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**MATERIAL ENGINEERING
AND AVIATION STRUCTURAL MATERIALS**

Part 1

METALS AND ALLOYS

Textbook

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T16

Запропоновано узагальнений підхід щодо вивчення курсу авіаційного матеріалознавства Розглянуто питання вибору конструкційних матеріалів для силових елементів авіаційних конструкцій, методи випробувань матеріалів, оцінювання механічних властивостей, основні шляхи зміцнювання конструкційних матеріалів. Основну увагу приділено сучасним сталям, алюмінієвим, титановим, корозійностійким сплавам. Наведено правила маркування сплавів, що використовуються в індустріально розвинутих країнах.

Для студентів, що вивчають курс "Авіаційне матеріалознавство".

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Generalized approach to studying aviation structural materials is suggested. Questions of structural materials selection for main load-carrying aviation structures are suggested. Procedures of structural material testing, estimation mechanical properties, ways of material strengthening are observed. Main groups of up-to-date steels, aluminium, titanium, corrosion resistant alloys are analyzed. Metals designation systems of leading metal manufacturing countries are considered.

For students studying course "Aviation materials".

Fig. 30. Table 19. Bibliogr.: 15 sources

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CONTENTS

Introduction	4
Theme 1. Fundamentals of metals and alloys theory	5
Theme 2. General properties of structural materials.....	14
Theme 3. Plastic deformation and recrystallization of metals	20
Theme 4. Steel structure and properties	26
Theme 5. Aluminium alloys	38
Theme 6. Magnesium alloys	44
Theme 7. Beryllium and lithium alloys	47
Theme 8. Titanium alloys	50
Theme 9. Copper alloys	56
Theme 10. Corrosion-resistant, high-temperature and heat resistant steels and alloys	61
Theme 11. Refractory metals and alloys	69
Theme 12. Steels and alloys with special properties	76
Appendix A Correspondence in designation of different countries (unions) standards	80
Appendix B Steels designation by European Norms	81
Appendix C Unified numbering system (UNS) of ferrous metals and alloys designation.....	88
Appendix D Table Designation of non-ferrous metals and alloys according to Unified Numbering System (UNS)	91
Appendix E Specific cost of structural metals and alloys	94
List of literature used	95

Introduction

One of the most valuable ability of an up-to-date successful mechanical engineer is feeling of structural material development directions and possession of knowledge about physical-mechanical fundamentals of structural materials. First of all main requirements to advanced structural materials are high-specific properties at practical economical availability and cost because these characteristics permit to realize practically aviation and aerospace structures with necessary reliability, quality and customer demands.

Appearing of a new structural material, technologies, re-sharing of world markets of raw materials and influence of social life requires continuous observation of material engineering science applied side. Conventional materials can't satisfy such strong design, manufacturing, operational and service restrictions of aerospace technique as minimal allowable safety factors, aerodynamic and radiation heating, short manufacturing cycle and lifetime at minimal cost, modular arrangement of aircrafts, simplified access to internal units. Nowadays special steels, aluminium, titanium, copper, nickel, lithium, beryllium alloys, high-temperature and heat-resistant materials are widely used in aerospace objects. Moreover a large variety of non-metal structural materials (glasses, ceramics, glass-ceramics, composites) are used for making aircraft main load-carrying elements.

The main objective of this book is to help a reader to arrange and classify structural materials, graduate levels of physical and mechanical properties, designate main milestones of structural material development and create consequent algorithm of selection structural material for exact application at known restrictions. Information gathered in this notes was drawn from series of published scientific articles, results of fundamentals studies conducted by well-known machine-building and aviation enterprises of Ukraine and other countries.

For more deep analysis of definite question the list of literature used and appendixes containing information about mostly used steels, aluminium, titanium alloys are shown at the end of this textbook. More specific info (for example, some numerical values) one has to seek in correspondent reference and guide books.

Theme 1. FUNDAMENTALS OF METALS AND ALLOYS THEORY

Crystalline structure of metals and alloys

All metals are crystalline substances having a particular system of ions arrangement in space, which is characterized by a crystal lattice.

The majority of metals used in engineering has a lattice of one of following types: space-centered cubic, face-centered cubic and close-packed hexagonal (Fig. 1.1).

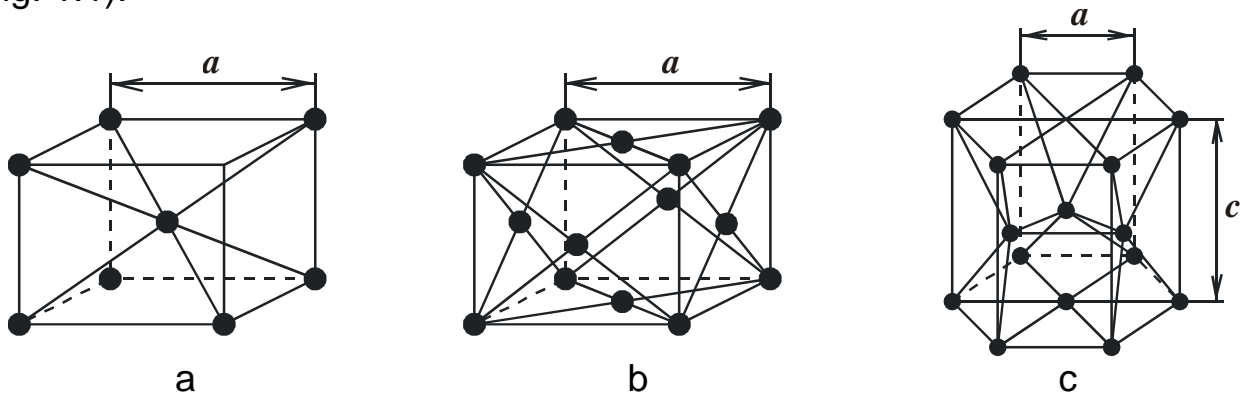


Fig. 1.1. Types of crystal lattices: a – body-centered cubic (BCC); b - face-centered cubic (FCC); c - close-packed hexagonal (CPH)

The crystal lattice is characterized by both types of a low level cell and also by its dimensions (in Fig. 1.1 - dimensions **a** and **c**). The lattice dimensions are measured in angstroms: $1\text{\AA}=10^{-10}$ m.

Some metals, for example, titanium, iron, tin can have different crystalline structure at miscellaneous temperatures. Each modification of crystalline structure is stable in particular temperature range and is marked by small characters of the Greek alphabet (α , β , γ , δ , etc.), for example: α -titanium, β -titanium, γ -iron. The transferring of one crystalline structure in another is called as polymorphism or allotropy (the polymorphic transformation takes place).

The pure metal does not satisfy the requirements to construction materials. Therefore not pure metals, but their alloys are mainly applied in engineering.

The concepts of alloy and phase are used at alloys composition research. Alloy is a composition obtained by alloying or sintering of two or more substances. The substances that are included in compound structure, called as components. A phase is a part of alloy with fixed chemical structure, with the same modular condition, identical type of a crystal lattice and interface with other parts of alloy.

The atoms of two or more elements participate in alloy formation. At their interaction following component can arise: liquid solutions, solid solutions, chemical compounds, intermediate phases and mechanical mixtures. Overwhelming number of metals unrestrictedly dissolve in each other in liquid state. Solid solution - single-phase structure with a crystal lattice formed by atoms of

alloy components. Component, which crystal lattice is saved, called as a solvent. Component, that does not save own crystal lattice, but returns the atoms in a solvent lattice, is called as miscible.

The main types of solid solutions: substitutional solid solutions (SSS) and interstitial solid solution (ISS). SSS can be of restricted and unlimited oxygen solubility. SSS are formed by replacement of solvent crystal lattice atoms with the atoms of dissolved component (Fig. 1.2, a, b). ISS are formed by arranging of dissolving component atoms in free interspaces between atoms of solvent crystal lattice (Fig. 1.2, c).

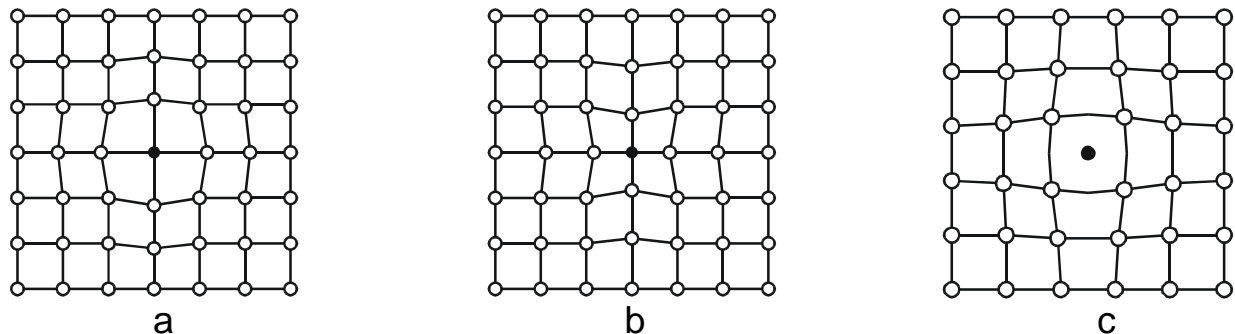


Fig. 1.2. Lattice distortion at solid solutions formation: a - atomic radius of dissolving metal is greater than atomic radius of a solvent in SSS; b - atomic radius of dissolving metal is less than atomic radius of a solvent in SSS; c - formation of ISS

Principles of crystallization

Crystallization is a metal and alloy conversion from liquid to solid state. This transformation is accompanied by formation of certain crystal lattice. The beginning of crystallization is accompanied by occurring of nucleus center in a melt. The further increase of crystals quantity and their sizes begins from these centers.

The crystallization process is quantitatively characterized by nuclei generation rate V_{cc} (measured in $\text{mm}^{-3}\text{s}^{-1}$) and solidification rate V_{cg} (measured in mm/s) - the Fig. 1.3.

At cooling of alloy up to chilling point a nuclei generation rate V_{cc} and solidification rate V_{cg} grow up. At certain degree of a supercooling they reach maxima, after that reduce to zero. Thus a nuclei generation rate V_{cc} and the number of nucleus centers grows faster, than solidification rate V_{cg} (Fig. 1.4).

The greater the nuclei generation rate and the less the solidification rate, the less is the size of a crystal. In this case the structure of metal will be more fine-grained.

The size of metal grain greatly influences on viscosity and toughness of metal. Heating temperature of molten metal, its chemical composition and presence at metal of ectogenic admixtures cause large effect on a grain size.

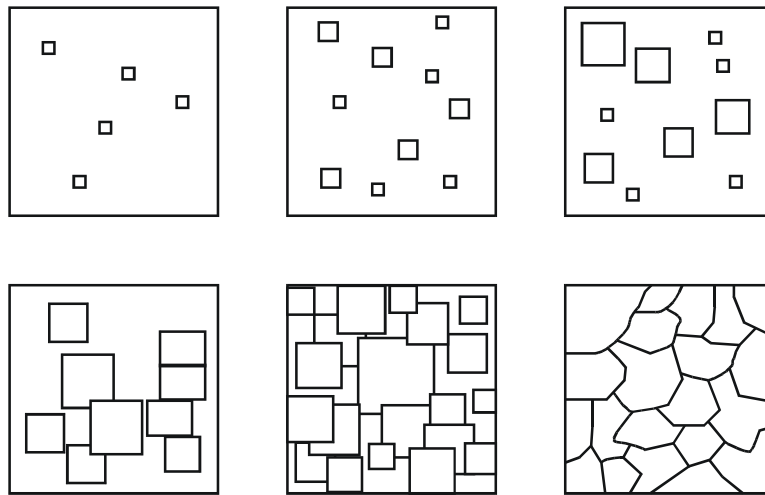


Fig. 1.3. Model of crystallization process

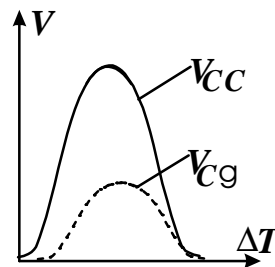


Fig. 1.4. Relationship between nuclei generation rate V_{cc} , solidification rate V_{cg} and degree of alloy supercooling

Fundamentals of alloys composition

An alloy is the substance obtained by melting or sintering of two or more components. Components are chemical elements or stable chemical compounds. Components can create one or several phases.

Phase is the simplest structural component of an alloy separated from other components by well-defined boundary. Properties of phase change sharply at the transition through its boundary.

For metal alloys typically following structural components can be observed:

- liquid solutions;
- solid solutions;
- chemical compounds;
- mechanical mixtures (heterogeneous structures).

Heterogeneous structures are mechanical mixture of pure components or other phases.

Eutectics – is double-phase (or multi-phase) mixture of crystals crystallizing simultaneously at constant temperature from liquid phase (for example, the mixture of lead and tin).

The equilibrium (phase) diagrams

It is necessary to know structure of alloy in a stable condition and during heat and cooling for definition of alloys properties and their melting temperatures, for selection of methods and conditions of heat treatment. In this case equilibrium diagrams in coordinates "temperature - composition" of alloy can be defined experimentally. With the help of the thermal analysis can be received the alloy **cooling curves** in coordinates "temperature of alloy - time of cooling" (Fig. 1.5, b). Inflection points and horizontal sections, which characterize critical temperatures of alloys, can be discovered on these curves. Critical points of alloys transformation then must be plotted in coordinates "temperature – composition" and smoothly connected with one another. There are some techniques of equilibrium diagrams plotting for multicomponent alloys. Let's consider for simplicity two-component systems.

The equilibrium diagram of the first kind

This diagram describes crystallization of alloys with components, dissolved unlimitedly in each other only in liquid state (for example like in a mixture of water and alcohol). Components cannot dissolve in each other and do not form chemical combinations in solid state. During process of crystallization alloy components form mechanical mixture called as eutectic. Examples of such components: lead-stibium, tin-zinc, lead-silver etc. General view of the first kind equilibrium diagram for components A and B is shown in Fig. 1.5, a.

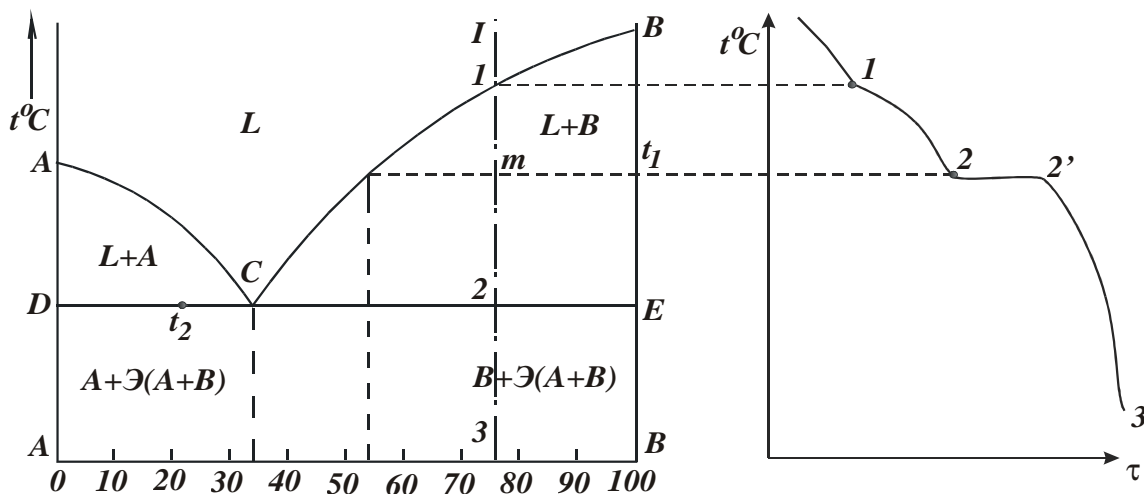


Fig. 1.5. The equilibrium diagram of the first kind (a) with relevant cooling curve (b)

On the Fig. 1.5 liquid phase composition: 53 % of A and 47 % of B. Solid phase composition is 100 % of B.

The line ACB is called as a **liquidus** line. It is a geometrical place of points where alloys crystallization begins. The crystals of component A crystallize

from a liquid melt L on a line AC. Crystallization of component A finishes on a line ADC. The crystals of component B crystallize from a liquid melt L on a line BC. Crystallization of component B finishes on a line DCE. The line DCE is called as a **solidus** line. The eutectic mixture of crystals (A+B) is formed on a line DCE in any point at constant temperature. A point C corresponds to alloy of **eutectic composition**. In this point the eutectic mixture (A+B) crystallizes only. Alloys with components concentration more to the left of a point C are called as **hypoeutectic**. Alloys with components concentration relevant to a point C are called as **eutectic**. Alloys with components concentration more to the right of a point C are called as **hypereutectic**.

