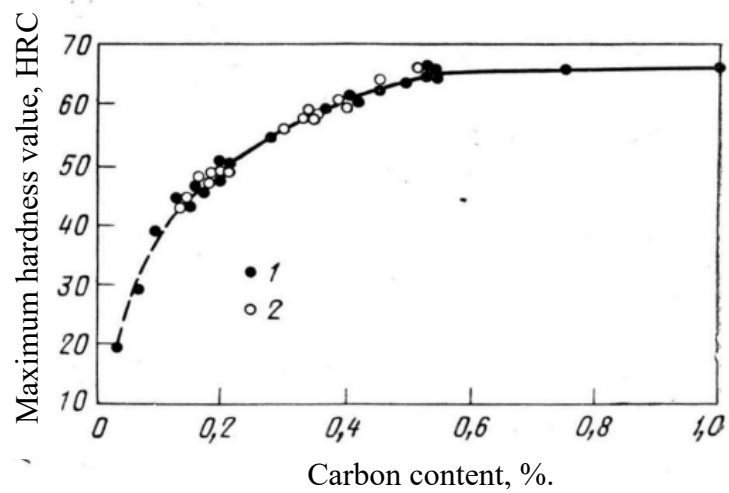


Figure 15.19 – Diagram of isothermal decomposition of austenite for eutectoid steel



a



b

Figure 15.20 – Microstructures of steels formed at different cooling rates

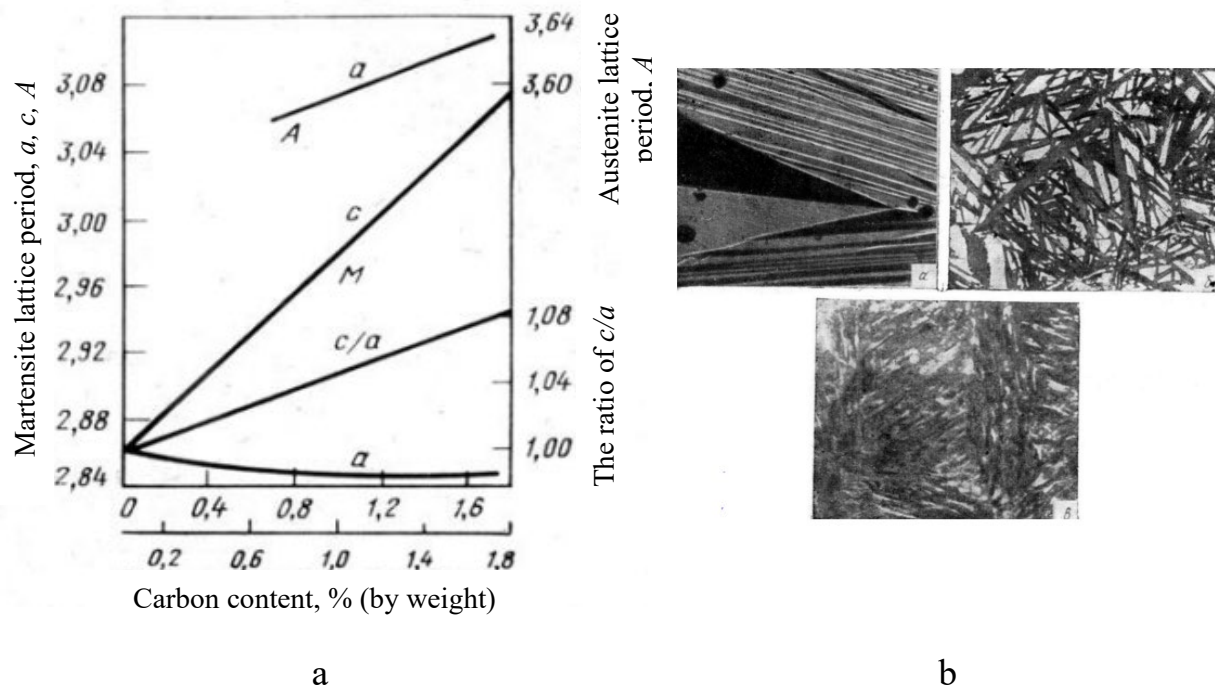


Figure 15.21 – The influence of carbon content on the microstructure and hardness of martensite

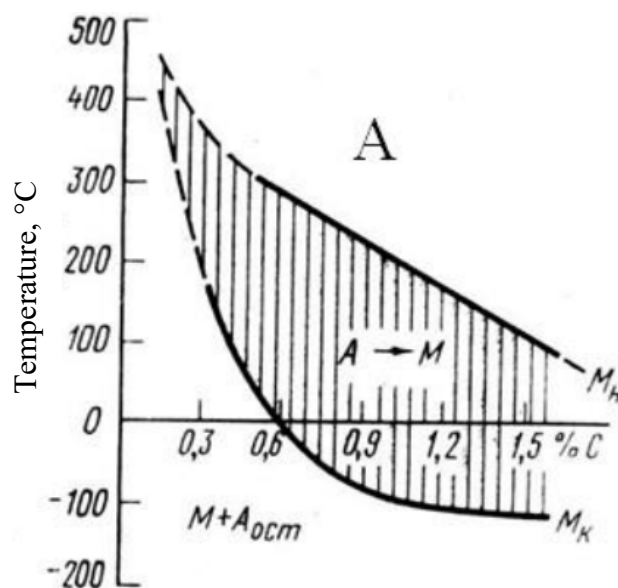


Figure 15.22 – The influence of carbon content on the crystal lattice and microstructure of martensite

Below a temperature corresponding to a minimum austenite stability of 550°C, bainitic transformation occurs. This is an intermediate transformation. Bainite is a ferrite-cementite mixture somewhat supersaturated with carbon and having a needle structure. Bainite combines elements of martensitic (diffusion-free) and pearlitic (diffusion) transformations. Bainite has high hardness, but less than martensite.



Figure 15.23 – The microstructure of bainite

15.4 The influence of alloying elements on the diagram of isothermal decomposition of austenite

Alloying elements, shifting the diagram of isothermal decomposition of austenite to the right, reduce the critical cooling rate – this is the lowest cooling rate at which a pure martensitic structure (V_{cr}) is formed (Fig. 15.24). This allows alloy steels to be cooled at a lower rate to obtain a martensitic structure. Carbon steels are cooled in water, and alloyed steels are cooled in oil. Alloying elements significantly affects the temperature range of the martensitic transformation. Most alloying elements lower the martensitic points. The influence of carbon affects the same direction.

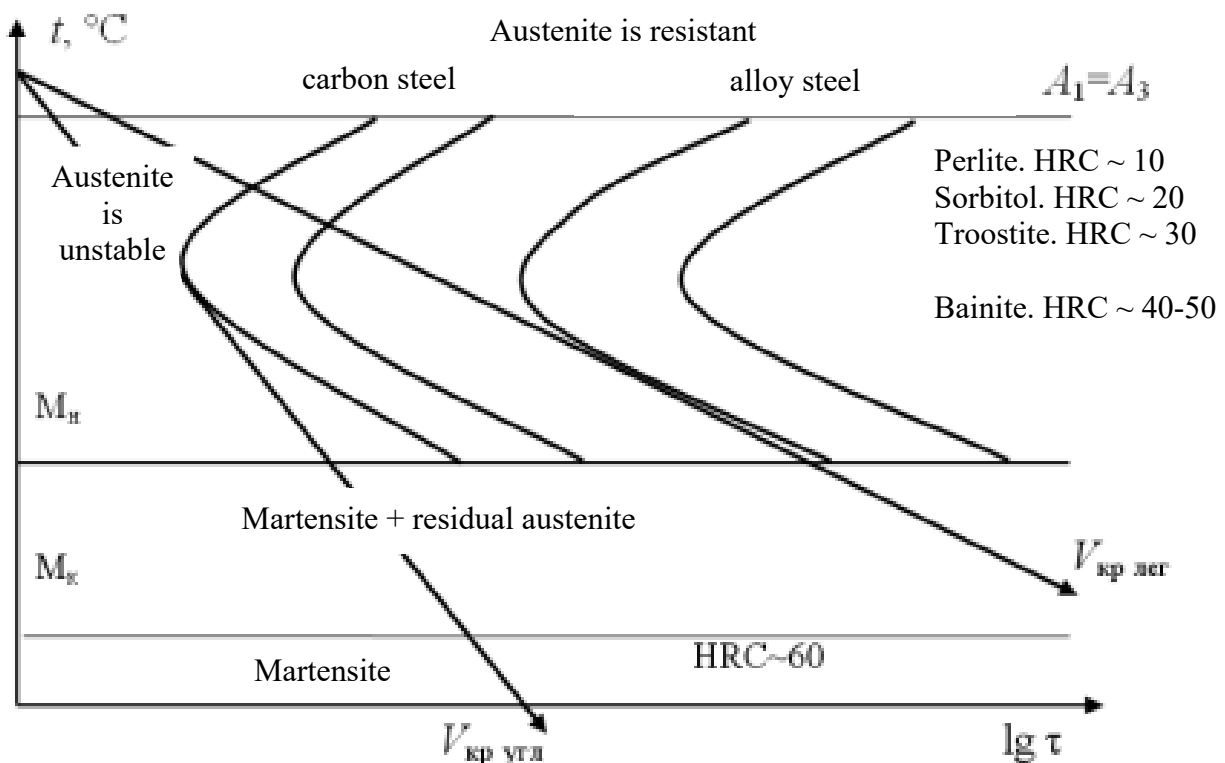


Figure 15.24 – The effect of carbon content on martensitic transformation temperatures

15.5 Austenite isothermal decomposition diagram for hypereutectoid and hypereutectoid steel

In pre-eutectoid steels on the line “Beginning of ferrite release” from austenite, ferrite first begins to precipitate (Fig. 15.25, a). In hypereutectoid steels on the line “Beginning of cementite precipitation” from cementite, cementite first begins to precipitate (Fig. 15.25, b).

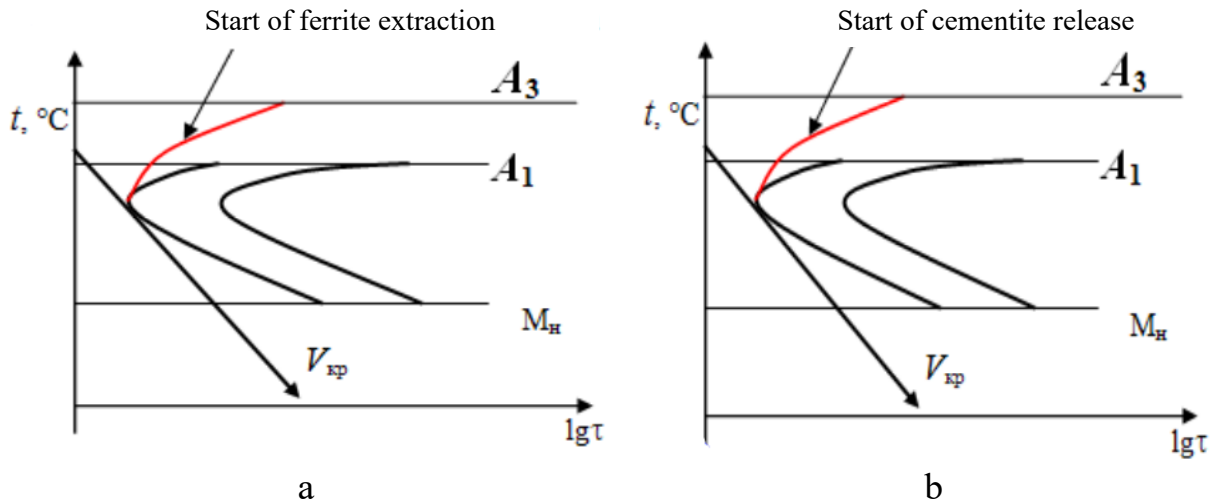


Figure 15.25 – Diagrams of isothermal decomposition of austenite for hypoeutectoid and hypereutectoid steels

TOPIC 16

TYPES OF HEAT TREATMENT. HARDENABILITY AND HARDENABILITY

16.1 The main types of heat treatment

Heat treatment (Fig. 16.1) consists in heating the steel to a certain temperature (t_n), holding it at that temperature (τ_n) and cooling at a certain speed ($V_{охл}$). The main factors of heat treatment – temperature, time, cooling rate.

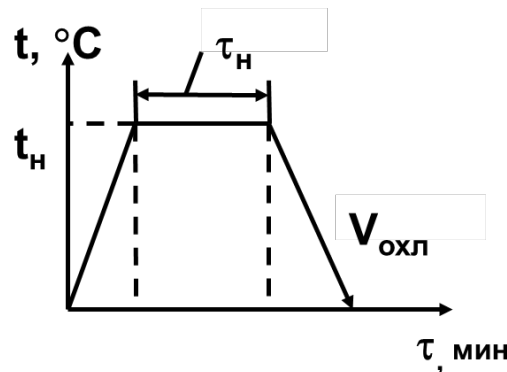


Figure 16.1 – Isothermal hardening diagram

The main types of heat treatment are: annealing; normalization; quenching; vacation.

Annealing, normalization, quenching – heating above A_{c1} or A_{c3} – phase transformations occur, tempering – heating below A_{c1} (Fig. 16.2).

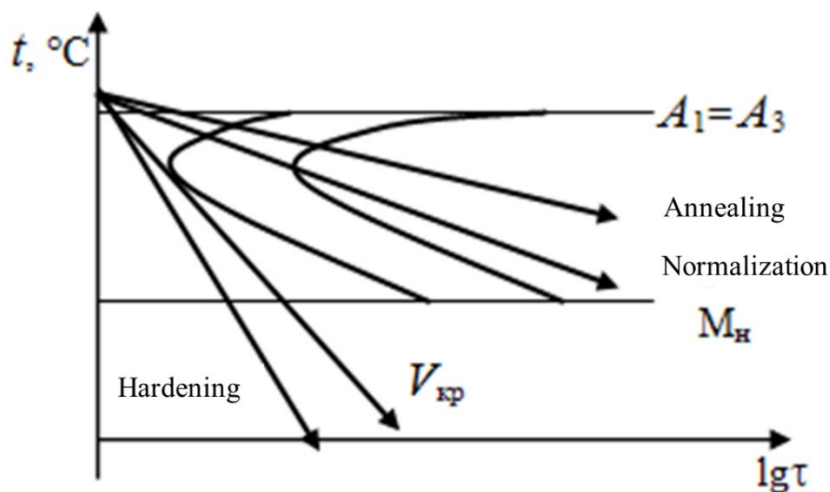


Figure 16.2 – Austenite transformation diagram during continuous cooling (CCT)

Annealing consists in heating to temperatures, as a rule, above critical A_{c1} , or A_{c3} , holding and slow cooling with the furnace.