The amount and composition of phases in alloy is determined by the **lever rule**. This rule can be used only in double-phase area of the diagram. Conode (or tie-line) is carried out up to intersection with liquidus and solidus lines at temperature t_1 for alloy of I-concentration in area BCE of the diagram. The cut nt_1 is taking as 100 %. According to the 1st lever rule for determination of the liquid phase amount q_{lp} in percentage it is necessary: to relate a cut mt_1 , opposite to a liquidus line, to all length of a cut and multiply it on 100 %, i.e.

$$q_{lp} = \frac{mt_1}{nt_1} \cdot 100\%.$$

Similarly the solid phase amount q_{sp} can be determined in percentage by the ratio of cuts mn and nt_1 :

$$q_{sp} = \frac{mn}{nt_1} \cdot 100\%.$$

The 2nd lever rule consists in following: the projections of conode intersection points with liquidus and solidus lines on concentration axis give necessary values of liquid phases and solid phases composition.

The equilibrium diagram of the second kind

This diagram describes crystallization of alloys with components, dissolved unlimitedly in each other both in solid and in liquid state (Fig. 1.6). Examples of such alloys: Fe - Ni, Fe - Cr, Cu - Ni, Fe - V, Cu - Al, Cu - Pt, Au - Ag. The equilibrium diagram of the second kind is shown in Fig. 1.6.

Let's consider a crystallization of alloy I. Point C marks the moment of appearing of solid solution crystals in a liquid phase L with density of point 1. Solid solution crystals having composition of point 2 appear at temperature t . In a point D solid solution crystals of point E composition will conform to the composition of alloy I. Thus, during crystallization from a liquid phase the crystals of variable composition may originate.

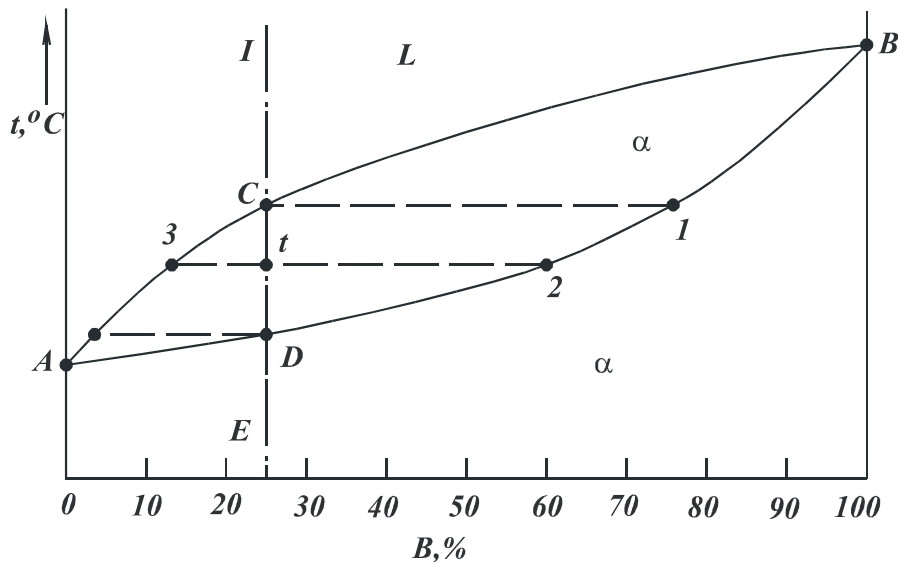


Fig. 1.6. The equilibrium diagram of the second kind. Line ACB is the liquidus line, line ABD is the solidus line

The equilibrium diagram of the third kind

This diagram describes crystallization of alloys with components, dissolved unlimitedly in each other in a liquid state. In a solid state they are dissolved limitedly and form a eutectic at crystallization. Figure 1.7 illustrates the equilibrium diagram of the third kind.

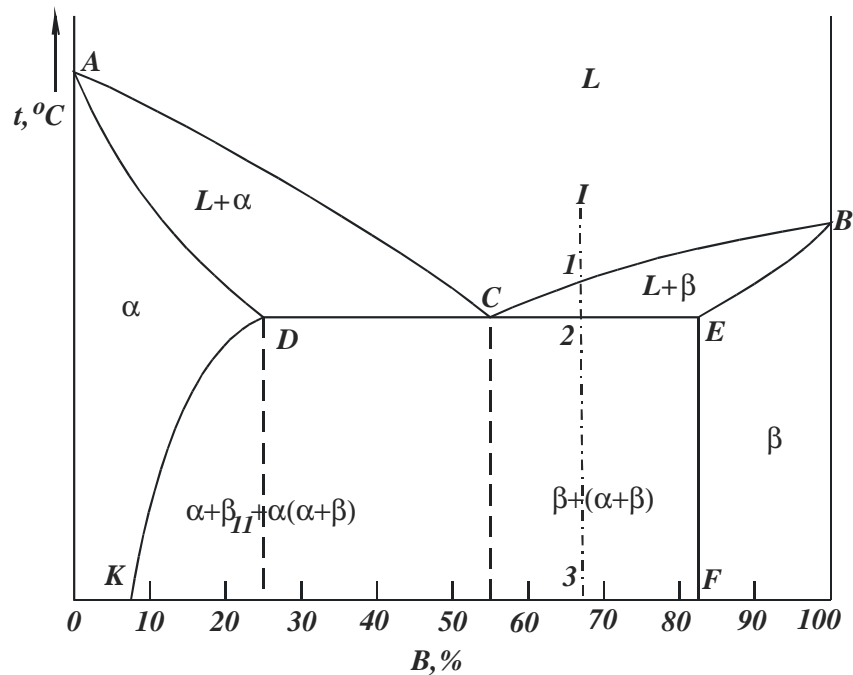


Fig. 1.7. The equilibrium diagram of the third kind. Line ACB - a liquidus, line $ADCEB$ - a solidus. DCE - a line of eutectic transformation. DK - a line of a limited solubility of component B in component A . EF - a line of a limited solubility of component A in a component B solutions crystals

In this diagram the pure components A and B can't crystallize. Solid solution of component A is called α . Solid solution of component B is called β . Line DCE shows the moment when mechanical mixture of solid is formed during crystallization of fluid phase with point C density. As solubility B in A can vary, line DK reflects temperature dependence of abundant crystals extraction. β_{II} – secondary phase enriched with a component B.

Typical iron-carbon diagram is shown at the Fig. 1.8.

The equilibrium diagram of the fourth kind

The equilibrium diagram of the fourth kind characterizes alloys, which components A and B can resolve unlimitedly in each other in a liquid state. Those components are insoluble in a solid state and form steady chemical combinations. The equilibrium diagram of the fourth kind is shown in Fig. 1.9. An example of binary alloy phase composition of which can be analyzed with the mentioned diagram is strontium-silver.

The line CE in Fig. 1.9 refers to chemical compound A_nB_m . A point C corresponds to melting point of chemical compound A_nB_m . The diagram has 2 eutectic points D and D'. The constant melting point and fixed components ratio are typical to chemical compound A_nB_m .

The diagram “composition of property”

The analysis of the equilibrium diagrams allows studying dependence of alloys properties from their structure. Russian metallurgist N.S. Kurnakov suggested the method of plotting diagram «composition of property» (Fig. 1.10). On these diagrams composition of an alloy of components A and B is measured along horizontal axis, and property of an alloy varies along vertical ones. With the help of these diagrams the alloys for particular purpose are selected.

Analysis of mentioned diagrams permits to make following practical conclusions:

- for strengthening alloys it is necessary to use alloying elements creating with main metal solid solutions or chemical compounds;
- thermal treatment of alloys is the most significant for alloying elements with variable solubility in main metal;
- good castability can be observed in alloys containing eutectics because of their low melting point and high fluidity;
- single-phase alloys possess better weldability and corrosion resistance;
- double-phase alloys are machined well;
- casting alloys with dendrite structure possess high wear resistance.

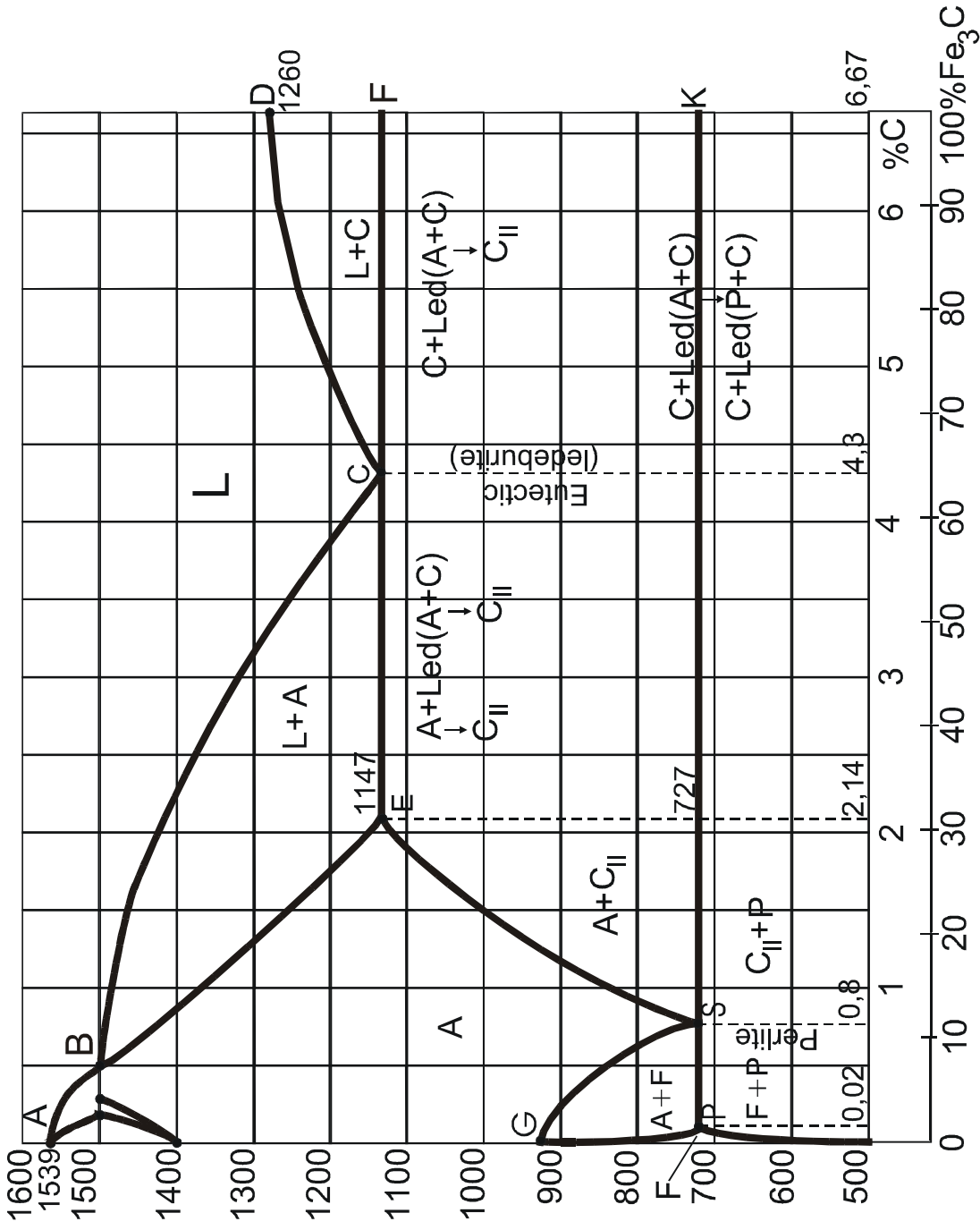


Fig. 1.8. "Iron-carbon" equilibrium diagram: L- liquid alloy; A- austenite; C- cementite; Led- ledeburite; F- ferrite; P- perlite; C_{II}- second-step structural change of solid alloy

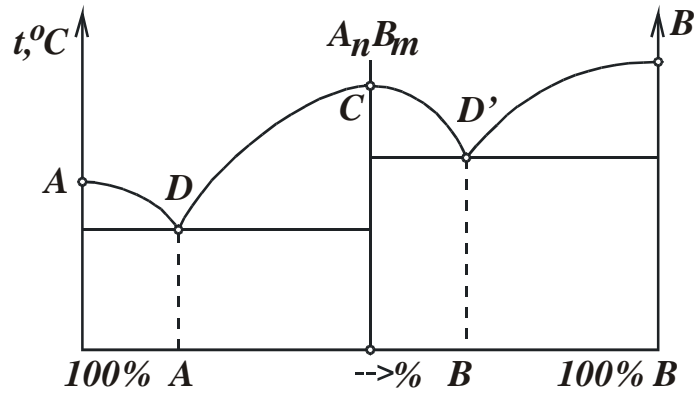


Fig. 1.9. The equilibrium diagram of the fourth kind

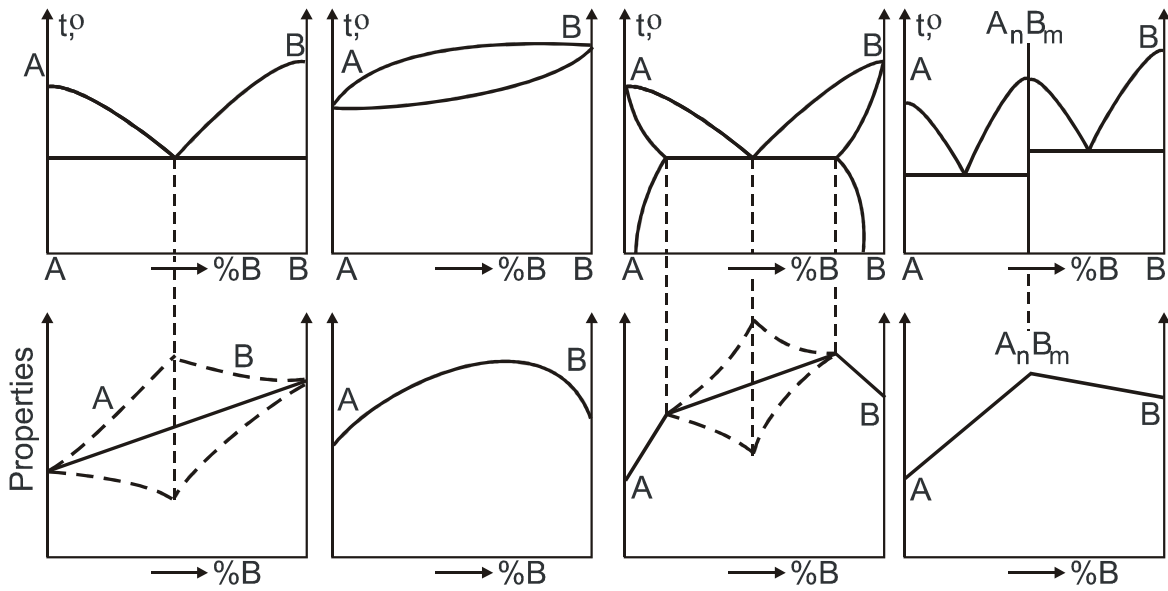


Fig. 1.10. Constitutional diagrams and correspondent "composition-properties" diagrams

Theme 2. GENERAL PROPERTIES OF STRUCTURAL MATERIALS

Mechanical properties of materials are the parameters defining materials behavior under action of applied external mechanical forces. Strain resistance of material (hardness) and resistance to rupture (toughness, viscosity) may be considered among mechanical properties. As a result of mechanical testing numerical value of mechanical properties can be gained. It is stress and strain values, at which a change of physical and mechanical state of a material takes place.

At estimation of mechanical properties of metal materials standard static testing of smooth specimen (on a tension, compression, bending, and hardness) and dynamic tests of specimen with indent (on impact strength) applied.

A term “static tests” refers to testing, at which the load, applied to specimen, increases slowly and smoothly. The tension test is carried out more often. The standard specimens are used for tension tests (Fig. 2.1).

The tests are carried out on the tearing machine. The tearing machine records the tension diagram of specimen (Fig. 2.2). The tension diagram of specimen is relationship between load, applied on a specimen and its absolute elongation (so called load-elongation curve).