Normalization – heating to temperatures above critical (A_{c1} or A_{c3} (A_{st})), holding and cooling in air.

Quenching – heating to temperatures above critical (A_{c1} , or A_{c3} (A_{st})), holding and cooling at a speed greater than or equal to critical.

Vacation – heating to a temperature below the critical A_{c1} , exposure and, as a rule, cooling in air.

Chamber resistance electric furnace CHO-3.6.2,5 / 13 (1300°C) allows thermal processing of various relatively large products – billets, gears, shafts, cases, pressure vessels, etc. – at temperatures of 700...1000°C (Fig. 16.3). The most efficient electric furnace is used in small-scale and single-unit production, as well as in repair and restoration sites.



Figure 16.3 – Chamber resistance electric furnace



Figure 16.4 – Vacuum chamber electric furnaces of resistance with screen thermal insulation of the Vega series



Figure 16.5 – Chamber gas furnaces for heat treatment

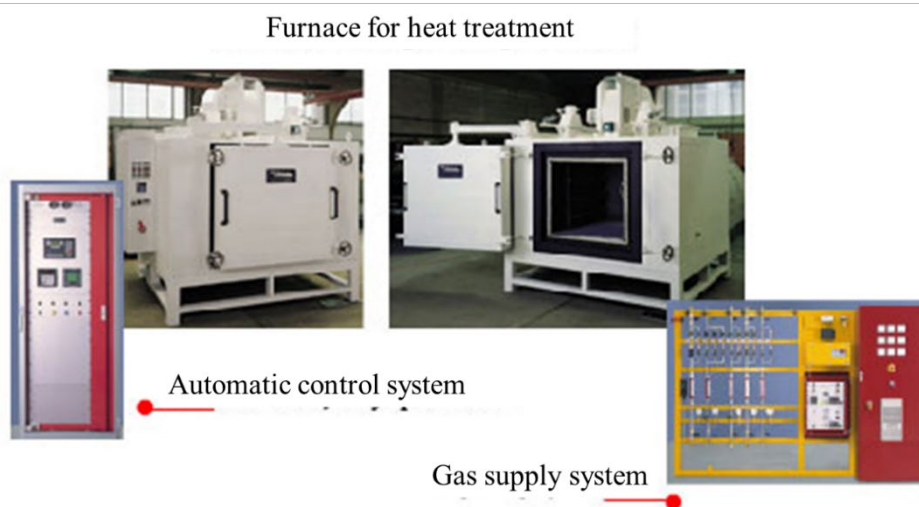
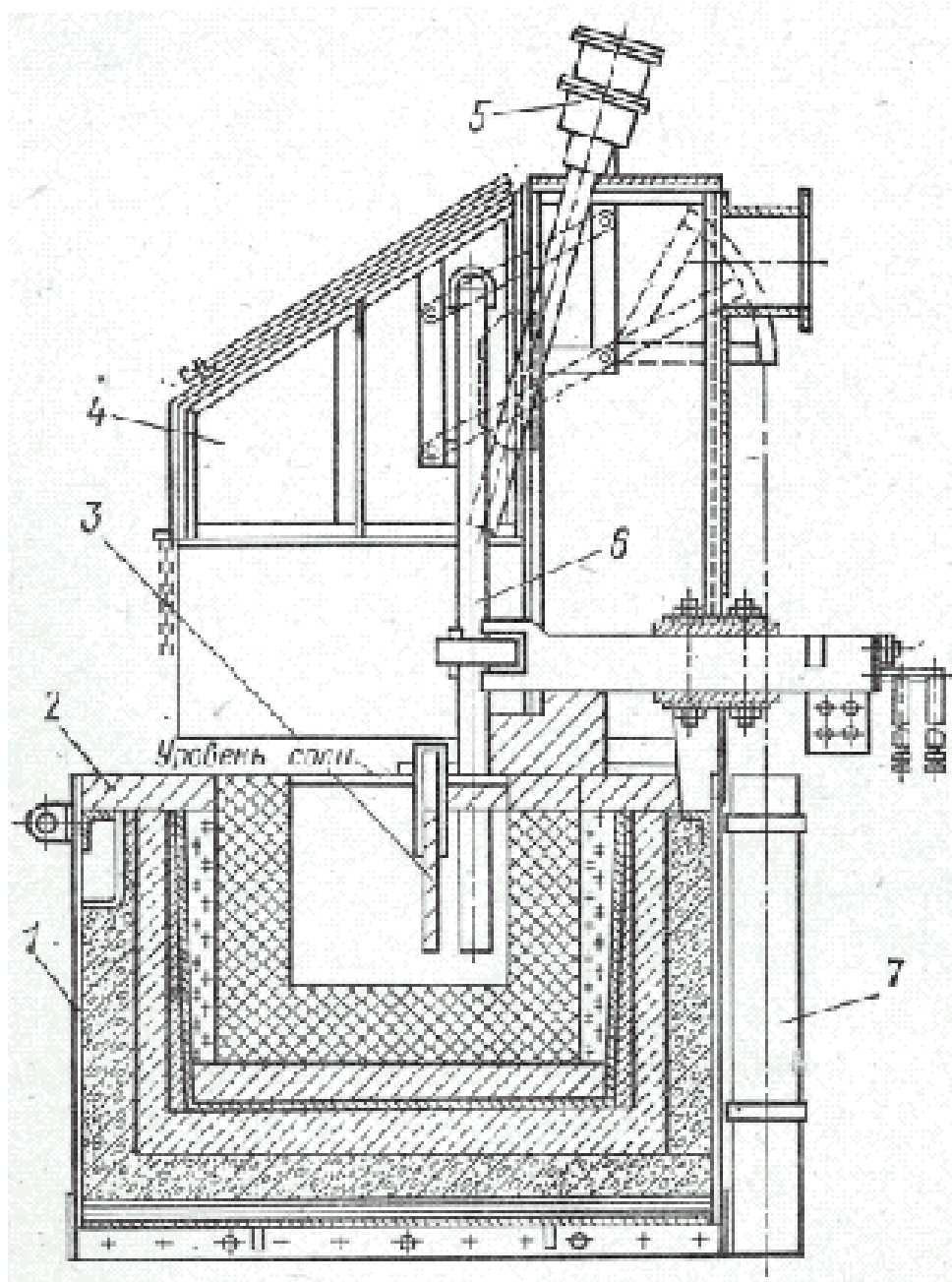


Figure 16.6 – Industrial electric furnaces for heat treatment



Figure 16.7 – Bogie-hearth heat treatment furnaces



1 – casing, 2 – lining, 3 – partition, 4 – umbrella, 5 – pyrometer, 6 – electrode group, 7 – counterweight

Figure 16.8 – Three-phase electrode bath furnace



Figure 16.9 – Gear quenching press KLINGELNBERG AH 400 S

16.2 Annealing

Annealing consists in heating to temperatures, as a rule, above critical A_{c1} , or A_{c3} , holding and slow cooling with the furnace.

The purpose of annealing:

- 1) Relieve internal stresses after preliminary processing (stamping, casting);
- 2) Improve machinability by cutting;
- 3) To correct the structure after preliminary treatment (for example, after overheating).

Annealing is a preliminary heat treatment (Fig. 16.10).

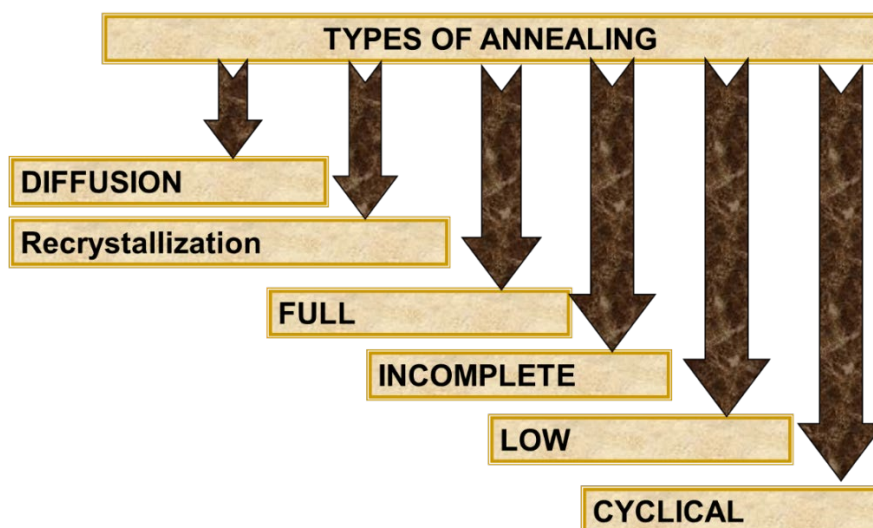


Figure 16.10 – Types of annealing

Depending on the purpose, there are various types of annealing. Diffusion annealing (homogenization) is carried out in order to reduce or eliminate the

heterogeneity of the chemical composition (Fig. 16.11). Temperature 1000...1100°C, long exposure. Recrystallization annealing (3) is used to remove cold-formed steel hardening $t_H = t_p + (100...50^\circ\text{C})$.

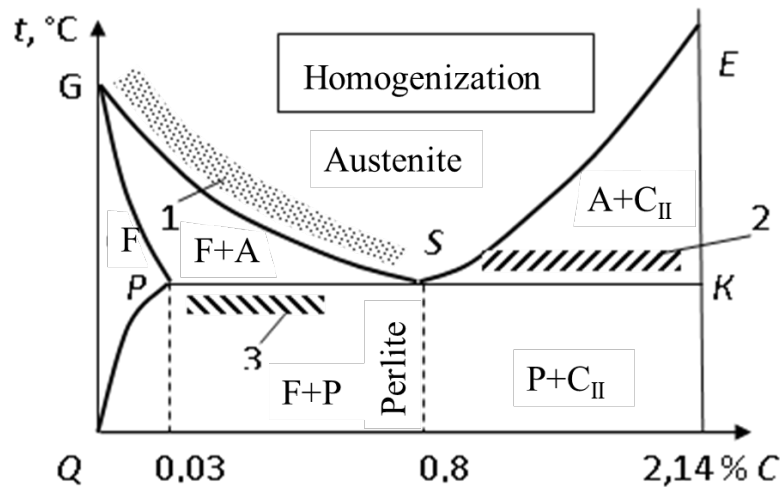


Figure 16.11 – Austenite transformation diagram during continuous cooling (CCT) with illustration of heat treatment modes

Complete annealing (1) is carried out with the aim of complete phase recrystallization for grinding grain and consists in heating 50...60°C above the critical point A_{c3} – $t_H = A_{c3} + (50...60^\circ\text{C})$. Incomplete annealing (2) – heating to temperatures 50...60°C above A_{c1} , is used to improve machinability. After incomplete annealing, carbides acquire a granular form, and a granular perlite structure form. Such annealing is also called spheroidization $t_H = A_{c1} + (50...60^\circ\text{C})$.

Granular perlite steels have lower hardness, temporary resistance and high ductility. Hypereutectoid tool steels give partial annealing.

Castings, welded joints, parts after machining, pressure are applied to low annealing (3) to relieve residual stresses. Temperature $t_H < A_{c1} = 500...650^\circ\text{C}$.

Cyclic annealing involves several heating and cooling cycles around the critical point A_1 (Fig. 16.12). The purpose of this annealing is to turn lamellar cementite into granular, i.e., get a rounded shape of carbide particles, which greatly improves the processing of steels by pressure and cutting. Annealing is not an economical operation; therefore, if possible, it is replaced by normalization.

A distinctive feature of isothermal annealing is that when it is carried out, the decomposition of austenite into a ferritic-cementite mixture occurs at a constant temperature. In other types of annealing, such a decomposition occurs during the cooling period under conditions of a continuous decrease in temperature.

After the decomposition of austenite has already occurred, the cooling rate is not significant, and therefore, cooling after isothermal exposure can be carried out in air (Fig. 16.13). This has certain advantages. Firstly, the process time is reduced, especially for alloy steels, which require very slow cooling during normal annealing. Secondly, the structure is more homogeneous, since the transformation of austenite

into perlite occurs at the same temperature, and not in the temperature range, as during ordinary annealing.

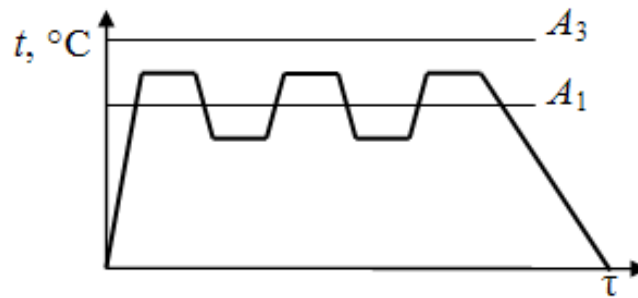


Figure 16.12 – Diagram of structural transformations of steel during annealing

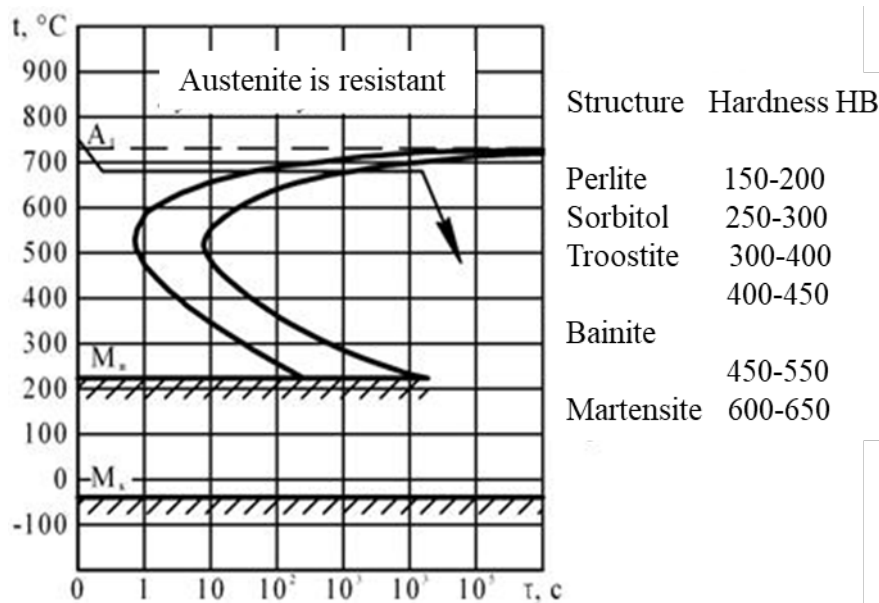
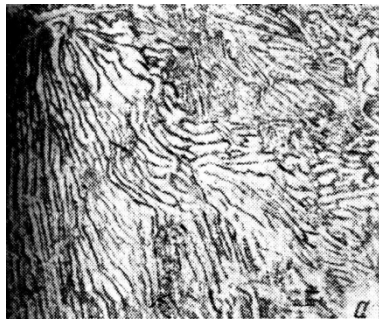


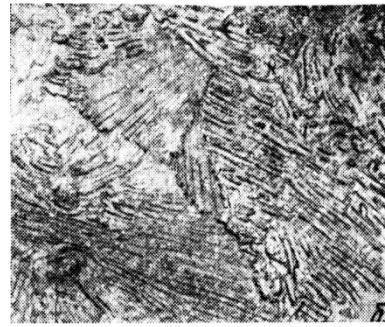
Figure 16.13 – Diagram of isothermal decomposition of austenite and characteristics of final steel structures

16.3 Normalization

Normalization is a heat treatment consisting in heating the steel above critical points, holding and subsequent cooling in air in order to grind grain and obtain a more uniform structure. After normalization, a dispersed ferrite-pearlite structure is formed – sorbitol or troostite. For medium-carbon alloyed steels, normalization is a hardening treatment (instead of hardening) because sorbitol or reedite structures that have a hardness of 40-45 HRC are obtained. Annealing and normalization are most often preliminary types of heat treatment.



a



b

Figure 16.14 – Perlite (a), sorbitol (b)

TOPIC 17

MAIN TYPES STEEL HEAT TREATMENT

17.1 Steel hardening

Quenching – heating to temperatures above critical (A_{c1} , or A_{c3} (A_{st})), holding and cooling at a speed greater than or equal to critical. This is a hardening heat treatment that is carried out to increase hardness and strength. Heating temperature the hypereutectoid steels are heated under quenching to $t = A_{c3} + (50...60^{\circ}\text{C})$. In this case, the steel acquires an austenitic structure. When cooled, austenite turns into martensite (a). Hypereutectoid steels under quenching are heated to $t = A_{c1} + (50...60^{\circ}\text{C})$. The structure of austenite and secondary cementite is formed. After cooling, the structure consists of martensite and cementite, which have high hardness (b).