On the tension diagram may be pointed:

- Stress, relevant to a maximum load, prior to fracture of a sample – $\sigma_B = P_B / F_0$;
- Stress, at which the sample distorts without magnification of tensile loading (physical yield strength) - $\sigma_S = P_S / F_0$;
- Maximal stress, at which the linear dependence between loading and elongation - $\sigma_P = P_P / F_0$ is still saved;

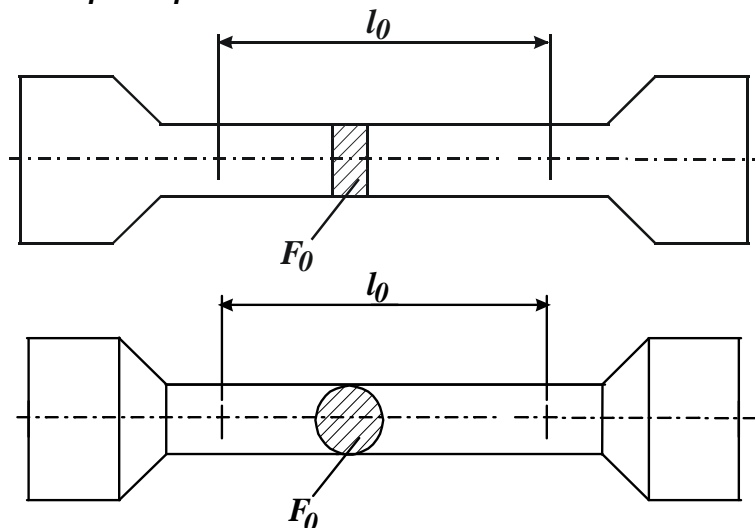


Fig. 2.1. Flat and round tension test specimens:
 l_0 - the base lengths of a specimen; f_0 - the original area of a specimen

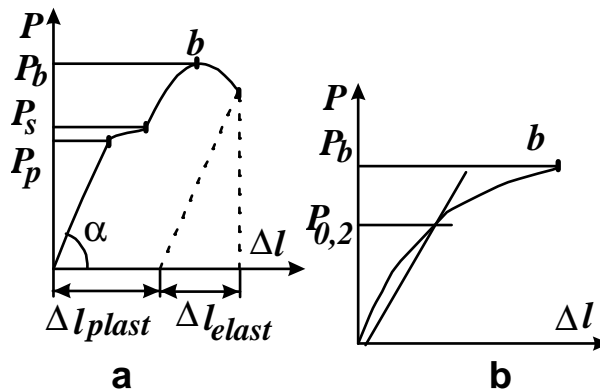


Fig. 2.2. The standard diagrams of metals tension: **a** - for ductile materials (there is a site of fluctuation); **b** - for brittle materials (the site of fluctuation would miss)

- for low-plastic materials the conventional yield strength - $\sigma_{0,2} = P_{0,2} / F_0$ is determined. It is the stress calling permanent elongation of a sample in 0,2 % from base length l_0 .

It is necessary to mark, that the mentioned above values of stress differ from reality. This difference is caused by variance of specimen cross-section at a tension.

At tension tests also performances of a toughness are determined:

- Aspect ratio $\delta = \frac{l_1 - l_0}{l_0} \cdot 100 \%$;
- Reduction of area $\psi = \frac{F_0 - F_1}{F_0} \cdot 100 \%$,

where l_1 and F_1 - accordingly length and area of a sample after fracture.

The tangent of an angle of inclination of a rectilinear segment of the phase diagram (see Fig. 2.2) determines a coefficient of elasticity of a material E .

Performances of materials $\sigma_{0,2}$, σ_B , δ , ψ , E are basic. They are included in the standard on materials delivery.

Compressive tests. These tests are applied for brittle materials (cast iron, the cast aluminium alloys). They are carried out similarly to tension tests. As a result of tests the ultimate compressive strength is determined.

Bending tests are carried out also for brittle materials. The concentrated loading is affixed to a sample lying on two sharp supports (Fig. 2.3). The ultimate bending strength is determined under the formula: $\sigma_{BEND} = \frac{M_{max}}{W}$, where M_{max} - maximal bending moment, W - section modulus of rectangular or round sample.

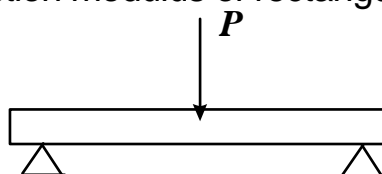


Fig. 2.3. The scheme of bending test

Fracture toughness test (impact strength). The brittle failure of many constructions happens at stresses not calling plastic deformation. The reasons of fracture are the micro-cracks originating in service. Therefore reliability of a construction is determined by resistance of metal to micro-crack extension. The scheme of sample testing on impact strength is shown in Fig. 2.4.

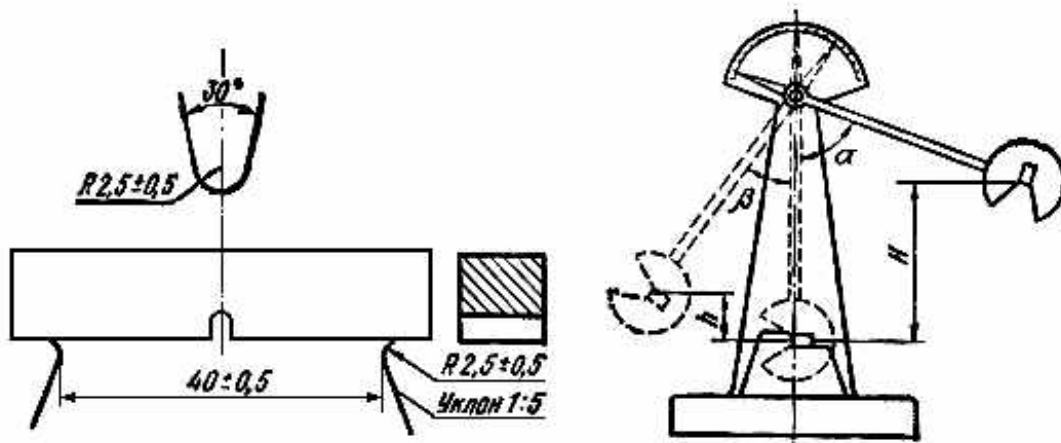


Fig. 2.4. Impact toughness test

The value of impact toughness is defined as the ratio of impact energy (potential energy of the falling pendulum) to the area of sample in the place of cut. Besides the numerical value of the impact toughness (impact strength frequently mean by the small character a) the character of a fracture - viscous or brittle is examined.

Tests of metals on hardness

Material hardness is a property to resist to the plastic deformation at contact effect in surface layer of a material. The measuring of hardness (without fracture of a sample or off-the-shelf component) allows to judge properties of a material. More often methods of Brinell, Rockwell and Vickers are applied to measuring hardness. The substance of these methods consists of impression in a surface of a sample indenter of the particular shape and fixation of an effort or depth of impression. The scheme of hardness test on Brinell, Rockwell and Vickers are shown in Fig. 2.5.

Brinell hardness test of metals and alloys. It is conducted by means of hardness measuring machine **ТШ-2М**. Hardened steel ball with diameter 2,5; 5 or 10 mm is indented into the test specimen. Brinell hardness HB (it is expressed in MPa or kg/mm²) is determined by the ratio of load R to the surface area of indentation mark:

$$HB = \frac{P}{F}, \quad F = \frac{\pi D}{2} \left(D - \sqrt{D^2 - d^2} \right),$$

where F - a surface area of a spherical impression. The Brinell hardness in digits expresses coefficient of hardness and after these digits it is agreed to write capital

characters HB. For example, 175HB (the hardness makes 175 kg/mm²). Diameter of a ball, applied loading and duration of endurance under power is selected in accordance with standard (ГОСТ 9012-59). Diameter of an impression is measured with the help of a reading microscope МПБ-2С with precision of **0,05** mm. There are tables of dependence of hardness from diameter of an impression and applied load. It is necessary to mark, that between a Brinell hardness number and ultimate stress limit of a material there is a approximate dependence $\sigma_B = K_1 \cdot HB$. The values of coefficient K_1 are given in the tables. Thus, knowing hardness of a material, it is possible to estimate ultimate strength, not rupturing a sample.

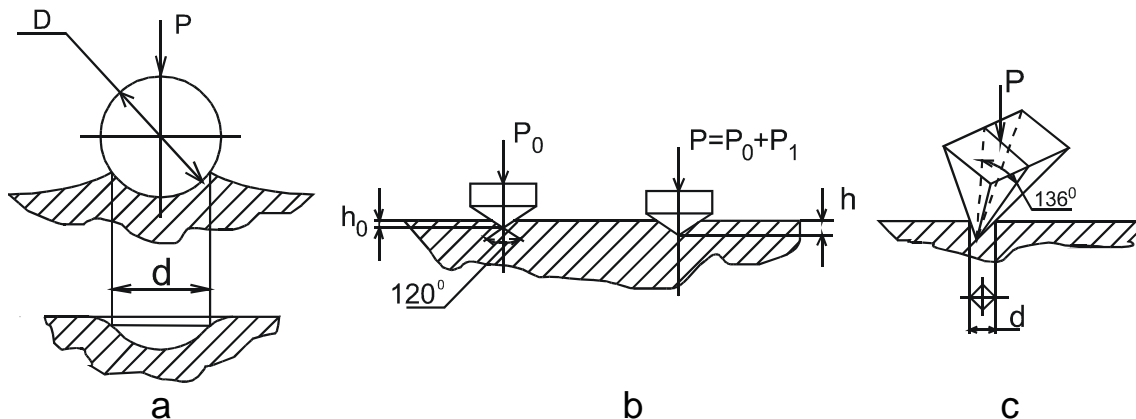


Fig. 2.5. The scheme of hardness test: a - on the Brinell; b - on Rockwell; c - on Vickers

Rockwell hardness test of metals and alloys. In this method a diamond cone or steel ball indents into a sample (ГОСТ 9013-59). The measuring of hardness is yielded with the help of a gear TK-2M. A gear has the indicator with several scales. The apex angle of a cone makes 120°, diameter of a ball – 1/16 inches (1,588 mm). The indicator is indented into a sample by 2 sequentially operating forces P_0 and P . The force P_0 is equal 98N. The force P amplify force P_0 up to 600N at impression of a cone and up to 1471 N at impression of a ball. The Rockwell hardness is evaluated under the formula:

$$HR = \frac{k - (h - h_0)}{c},$$

where h_0 - depth of implantation of indenter under operation of the initial load, mm; h - depth of implantation of indenter under operation of a total loading, mm; $k=0,26$ mm for a ball and 0,2 mm for a cone; c - scale value of an indicating meter relevant to implantation of a tip on 0,002 mm. The Rockwell hardness is a dimensionless quantity, counted on a scale of the measuring instrument. The Rockwell hardness is marked in digits describing coefficient of hardness, and characters, following to them, HRC, HRA or HRB. For example, 60 HRC - the character C - means a scale, on which measuring was fulfilled. Scales C, A, B are applied depending on guessed hardness of a material (C - more hard; A, B - less hard).

The Vickers hardness. The measuring is carried out in accordance with

ГОСТ 2999-75. It consists in impression of a diamond tip shaped as regular tetrahedral pyramid into the sample. Then measuring of the diagonal of an impression (in millimeters) is carried out. The diamond hardness is determined according to dependence:

$$HV = 0,189 \frac{P}{d^2},$$

where P - impression load expressed in Newton. The load can vary in a range of 9,8...980 H. The Vickers hardness is notated by digits describing coefficient of hardness and characters HV. For example, 240 HV. This method may be used for hardness test of details of small width and thin surface layers having high hardness. There are tables permitting mutually to translate Rockwell, Brinell, and Vickers hardness.

Mechanical characteristics at variable (cyclic) loadings

The prolonged effect on metal of repeatedly - alternating stress can cause a cracking and fracture even at stresses below $\sigma_{0,2}$. Accumulation of damages in metal under influence of cyclic loads is called as fatigue. Property of materials to resist to fatigue term as fatigue life.

According to the ГОСТ 25502-79 the fatigue tests are carried out for definition of endurance strength (Fig. 2.6, a).

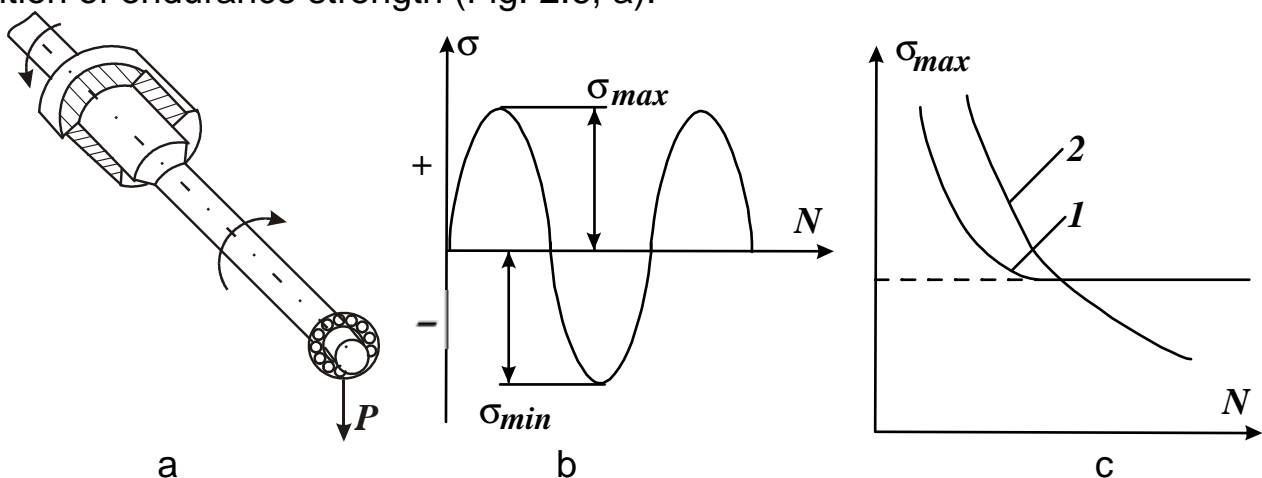


Fig. 2.6. Fatigue tests of specimens: a - scheme of tests; b - the diagram of specimen loading; c - fatigue curves (Wöhler curve) (1- having a horizontal segment; 2- without horizontal segment)

The **endurance strength** - maximum rating of stress of a loading cycle, at which fatigue failure of specimen does not happen. The number of loading cycles is set previously. A **loading cycle** - set of variable values of stresses for one period of their change. The number of loading cycles equals usually 10^7 for steels and 10^8 for light and non-ferrous alloys. If the maximal loading cycle stress is equal modulo to minimum algebraic value of stress, this loading cycle is called symmetric - i.e. $\sigma_{max}/\sigma_{min} = -1$ (Fig. 2.6, b). Mean Endurance

strength at a symmetric loading is marked as σ_1 . By results of tests the fatigue curves (Fig. 2.6, c) may be plotted.

Non-metallic inserts, the cracks, corrosion considerably reduce endurance strength of materials.

Wear tests

At friction of conjugate surfaces the wear of a material - detachment it from a surface of a material or increase of its residual strain takes place. Property of materials to resist material deterioration and particles removing from the surface is called as **wear-resistance**. Numerically wear-resistance is evaluated by the wear rate (for example GOST 27674-88). The following wearing test methods may be distinguished: at slide with lubricant and without lubricant (Fig. 2.7); a wear by abrasion with lubricant and without lubricant; a wear at a rolling without lubricant. As a result of tests friction coefficients of a material about material, temperature range of operation, mass removing of materials for a time unit are determined. Mainly degree of wear is measured by mass removing:

$$\Delta h = \Delta m / \rho S$$

where Δh - the thickness of lost layer; Δm - mass of lost material; ρ - material density; S - area of wear.