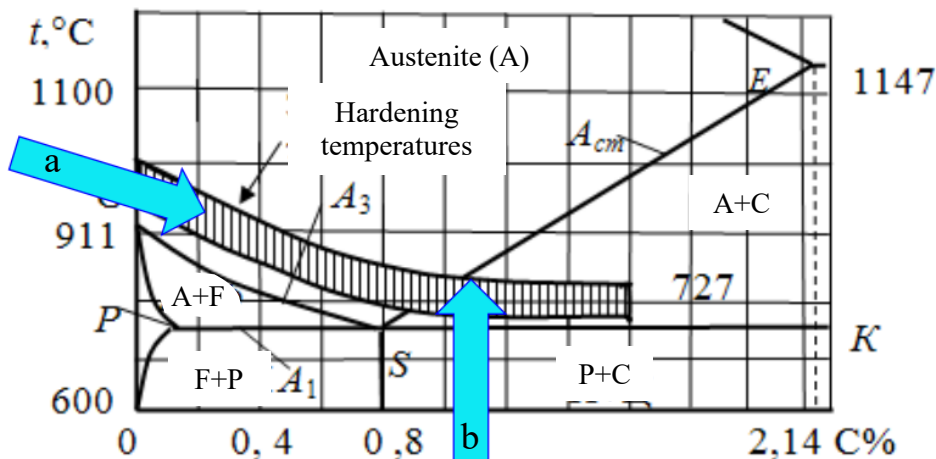


Figure 17.1 – Tempering temperature schedule on the iron-carbon phase diagram

17.1.1 Selection of quenching coolant

Cooling during hardening is carried out with a speed greater than or equal to the critical – $V_{\text{cool}} > V_{\text{cr}}$. Quenching coolants are water and oil. Water cools very quickly and oil cools slowly. Alloy steels with low V_{cr} should be cooled in oil, and carbon steels with high V_{cr} should be cooled in water. When cooled in water, large internal stresses can occur, leading to warpage of the product and the appearance of cracks.

During hardening, two types of stresses arise: thermal and structural. Thermal stresses arise as a result of temperature differences across the cross section. Structural stresses are associated with structural changes – the volume of martensite is greater than the volume of austenite. The ideal cooler is quick cooling in the M_n - M_k interval to prevent the decomposition of austenite into ferrite and cementite and slow cooling in the M_n - M_k interval to reduce structural and thermal stresses.

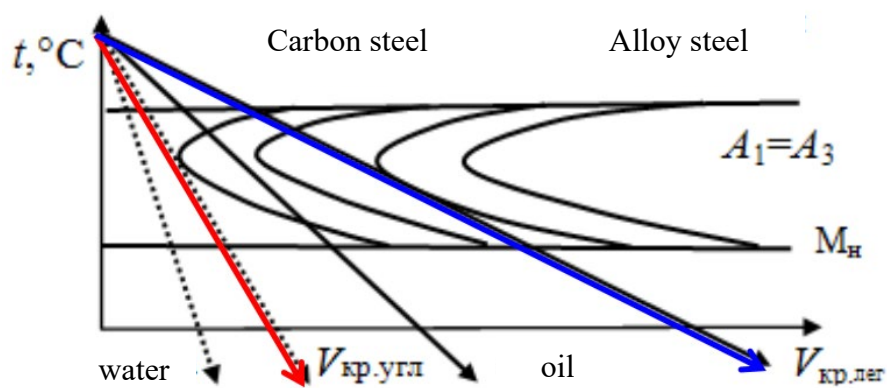


Figure 17.2 – Selection of quenching medium depending on steel hardenability

Table 17.1

Steel	Structure after cooling	
	in water	in oil
Carbon steel	M	M + T
Alloy steel	M	M

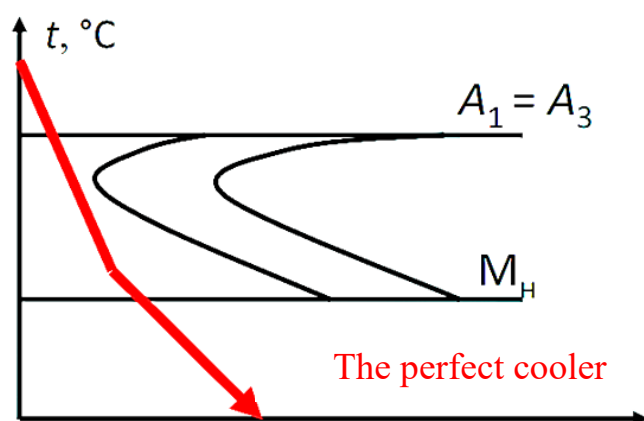


Figure 17.3 – Austenite transformation diagram

17.1.2 The choice of heating medium products

The easiest way to heat products is to heat the air in the oven. But such heating is accompanied by oxidation and decarburization of the surface of the products. To protect the surface of products, heating can be carried out in vacuum furnaces, in furnaces with gas protective media (argon, hydrogen), in molten salts (NaCl, BaCl₂) and metals. The exposure time τ is calculated in such a way as to ensure the heating of the entire cross section to complete phase transformations and redistribution of carbon. If the heating is carried out in a vacuum or a gaseous medium, then take $\tau = 1 \text{ min/mm}$ of the thickness of the part.

17.2 Special types of hardening

In the practice of heat treatment, special types of hardening are used that reduce the internal stress (Fig. 17.4): with undermining (2), intermittent (in two environments) (1), stepwise (3), isothermal (4).

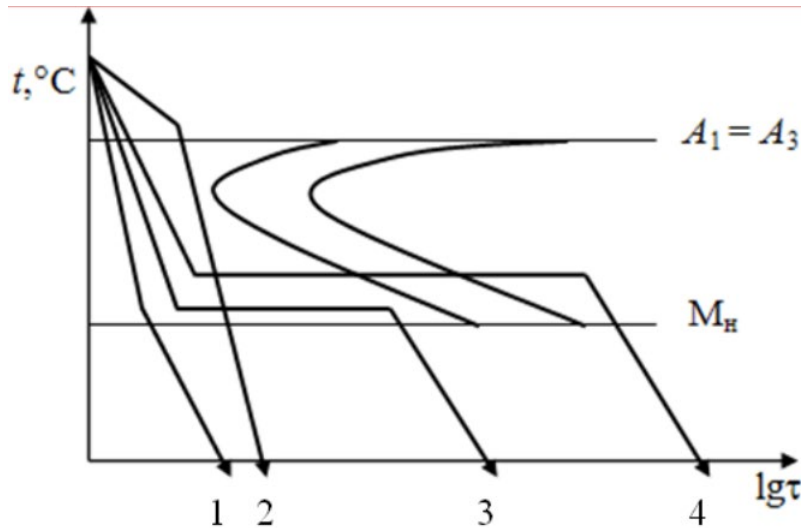


Figure 17.4 – Special types of hardening

In the first three types of hardening, the martensite structure is obtained, a significant reduction in thermal stresses is achieved, and in stepwise, a complete removal of thermal stresses is obtained. After isothermal hardening, a bainite structure is obtained, which includes ferrite somewhat supersaturated with carbon. There is a decrease in structural stresses. With isothermal hardening, there are practically no internal stresses.

17.3 Steel tempering

Vacation is the final heat treatment, which consists in heating the steel to a temperature below the critical point A_{c1} , holding and cooling, usually in air (sometimes in oil). Purpose of vacation:

- To remove partially or completely internal stresses that occurred during hardening;
- Get the necessary structure to ensure the necessary operational properties.

Depending on the properties that need to be obtained, there are three types of vacation: low; average; high.

17.4 Low vacation

Low tempering is carried out at a temperature of $150\text{--}250^\circ\text{C}$. At the same time, internal stresses are removed by $1/3$, and the hardness remains high. It is carried out for tools, bearings, parts surface hardening and cementation.



Figure 17.5 – Martensite quenching turns into vacation martensite: $M_z \rightarrow M_o$

17.5 Average steel vacation

Average tempering is carried out at a temperature of 300-450°C mainly for springs and springs. Average tempering provides high limits of elasticity and endurance, since during the tempering process martensite breaks up into a dispersed ferrite-cementite mixture, called tempering troitite, in which cementite inclusions have a granular shape. At the same time, internal stresses are removed by 2/3. It is carried out for springs and springs.

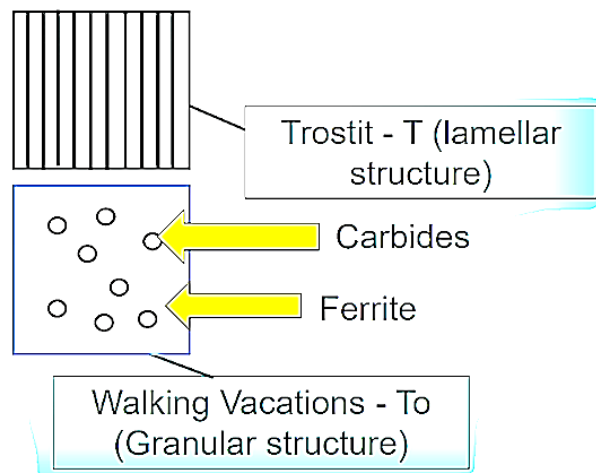


Figure 17.6 – $M_z \rightarrow F + T_s \rightarrow T_o$

Lamellae structures are formed during the decomposition of austenite (Fig. 17.7, a). Granular structures are formed during the decay of martensite during tempering (Fig. 17.7, b).

17.6 High vacation

High tempering is carried out in the temperature range 500-680°C. In this case, martensite decomposes into a ferrite-cementite mixture and the process of enlargement of carbide (cementite) particles of a spherical shape. In this case, internal stresses are completely removed. The ductility and toughness increase, the conditional yield strength is kept at a sufficiently high level.

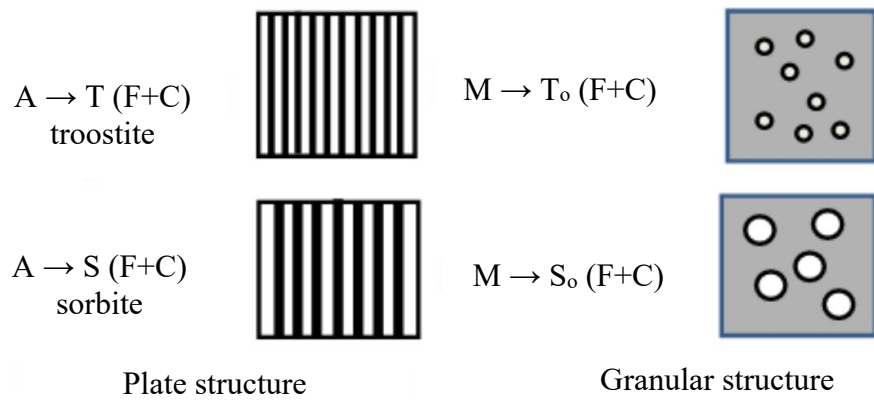


Figure 17.7 – Decomposition of austenite and martensite

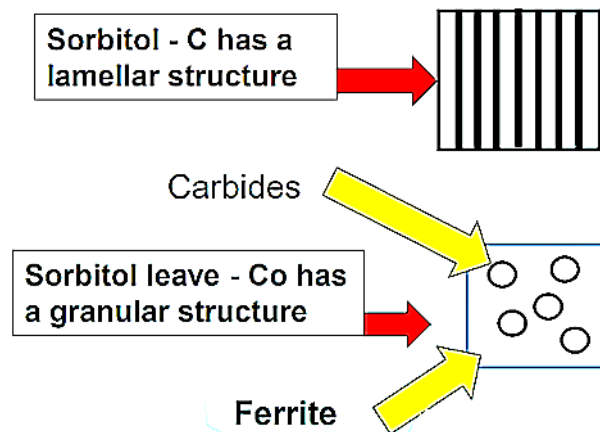


Figure 17.8 – $M_z \rightarrow F + C \rightarrow S_o$

High tempering is called improvement. Improvements are made for parts that operate under shock loads, such as shock shafts and connecting rods. Granular structures provide the best combination of strength, ductility and toughness.