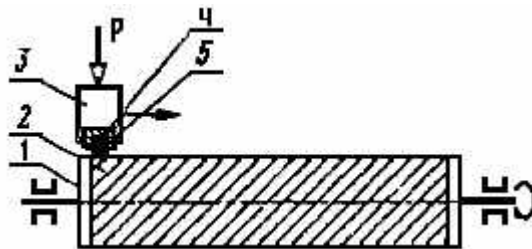


Fig. 2.7. Typical scheme of wear resistance measuring

Metal structural materials

The metal construction materials are applied in constructions of flight vehicles and mechanical engineering. Despite of broad application of non-metallic materials and composites it is impossible to completely refuse from application of metal materials. Carbon and alloyed steels, cast irons, brass, bronze, copper-nickel alloys can be considered among the materials with high hardness and good processing behavior. It is possible to refer aluminium, magnesium, titanium, beryllium alloys, composites with metal matrixes and filaments to metal materials with a small density and high unit strength. Fallen into corrosion-resistant materials, heat-resistance materials, high-temperature and heat resisting materials, radiation-resistant materials, corrosion-resistant materials may be referred to the materials, resistant to effect of temperature and exterior operating temperature.

Theme 3. PLASTIC DEFORMATION AND RECRYSTALLIZATION OF METALS

Considerable structural changes caused by displacement of atoms in a lattice appear at different technological operations (blacksmithing, extrusion, rolling) in metals and alloys. The displacement of atoms depends on magnitude of effective stresses. At small deforming stresses displacements of crystal lattice atoms are small and also can be converted, i.e. after removal of load the atoms return to initial places. The strain in such cases is named **elastic**. As the elastic deformation is not accompanied by residual changes in structure, the properties of strained metals do not vary. It is conditionally accepted, that the residual strain at a rate of 0.2 % from primal length of a sample may be considered as the boundary between elastic and plastic strains.

At increase of stress higher than a limit of elasticity the considerable displacement of atoms concerning final equilibrium positions are watched. After removal of load the atoms do not return in the former positions. Thus the properties of materials vary. The residual strain is named plastic.

It is conditionally accepted, that as the boundary between elastic and plastic strains the residual strain at a rate of 0,2 % from primal length of a sample might be considered. A stress appropriate to this strain is accepted to name by yield point of material.

Atomic-crystalline structure of materials

The real structure of industrial alloys represents the set of a great number of separate irregular-shaped crystals - grains or crystals with different orientation. The grains consist of separate fragments, disorientated relative to each other on some degrees, and fragments - from units with disorientation angles in some minutes. Inside units the structure is close to theoretical.

The physics of a plastic deformation

The repositioning of atoms at a plastic deformation happens by a slip of one part of metallic chip relative to another. The slip is carried out under an operation of shearing stresses. The shear stresses are oriented on slip planes. The slip planes are sown densely by atoms and have small adhesion forces. If the planes are packaged densely by atoms and are located in relation to operating load so, that the shearing stresses are small, the slip on this system of planes will be absent. At a plastic deformation there are two possible versions of atoms migrations: twinning and slip.

The strain by twinning usually happens at low temperatures and at high speeds of deformation, when the slip is difficult. The turn of particular parts of a crystal in a plane of a strain in this case is watched. Thus the lattice becomes a mir-

roring of adjacent, undeformed lattice areas (Fig. 3.1).

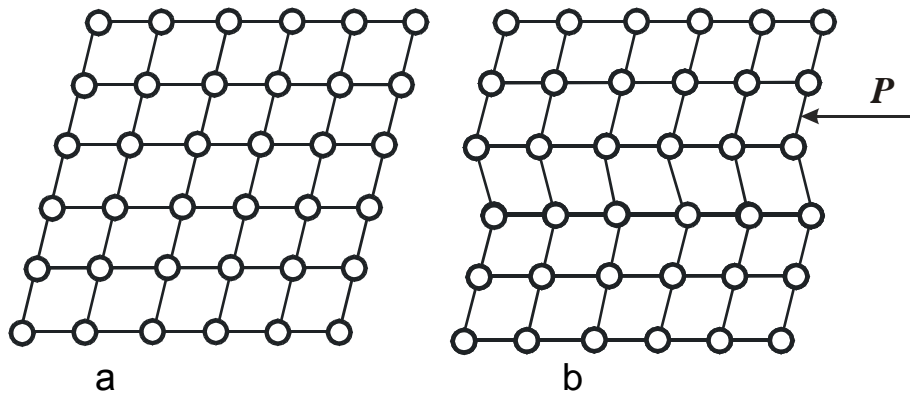


Fig. 3.1. The scheme of crystal deformation by twinning:
a - initial state; **b** – the load application and twin formation

There are twinning bands (twins) appearing in a crystal. Within the bounds of one grain there can be some twins.

The strain of metals by slipping is watched most frequently. The displacement of atoms on slip planes during a plastic deformation appears as slip lines, which can be watched under a microscope. The more degree of a strain, the more richly slip lines place. At large strains they almost drain. At small increase one slip line is visible. Actually it is the whole group of lines located from each other on small distances. If the slip appears on several systems simultaneously, the grids from slip lines are determined on macrosection.

At a plastic deformation metals hardening is watched. Process of slip and nature of metals hardening are explained fully on the basis of the dislocation instrument of a plastic deformation.

The dislocations are the linear imperfections of a crystalline metals structure. They are usually located along edges of an incomplete plane (edge dislocation) or along a line of shift of one part of a crystal relative to another (screw dislocation).

In the dislocation theory the following assumptions are adopted:

- The slip is spread on a plane sequentially, not simultaneous;
- The slip starts from places of violation of a lattice, which should be or arise in metal (crystal) at its loading.

Let's consider the physics of a plastic deformation on an example of migration of a linear or edge dislocation in crystal (Fig. 3.2). The considered phenomena are similar at migration of screw and other dislocations.

Let's assume there is a linear dislocation A (see Fig. 3.2) (perpendicular to sectional plane of crystal) on the edge of incomplete plane. Under the action of shift stress called by force P, the atoms of an incomplete plane I-I are shifted to the right (are shown by black points) in a position I' -I'.

The top of the whole plane II-II will remove to the right too (a-b). In the particular moment there a break of the whole plane II-II appears on a horizontal plane N-N. Thus the plane I-I is integrated with bottom of a plane II-II. Thus the

whole plane (shown by a shaped line) will be formed. The top of a former whole plane II-II becomes incomplete (it is shown by a shaped line in Fig. 3.2, a). The dislocation from a position A was transferred on one interatomic distance to the right to positions B.

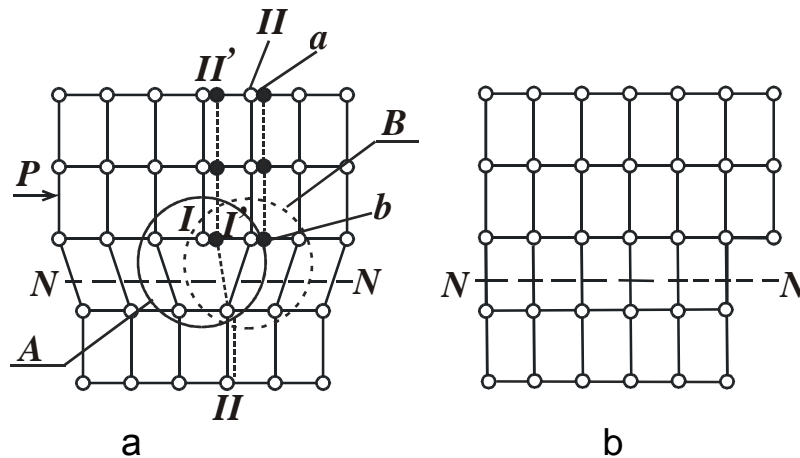


Fig. 3.2. Migration of a dislocation A on one interatomic distance in a position B (a), (b) - exit of a dislocation on a crystal edge and formation of shift on a plane N-N on one interatomic distance

Under the action of shear stresses the dislocation will displace sequentially in a slip plane, until the surface of a crystal will be reached (Fig. 3.2, b). In result there will be a shift in a crystal on a slip plane on one interatomic distance, though all atoms in this plane did not displace simultaneously. It also explains the fact, that the real resistance to shift is much less then theoretical. The theoretical resistance to shift can be estimated by Fraenkel's formula

$$\tau_{max} = \frac{b}{a} \cdot \frac{G}{2\pi},$$

where a - distance between shearing sectional areas; b - interatomic distance in a direction of shift; G - a shearing modulus.

Interatomic distance a on an order of magnitude is equal to interatomic distance in a direction of shift b . It follows, that

$$\tau_{max} = \frac{G}{2\pi}.$$

The experiments display, that the dislocation density during a plastic deformation is increased from 10^7 cm/cm³ (in annealed metal) up to $10^{12}...10^{13}$ cm/cm³ in extreme strained state. Thus, during a plastic deformation new dislocations appear.

For security of final shifts it is necessary to transfer up to the boundary of a crystal or grain a great number of dislocations. Therefore not only dislocations, available in metal, participate in such process but also newly generated.

The process of plastic deformation is accompanied by hardening of metal that is stipulated by increasing of resistance of crystalline structure to migration of dislocations. Except of hardening, the plastic deformation results in lowering

of toughness, corrosion resistance, electro- and thermal conduction.

The set of all changes in structure and properties of distorted metal is named as a work hardening. Practically the strengthening is the most important result of a strain.

The resistance of metal to dislocations migration increases under an operation of the following factors:

a) Turn of slip planes relative to operating force. Thus the slip planes tend to settle in parallel to principal direction of a strain. That is the angle between operating force and slip plane is gradually decreased, and the stress in a slip plane reaches the critical value at large loadings. Thus, some portion of hardening deposited by a strain, is explained by geometry of the strain itself;

b) Increase of a dislocation density. It results in considerable distortions of a spatial crystal lattice. They arise at interaction of dislocations with each other (their intersection) with other imperfections of a crystal lattice;

c) Brake of dislocations action on obstacles: the boundaries of units, grains, actuations of other phases. As in different grains of substantial metals the alignment of crystallographic planes is various, the boundaries of grains are an insuperable barrier to dislocations. The dislocations accumulate on the boundary of a grain and create large internal stresses. These stresses, in turn, actuate dislocations in adjacent grains. Thus, through the boundary of grains the migration of dislocations is transmitted by a relay way;

d) Effect of admixtures and atoms of alloying elements. The hardening of metals and alloys at a plastic deformation results in exhaustion of the metal toughness and restricts capabilities of deriving of composite details for one machining step. On the other hand, with the help of a work hardening it is possible to increase structural strength practically of all present metals and alloys.

The plastic deformation causes turn of slip planes. As a result of it the metal acquires particular alignment of crystalline structure, so-called **texture**. The grain-oriented metal has the brightly expressed anisotropy of properties.

Besides distortions of atomic-crystalline structure in plastically deformed metal the microstructure varies also. The strain calls subdivision of grains, which are stretched along a force direction. The metal acquires a filamentary structure, the internal residual stresses appear in it.

Distorted metal is in extremely nonequilibrium and thermodynamically unstable state. This condition at a room temperature for the majority of metals and alloys can be saved very long.

Effect of heating on properties of distorted metals

At heating the plastically deformed metals gradually restore the structure and properties and pass in a stable state. This transition can be dissected on two stages: **return** and **recrystallization**.

The **return** is watched at rather low-level heating temperatures (about

20 % from melting point) and is divided in turn on two phases: **recovery** and **polygonization**.

The recovery is accompanied by diffusive migration and mutual cancellation of dot imperfections. Thus the elastic distortions of a lattice are eliminated and physical properties of metal are restored partially.

Polygonization happens at more heating. It is accompanied by changes in a block structure of grains owing to reallocation and elimination of linear imperfections - dislocations. It results in further removal of elastic distortions of lattice and fuller restoring of physical properties. The strength properties at return do not vary, and the toughness is substantially restored.

The **recrystallization** flows after return at more heat called **temperature of recrystallization**. It is possible to define approximately this temperature for commercially pure metals under the formula of A. Bochvar:

$$T_{recr} = 0,4T_{melt},$$

where T_{recr} - absolute minimum temperature of recrystallization in absolute degrees; T_{melt} - absolute temperature of melting for given metal.

A. Bochvar's formula is applied for degrees of deformation not less than 40...50 % that most frequently meet in practice.

Temperature of recrystallization increases at increase of admixtures amount or at presence of alloying elements.

The centers of recrystallization on which accumulate atomic layers with an undistorted crystal lattice appear during recrystallization. Forming of new equilibrium grains is watched. These grains frequently differ in magnitude from grains of initial undeformed metal.

The origin of grains and their growth up to a mutual contact at temperature higher than temperature of recrystallization is named as **primary recrystallization** or **handling recrystallization**.

After handling recrystallization the restoration of mechanical and plastic properties of metals is watched. And the mechanical characteristics depend on magnitude of a grain.

It is established, that the magnitude of the recrystallized metal grain depends on heating temperature and degree of a prior plastic strain (Fig. 3.3).

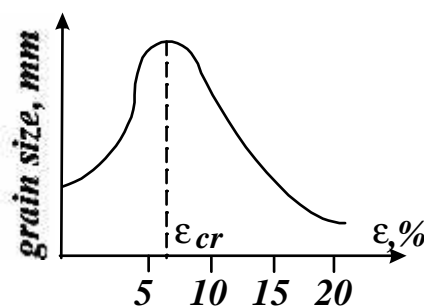


Fig. 3.3. A size of grid after recrystallization at particular temperature depending on a degree of a prior strain

The strain degree, after which as a result of posterior recrystallized annealing very large grain derivatives, is named as a critical degree of a strain - ϵ_{cr} . As a rule, it is a small degree of a strain (for iron 5 ... 6 %; for dilute steel 7 ... 15 %; for copper about 5 %; for aluminium 2 ... 3 %). At a critical degree of a strain in metal the small number of centers of recrystallization will be derived, and the grain grows large. At $\epsilon = \epsilon_{cr}$ the amount of centers of recrystallization increases and the magnitude of a grain after recrystallization decreases.

Cold and hot plastic deformation

All explained above relates to a cold plastic deformation, which is accompanied by a work hardening bounding its marginal capabilities. For restoring a toughness of distorted metal it is necessary to conduct recrystallization annealing.

Hot plastic deformation (or non-cutting shaping) is carried out at temperatures above than temperature of recrystallization. In this case the process of recrystallization follows a strain and fractionally or completely removes effect of hardening. Therefore in a hot condition the metal is not hardened and its forming is possible with considerable degrees of a plastic deformation.

Theme 4. STEEL STRUCTURE AND PROPERTIES

Steel is the name of iron alloys with carbon, containing carbon up to 2.14 %. Alloys of iron with carbon in amount of 2.14...4 % called as cast iron. The steel density varies within the limits of 7.7...7.8 g/cm³. Pure iron - the basis of any steel - has 2 polymorphic transformations.

Steel can be classified by the chemical compound, by the way of manufacture, by destination and way of manufacture. According to the chemical compound all steels are divided on carbonaceous and alloyed.

According to the contents of carbon steel can be divided into low-carbon (carbon less than 0.3 %), medium-carbon (carbon from 0.3 up to 0.5 %), high-carbon (carbon more than 0.5 %).

According to the contents of alloying elements steels can be divided into low-alloyed (amount of alloying elements ≤ 3 %), medium-alloyed (amount of alloying elements from 3 up to 10 %), high-alloyed (amount of alloying elements ≥ 10 %).

According to the designation steel may be divided into structural steels of general purpose, structural steels of special designation, steel with the special chemical and physical properties, tool steel.

According to the way of manufacture all steels are subdivided into steel of ordinary quality, qualitative, high-quality, especially high quality.

Steels of ordinary quality. This group unites steel with the contents of carbon up to 0,6 %. There are some special requirements to them during melting and casting. They contain the increased amount of nonmetallic inclusions (harmful impurity of sulfur and phosphorus up to 0,08 % of each element). They are supplied by three groups:

- Group A - with the caused mechanical properties: Ст0, Ст1,... , Ст6;
- Group Б - with the caused chemical compound: Б Ст0, Б Ст1,..., Б Ст6;
- Group В - with the caused mechanical properties and a chemical compound: В Ст0, В Ст1,..., В Ст6.

Letters Ст designate a word steel. Figures in mark - ordinal number of steel on the standard ГОСТ. If there are no small Russian letters after Figures, it means that steel is deoxidized by aluminium, by manganese and by silicon and it is named as killed steel. If after Figure there are letters **пс** (for example, Ст3пс), we have so called semi-killed steel. It is deoxidized by aluminium and by manganese. If after Figure there are letters **кп** (for example, Ст5кп), the steel is called **rimmed**. It is deoxidized only by manganese or silicon.