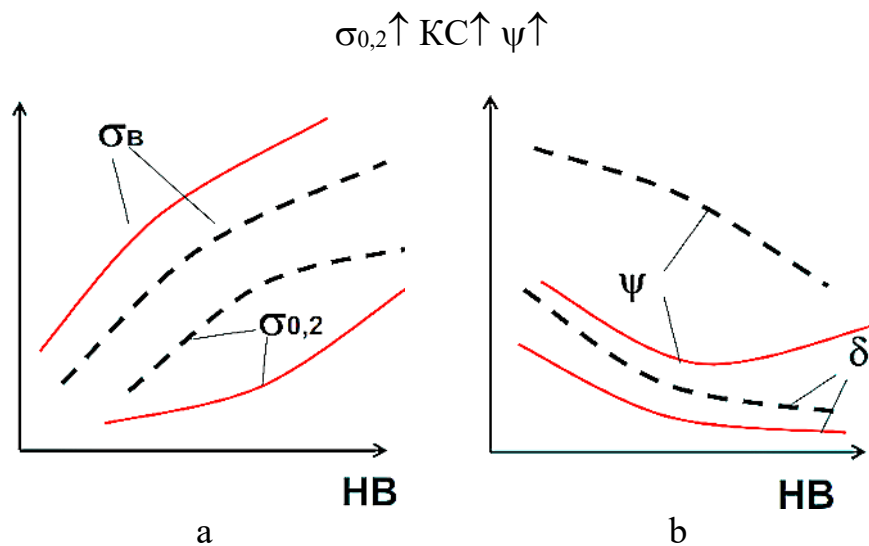
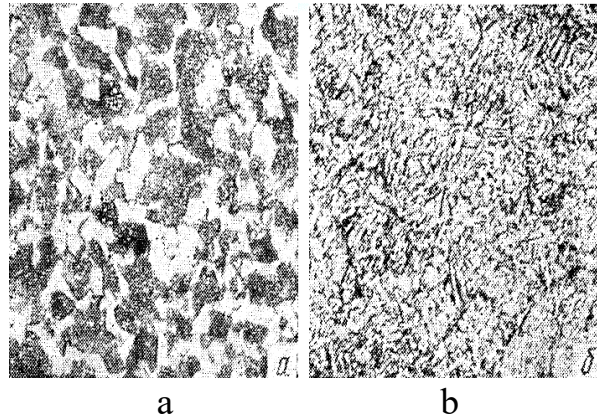
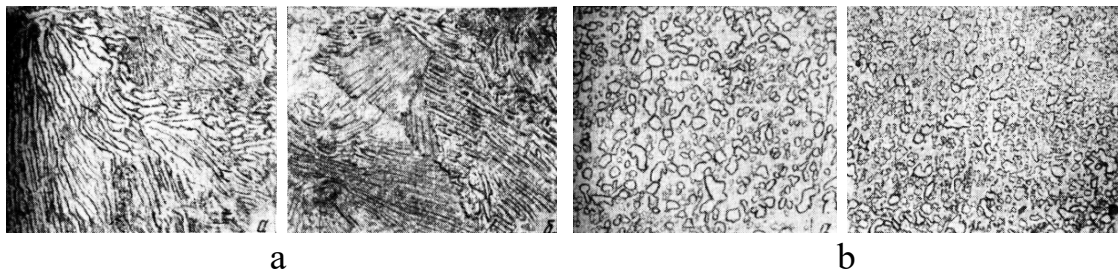


Figure 17.9 – Diagram of isothermal (a) and stepwise (b) hardening



a – annealing, b – improvement

Figure 17.10 – Comparison of the structure of steel 30HGSA after annealing and improvement



a – lamellar structures (F + C-lamellar), b – granular structures (F + C-granular)

Figure 17.11 – Comparison of the structure of steel with 0.6% carbon after annealing (a) and improvement (b)

17.6.1 Vacation

With an increase in tempering temperature, internal stresses decrease, hardness and strength decrease, ductility and toughness increase.

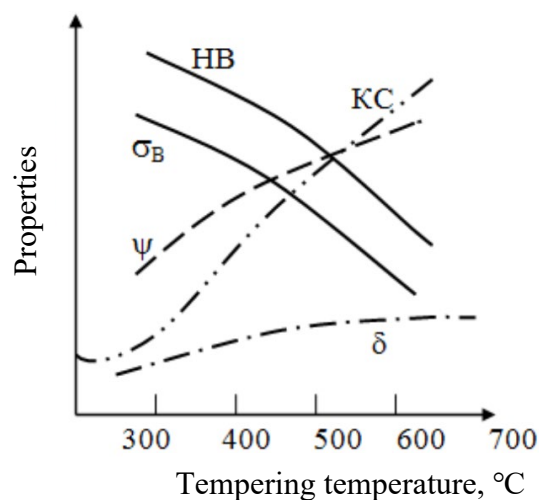


Figure 17.12 – Dependence of mechanical properties of steel on tempering temperature

TOPIC 18

HARDENABILITY AND HARDENABILITY BECOME

18.1 Steel hardenability

Hardenability is the ability to increase hardness during hardening. After quenching, a martensite structure is formed. The hardness of martensite depends on the carbon content. The more martensite is supersaturated with carbon, the higher its hardness. Thus, hardenability depends on the carbon content. Alloying elements practically do not affect hardenability.

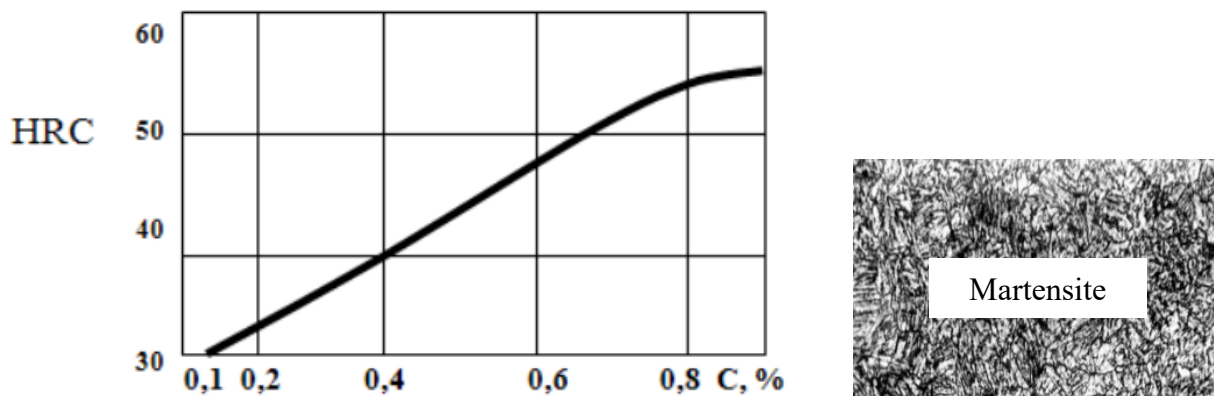


Figure 18.1 – Dependence of the maximum hardness of hardened steel on carbon content

By hardenability is understood, the ability to become hardened to a certain depth. During quenching, the maximum cooling rate is achieved on the surface of the part. As you move away from the surface, the cooling rate decreases. Hardenability is determined by the critical cooling rate V_{cr} , which depends on the composition of the steel and the cooling medium (Fig. 18.2).

If the actual cooling rate in the core of the product is less than the critical speed, then the hardenability will not be through. If the actual cooling rate in the core of the product is equal to or greater than the critical V_{cr} , then the hardenability is through. For a quantitative assessment of hardenability, the diameter d_{cr} is used, which is the maximum diameter of a cylindrical sample, hardened through and through in this cooler. The critical diameter depends on the presence of alloying elements. For steel 40 $d_{cr} = 12$ mm (Fig. 18.3).

Most strongly increase hardenability manganese, chromium, nickel, cobalt. The effective effect of boron on hardenability is manifested when it is contained in steel in an amount of 0.002-0.006 %. When alloying steel with several elements, hardenability can be increased most significantly. Steel 40 has a hardenability worse than steel 40X (Fig. 18.4). And 38HGSA steel has better hardenability than 40X steel. It is advisable to introduce several different alloying elements.

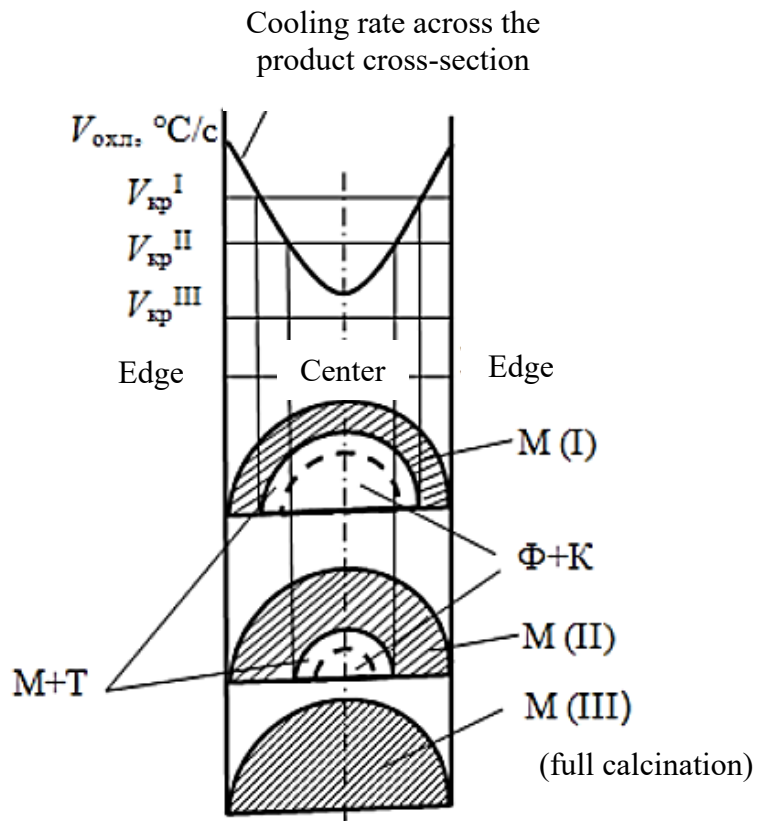


Figure 18.2 – Diagram showing the dependence of hardening depth on steel hardenability

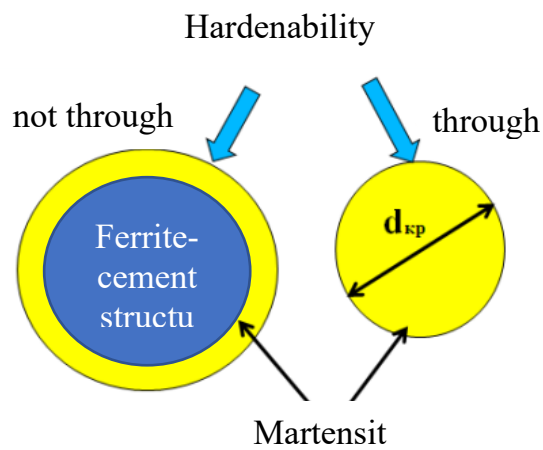


Figure 18.3 – Steel hardenability chart

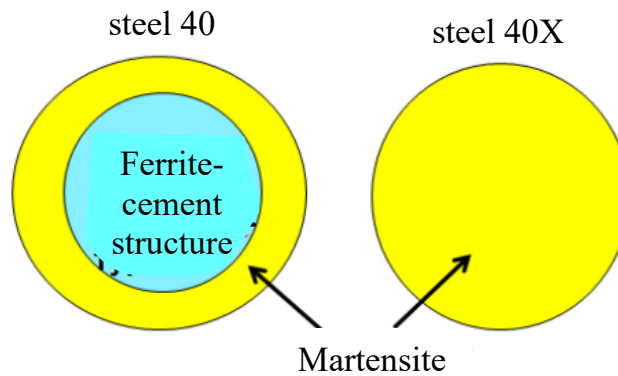


Figure 18.4 – Comparison of the hardenability of steels 40 and 40X

18.1.1 Factors Affecting Steel Hardenability

Quenching in water provides a larger critical diameter than in oil (Fig. 18.5). Alloying elements increase hardenability, which can be demonstrated by the hardenability band of steels containing the same amount of carbon (0.4 %), but with different degrees of alloying (Fig. 18.6).

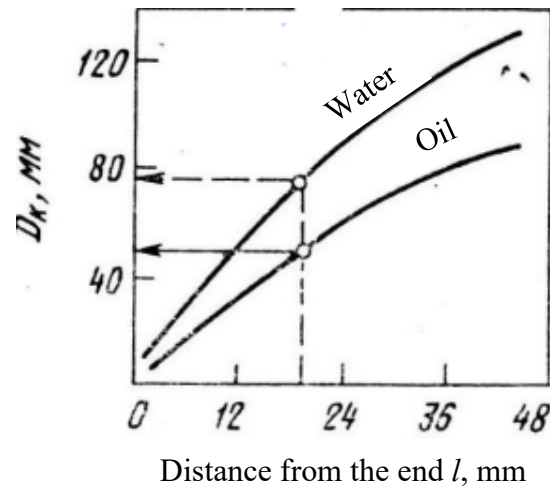


Figure 18.5 – Hardness of steel during quenching in water and oil

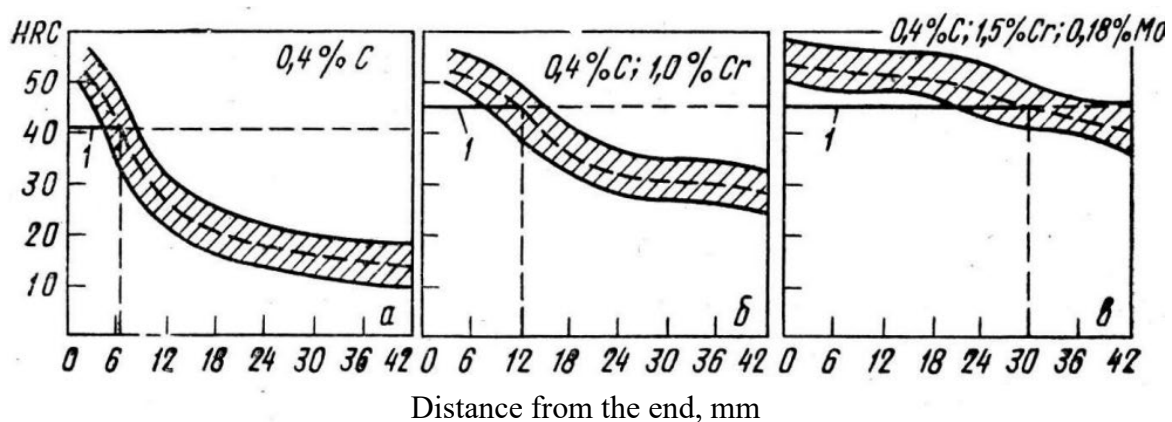


Figure 18.6 – The effect of alloying on the hardenability of steels with the same carbon content

18.2 Steel heat treatment defects

The main defects during heat treatment include:

- Insufficient hardness;
- High hardness;
- Warping and cracking;
- Oxidation and decarburization.

Insufficient hardness can be caused by the following reasons:

– V_{hok} during hardening was less than V_{crh} . Critical (carbon steel was cooled in oil, not in water);

– The temperature of the heating for hardening is lower than the required temperature,

– High temperature vacation.

This type of marriage can be corrected by repeated heat treatment in the correct mode.

High hardness, as a rule, is due to the fact that the tempering temperature was lower than required. This type of marriage can be fixed by a second vacation:

– Warping is an asymmetric deformation of parts (the part is heated and a force is applied in the press).

– Cracks are an incorrigible type of marriage.

– In order to avoid oxidation and decarburization, heating should be carried out in a protective gas environment, vacuum, metal melts, salt baths.

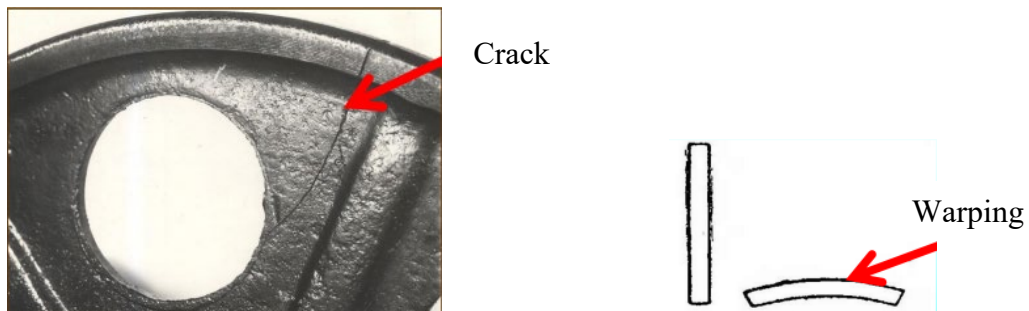


Figure 18.7 – Typical heat treatment defects: cracks and warping

– Warping is an asymmetric deformation of parts (the part is heated and a force is applied in the press).

To prevent warpage and cracks, you must: apply special types of hardening; after machining before quenching, conduct annealing to relieve stress; long products to heat and cool in an upright position and other methods.

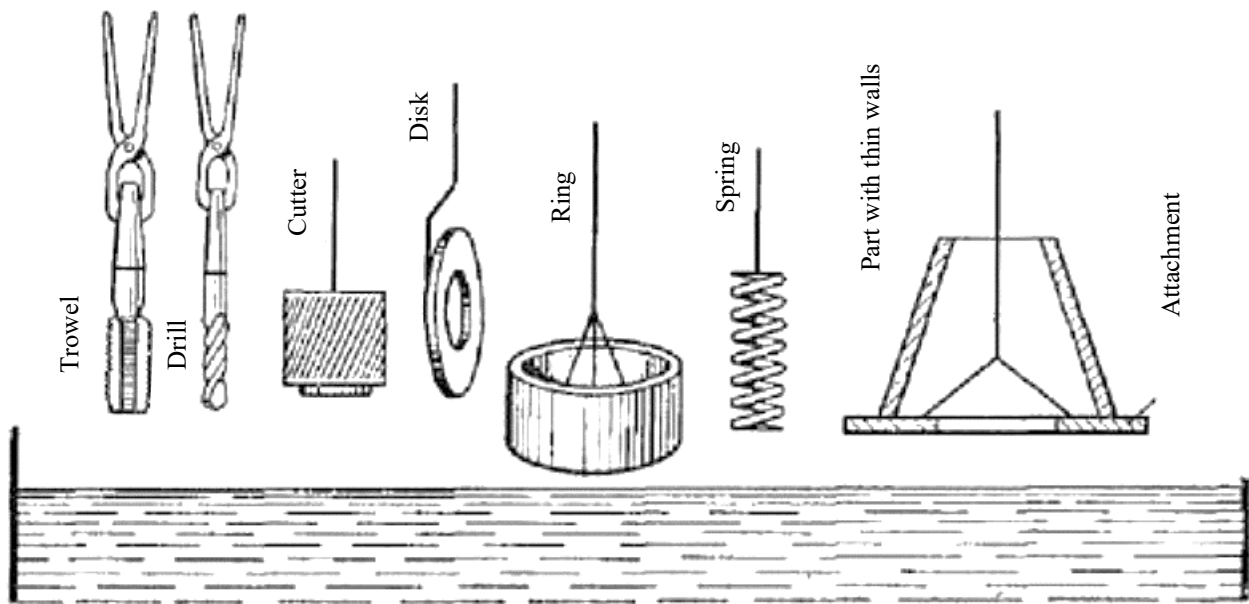


Figure 18.8 – Hardening of steel parts of various shapes

TOPIC 19

SURFACE METHODS HARDENING MACHINE PARTS

19.1 Surface hardening methods for machine part

1 – methods of surface heat treatment without changing the chemical composition of the material;

2 – methods of heat treatment with a change in the chemical composition of the surface layers.

The first group includes various methods of surface hardening, and the second one includes methods of chemical-thermal treatment (CT). Parts are subjected to surface hardening, the surface layers of which wear out intensively during operation, and the inner layers must resist cyclic and significant dynamic loads, so the core of the part must be viscous and sufficiently ductile, and the surface should be hard and wear-resistant.

19.2 Surface hardening

Surface hardening is carried out by two methods with gas-flame and induction heating.

1) Induction hardening is carried out by heating the surface of the product with high-frequency currents – hardening of high-frequency currents.

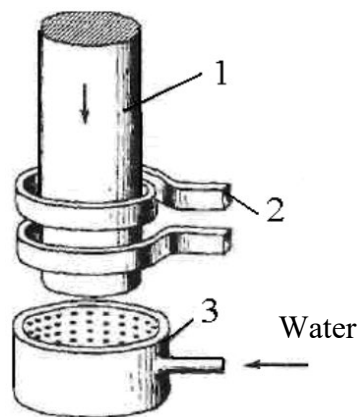


Figure 19.1 – Induction hardening machine

The current penetration depth and, accordingly, the quenching depth δ depends on the current frequency (f):

$$\delta = \frac{\alpha}{\sqrt{f}}$$

α – depends on the chemical composition of the steel.

Heated areas are cooled with water from a shower device – a sprayer. After surface hardening, low tempering follows to partially relieve stress without a noticeable decrease in hardness.

Hardening of HFC is used for medium-carbon steels with a carbon content of mainly 0.4...0.45 %. An example of such steels is 40, 45, 40X, 40XN, etc. The advantages of hardening HFC:

- High performance.
- Automation capability.
- Fine grain.
- Lack of warpage.
- Compressive stress.
- Ecological cleanliness.

Disadvantages:

- For each part, an inductor of a certain shape is required.
- Inability to process local areas in hard-to-reach places and on the plane.

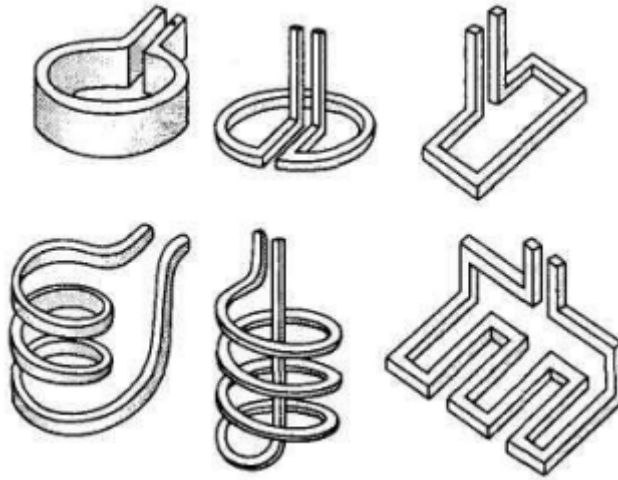


Figure 19.2 – Inductors

2) When gas-flame hardening, the surface of the product is heated with an acetylene-oxygen flame using a burner.

The burner is moved along the part, the surface of which is heated above A_{c3} . The heated part is cooled by water. The degree of heating of the surface layer is controlled by the power of the flame and the duration of its exposure.

1) Hardening of HFC requires the use of special equipment and is advisable mainly in mass production.

2) For gas-flame surface hardening, the simplest devices and equipment are used. This hardening is a widely used manufacturing process.

19.3 Laser hardening

Laser radiation intensely heats the surface of the material to supercritical temperatures, and after the termination of the radiation, the heated section is cooled

by heat removal into the inner layers of the metal, which leads to the formation of quenching structures and an increase in the hardness of the surface layer. Laser processing technology is divided into pulsed and continuous. Pulse processing is carried out on solid-state lasers. The largest coarse impulse quenching is 200-250 microns. To increase the processing area and the depth of hardening, continuous wave lasers are used. The power of process lasers for heat treatment is more than one kilowatt.

Laser hardening benefits:

- 1) Local exposure to the material;
- 2) The ability to handle hard to reach places;
- 3) Fast software process control;
- 4) The possibility of hardening both with reflow and without reflow;
- 5) The hardness and wear resistance of the metal in the hardened zone increases several times due to the production of fine grain, highly dispersed martensite.
- 6) No warpage.



a



b



c

a – Medical tool hardening, b – Circular Saws, c – Appearance of the blade of a kitchen knife with various hardening modes

Figure 19.3 – Examples of surface hardening of steel products

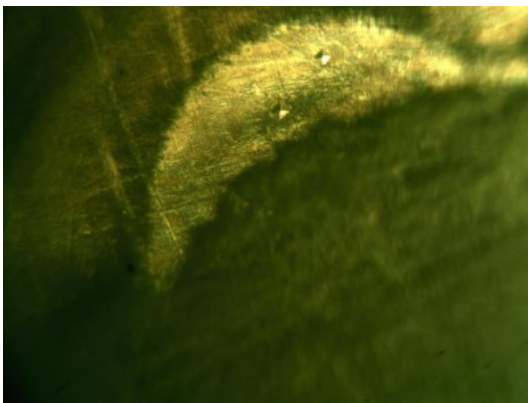


Figure 19.4 – Laser quenching zone (without surface melting)

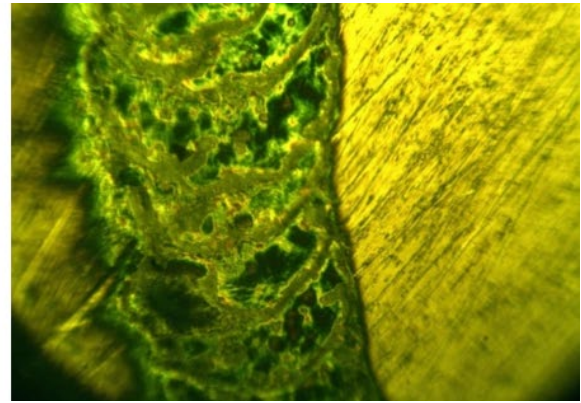
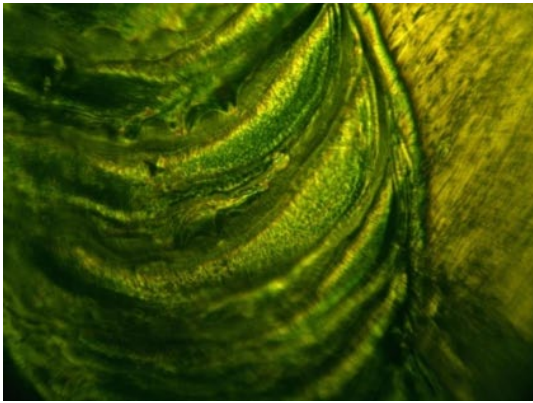


Figure 19.5 – Surface hardened laser hardening

Disadvantages of laser hardening:

- 1) Higher energy costs;
- 2) Low productivity;
- 3) The shallow depth of the hardened layer;
- 4) The high cost of equipment and the process itself.



Figure 19.6 – Complex for hardening cylinder liners of diesel engines, laser power 1.5 kW

19.4 Chemical heat treatment

Chemical-thermal treatment (CT) consists in saturating the surface of a product with a certain element in combination with heat treatment. The chemical and thermal treatment process consists of three stages:

- 1) Dissociation
- 2) Adsorption
- 3) Diffusion.

Dissociation – obtaining an element in an active atomic state. Adsorption is the absorption of the surface of an element in an active atomic state. Diffusion – penetration of an element into the interior of a part. Types of CT – cementation, nitriding, nitrocarburizing, diffusion metallization, etc.

The advantages of CHT compared to surface heat treatment:

- 1) provides a higher hardness and wear resistance of the surface due to a change in chemical composition;
- 2) allows you to process parts of any shape;
- 3) ensures that the layer thickness is uniform over the entire surface of the part;
- 4) allows you to more accurately obtain a given layer thickness.

Factors of the CHT process that affect the depth of the resulting diffusion layer are the duration of the process and its temperature. Saturation depends on time a little. To increase the depth by 3 times, the duration of the process must be increased by approximately 10 times. A more powerful factor is temperature. To obtain a layer of the required depth, it is necessary to heat above A_{c3} , where diffusion actively proceeds. The thickness of the diffusion layer, *ceteris paribus*, the greater, the higher the concentration of the alloying element.

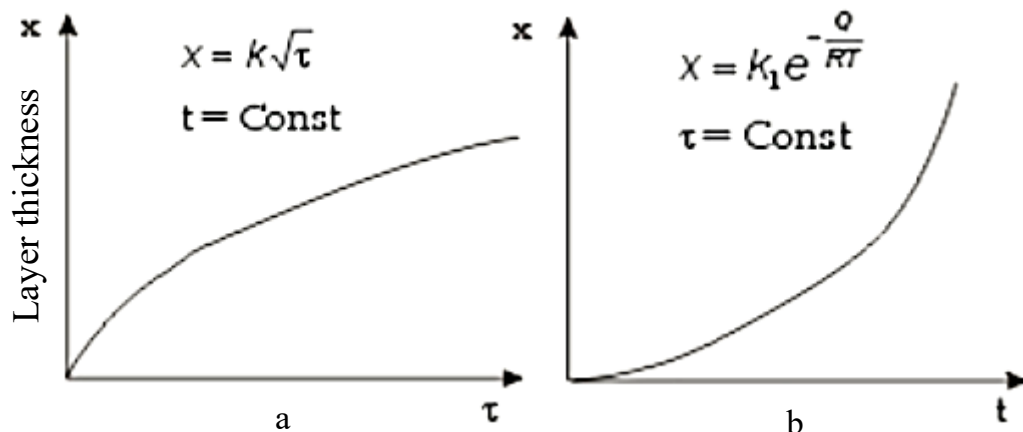
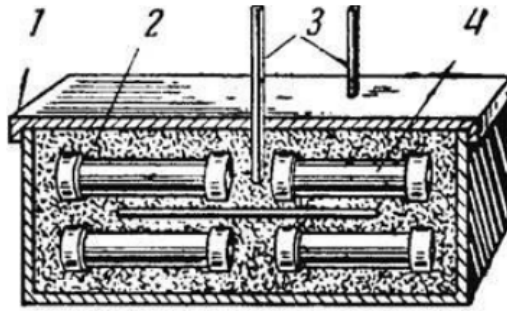


Figure 19.7 – Curves of saturation layer thickness versus duration (a) and holding temperature (b)

19.5 Cementation

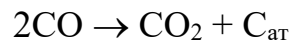
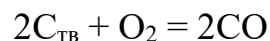
Cementation is the saturation of the surface of the product with carbon. Cements are subjected to steel containing $C \leq 0.3 \%$ – 20, 18XГТ, 20Х, 20ХГМ. Cementation is carried out in two ways: in a solid carburetor mash and in a gaseous medium. According to the first method cementation is carried out in a solid carburetor consisting of charcoal and carbonate salts of sodium or barium.