Qualitative steels. According to the chemical compound it is carbonaceous and alloyed steel. There are more strict requirements to steel at melting and casting, than to steel of the ordinary quality. They contain carbon not more than 0.8 %, sulfur and phosphorus about 0.035 % of everyone. They are marked as follows: at first there is a two-digit number - it shows the contents of carbon in one hundredths of a percent. Then title Russian letters go. These letters show presence of alloying ele-

ments. After each letter there may be a number. This number indicates the content of the alloying element in percents. If after the letter there is no number then the contents of alloying element is approximately 1 %. Exceptions are molybdenum, vanadium, titanium and boron. The content of molybdenum, vanadium and titanium does not exceed usually 0.1...0.3 %, boron – 0.005 %. In tool steel (they they are designated by capital letter Y and by the following after it numbers) carbon content is measured in the tenths of percentage.

To understand reasons of some metals and alloy high cost is very useful to analyze its quantity in earth crust (or in oceans):

Al – 7.5 %, Fe – 4.2 %, Mg – 2.4 %, Ti – 0,61 %, Ni – 0.018 %, Cu – 0.007 %, Be – $4.2 \cdot 10^{-4}$ %, W – $1.0 \cdot 10^{-4}$ %.

Alloying elements are designated by the following letters: A-nitrogen, Б- niobium, В tungsten, Г-manganese, Д-copper, Е-selenium, К-cobalt, Н-nickel, М-molybdenum, П-phosphorus, Р-boron, С-silicon, Т-titan, Ф-vanadium, Х- xром, Ц-zirconium, Ч-rare-earth metals, Ю-aluminium.

Example of decoding of mark: Steel 45-quality constructional steel with the carbon contents 0.45 %. Steel Y12 - tool steel with the carbon contents 1.2 %. Steel of mark 30ХГС- qualitative alloyed steel with the carbon contents 0.3 %, alloyed by chromium, manganese and silicon in volume 1 % of each element.

High-alloy steel. This group includes alloy steels, melted in the electric furnaces. The content of sulfur and phosphorus in them does not exceed 0,025 %, and carbon - not more than 0,07 %. These steels are marked just as quality steels, and at the end capital letter А is placed. For example - 12X2H4BA.

Especially high-quality steel. They are melted in the electroslag furnaces with the electroslag remelting. The content of sulfur and phosphorus in them is not more than 0,015 %. Content of carbon and alloying elements is defined just as for quality fine steels, and at the end is placed capital letter Ш through the dash. For example - 18X2H4B-Ш.

The marks which have been not included in ГОСТ, are marked by letters ЭП, ЭИ, ДИ and the following behind them serial numbers of alloys. These letters designate that steels are tested or their properties will be investigated.

There are several world leading industries having their own designation systems for metals and alloys. Any designation system is based on state, branch or enterprise local standards used in each country of union. Typical Correspondence between countries and their standard designations is shown in **Appendix A**.

American designation systems for steels and alloys

There are several organizations in the USA using their own **designation systems for steels and alloys, they are:** AISI, ANSI, AMS, ASI, API, ASME, ASTM, AWS, SAE, UNS. Mostly AISI (American Iron and Steel Institute), SAE

(Society of automotive engineers), ASTM and UNS can be met in popular technical literature.

The AISI and SAE systems use four- (AISI) or five-digit (SAE) number, where first two numbers refer to major alloying elements present and last two or three numbers refer to the carbon percentage. An AISI 1040 steel is plain medium-carbon steel with 0.40 % C. SAE 10120 steel is plain-carbon (high-carbon) steel containing 1.2 % C. AISI 4340 steel is an alloyed steel containing 0.4 % C.

If the first digit is 1 it means plain carbon steel (the second digit can be 0, 1, 2 or 5 depending on steel de-oxidation type); 2– is nickel steel; 3 is chrome-nickel; 4 is molybdenum; 5 is chromium; 6 is chrome -vanadium; 7 is tungsten; 8 is vanadium; 9 is siliceous with manganese. For example, AISI steel 1045 corresponds to Ukrainian steel Сталь 45; steel 5140 corresponds to steel 40X.

Moreover letters L, S, N, LN, F, Se, B, H, Cu can follow first digits, be entered between them or even stay before them. These letters mean auxiliary alloying elements (B- boron, L- lead, for example 51B60 or 15L48), steel application (M- for steel of ordinary quality, E – melting in electrical oven) or manufacturing method (H- high hardenability, for example 304H).

Stainless and corrosion resistant steels are designated by three digits XXX and following letters (if necessary). Austenite steels begin with 2XX or 3XX, ferrite and martensite steels belong to class 4XX. Last two digits are ordinary numbers (not percents of something). Following letters mean alloying elements (430 F has high phosphorus contents, Se- selenium is added).

Classification by ASTM specification includes letter A (i.e. ferrous metal), ordinary number of standard and steel grade designation. By default American measuring system is adopted. letter M follows standard number of metrical system is used.

For example A 516/A % 16 M-90 Grade 70 means: A- ferrous metal, 516 is standard number (516M is standard with metrical units), 90 is year of standard publishing, Grade 70 is steel grade, 70 means minimal guaranteed margin of strength for this steel (in ksi units, that corresponds to 485 N/mm²).

European (EU) designation systems for steels and alloys

This designation system is based on standard EN 10027 (grounded on **German** designation system) and consists of two parts, part one tells how to designate steels, part two – how to give ordinary number of a steel inside of the group.

Part 1. All steels are divided into two groups: group 1 includes steels with definite application, mechanical or physical properties, group 2 joins steels with definite chemical composition.

Group 1. Designation consists of one or several letters (meaning steel application), then numbers are followed (mean properties). Auxiliary last symbols can be presented (mean application or conditions of supplying). See **Appendix B**, Table B.1.

Group 2. Group 2 considers designation by composition (part 1) and purity and application (part 2). See **Appendix B**, Table B.2.

Part 2. Steel enumeration in a group by application and purity.

Ordinary number mask is 1.XXXX – for steels; 0.XXXX- for cast irons; 2.XXXX- Ni, Co high-temperature alloys; 3.XXXX- ferrous alloys. First two XX mean ordinary number of steel group, last two XX – ordinary number of a steel in a group. See **Appendix B**, Table B.3.

In **France** nowadays European designation system is used but some distinctions are presented. They are combinations of conventional symbols of chemical elements (used in periodic table) with simple English letters used for alloying elements designation (Table B.4).

Table 4.1. Symbols used for designation alloying elements in French standard

Element	Designation symbol	Element	Designation symbol
Nitrogen	Az	Cobalt	K
Aluminium	A	Silicon	S
Boron	B	Manganese	M
Vanadium	V	Copper	U
Tungsten	W	Molybdenum	D
Zirconium	Zr	Nickel	N
Niobium	Nb	Phosphorus	P
Titanium	T	Chromium	C

Japan designation systems for steels and alloys

Japan designation system contains several letters and numbers. Letters mean group to which the steel belongs, numbers – ordinary number in the group or definite property (carbon contents, ultimate strength etc).

Structural steels. Designation begins from **SSxxx**, where xxx means minimal guaranteed ultimate strength of a steel in N/sq.mm (for example, SS330, SS490 etc).

Structural qualitative steels are designated with **SxxC**, where consequent numbers xx shows carbon percentage in hundreds of percents: S12C ($\approx 0.12\%$ C); letter K is presented for qualitative steels (low P and S contents) – S15CK.

SF- steel for forgings (SFVC 1, SFVA F21 A); **SP** – steel for sheet metals (SPHC, SPHD, SPHT, SPCD); **SPVxxx** – for manufacturing high pressure vessels (SPV 355 means steel with ultimate strength 355 N/sq.mm); **ST-** steels for tubes manufacturing (STK 290, STKM 16 C); **SRxxx** or **SDxxx-** for metal rods (SR 235); **SWR** – for rolled steel articles (SWRM 6); **SUMxx-** for automatic steels (SUM 12); **SVxxx** – steels for rivets (SV 400); **SBCxxx** – steels for

chains; **SUPx** – steels for springs.

Alloyed steels. Designation includes first letter S then letter meaning main alloying elements (C-chromium, M- molybdenum, N-nickel, S-silicon, A-aluminium). Then one, two (mean ordinary number of steel in the group) or three (first mean ordinary number in the group, last two – carbon contents in hundreds of percent) numbers can follow. Last letter H means steel hardenability (SMnC 443 H). For example:

- SNC 815 means steel alloyed with Ni and Cr, number 8, 0.15 % C;
- SCr 420 (alloyed with Cr, 0.2 % C);

Tool steels. Designation of carbon steels consist of letters **SK** and ordinary number in a group (SK 2, SK 6). For alloyed ones – **SKD, SKS, SKT** ordinary number of a steel is added. **SKH** – for fast-cutting steels; **SUJ** – for bearing steels.

Corrosion resistant steels. AISI system is used for designation, for example SUS 410, SUS 321 H.

High-temperature steels. SUHx(xx). SUH4, SUH 310.

Introduction to the Unified Numbering System of Ferrous Metals and Alloys

The Unified Numbering System for Metals and Alloys (UNS) provides means of correlating many internationally used metal and alloy numbering systems currently administered by societies, trade associations, and those individual users and producers of metals and alloys. This system avoids the confusion caused by the use of more than one identification number for the same metal or alloy, and the opposite situation of having the same number assigned to two or more different metals or alloys. It provides the uniformity necessary for efficient indexing, record keeping, data storage and retrieval, and cross-referencing.

CA UNS designation is not, in itself, a specification, because it establishes no requirements for form, condition, property, or quality. It is a unified identifier of a metal or an alloy for which controlling limits have been established in specifications published elsewhere.

The UNS establishes 9 series of designations for ferrous metals and alloys. Each UNS designation consists of a single-letter prefix followed by five digits. In most cases the letter is suggestive of the family of metals identified: for example, **F** for cast irons, **T** for tool steel, **S** for stainless steels (see **Appendix C**).

Although some of the digits in certain UNS designation groups have special assigned meanings, each series of UNS designations is independent of the others in regard to the significance of digits, thus permitting greater flexibility and avoiding complicated and lengthy UNS designations.

Wherever feasible, and for the convenience of the user, identification "numbers" from existing systems are incorporated into the UNS designations. For example, carbon steel presently identified by the American Iron and Steel Institute as

"AISI 1020" is covered by the UNS designation "G10200".

The UNS designation assignments for certain metals and alloys are established by the relevant trade associations which in the past have administered their own numbering systems; for other metals and alloys, UNS designation assignments are administered by the Society of Automotive Engineers (SAE). Each of these assigners has the responsibility for administering a specific UNS series of designations. Each considers requests for the assignment of new UNS designations, and informs the applicants of the action taken. UNS designation assigners report immediately to the office of the Unified Numbering System for Metals and Alloys the details of each new assignment for inclusion into the system.

The listed cross-referenced specifications are representative only and are not necessarily a complete list of specifications applicable to a particular UNS designation.

Introduction to the Unified Numbering System of Nonferrous Metals and Alloys

Unified numbering system (UNS) is a system of designations established in accordance with ASTM E527 and SAE J1086, Recommended Practice for Numbering Metals and Alloys. Its purpose is to provide means of correlating systems in use by such organizations as American Society for Testing Materials (ASTM) and Aluminium Association (AA), as well as individual users and producers.

UNS designation assignments are processed the ASTM, or other relevant trade associations. Each of these assigners has the responsibility for administering a specific UNS series of designations. Each considers requests for the assignment of new UNS designations, and informs the applicants of the action taken. UNS designation assigners report immediately to the office of the Unified Numbering System for Metals and Alloys the details of each new assignment for inclusion into the system.

The UNS number is not in itself a specification, since it establishes no requirements for form, condition, quality, etc. It is a unified identification of metals and alloys for which controlling limits have been established in specifications published elsewhere.

This designation system establishes 9 series of designations for nonferrous metals and alloys. Each UNS designation consists of a single-letter prefix followed by five digits. In most cases the letter is suggestive of the family of metals identified: for example, **A** - for aluminium, **C** - Copper and Copper Alloys, **Z** - Zinc and Zinc Alloys, etc (see **Appendix D**).

The UNS provides a means of correlating many internationally used numbering systems currently administered by societies, trade associations, and individual users and producers of metals and alloys, thereby avoiding confusion caused by use of more than one identification number for the same material and by the opposite situation of having the same number assigned to two or more entirely different materials. It provides, also, the uniformity necessary for efficient indexing, record keeping, data storage and retrieval, and cross referencing.

Cast irons structure and properties

Cast irons are alloys of iron and carbon containing more than 2.14 % of carbon (typically up to 4.3 %). Very frequently they are allowed with 0.5...3 % of silicon. Distinctive feature of cast irons crystallization is creation of eutectics mainly consisting of cementite and graphite. Depending on this composition all cast irons can be divided into **white** and **grey**.

Generally white cast irons are quite hard and brittle due to large contents of cementite and not used in machine-building. Rarely whitening of root necks of shafts and drawing rolls is conducted to increase hardness and wear resistance locally.

Grey cast irons contain majority of carbon in form of graphite. Depending on graphite inclusion shape grey cast irons can be subdivided into **grey ferrite-perlite**, **malleable** and **high-strength**. Presence of graphite reduces strength but increases ductility, reduces friction coefficient and improves dynamic and frequency properties. According to GOST grey ferrite-perlite cast irons are designated with letters СЧ (серый чугун) and two consequent digits that mean average value of ultimate strength in kg/mm^2 . Application of grey ferrite-perlite cast irons: internal combustion engine cylinder block, cylinder head, cylinder barrel, pump case, clutch drums. Grey perlite cast irons are recommended for articles operating at high dynamic loads and severe wear conditions: gear, spindle, piston rings).

Composition of **malleable cast iron** is feather-like (or flake) graphite. Generalized designation according to the GOST system is КЧХХ (where КЧ means ковкий чугун, digits ХХ mean ultimate strength in kg/mm^2). Recommended application – high statically, dynamically and wear loaded articles: couples, asterisk, brake shoe, ore milling drum blades etc.

High-strength cast iron contains mainly nodular (perfect sphere-like) graphite and are used for dynamically loaded articles (crank-shafts, gears, forming rolls, brake drums). Designation for high-strength cast irons is ВЧХХ (ХХ mean ultimate strength in kg/mm^2 , for example ВЧ50 ($\sigma_B=50 \text{ kg/mm}^2$)).

According to AISI designation system grey cast irons are divided by classes: from Class 20 up to Class 80, where numbers mean average tensile strength in kpi (1000 psi). Malleable cast irons are designated by grades: Grade 32510, Grade 70003 etc. Designation of typical high-strength cast irons are Grade 60-40-18, Grade 80-55-06 etc, where first number means ultimate tensile strength (psi), second – yielding strength (psi), third – maximum elongation (in %).

Example of correspondence between different steel designation systems is considered in the Table 4.2.

Table 4.2. Correspondence between different steel designation systems

Steel type	Designation system										Application	
	GOST	UNS	AISI/SAE	JIS	AFNOR NF	EN	DIN	% C				
Plain carbon	Сталь 45	G1045	1045	–	–	C45E 1.1191	–	–	0.45			Crankshaft, connection rod, gear, plunger, spindle, friction disk, clutch, stud, forming roll
	Y7 Y12A	W1 12 –	W1-1.2C –	SK7 SK2	XC65 XC120FINC	CT70 CT115	C70W2 C115W2	0.7 1.2			For cutting tools: cutter, mills, drills, saw, hammer, chisel	
Alloyed	30XM	G40320	4032	–	–	32CrMo4	–	–	0.3			High-loaded articles
Corrosion resistant	08X18H10	S30400	304	SUS304	–	1.4303	X5CrNi18-10	0.08			For operation in wet, salt, low alkali and acid atmosphere	

Thermal and chemical-thermal processing of steel

Thermal processing consists of in change of structure and properties of a material by thermal influence on a material, i.e. by heating and cooling.

The basic forms of heat working are the following:

1. Heat treatment of single-phase alloys. At heating and cooling there is no change of structure and number of phases. Pure metals are subject to this kind of heat treatment.

2. Heat treatment of two and multiphase alloys. At heating and cooling solubility, structure and number of phases change. Aluminium, magnesium and heat resisting nickel alloys are exposed to this kind of heat treatment.

3. Heat treatment of two and multiphase alloys. During the heating and the cooling the solubility of the alloy components changes. It is connected with polymorphic transformations. Titanic alloys, majority constructional and tool steel are exposed to this kind of heat treatment.

4. Heat treatment at which saturation of a superficial layer of a detail by chemical elements is produced.

Now thermomechanical processing is widely applied. There is deformation of a detail and structural transformations in it simultaneously during thermomechanical processing.

The basic forms of steel thermal processing: annealing, normalization, volumetric hardening, tempering, sub-zero treatment, surface hardening.

Annealing. The basic purpose of annealing - reduction of hardness of an alloy with the purpose of increase of its plasticity and alignment of steel structure after mechanical thermal processing. During annealing steel cooling will be carried out together with the furnace.

Normalization. Normalization differs from annealing in terms of the cooling conditions. Cooling will be carried out on quiet air. After the normalization steel acquires pearlite, martensite or austenitic structure. Hardness after normalization became higher, than after annealing. Steel structure after normalization became fine-dispersed.

Hardening and ways of hardening. Hardening is carried out for increase of durability and hardness of steel. After hardening steel acquires martensite structure. Cooling of details after heating is made in water, mineral oil, solutions of alkalis and salts. Depending on rate of cooling there are several hardening processes (they are enumerated with an increase in rate of cooling):

- at slow rate of cooling is formed ferrite-cementite mixture;
- during the cooling with the higher, so-called, critical speed occurs diffusionless martensite transformation;
- austempering, in this case the hardness of steel is reduced, and toughness rises;
- martempering, is adapted for averting of warping and crack formation;
- quenching in two coolers (first in the water, then in oil), is applied to

prevent hogging and formation of cracks;

- hardening in one cooler - continuous hardening. It is the most widespread hardening process.

During the development of technological process of hardening it is necessary to take into account hardenability and hardening characteristics of steel. Hardenability - ability of steel to receive hardening. Hardening characteristics - depth of penetration of the tempered zone.

Tempering. It is applied to increase viscosity of steel after training. Tempering consists in heating of detail to the certain temperature and cooling in air or furnace. Depending on temperature 3 forms of the tempering are distinguished: low, average and high.

Low temperature tempering is carried out at temperatures up to 250°C. It is applied to reduction of residual stress and decrease of hardness. Tool and details after surface hardening are subjected to low temperature tempering.

Average tempering is carried out at temperatures 350...500°C. It promotes increase of a limit of steel elasticity. It is used for the details from which it is required good elastic properties – springs, etc.

High tempering is carried out at temperature 500...600°C. It is the most widespread kind of tempering. It is applied to details from which high corrosion resistance is required. The limit of endurance of details also raises: the relation σ_{-1}/σ_B after high tempering approximately equals 0.45...0.5. The combination of quenching and high tempering, or so called **heat refining** is the most widely used kind of heat treatment.

Sub-zero treatment. It is applied to eliminate residual austenite in steel. Residual austenite results in decreasing of hardness of the tempered steel, changes its magnetic properties, leads to a change of the detail dimensions during storage. Sub-zero treatment consists in cooling of steel up to temperature -50...140°C in the dependence on the required precision of dimensions. Sub-zero treatment in cooling chambers with the help of liquid nitrogen is performed.

Surface hardening. By surface hardening only surface of detail may be strengthened. Thus the core of a detail remains viscous. Heating of the detail surface is accomplished by high-frequency currents (microwaves) or by laser beam. Current frequency during the microwave tempering is 0.1...0.5 MHz, and the thickness of the hardened layer is from the tenths of millimeter to several millimeters. Medium-carbon steel is strengthened by the microwave tempering. Cooling is manufactured in the water. After the microwave tempering, low temperature tempering is utilized. By laser treatment steels, cast irons and nonferrous alloys are strengthened. Basic purpose of laser thermo-strengthening - increase in the wear resistance of the details, which work in friction conditions.

Scheme of quenching hardening by high-frequency currents is shown on Fig. 4.1.

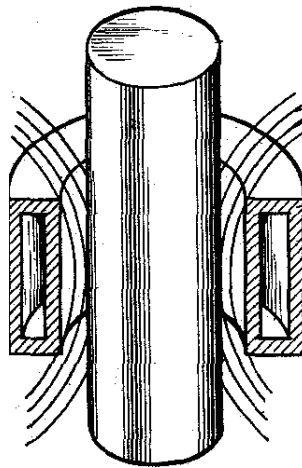


Fig. 4.1. Scheme of induction heating for superficial hardening

Chemical-thermal processing of steel

Thermo-chemical treatment is the combination of metallurgical technology with the heat treatment. Metallurgical technology - saturation of the surface layers of detail by different chemical elements. The subsequent heat treatment finally forms the physicochemical and mechanical properties of the surface layers of part. Practically all steels are subjected to thermo-chemical treatment. During this kind of treatment the properties of the medium, in which the process of saturation is conducted, play an important role. This medium can be solid, liquid and gaseous.

Cementation. It is saturation of the detail surface by carbon for reception of high hardness and wear resistance of a superficial layer. Cementation is conducted in the solid (Fig. 4.2) or gaseous medium. Details are placed into the boxes with charcoal and then heated up to the temperature 930...950°C. Process of cementation is very long. Thickness of the cemented layer is about 0.8...1.2 mm, the contents of carbon – 0.8...1 %. After cementation the hardening, the normalization and the tempering are conducted.

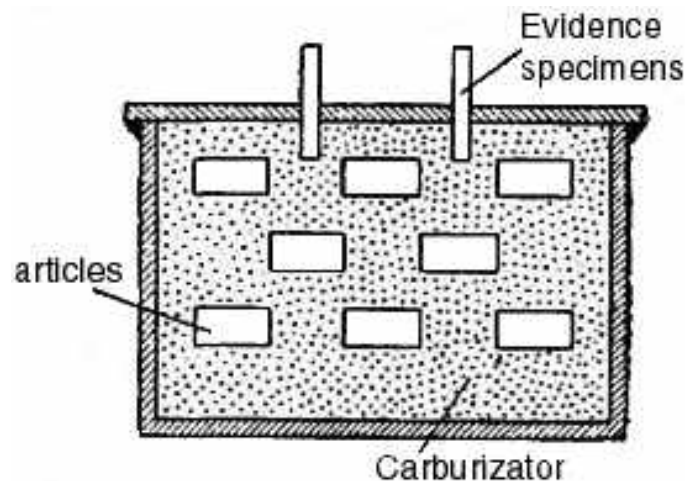


Fig. 4.2. Principal scheme of cementation in solid medium

Nitriding. It is saturation of the surface layer of detail by nitrogen. Nitriding raises hardness, cyclic strength, corrosion resistance of steels. It is conducted in the medium of ammonia at a temperature 500°C. The depth of the nitrided layer is 0.3...0.4 mm. Alloy steels are subjected to nitriding.

Cyanidation. It consists in simultaneous saturation of a superficial layer of a detail by carbon and nitrogen. Cyanidation is carried out in liquid and gaseous environments at temperatures 700...950°C. During liquid cyanidation details are located in baths with cyanic salts, during gaseous - on medium of hydrocarbons and ammonia. Cyanidation is applied to increase resistance of cutting tool. Depth of cyanidation layer is approximately 0.03...1,1 mm. The oil quenching and low temperature tempering are conducted after cyanidation.

Aluminizing. It is saturation of a superficial layer with aluminium. The purpose of aluminizing - increase of heat resistance. At aluminizing on a surface of steel film of oxide Al_2O_3 is formed. The method of aluminizing is frequently applied. Aluminizing is carried out at temperatures 1000...1050°C. Depth of aluminizing layer is about 0.3...0.8 mm. After aluminizing the annealing is carried out. Cheap low-carbon steel is subjected to aluminizing. The aluminized details are used for manufacturing the parts, subjected to the action of the incandescent gases: the details of the combustion chamber, jet nozzle, exhaust pipes, etc.

Chrome-plating. It is saturation of the surface layer of detail by chromium. It is used for increasing of hardness, wear resistance and corrosion resistance of aviation details. Diffusion and electrolytic chrome-plating is distinguished. Chrome-plating is carried out at temperatures of 1000...1050°C. The thickness of the chrome-plated layer is 0.1...0.2 mm.

Siliconizing. It is saturation of the surface layer of detail by silicon. On the surface of steel the oxide film SiO_2 is formed. Siliconizing by powder method is widely used. Siliconizing is conducted at temperatures 900...1000°C. The thickness of the siliconized coating is 0.6...1.4 mm. Siliconizing is used for increasing in heat resistance and acid-resistance of details.

Boronizing. It is saturation of the surface layer of detail by boron. Are used for the boronizing both liquid and gaseous methods. Boronizing is conducted at temperatures 930...950°C. The thickness of the alloyed layer is about 0.1...0.2 mm. Boronizing is carried out for increasing the abrasive hardness of parts, corrosion resistance and acid-resistance. Boronizing is used for the bushings of pumps, exhaust, bending and molding dies. Durability of parts after boronizing is 2-10 times raised.

Theme 5. ALUMINIUM ALLOYS

Aluminium alloys came for the replacement of wooden aviation constructions at the beginning of the 20-th century. Process of obtaining aluminium is very expensive. About 20 MWt·h of the electric power is expended for obtaining one ton of aluminium. The modern civil airplane consists of aluminium alloys on 70...80 %.

The properties of aluminium alloys vary within wide range of limits: there are high-strength alloys with tensile strength up to 700 MPa. High-plastic alloys have tensile strain up to 50 %. The high-temperature alloys can work at temperatures up to 500°C. Low-plastic alloys have a modulus of elasticity up to 220 GPa.

The most characteristic property of aluminium is its density of 2.7 g/cm³. The coefficient of the linear temperature extension is about $24 \cdot 10^{-6}$ 1/deg.

Aluminium is the metal of grey colour. It has melting point 660°C. Tensile strength of technical aluminium is 80 MPa, the modulus of elasticity - 70 MPa, tensile strain – 35 %. Aluminium possesses high heat- , electrical conductivity, it is chemically active metal. It is covered easily with the oxide film, which shields it from interaction with different media. Technical aluminium is made in the form of sheets, profiles, rods, wire. The most frequently utilized alloying elements: copper, zinc, magnesium, silicon, iron.

Classification and designation of aluminium alloys

According to the technological criterion aluminium alloys are divided into deformable and casting. The deformable (or malleable) alloys divide on those strengthened by heat treatment and not hardened by heat treatment. The special aluminium alloys, obtained by the methods of powder metallurgy, carried to the separate group: the sintered aluminium powders and the sintered aluminium alloys. The slugs, obtained by the methods of powder metallurgy, are machined by pressure; therefore it is possible to carry them to the malleable alloys.

In the industry more than 100 grades of the alloys marks are utilized. In our country marking the former Soviet Union is utilized. Abroad (for example, in the USA marking is different – digital. Aluminium alloys are marked by letter A and several numbers and letters. Examples of marking pure technical aluminium - A00, A0, A1 - number designate the percentage of the purity of aluminium. In USA equivalent alloys by properties and composition are of group 1XXX, for example 1100.

In cast alloys after A follows the letter Л (for example АЛ2, АЛ4). In alloys for the forging and stamping - K, and then number - ordinal number of alloy.

The alloys of the system **Al+Cu+Mg** are called duralumins and they are designated by the character Д (example alloys Д16, Д20). The alloys of the system **Al+Zn+Cu+Mg** are called high-strength and they are marked by the character B - (for example, B95 (USA equivalent is 7075 Al-alloy)).

Alloy Avial is designated as AV. The alloys of aluminium with magnesium are marked AMr, and with manganese - AMц.

After principal notation the letters, which determine the form of working the alloy, can follow: M - annealed; T - after tempering and natural ageing; T1 - after quenching and artificial ageing, etc. For example, Д16T (the USA equivalent is 2024 Al-alloy).

In USA two designation system of casting Al alloys are used: Aluminium Association (AA) developed by American National Standard Institute (ANSI) and UNS.

By AA system Al-alloys are designated by tree digits depending of composition of alloying elements system (first digit shows it): 2XX – Al+Cu, 3XX – Al+Si+Mg or Al+Si+Cu, 4XX – Al+Si, 5XX – Al+Mg, 7XX – Al+Zn, 8XX – Al+Zn. For example Al alloy 360.

For designation of deformable Al-alloys generally AISI and SAE systems are used.

Table 5.1 shows a four-digit number, which identifies aluminium, either in its commercially 'pure', or in its alloyed state. The first digit of the designating code represents the major alloying element, while the second digit of the code indicates a specific alloy modification, such as controls over impurities.

The last two numbers of the 1xxx group indicate the hundredths of 1 % above the 99 % of pure aluminium (no major alloying element). The second digit indicates modifications in impurity limits. If the second digit is zero, there is no special control on individual impurities. Digits 1 through 9, which are assigned consecutively as needed, indicate special control of one or more individual impurities. The last two digits indicate specific minimum aluminium content. Although the absolute minimum aluminium content in this group is 99 %, the minimum for certain grades is higher than 99 %, and the last two digits represent the hundredths of a per cent over 99. Thus, 1030 would indicate 99.30 % minimum aluminium without special control on individual impurities. The designations 1130, 1230, 1330, etc.. indicate the same purity with special control on one or more impurities. Likewise. 1100 indicates minimum aluminium content of 99.00 % with individual impurity control. For example, if 75 were the last two digits, the metal would be 99.75 % pure.

The 2xxx to 8xxx groups use the last two digits to identify the different alloys in the group.

In the 1xxx group, commercially pure aluminium (over 99 % pure) is good for corrosion resistance, has good electrical and thermal conduction properties, is easy to work but is not very strong.

The 2xxx group uses copper as its major alloying element. The major benefit of copper is a large increase in strength, although if the alloy is not correctly heat-treated, intergranular corrosion occurs between the aluminium and copper grains within the metal. These are probably the commonest aluminium alloys used in aircraft constructions.

The 3xxx group has manganese as its major alloying agent and it is not possible to heat-treat.

Table 5.1. USA identification system for deformable Al-alloys

Code	Major alloying element
1XXX	Aluminium (commercially pure)
2XXX	Copper
3XXX	Manganese
4XXX	Silicon
5XXX	Magnesium
6XXX	Silicon + Magnesium
7XXX	Zinc
8XXX	Other elements

The 4xxx series utilizes silicon as its major element. This lowers its melting point and improves its welding and brazing capabilities.

The 5xxx group has magnesium as the main alloying element. This is good for welding and corrosion resistance although, if exposed to high temperature or cold working, it can corrode quite badly.

The 6xxx group has silicon and magnesium added to the aluminium. This makes the alloy heat-treatable and with good forming and corrosion resistance properties.

The 7xxx alloys are made harder and stronger by the addition of zinc. These are difficult to bend and are more often used where flat plates are required.

The second digit indicates alloy modification. If the second digit is zero, it indicates the original alloy: digits 1 through 9, which are assigned consecutively, indicate alloy modifications. The last two digits have no special significance, serving only to identify the different alloys in the group.

According to UNS system designation begins from letter C and following five digits (see **Appendix D**).

In EU casting Al-alloys are classified by norm EN1676:1996 which suggests to use preliminary letters EN AB and then 5 digits. All alloys are divided by four groups depending on alloying system: 2XX – Al-Cu, 4XX – Al-Si-Metal, 5XX – Al-Mg, 7XX – Al-Zn (for example system of Cu-Si-Metal - EN AB-45000). Besides numerical system direct designation of used alloying elements can be met: EN AB-Al-Si6Cu4 (numbers mean percentage of alloying elements).

In Japan combination of letters AC or AD and following numbers 1, 2, 3... show definite system of alloying, letters after numbers mean specific alloying element and last number means an alloy purity: for example AC1A.1, AD14.2 (standard JIS H2211).

In France (standard NF-57-702) designation begins with A (aluminium), then symbols of alloying elements and their average percentage follow, where the last letter means main alloying element. For example, A-S5U3G, where S5 — silicon, 5 %; U3 — copper, 3 %; G — magnesium is the main one.

Very frequently in all aluminium designation systems the type of applied consequent thermal treatment follows by main designation (typically letter T and corre-

spondent number are used for designation) (Table 5.2).

Table 5.2. Designation of Al-alloys thermal treatment by GOST

T1	Artificial ageing (without quenching)
T2	Annealing
T4	Quenching only
T5	Quenching and short (unfinished) artificial ageing
T6	Quenching and artificial ageing
T7	Quenching and stabilizing tempering
T8	Quenching and tempering

Heat treatment of aluminium alloys

The alloys on the basis of aluminium have a limited solubility. The effect of thermal strengthening of aluminium alloys is based on this phenomenon. The mechanism of heat treatment is identical for the majority of alloys.