1 – box; 2 – carburetor; 3 – “witnesses”; 4 – details
Figure 19.8 – Packing parts in a cement box

Parts are cleaned of dirt, oil, scale and packaged in a cementation box. At the bottom of the box, a carburetor is poured with a layer of 25-30 mm, the first row of parts is laid on it. The distance between the parts should be 15-20 mm, and between the parts and the box wall 15-25 mm. A carburetor is poured onto the first row of parts and the next row of parts is laid, the carburetor is again filled, and so on until the box is filled to the top. On top of the box is closed with a lid and coated with clay.

When heated under conditions of oxygen deficiency, incomplete combustion of coal occurs and carbon monoxide appears, which dissociates with the formation of atomic carbon.



Carbon salts are necessary to enrich the atmosphere with carbon monoxide.



Atomic carbon is adsorbed and diffuses into the surface layer of the workpiece, as a result, its mass content in austenite increases, then, upon reaching the solubility limit, cementite is formed $3Fe + C = Fe_3C$. Surfaces not subject to carburization are isolated from the carburetor by coating them or copper-plated by electrolysis. The depth of cementation is usually 0.5-3 mm; cemented blanks contain in the surface layer of 0.95-1.1 % C.

Disadvantages of cementing in a solid carburetor:

- 1) Long process time (it is necessary to warm the boxes);
- 2) Pollution of premises by dust during the grinding of charcoal;

3) Inability to harden parts directly from cement heating. Cementation in a solid carburetor is a low-productivity process, has limited application and is used in small-scale production.

In gas cementation, the atomic carbon necessary for cementation is formed during the decomposition of hydrocarbons and carbon monoxide contained the cemented gases. The main hydrocarbon is methane (CH_4), the decomposition of which when heated occurs by the following reaction: $\text{CH}_4 = \text{C} + 2\text{H}_2$. Parts that are not carburised are coated with electrolytic copper and insulated with special coatings. Gas cementation of parts is carried out at the same temperature at which cementation is carried out in a solid carburetor, that is, at 910–930°C. The speed of the process in a gas environment is 0.15 mm/h.

Atomic carbon is adsorbed on the surface of a part having an austenite structure. The concentration of carbon in the surface layer should be 0.8-1.0 %. To obtain high contact fatigue, the carbon content can be increased to 1.1-1.2 %.

The benefits of gas cementing:

- 1) You can get a given concentration in the carbon in the layer.
- 2) The duration of the process is reduced.
- 3) The ability to automate the process.
- 4) The ability to conduct heat treatment directly from the furnace.

After cementation, the structure of the surface layer of the part, which contains 0.8-1.0 % carbon, consists of perlite (P) and a small amount of cementite (C). This is a hypereutectoid zone. The next layer is with a carbon concentration of 0.8 % carbon. This is a eutectoid zone with a pearlitic (P) structure. Behind it is a hypereutectoid zone with a perlite-ferrite structure (P+F), in which the carbon content is less than 0.8 %. This zone smoothly passes into the core structure (F+P) with a carbon content of 0.15-0.3 %. The depth of cementation is estimated by the effective thickness of the cemented layer l , which is the total depth of the hypereutectoid, eutectoid, and half of the transition Hypereutectoid zone.

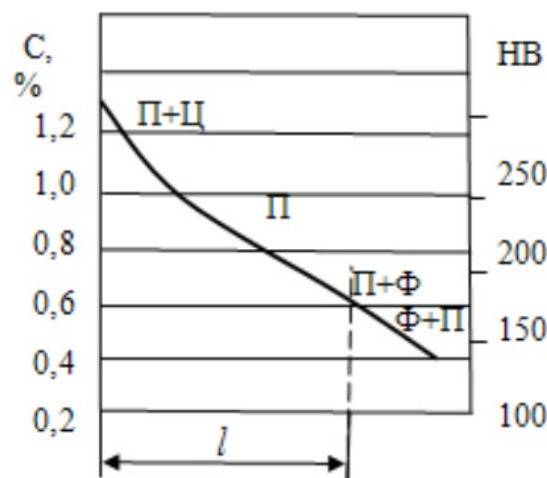
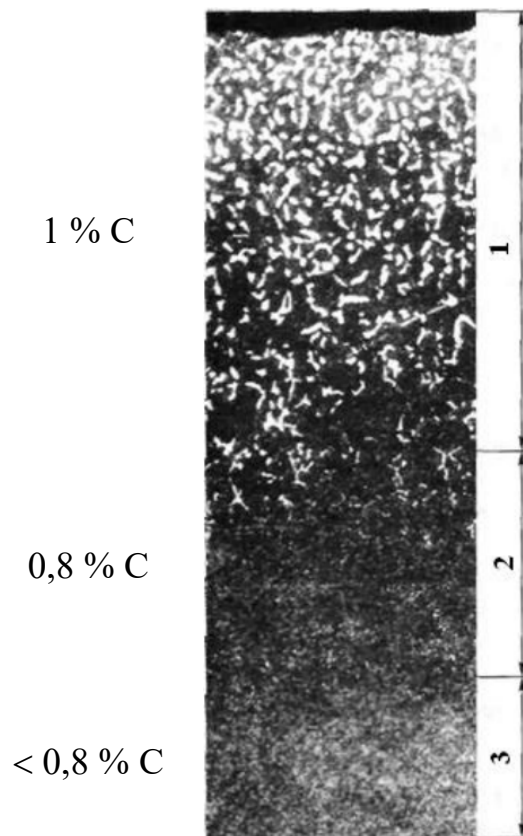


Figure 19.9 – Distribution of carbon and hardness across the cross-section of a part after cementation



1 – hypereutectoid zone; 2 – eutectoid zone; 3 – hypereutectoid zone
 Figure 19.10 – The microstructure of the diffusion layer after cementation of low-carbon steel, x200

The temperature of gas cementation is 910-930°C (higher than A_{c3} , since only austenite is well saturated with carbon), a layer with a depth $\sim 1.2-1.5$ mm is formed in 12-15 hours. Cementation is subjected to: shafts, gears, ball bearings. The disadvantages of cementing are high temperature and duration; large grain grows. Cementation provides a favorable distribution of carbon from the surface to the core (gradually decreasing). However, it does not allow to obtain the required operational properties (high surface hardness, high wear resistance and high fatigue strength).

To obtain the necessary properties, the product after cementation must be subjected to hardening, which can be carried out in various modes. With this treatment, it is possible to fix the structure and grind the grain of the core and cemented layer, which inevitably increases during prolonged exposure at high cementation, obtain high hardness in the cemented layer and good mechanical properties of the core, eliminate the carbide network in the cemented layer, which can occur when it is saturated with carbon to a hypereutectoid concentration. In most cases, especially when treating hereditarily fine-grained steels, hardening from 820-850°C is used.

Hardening after cementation can be carried out according to the following modes:

I mode (Fig. 19.11, a): directly from the furnace where the cementation was carried out. This mode is suitable when gas cementation is carried out and when the steel is naturally fine-grained.

II mode (Fig. 19.11, b): with cement heating, cooling is carried out at room temperature, and then heating under quenching to a temperature above A_{c1} , which leads to grinding of the grain of the cemented layer.

III mode (Fig. 19.11, c): to obtain fine grain both on the surface and in the core, the first hardening is carried out from a temperature above A_3 to fix the structure of the core, the second from temperature above A_1 to obtain the necessary properties of the surface layer.

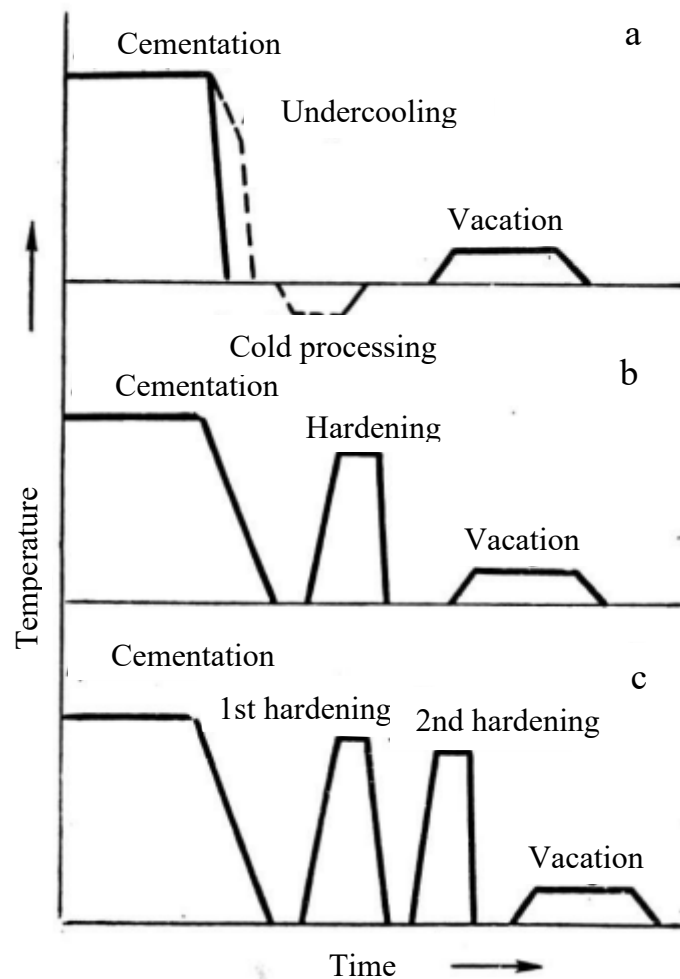


Figure 19.11 – Hardening modes after cementation

19.5.1 Cementation and heat treatment

Doping with Ti, Mo, and V inhibits grain growth. With cement heating, the grain does not grow. The structure on the surface is tempering martensite and carbides, in the core – for alloy steels – low-carbon martensite or bainite, for carbon – sorbitol.

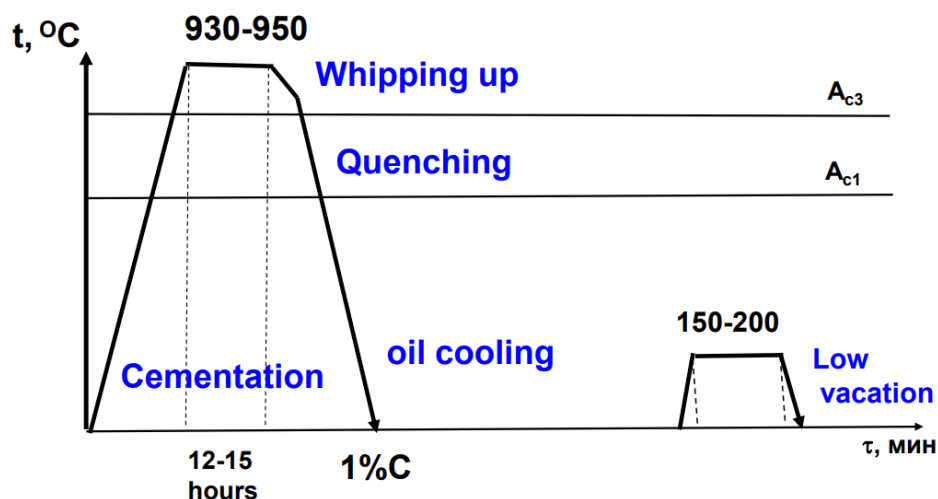


Figure 19.12 – I mode hardening after cementation

The structure on the surface is tempering martensite and carbides, at the core is low-carbon martensite, pearlite class structures. This mode of heat treatment is used for not very loaded parts, in which it is necessary to fix only the structure of the cemented layer.

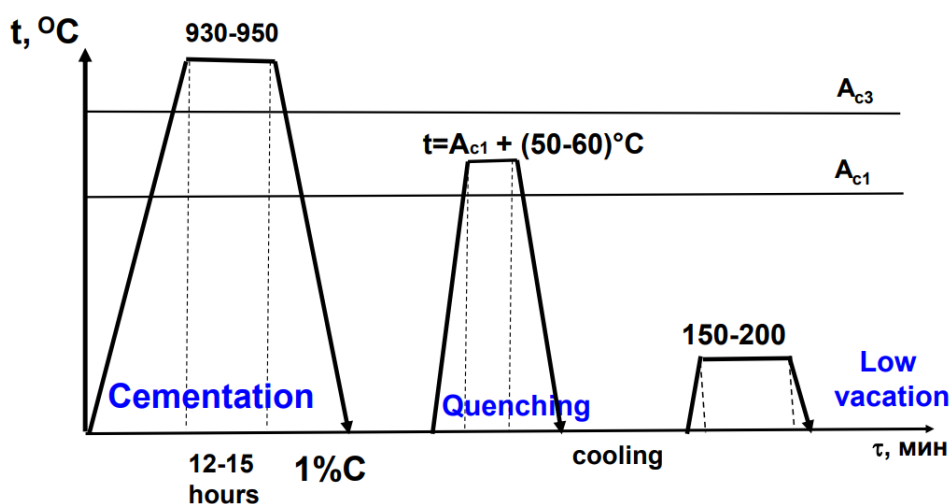


Figure 19.13 – II mode hardening after cementation

The structure on the surface is tempering martensite and carbides, in the core – for alloy steels – low-carbon martensite or sorbitol, for carbon – sorbitol. Such heat treatment is used for heavily loaded friction parts of machines that experience dynamic loading under operating conditions.

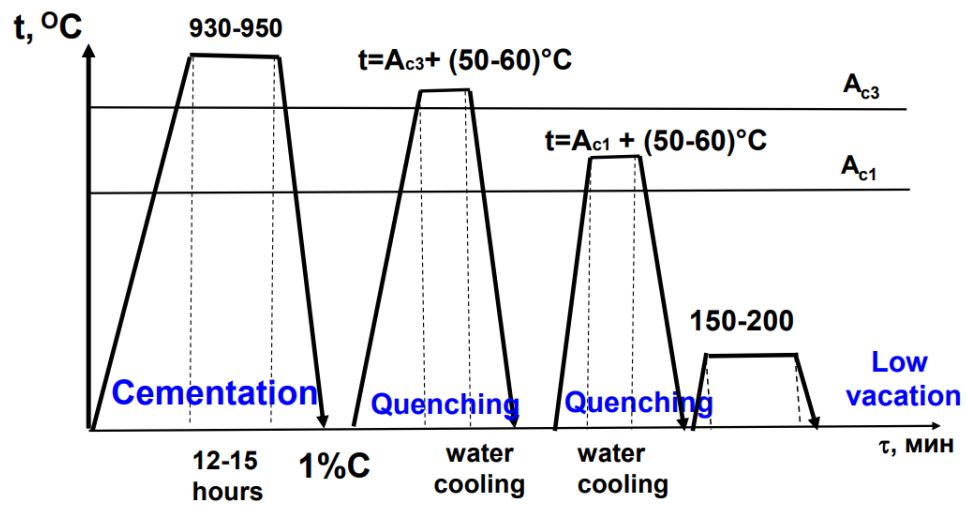


Figure 19.14 – III mode hardening after cementation

TOPIC 20

METHODS OF SURFACE HARDENING OF MACHINE PARTS

20.1 Nitriding

Nitriding – saturation of the surface layer of a product with nitrogen in an atomic state, which is obtained by decomposition of ammonia NH_3 .

Details: cylinder liners, long patterns that practically do not deform during the nitriding process, other measuring instruments. Nitriding Modes:

1. The heating temperature is $500\text{--}520^\circ\text{C}$, the layer depth is $0.2\text{--}0.5\text{ mm}$.

2. Nitriding time – 0.01 mm layer is formed in about 1 hour.

The high hardness of the nitrided layer (up to 1200 HV) is mainly due to two factors: obtaining nitrogen ferrite and the formation of solid nitrides (e.g., AlN).

Benefits:

- 1) Low temperature, so there is no warping;
- 2) High wear resistance (due to the formation of nitrides);
- 3) Increased corrosion resistance;
- 4) Increases the endurance limit;
- 5) Hardness is maintained up to 550°C (cylinder liners).

Disadvantages:

- 1) The duration of the process;
- 2) A smaller layer thickness than cementation limits contact loads on the surface of the part.

Nitriding is the final process.

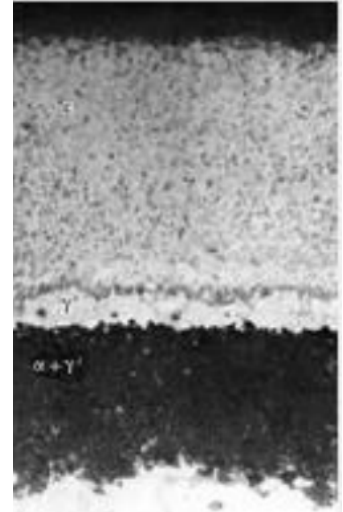
Nitriding steel: 38XMFOA, 38X2MFOA ($0.38\% \text{ C}$, $2\% \text{ Cr}$, $1\% \text{ Mo}$, $1\% \text{ Al}$). These steels are called nitroloies, i.e., steels that contain chromium, aluminum, molybdenum – elements that form solid nitrides – CrN , MoN , AlN – the hardest.

Processing Technology:

- 1) Before nitriding, the steel is subjected to improvement – hardening and high tempering so that the core is viscous and strong at the same time;
- 2) Nitriding;
- 3) After nitriding, no heat treatment is carried out, and if necessary, only the final mechanical process.

To intensify the process, apply:

- 1) Liquid nitriding is a tenifer process;
- 2) The liquid bath contains cyanide salts containing a CN group, carbon, and nitrogen.



Temperature – 500-520°C. Layer thickness – 0,015 mm, time – 3 hours.
High hardness carbonitrides are formed, such as Cr (CN).

20.2 Cyanide and nitrocarburizing

20.2.1 Cyanide

Cyanidation is the simultaneous saturation of a surface with carbon and nitrogen. The structure and properties after cyanidation are largely dependent on the process temperature.

Distinguish cyanide:

- 1) Liquid;
- 2) Gas.

High temperature and low temperature.

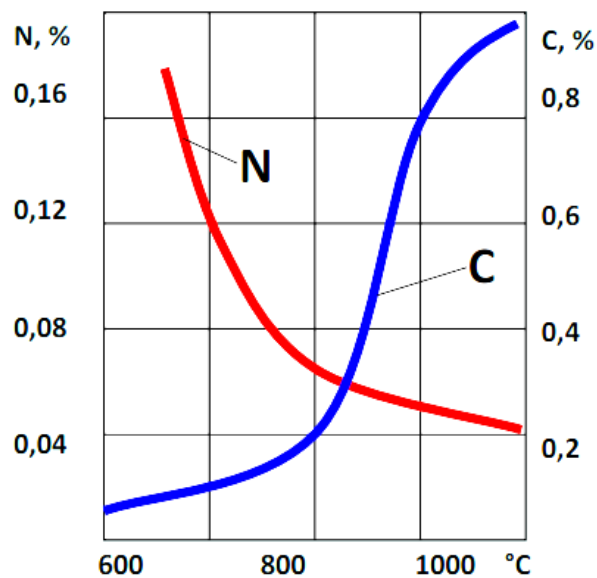


Figure 20.1 – Dependence of nitrogen (N) and carbon (C) concentrations on temperature during nitrocarburizing

Liquid cyanidation – in molten salts that contain sodium cyanide NaCN and Na₂CO₃.

High temperature: at $t = 820-860^{\circ}\text{C}$ in 1 hour you can get a layer of 0.3 mm. Then they conduct hardening and low tempering.

Advantages:

- 1) Temperature is lower than with cementation; grain grows less;
- 2) Higher hardness (due to the formation of carbonitrides);
- 3) The ability to conduct hardening immediately after cyanidation.

Low-temperature cyanidation is carried out at a temperature of 550-600°C for all steels (most often for high-speed steel tools). It is preceded by improvement. A significant drawback of cyanidation is the toxicity of cyanide salts, which requires the adoption of special measures to protect labor and the environment. Low-temperature cyanidation of a tool made of high-speed steel increases its

resistance by 1.5-2 times. The tool undergoes cyanide after final heat and machining, including sharpening and grinding. Exposure from 5 to 45 minutes at a temperature of 540-560°C allows you to get a cyanide layer with a thickness of 0.015-0.04 mm.

20.2.2 Nitrocarburizing

Nitrocarburization – the process of simultaneous saturation of the surface with nitrogen and carbon is carried out in a mixture of gases CH_4 and NH_3 . The process temperature is 840-860°C, the layer depth is 0.8-1.0 mm.

Nitrocarburizing modes: the heating temperature is 840-860°C, the layer depth is 0.8-1.0 mm.

Heat treatment: Quenching low vacuum.

Structure:

- 1) Fine crystalline martensite;
- 2) Dispersed carbonitrides.

Steel: 20, 20X, 18XГТ, 20XГМ, 20XГТ, 20XГНП, 20X2H3A, 30XГТ. 90 % of parts at the VAZ are nitrocarburized.

Benefits:

- 1) The temperature is lower than with cementation; less warping and hardening can be done immediately after nitrocarburizing;
- 2) Less grain growth;
- 3) Higher hardness and wear resistance (carbonitrides are formed);
- 4) Process safety (no toxic cyanide salts);
- 5) The ability to control the process;
- 6) The cheapness of the process (the cost of cementing gas and ammonia is lower than the cost of cyanide salts).

Steel: 20, 20X, 18XГТ, 20XГМ, 20XГТ, 20XГНП, 20X2H3A, 30XГТ. 90 % of parts at the VAZ are nitrocarburized.

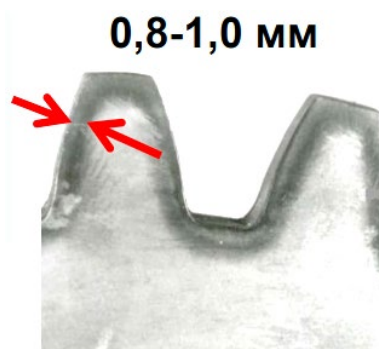


Figure 20.2 – Depth of cemented layer

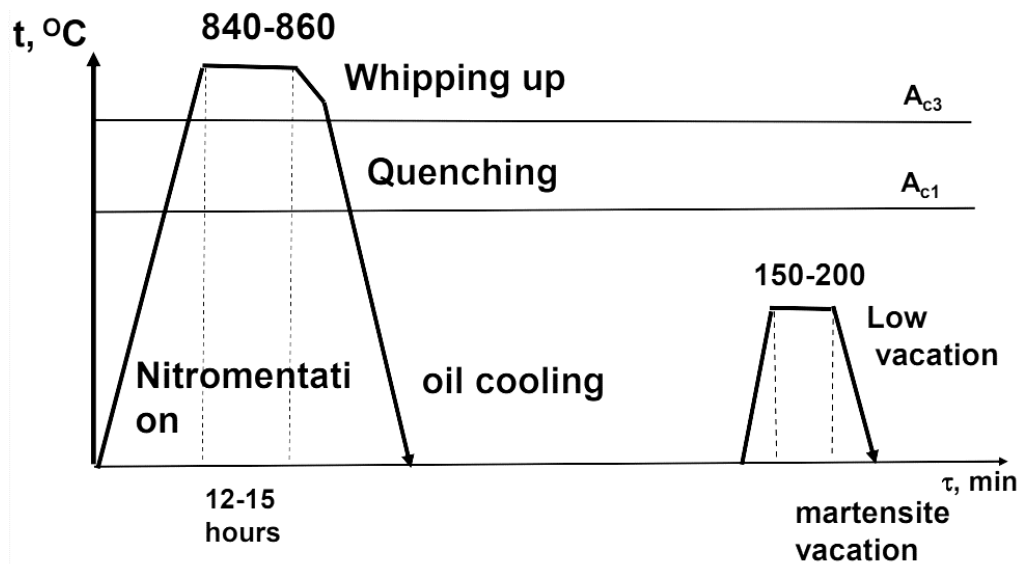


Figure 20.3 – Nitrocarburizing mode and steel heat treatment

20.3 Diffusion saturation of parts with metals

Many parts require high heat resistance, corrosion resistance, wear resistance, and hardness. Such parts are saturated with chromium, aluminum, zinc. Traditional methods for producing such coatings are aluminization (aluminization) and chromium plating.

Aluminizing steel is the surface saturation of low carbon steel with aluminum to increase its corrosion resistance. Apply alitization in a solid, liquid, and gaseous medium, as well as electrolytic alitization. The thickness of the aluminized layer is 0.1...1.0 mm. As a result of alitizing, the steel acquires a high scale resistance (up to 850-900°C), since a dense aluminum oxide film forms on the surface of the aluminized products during heating Al_2O_3 , protecting the metal from oxidation. The hardness of the aluminized layer (on the surface) is up to 500 HV; the wear resistance is low.

Chrome plating is the process of saturation of the surface layer of steel with chromium to increase corrosion resistance and heat resistance, and when chrome plating high-carbon steels, to increase hardness and wear resistance.

Low-carbon and alloy steels are subjected to chromium plating at 1000-1050°C for 6-12 hours, depending on the required thickness of the hardened layer (0.15...0.20 mm).

There is diffusion chromium plating in a solid medium, gas, and liquid chromium plating.

The surface hardness of parts made of chromeplated low-carbon steel is low – NV 180-280, and parts of high-carbon steel reach NV 1350 and exceed the hardness of not only cemented and hardened steel, but also nitride.

Steel with content $C > 0,3 \%$ after chromium plating, they are quenched and low tempered. The structure is temperedmartensite and chromium carbides and other elements. The heat resistance of chrome steel is limited to a temperature of 800°C.

Various parts are subjected to chrome plating: compressor valves, pump sleeves, dies for cold heading, etc.

TOPIC 21 BASICS OF DOPING THEORY

21.1 The influence of alloying elements on the type of diagram Fe-Fe₃C

Alloying elements affect the appearance of the state diagram and the position of critical points:

- 1) Most l. shift critical points S and E to the left;
- 2) Cr raises A_{c1} and lowers A_{c3} , i.e., the austenite region narrows;
- 3) Mn and Ni reduce A_{c1} and A_{c3} ;
- 4) Si, W, Ti, V, Al, Co increase A_{c1} and A_{c3} .

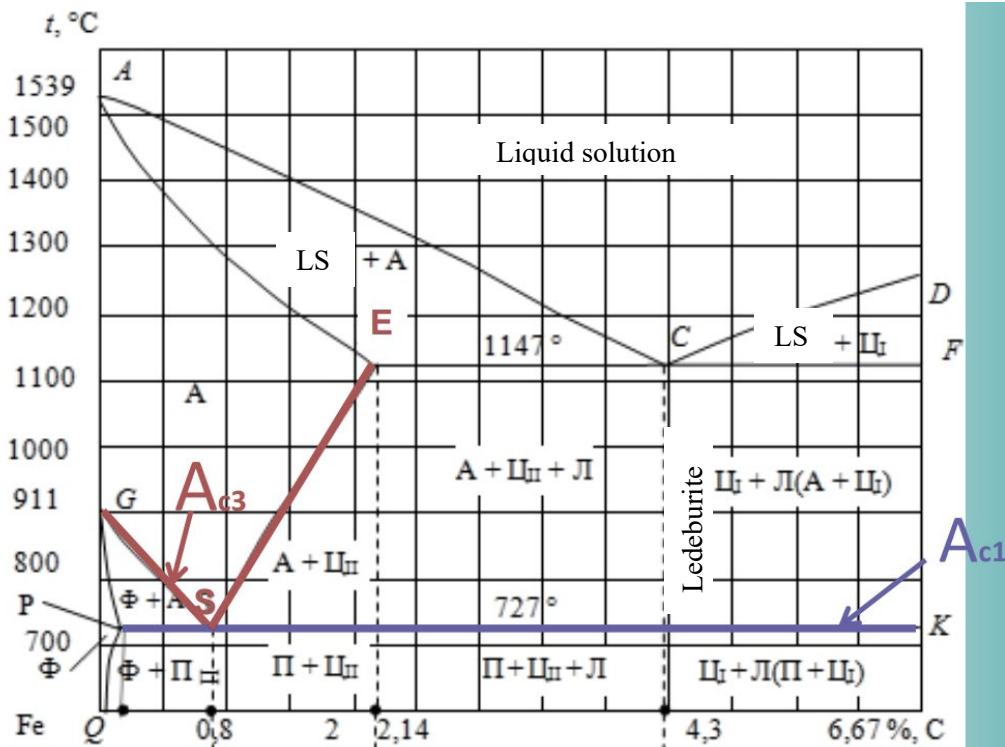


Figure 21.1 – State diagram Fe-Fe₃C

21.2 The effect of alloying elements on the properties of ferrite and carbides

All alloying elements that dissolve in ferrite cause a change in their properties: strength increases, and ductility and toughness decrease.

Ferrite is especially hardened in Si and Mn (1...2 %). All L.E. can be divided into two groups: Necarbideforming. Carbideforming.

Necarbide-forming – nickel, silicon, aluminum, cobalt, copper. These elements affect only the properties of ferrite.