For the strengthening of aluminium the tempering and the ageing are used. For eliminating the nonequilibrium structures different forms of annealing are used. Tempering consists of several stages:

1. Heating alloy to a temperature, at which excess intermetal phase is dissolved in aluminium almost completely.
2. Alloy is carried at this temperature the specific time.
3. Rapid cooling down to room temperature is manufactured (quenching).

During heating of the alloy higher than tempering temperature occurs the burning of grains and the appearance of cracks between the grains.

Ageing of aluminium alloys

After quenching aluminium has low-level strength and high plasticity. For an increase in strength natural and artificial ageing is used (Fig. 5.1). During the natural ageing the alloy is maintained several days at a normal temperature, during the artificial – 10...24 hours at a temperature 150...200°C. If after natural ageing we heat alloy to the temperature 240...250°C (so-call over-ageing occurs), keep it 3...5 minutes and cool it, then the effect of strengthening disappears. The properties of alloy become analogous the properties of freshly hardened aluminium. This phenomenon is called recovery. If after recovery we carry out ageing, then the corrosive properties of alloys will be improved.

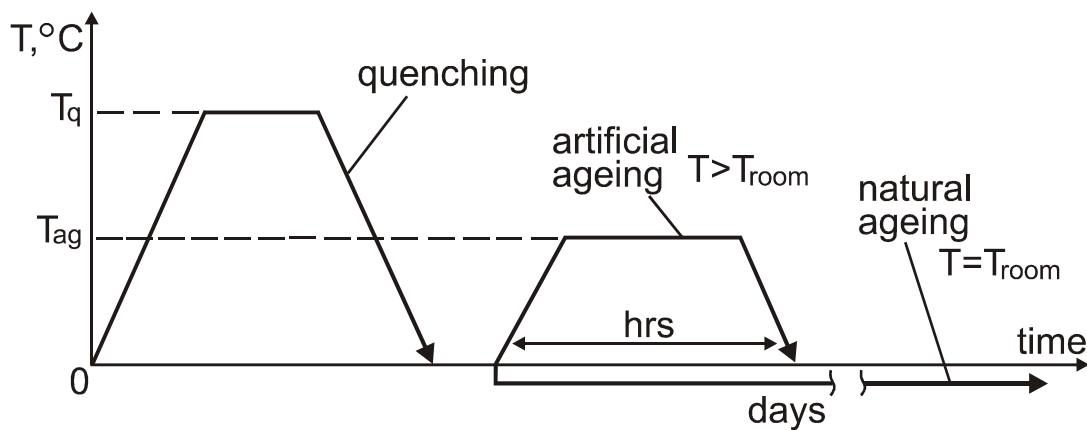


Fig. 5.1. Graphical presentation of typical Al-alloy treatment

Deformable aluminium alloys hardened by heat treatment

Among them duralumins may be considered, for example, alloy Д16. The strengthening is reached by quenching and natural ageing. For increasing corrosion resistance are used the cladding (deposition of the thin layer of commercially pure aluminium), the anodizing, the nitriding.

Forging and stamping materials are characterized by high plasticity and good casting properties. (For example, AK6 and AK8).

High-temperature alloys. They are utilized for the parts, which work at a temperature to 300°C (pistons, the cylinder head, and compressor blade). They are strengthened by tempering and artificial ageing. Representatives - Д20, AK4-1.

Deformable aluminium alloys not hardened by heat treatment

They include the alloys of aluminium with magnesium (or manganese). The effect of tempering and ageing on them practically does not act. Strengthening is achieved due to the formation of solid solution and formation of excess phases. Alloys of this type are used in the annealing state and are utilized for obtaining the parts by the method of cold sheet stamping and bending: AMц, AMr and Avial. They are used for manufacturing the capacities for the liquids, the manifolds.

Casting aluminium alloys

They have high fluidity and small shrinkage. The systems of alloys are applied: **Al+Si**, **Al+Cu**, **Al+Mg** and alloying elements **Mn**, **Ni**, **Cr**, **Ti**, **Zr**, **B**, **V**.

The castings are exposed to different forms of heat treatment:

1. Artificial ageing. Temperature of ageing is 175°C ; the time of ageing is 5...20 hours. Tempering is not conducted. Examples of such alloys - АЛ3, АЛ4, АЛ5.

2. Annealing at a temperature 300°C during 5...10 h; cooling in air. It is used for decreasing the foundry and residual stresses.

3. Quenching and natural ageing. Temperature of tempering 510...550°C.

4. Quenching + the short-term ageing during 2...3 hours. The temperature of ageing 150...175°C. After heat treatment alloys gain high strength and plasticity.

5. Quenching and complete artificial ageing. Temperature of ageing 200°C, the time of ageing 3...5 hours. This form of treatment allows receiving high strength, but small plasticity.

6. Quenching and the stabilizing tempering. Temperature of the tempering 230...250°C, the time of tempering 3...10 hours. It is used for the stabilization of the structure of casting.

7. Quenching and the moderating tempering. Temperature of the tempering 240...250°C, the time of tempering 3...5 hours. It increases plasticity and stability of the dimensions of half-finished material.

Silumins and heat resisting cast alloys

The alloys of **Al+Si** are called silumins. The castings have good casting properties and high density. They are not exposed to heat treatment. A characteristic representative - АЛ2.

Heat resisting cast alloys - АЛ1, АЛ19, and АЛ33. They are used at temperatures 275-300°C. They are heat-treated by quenching and ageing; alloyed with **Mn, Ti, Ni, Ce, Zr**.

The ultimate strength of some aluminium alloys: cold-hardened АМц has $\sigma_B = 220$ MPa; Д16, quenching + the natural ageing - $\sigma_B = 450$ MPa; В95, quenching + the artificial ageing $\sigma_B = 600$ MPa.

Theme 6. MAGNESIUM ALLOYS

Most of all magnesium is dissolved in the sea water. Technology of obtaining magnesium from the ores is very expensive. The production of magnesium is accomplished by an electrolytic and thermal method from the dolomite ((CaMg)CO₃) and the magnesite (MgCO₃). Magnesium is one of the metals like aluminium where very little post refining of the metal is conducted, other than the removal of physical impurities such as electrolyte and oxide (although some processes are available).

Magnesium is the metal of silver color. Its melting point is 650°C. It has CPH (close-packed hexagonal) lattice. Its density is 1.74 g/cm³, modulus of elasticity $E = 45$ GPa, the ultimate strength 180 MPa, tensile strain 12 %. Magnesium is chemically active metal. It is oxidized in air with the formation of oxide film. Magnesium alloys are welded well, and easily machined. Magnesium in air burns at a temperature 623°C.

Magnesium forms continuous solid solutions only with cadmium. Iron, copper, silicon, nickel, decrease corrosion resistance of magnesium. The most common alloying elements are: zirconium, manganese, beryllium, aluminium, zinc. Thorium, neodymium, cerium improve the heat resistance of magnesium at a temperature 250...300°C.

Classification and designation of magnesium alloys

According to the technological criterion magnesium alloys are divided into those deformable and casting. Deformable alloys are marked by letters MA, casting – by letters МЛ, after which follows the ordinal number of alloy and sometimes the form of heat treatment.

According to the density magnesium alloys are divided into the light and the superlight. Superlight alloys have a density 1.3...1.6 g/cm³. According to operating temperature magnesium alloys are divided into:

- 1) the alloys of the general purpose
- 2) the heat-resistant alloys, which work at temperature up to 200°C;
- 3) the high-strength alloys, which work at temperatures 250...300°C;
- 4) the alloys, intended for the work at cryogenic temperatures.

In the USA and some other countries ASTM designation is used. It provides chemical composition and as-received condition. Designation includes two letters meaning two main alloying elements and numbers (after each letter) expressing alloying elements quantity in percents. Then letters A, B, C can be followed. They mean an alloy purity (A is the most pure). Symbol X means that an alloy is not included to standard row yet. Following letters can be used for alloying elements designation: A - aluminium, H - thorium, Z - zinc, E – rare-earth metals, M - manganese, L - lithium, K or W - zirconium, Q - silver. For example an alloy AZ31B contains 3.0 % Al, 1.0 % Zn, has average purity (impurity of Fe and Ni are presented).

In British standard BS magnesium alloys designation includes symbols MAG and is followed by an ordinary number. Deformable alloys have auxiliary letter meaning method of manufacturing (E – rods (extruded), S – sheets (rolled)). For example, MAG-S-151, MAG-E-21.

In Japan letter designation is used: MC (Magnesium Casting alloys), MP (Plate), MB (Bar), MS (Shape) with the consequent ordinary number of an alloy: MC3, MP5.

Besides above-mentioned standard commercial names of alloys can be met: ASTM alloy AZ31 (USA) has British equivalent MAG-11, German – MgAl3Zn, Magnezal W383 etc.

The common magnesium alloys used in foreign countries are shown in Table 6.1.

Table 6.1. Common magnesium alloys

Alloy designation	Alloying Additives	Uses	Reasons for use
AZ91	9.0 % Al 0.7 % Zn 0.13 % Mn	General casting alloy	Good castability, good mechanical properties at T<150°C
AM60	6.0 % Al 0.15% Mn	High pressure die casting alloy	Greater toughness and ductility than AZ91, slightly lower strength. Often preferred for automotive structural applications
AZ31	3.0 % Al 1.0 % Zn 0.2 % Mn	Wrought magnesium products	Good extrusion alloy
ZE41	4.2 % Zn 1.2 % RE 0.7 % Zr	Specialist casting alloy	Rare earth addition improves creep strength at elevated temperatures. Pressure tight
AS41	4.2 % Al 1.0 % Si	General casting alloy	Better creep resistance than AZ91 at elevated temperatures but lower strength

Heat treatment of magnesium alloys

Magnesium alloys may be exposed to the following forms of heat treatment:

1. Ingots and casts subject to homogenization and annealing at a temperature 400...420°C for of 15...30 hours.
2. For eliminating of work hardening and decreasing the anisotropy of properties recrystallization annealing is used at a temperature 250...350°C.
3. Hardening at a temperature 380...540°S and artificial ageing. Heating is

manufactured during 4...24 hours, ageing – 15...20 hours.

Deformable magnesium alloys are supplied in the form of rods, bands, profiles, forgings. They have reduced-plasticity at low temperatures. Therefore they are processed by pressure at high temperatures. According to the presence of the alloying elements magnesium alloys can be divided:

- System **Mg+Mn**. It has increased corrosion stability and weldability (for example, the alloy MA8 which contains some cerium);
- System **Mg+Al+Zn+Mn** (alloy MA2-1). It is well rolled and is treated by a sheet-metal stamping;
- System **Mg+Zn+Zr** (alloy MA14, MA15, MA20). It has high values of a mechanical strength;
- System **Mg+rare earth elements** (neodymium, zirconium). Examples of such alloys are MA11, MA12. They have high strength.
- System **Mg+Li** (ultra-light alloys). Examples of alloys are MA18, MA21. They have a low density and high toughness.

Casting magnesium alloys. Their chemical composition is close to deformable alloys. Three systems of alloys are used:

- System **Mg+Al+Zn**. examples - МЛ4, МЛ5пч (пч - heightened purity), МЛ6. These alloys are applied in cryogenic engineering.
- System **Mg+Zn+Zr**. Examples of alloys МЛ12, МЛ15, МЛ17, МЛ18. Have high strength properties, high-temperature strength. The alloying by a cadmium, niobium, silver is applied.
- System **Mg+Zr+ rare earth elements**. Examples of alloys are МЛ10, МЛ11, МЛ19. They have high strength and high-temperature strength.

Application of magnesium alloys in aircraft construction. They are applied for manufacturing the details with heightened corrosion resistance, high impermeability working in conditions of marine atmosphere, for middle- and high-loaded details working at high temperatures: necks of petrol tanks, armature, bodies of pumps, details of drives, gears, lids of landing gear bays, wheels bushings (SR-71B spy plane), body cases of vehicles, photo and video cameras, binoculars, TU-95 airframes, hinges, load-carrying elements of X-22 rocket.

Theme 7. BERYLLIUM AND LITHIUM ALLOYS

Beryllium alloys

Beryllium is metal of light-grey color, density 1.85 g/cm^3 and melting point 1284°C . It has two polymorphic modifications: HCP-Be exists up to 1250°C , then it transforms to BCC-Be. It unites a variety of physical/mechanical/technological and operating properties which make it the most prospective raw material for aviation and cosmonautics. By specific strength and modulus beryllium overexceeds aluminium, magnesium, titanium and steel alloys (specific strength is twice more than steel and Be-alloys keep this ratio up to 600°C). Beryllium possesses high electrical- and heat-conductivity near to Al ones. Corrosion resistance of Be up to 700°C is very high.

Beryllium is quite rare metal, its quantity in earth crust is $5 \cdot 10^{-4} \%$, nevertheless near 40 Be mineral are known. The most known is beryl. Commercially pure Be has purity up to 99,98 % and is produced mainly by powder metallurgy methods. Quite ductile Be can be reached ($\epsilon=140 \%$) after multiple remelting ($T=800\dots 1100^\circ\text{C}$). Even low amount of impurities make it brittle. Be is dangerous for human being due to toxicity and radioactivity. But beryllium in compounds after treatment is nonhazardous.

Semi-finished Be articles are produced as sheets, tubes, rods. Machining of Be is difficult and required super-hard cutting tools. After hot forming it is possible to reach strength up to 700 MPa, strain 7...10 %, elasticity modulus $E=300 \text{ GPa}$, impact toughness 5 J/cm^2 .

Main drawbacks of Be is high cost (see **Appendix E**), raw material shortage, expansive processing and low brittleness threshold.

For manufacturing alloying elements the following elements can be used: Al, Mg, Ag, Li, Ni, La, Gd, Zr. It can be seen from the phase diagram that solubility of Al in Be is very poor therefore solid particles of Be can be distributed in Al matrix. Generally 24...43 % of Al can be added to Be. Special aviation alloy **Lockalloy** ((Be + 38 % Al)) was developed by Lockheed firm. At room temperature it has $\sigma_e=600 \text{ MPa}$, $\sigma_{0,2}=570 \text{ MPa}$, $\epsilon=1 \%$.

Al-Be alloys can be strengthened by adding silver and magnesium. Very ductile matrix phase can be obtained after adding 60 % of silver to beryllium.

Beryllium bronze is quite known structural material in machine-building and aviation. It contains copper with 2...5 % of Be (strictly speaking it is copper alloy). The alloy БрБ2 (Cu+2 %Be) is wide spread. It can be strengthened by quenching and consequent artificial ageing. Properties of this alloy after thermal treatment are: $\sigma_e = 1200 \text{ МПа}$, $\epsilon=4 \%$. Be bronze is used for manufacturing springs at wide temperature range with high fatigue and corrosion properties.

One more advantage of Be bronzes is non-magnetic property and sparkless behavior at impact. Therefore large variety of impact tools (hammers, wrenches, screws, nippers, chisels etc) for using in explosive-dangerous indus-

tries is produced from it.

By technological criteria Be-alloys can be divided into **deformable** and **casting**. **Casting** alloys (ЛБС-1, ЛБС-2, ЛБС-3) are used for frames, hinges, casings. Main alloying elements are: Al (24...34 %), Ni (3...6 %), Mg (0.1...0.8 %) and other at less quantity. Mechanical properties of ЛБС alloys: $\sigma_{\epsilon}=220...280$ MPa, $E=200$ GPa, $\epsilon=1...3$ %.

Anodizing and polymeric protective coatings permit to elevate corrosion resistance of Be-alloys.

Deformable Be-alloys can be strengthened by consequent alloying with Cu, Ag, Ni, Co, Fe. Be-Ni binary system is the strongest - $\sigma_{\epsilon}=350$ MPa at room temperature and 280 MPa at 500°C. Deformable alloys ВБД-1 and ВБД-1П (i.e. powder metallurgy) are representatives of Be-Ni system alloyed with titanium (0.8..1.2 %). $\sigma_{\epsilon}=550$ MPa at 20°C and 170 MPa at 700°C.

Application of beryllium in aircraft and rocket structures:

- brake drums of landing gear wheel (two times less comparing with steel ones, heating temperature at braking 150...170° less);
- airplane fuselage (“Phantom”, “Boeing-747”), guided missile case;
- ruder of Fighter (weight 40 % less, rigidity 5 times more comparing with conventional Al one);
- horizontal stabilizers, ailerons, front flaps, lids of landing gear bay.
- skin and combustion chamber of “Gemini” aircraft, “Minuteman” rocket, “Apollo”, engine elements of “Mariner-71” (weight was 7,7 kg only);
- solar antenna panels, optical telescope mirrors (“Apollo-12”), exhaust nozzle and heat protection skin of spacecrafts, containers for scientific apparatus.