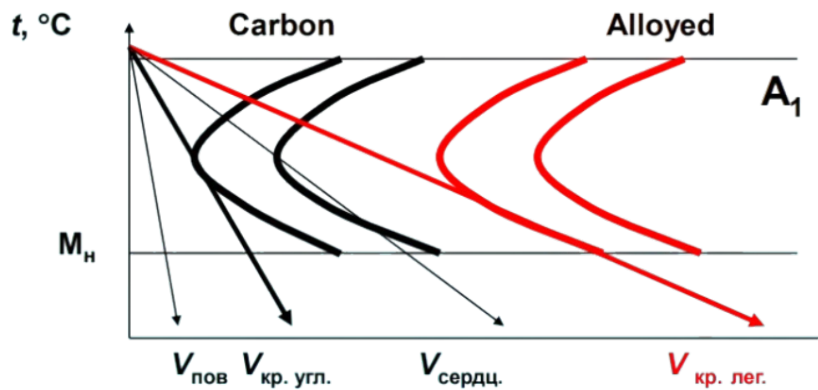
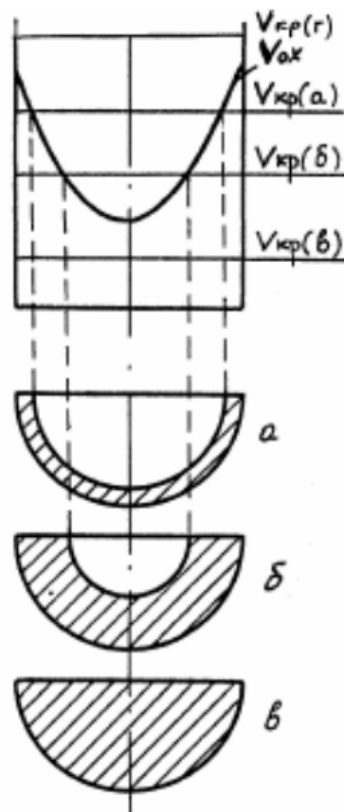


Figure 21.4 – The effect of alloying on the hardenability of steel

Table 21.1 – Properties of steel 40 with lamellar and granular structure

Structure type	The properties					
	σ_B , MPa	$\sigma_{0.2}$, MPa	δ , %	ψ , %	KCU, J/cm ²	T _{хр} , °C
Lamellar (after normalization)	570	320	17	40	50	–40
Granular (after improvement)	700	550	20	60	120	–90



Martensite will form only in those layers where
 $V_{охл} > V_{кр.}$
In alloy steels:
 $V_{Cool\ surface} > V_{кр}$
 $V_{core\ cooling} > V_{кр.}$

Figure 21.5 – Hardenability of the part over the cross section depending on the critical cooling rate

21.4 The influence of alloying elements on the processes that occur during tempering

Alloying elements delay the decomposition of martensite into ferrite and carbides and inhibit the growth of carbides (especially Cr and Mo). Alloy steels retain the structure of tempering martensite up to a temperature of 400...500°C and more. Therefore, the main purpose of alloying for tool steels is to increase heat resistance.

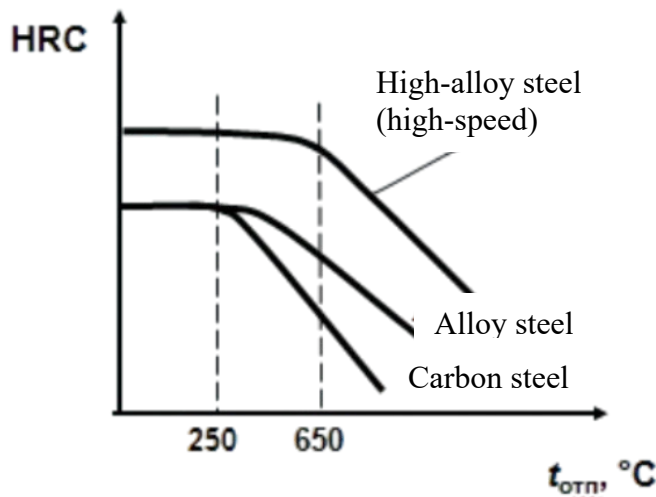


Figure 21.6 – Higher hardness in alloy steel

After quenching and tempering, steel may exhibit a tendency to temper brittleness, which is expressed in a decrease in toughness and an increase in the temperature of the transition of steel from a viscous to a brittle state. There are two kinds of temper fragility. Temper brittleness of the first kind – at temperatures 250-350°C. Temper brittleness of the second kind takes place after tempering at temperatures above 500°C and slow cooling (usually in air). Temper brittleness of the first kind can be eliminated by increasing the temperatures or holding time. Temper brittleness of the second kind can be prevented by rapid cooling.

21.5 Effect of alloying elements on grain size

Most L.E. reduce the tendency of austenitic grain to grow (except for Mn and B, which contribute to grain growth). V, Ti, Nb, Zr, Mo, W form excess dispersed carbides that inhibit the growth of austenitic grain and increase strength of steel. Elements that do not form carbides (Ni, Co, Si) have a relatively weak effect on grain growth.

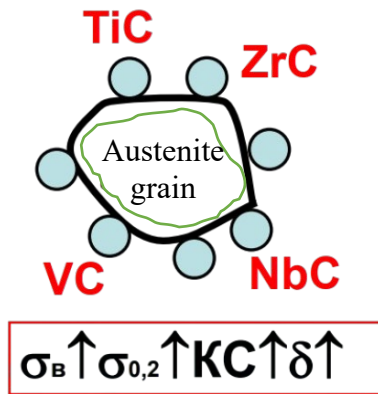


Figure 21.7 – The influence of carbide-forming elements on the grain size of austenite

21.6 Effect of alloying elements on cold brittleness threshold

Alloying elements shift txp to higher temperatures. The exception is Cr in an amount of up to 1-2 % and Ni. An example of such steels – 30XC, 40XHMA, 30XTC. The best option is the simultaneous doping with carbide-forming and non-carbide forming elements. 35XHM – carbide-forming elements Cr and Mo, Ni – non-carbide forming. Instead of Ni, you can use Si.

TOPIC 22

ALLOY STEEL CLASSIFICATION

Classification of alloy steels according to various criteria:

- 1) By chemical composition;
- 2) By appointment;
- 3) By structure.

Classification of alloy steels by chemical composition:

- 1) Low-alloy: Σ alloying elements (a. e.) $< 2,5 \%$;
- 2) Medium-alloyed: Σ a. e. $= 2,5-10 \%$;
- 3) High alloyed: Σ a. e. $> 10 \%$.

Classification of alloy steels by purpose:

- 1) Structural;
- 2) Instrumental;
- 3) Special.

22.1 Structural classification of steels

Alloy steels are divided into five classes based on the structure that forms when steel is cooled in air:

- 1) ferritic ("C" less than 0.1 % and more chromium 12 %); steel: 08X13, 12X17;
- 2) pearlite. This group includes most structural steels: 20X, 40X, 38XC, 35XГC; 60C2;
- 3) martensitic ("C" $> 0.1 \%$ and a large amount of chromium); steel: 30X13, 40X13; silchromes 40X9C2;
- 4) austenitic (chromium-nickel steels); steel: 12X18H10, 110Г13
- 5) ledeburite – "C" $> 0.8 \%$, high-speed steels; steel: P9, P18, P6M5.

22.2 Classification of alloy structural steels by purpose

- Cemented $C < 0,3 \%$;
- Improved $0,3 \leq C \leq 0,55 \%$;
- Spring-spring $0,55 < C \leq 0,7 \%$;
- Ball-Bearing $C \approx 1 \%$.

22.3 Cemented steels

Carbon with non-hardening core (steel 15, steel 20) – for parts that do not experience heavy loads.

With a weakly hardening core (steel 20X, 20XH) – for medium-loaded parts.

Highly hardened core (steel 18XГТ, 20XГП, 18X2H4BA) – for heavily loaded parts.

The general heat treatment mode includes: cementing, quenching, low vacation.

The structure in the surface layer is tempering martensite, high carbon and carbides.

22.4 Improved steels

Improvements include medium-carbon unalloyed (steel 35, 40, 45) and alloy steels. Of the carbon steels, steel 45 is the most common. Alloyed steels are used for larger and heavier critical parts. Chrome-silicon and chromiumsilicon manganese steels (30XГCA, 35XГCA, 38XC etc.). Nickel Chromium Steel 40XH, 45XH, 30XH3A has a good combination of hardenability and viscosity. So, steel 30XH3A calcined in sections up to 100 mm.

Table 22.1 – Dependence of the critical diameter of the steels being improved on the degree of their alloying

Group	Steel grade	Critical diameter, D_K mm
I	40, 45	~10
II	40X, 40XP	before 20
III	35XГC, 40XГC	before 30
IV	40XHM, 40XГP	before 40
V	38XH3MΦ	more 100

Improved steels are subjected to hardening and high tempering. The structure after such heat treatment is sorbitol-tempered. Improved steels (40, 40X, 35XГC) alloy with the aim of increasing hardenability. The larger the section of the part, the more alloy steel should be used. The critical diameter in the steels to be improved is in the range of 10 mm to 100 mm.

Chromium-nickel-molybdenum steels are the best structural steels with the deepest hardenability and high toughness. These include steel 30XH2M, 40XH2MA, etc. These steels are used for the manufacture of critical large parts with a cross section of 100 mm or more, operating in difficult conditions. When choosing a steel grade, it is necessary to take into account the conditions of its work and the loads that it experiences, design, and dimensions.

22.5 Spring steel

Spring-spring steels are used for the manufacture of springs and springs. Under the action of the load, the springs and springs are deformed, and after the termination of the load, they restore their original shape and size. In this regard, the main requirement for steels for springs is high conditional yield strength – $\sigma_{0.2}$.

Springs and springs are made from:

1) Carbon steel. From steels 65, 70, 75, are made springs that experience low voltage;

2) Alloy structural steels.

Spring-spring steels are alloyed with elements that increase the yield strength, bringing it closer to the value of temporary resistance σ_B : Si, Mn, Cr, V, W. Particularly, silicon and manganese (steel 65Г, 60С2). For the most demanding and heavily loaded springs, steel is used. 50ХΦА, 50ХГΦА. The steels of this group are heat treated: hardening, average vacation. The structure of the steel after such processing is reed.

22.6 Ball Bearing Steel

Ball-bearing steels are used for the manufacture of rolling bearings. Rings, balls, and rollers are subjected to high-specific loads, abrasion, chemical wear due to contact with the atmosphere or grease containing impurities. Therefore, the main requirements for ball-bearing ship steel are hardness and wear resistance. The carbon content is about one percent and chrome is necessarily part of it.

In the designation of steel grade ІІХ6, letters «ІІХ» are deciphered as ball-bearing chromium; the numbers following them indicate the content of chromium in steel in tenths of a percent – 0,6 %. Marks: ІІХ6, ІІХ9, ІІХ15, ІІХ15СГ (1,5 % Cr, 1 % Si and Mn). Chromium increases the hardenability of steel; a further increase in hardenability is achieved by the introduction of manganese and silicon. Ball Bearing Heat Treatment: annealing; quenching (800-860°C); low vacation (150-160°C).

The structure is tempering martensite with evenly distributed small excess carbides. The more chromium in the steel, the greater the value of the critical diameter. In steel ІІХ6, the critical diameter is 10 mm, in steel ІІХ9 – 15 mm, in steel ІІХ15 – 25 mm, and in steel ІІХ15СГ – 65 mm when cooled in oil.

Literature

1. Технологія конструкційних матеріалів / М. А. Сологуб та ін. ; ред. М. А. Сологуб. Київ : Вища шк., 2002. 374 с.
2. Пахаренко В. Л., Марчук М. М. Матеріалознавство та технологія конструкційних матеріалів (металургія, ливарне виробництво) : навч. посіб. Рівне : НУБГП, 2009. 183 с. URL: <https://foundry.kpi.ua/wp-content/uploads/2020/05/paharenko-vl-materialoznavstvo-ta-tehnologiya-konstrukcijnyh-materialiv-metalurgiya-lyvarne-vyrobnytvo.pdf>.
3. Foundry Shop Manual. O Scribd, Inc. URL: <https://scribd.com/document/139786812/Foundry-Shop-Manual>.
4. Groover M. P. Fundamentals of Modern Manufacturing. Materials, Processes, and Systems. 4th ed. JOHN WILEY & SONS, INC., 2019. 1028 p. URL: <https://tusharaneyrao.wordpress.com/wp-content/uploads/2019/12/fundamentals-of-modern-manufacturing-materials-processes-and-systems.pdf>.
5. Хричиков В. Е., Меньяло О. В. Ливарне виробництво чорних і кольорових металів : навч. посіб. 2-ге вид. Дніпропетровськ : НМетАУ, 2015. 89 с. URL: https://nmetau.edu.ua/file/livarne_virobnitstvo_chornih_ta_kolorovih_metali_v._navchalniy_posibnik.pdf.
6. Hirose A., Shibayanagi T., Yamaoka H. Welding and Joining of Advanced Materials. *JOURNAL OF THE JAPAN WELDING SOCIETY*. 2011. Vol. 80, no. 5. P. 431–433. URL: <https://doi.org/10.2207/jjws.80.431>.
7. Bowditch W. A., Bowditch K. E., Bowditch M. A. Welding technology fundamentals. 3rd ed. 2005. 470 p. URL: <https://archive.org/details/weldingtechnolog0000bowd/mode/2up>.
8. Discovering Oxyacetylene Welding & Cutting. *Manitoba Agriculture, Food and Rural Initiatives*. P. 1–34. URL: <https://www.kansas4-h.org/projects/engineering-technology/ag-mechanics/docs/Gas%20Welding%20Activity.pdf>.
9. Солодкий В. І., Плівак О. А. Різальний інструмент. Лабораторний практикум. Друге видання [Електронний ресурс] : навч. посібник для студентів спеціальності 131 – прикладна механіка. Київ : КІП ім. Ігоря Сікор., 2020. 224 с. URL: <https://ela.kpi.ua/server/api/core/bitstreams/4df74f5f-991c-458b-991f-0a9a459ec022/content>.
10. Todd R. H., Allen D. K., Alting L. Manufacturing Processes Reference Guide. New York : Industrial Press Inc., 1994. 486 p. URL: https://books.google.md/books?id=6x1smAf_PAcC&pg=PR3&hl=uk&source=gbv_selected_pages&cad=1#v=onepage&q&f=false.

11. Говорун Т. П., Гапонова О. П., Марченко С. В. Матеріалознавство та технологія матеріалів (у схемах і завданнях) : навч. посіб. Суми : Сум. держ. ун-т, 2020. 163 с. URL: <https://essuir.sumdu.edu.ua/handle/123456789/77378>.

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