Lithium alloys

Lithium is metal with silver color, very ductile and light (density 0.53 g/cm³ that two times less than water has). Melting point is 180°C, boiling point is 1340°C. Crystalline lattice is BCC. Lithium is very chemically active metal and requires special measures at processing. It has high corrosion resistance, electrical and thermal conductivity.

As structural metal Li is mainly used as alloying element for other light metals like aluminium, magnesium, copper, cadmium, lead, zirconium, scandium. Adding of Li to these alloys permit to get new ones with high specific strength and modulus.

Main drawback of lithium is high cost of manufacturing, chemical activity and relatively low strength.

Deformable Li-alloys are processed with forming, welding and rolling.

The most well-known Li-alloys for aerospace application are 1420 (Al-Mg-Li

(1.8..1.9 %)) and 1450, 1451, 1460 (Al-Cu-Li). 1420 alloy is used for spacecrafts load-carrying structures, Su-37 load-carrying elements, MIG-29 welded airframe and 1460 alloy – for rocket fuel tanks (for example SpaceX welded fuel tank). Lithium is used for manufacturing high-strength armor ceramics (Al-Li-SiC) with variable solidification point (near room temperature). Doors, door frames, wheels, formed thick-walled strictures of Airbus airplane wings were produced from 1933 Al-Li alloy. The profit is 20..25 % weight reduction.

Lithium influences significantly on micro-structure of aluminium alloys elevating alloys crack resistance at low and high temperatures. Al-Li-alloy 2091 (Russian designation 1430, 1440) after consequent T8X quenching, 3 % cold working, and artificial ageing overexceeds well-known and widely used 2024T3 Al-alloy having multiple advanced properties. Main drawback of Al-Li alloys is low ductility at lost strong state. Density of new Li-containing alloys approximately 10 % less and elasticity modulus 10% more comparing with conventional Al-alloys.

Alloys 1450, 1451 (sheets) are pretenders for replacement well-known B95 high-strength Al-alloy.

Conditions of quenching and ageing influence significantly of final mechanical properties of Al-Li and Mg-Li alloys.

Theme 8. TITANIUM ALLOYS

Titanium and its alloys are utilized mainly in aviation and space technology. Titanium alloys possess high specific strength, especially in the range of temperatures 300...600°C.

Obtaining. Source material for titanium is titanium ore (the rutile - TiO_2 , the ilmenite $\text{FeO}+\text{TiO}_2$). The enriched ores are treated with iodine and so TiI_4 is obtained or chlorine, and thus TiCl_4 may be received. The obtained substances are restored by metallic magnesium. The obtained titanium sponge is milled, is sintered and is remelted in the vacuum-arc furnaces. Technology of titanium obtaining is expensive. World obtaining of titanium is more than 100 hundreds ton.

Titanium dioxide is the most important pigment in world industry. It is widely (in near 70 % of non-organic pigments and in 90 % of white pigments) used in cellulose-paper, pain-varnish, rubber-manufacturing, glass-ceramic, welding (electrodes), high-temperature measuring devices branches of industry. Majority of titanium ores are mined in Australia, Canada, South Africa etc.

Properties. Titanium is a non-magnetic metal of gray color. Density of titanium is approximately 4.5 g/cm^3 . Melting point equals 1668°C . Tensile strength equals 300...550 MPa. It has 2 allotropes: there is α -titanium (CPH lattice) to the temperature 882°C and β -titanium (BCC-lattice) at temperatures higher than 882°C . A small modulus of elasticity – 112 GPa – is a drawback of titanium. Commercial titanium is well machined by pressure. Form of the delivery of semi-finished products - from the sheets to the hot-rolled parts. It is strengthened by plastic strain in 2 times. There are 2 marks of the commercial titanium – BT1-00 and BT1-0 (content of titanium in them 99.5 %).

Interaction of titanium with alloying elements

Titanium alloys are used more widely, than commercial titanium. The alloying of titanium with iron, by aluminium, by manganese, by chromium, by tin, by vanadium, by silicon increases its strength, but reduces plasticity and toughness. Aluminium, zirconium, molybdenum increase the heat resistance of titanium. Molybdenum, zirconium, niobium, tantalum, and palladium increase corrosion resistance of titanium in the solutions of acids. The alloying elements have a great effect on the polymorphic transformations of titanium. According to the influence on titanium all alloying elements may be divided into the α -stabilizers, the β -stabilizers and neutral (Fig. 8.1). So called α -stabilizers increase the temperature of the polymorphic transformation of alloy and expand the domain of existence of α -titanium (**Al, N, O**). So called β -stabilizers reduce the temperature of the polymorphic transformation of alloy and expand the domain of existence of β -titanium (**Mo, V, Mn, Fe, Cr, Nb, Ta**). β -stabilizers are divided into 2 subgroups: isomorphous (with the high concentration of the alloying elements β -solution is retained to room temperature) and forming the

eutectic (at a low temperature the eutectic decomposition of β -phase occurs - $\beta \rightarrow \alpha + \text{TiX}$). The neutral alloying elements little influence the temperature of polymorphic transformation (**Hf, Zr, Sn**).

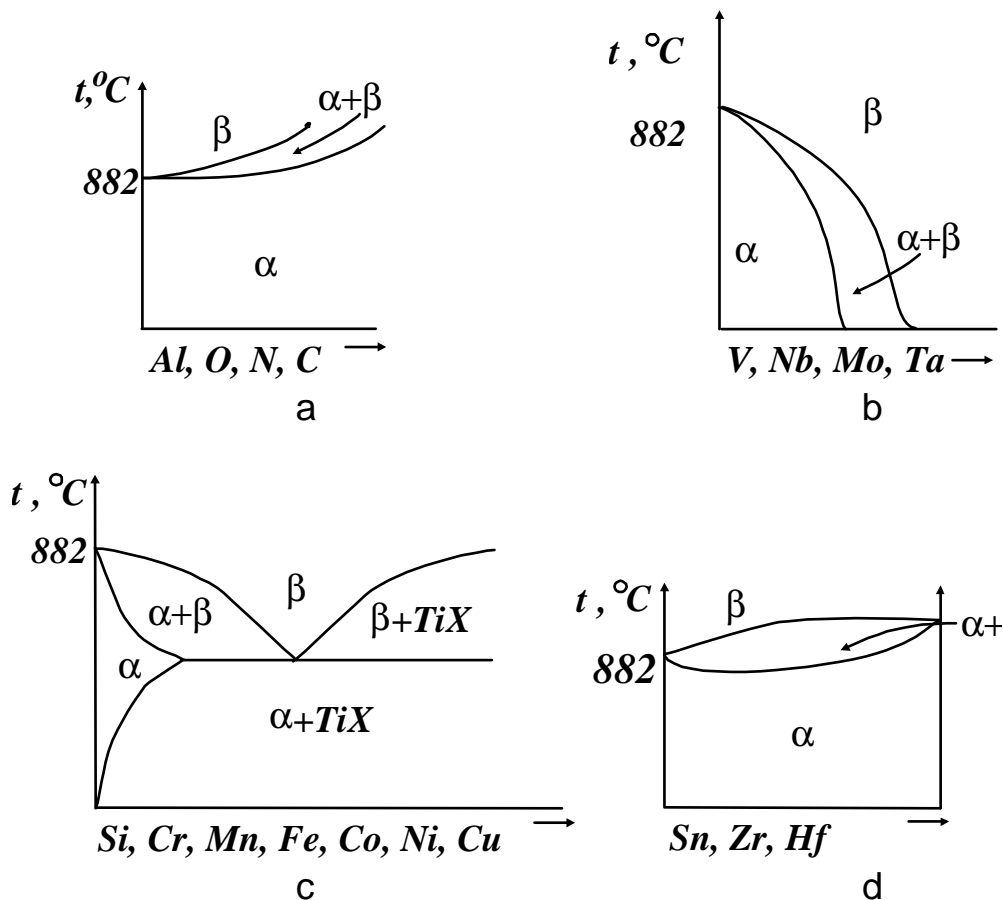


Fig. 8.1. Influence of the alloying elements on the polymorphic transformation in titanium alloys: a - α -stabilizers; b, c - β -stabilizers; d - the neutral alloying elements

Classification of titanium alloys

The classification of titanium alloys is formed according to the type of the structure, obtained with the annealing of titanium:

- 1) the α - alloys (they contain exclusively α - phase);
- 2) pseudo- the α - alloys (structure contains β - phases not more than 10 %);
- 3) ($\alpha + \beta$)- alloys (they contain α and β - phases);
- 4) the β - alloys (they contain exclusively β - phase);
- 5) pseudo- the β - alloys (they contain α - phases not more than 10 %);
- 6) alloys on the basis of intermetal compounds.

According to the capability for strengthening after ageing titanium alloys are divided into heat-treatable and those not hardened thermally. According to the

technological criterion titanium alloys are divided into deformable and casting. According to the purpose titanium alloys are divided into: welded, high-strength, high-temperature, corrosion-resistant, alloys with the special properties. Titanium alloys in the form of castings, profiles, forgings, sheets, pipes and bands are supplied. According to Ukrainian rules titanium alloys are marked by large Russian letters OT, BT, ПТ. Then the numbers follow, which designate the ordinal number of alloy. If there are 2 and more numbers, then they are written through the dash. After numbers can follow the letter, which designates the purpose of alloy, its special composition etc. Here are some examples of titanium alloys marking: OT4, OT4-1, BT5, BT15, BT3-1, ПТ7М, BT5Л, BT6C. The foreign markings of titanium alloys: Ti317, Hylite-20, TA5E, LT32, Ta6V.

The welding alloys. They include the alloys on the basis of system Ti-Al-Mn (alloys OT4, OT4-1 possess ultimate strength to 700 MPa); Ti-Al-Sn (BT5-1 - they possess ultimate strength to 750 MPa); Ti-Al-Zr-Mo-V (BT20 - ultimate strength up to 950 MPa). These alloys are not strengthened by heat treatment. High pressure cylinders are made from the alloy BT6C. This alloy is strengthened by heat treatment.

High-strength alloys. As a rule, they are designated by letters BT. High-strength alloys have ultimate strength more than 100 MPa. Such value of strength is reached by heat treatment or alloying. The hardenability of titanium alloys is 30-150 mm. In the industry the alloys are used: BT6, BT14, BT22, BT3-1, BT16, BT22, BT15. Alloy BT22 after quenching and ageing has a limit of strength 1400 MPa. Alloy BT16 is developed specially for the fastenings (bolts, stud pin, etc.). It is characterized by the lowered sensitivity to the stress concentration and possesses high plasticity.

High-temperature alloys. They include the α -alloys and ($\alpha+\beta$)-alloys. As the alloying elements aluminium, zirconium, tin, molybdenum, niobium, chromium, silicon are utilized. The most frequently used alloys are BT3-1, BT8, BT9, BT25, BT18, BT35, Ti6242, Ti-17, WL 3.7154 (Germany). Their typical composition is Ti+6 %Al+2 %Sn+4 %Zr+6 %Mo (UNS designation is UNS 56260). As an example it is possible to note that the alloy BT25 has a long-term strength which is equal to 650 MPa for 100 hours of loading at a temperature of 500°C. The lifetime of this alloy at this temperature is approximately 6000 hours. Alloy BT28 is the most high-temperature titanium alloy, which can be used at temperature 600...650°C for turbine disks, pipes, impellers, tools.

Alloys with the special properties

They include:

1. The alloys with increased corrosion resistance in the acid media. Examples - special alloys 4201 (it is alloyed with 30 % of molybdenum, 0.5 % Zr) and 4200 (it is alloyed with 0.2% of palladium). Typical composition of such alloys is Ti+6 %Al+2 %Nb+1 %Ta+1 %Mo.

2. The alloys are intended for the work at cryogenic temperatures. Example - alloys BT5-1к, BT6к (“к” means cryogenic). They are not embrittled at low temperatures.

3. The alloys on the basis of inter-metal compounds. They are divided into 2 groups: high-temperature (example - alloy CT5 - on the basis of the inter-metal compound Ti_3Al) and with the increased plasticity in the cold state (Nitinol - on the basis of the intermetallic compound TiNi). **Nitinol** is called as a metal with the “memory of form”. If to deform it at room temperature and to heat to the specific temperature, then part from this alloy takes the initial form of the undeformed rod. The antennas of spacecraft, tightening bushings of tubes, stoppers, flexible contacts, teeth correcting brackets are made from this alloy.

Casting titanium alloys. Their application is limited by active interaction of titanium with the lining materials and by atmospheric gases. The shrinkage of titanium is about 2...3 %. Density of castings is high. The alloys BT5Л, BT9Л, and BT3-1Л are widely utilized. Alloy BT3-1Л is intended for manufacturing the parts, which work at temperatures 500...550°S . Besides of alloy BT5Л the remaining casting alloys may be subjected to annealing.

Heat treatment of titanium alloys. The most common operations of the heat treatment of titanium alloys are those: annealing, quenching and ageing. Heat treatment is conducted in the vacuum ovens or in the furnaces with protective atmosphere. Annealing is carried out for the equalization of structure, phase composition, increase in the plasticity of alloy, elimination of residual stresses after machining. Annealing can be dual or isothermal. Annealing consists in the heating to the temperature higher than recrystallization temperature, in the holding at this temperature and in the cooling according to the specific rules. During the double annealing after the first cooling in air, reheating to the specific temperature, holding and cooling are provided. Isothermal annealing eliminates the first cooling after heating to recrystallization temperature. After the first holding in the furnace the transfer of part into another furnace with the lower temperature is fulfilled and annealing below the critical range is manufactured.

The strengthened heat treatment consists in the quenching at temperatures 780...980°C, the heating to the temperatures of ageing 450...620°C and the ageing for 0.5...25 hours (all conditions must be selected according to handbooks for each alloy).

Thermochemical treatment. The purpose of thermochemical treatment is increasing the wear resistance, fatigue strength, corrosion resistance, heat resistance of alloy. The cementation, the nitriding, the cyanidation, oxidizing, saturation by brass are used for saturation by the alloying elements. Nitriding is the most spread strengthened operation. It is conducted in the nitrogen atmosphere and argon. The method of the ionic nitriding of titanium is promising. The depth of the nitrided layer is from 0.06 to 0.3 mm.

The special features of titanium alloys machining

Titanium alloys possess a good weldability, but they require the holding of strict conditions of conducting the welding (in the medium of shielding gas, with the subsequent annealing of weld, etc.). The handling by pressure is conducted in the cold and hot state. Forging, die forging and sheet stamping are used as the main kinds of machining. Titanium is sensitive to the high deformation rates. The strains during the stamping at low heating temperatures for titanium alloys are higher than for the steel blanks by 20...30 %. The temperature interval of the hot deformation of alloys is completely determined by the temperature of their polymorphic transformation. The low thermal conductivity of titanium and the increased adhesion of the sheared material for cutting tool are the special features of cutting. Chemical treatment of finished articles is frequently the final stage of mechanical heat treatment (chemical milling).

Application of titanium alloys. In the flight vehicles titanium alloys are utilized for manufacturing the skins, which are heated to temperatures 450...600°C (at the flight speeds $M=3...3.5$), the front wing edges, stabilizers, ailerons; for the elements of primary structure – wing spars, ribs, frames, etc; for firewalls, air ducts, hydro-wires, fuel tanks; for blades and disks of the compressors of engines; for the landing gear doors, flaps, mufflers, valves, rods, cowlings of engines, external combustion chamber housings, jet nozzles, manifolds, blades of propellers, small hatches, weapons, eyeglass fame, medical implants, jewelry, sport equipment, case of mobile phones, golf club head, hinges etc.

Alloys with strength up to 1200 MPa are used in a wide variety of airframe applications from small fasteners weighing a few grams to landing gear trucks and large wing beams weighing up to 1 ton. Currently titanium makes up to 10 % of empty weight of aircraft such as the Boeing 777.

Some of the Ti-alloys are grouped by their relative usages (Table 8.1).

Table 8.1. More widely used titanium alloys in aircraft applications

Ti-alloy	Applications
Ti6Al4V	Workhorse, general purpose high strength alloy
Ti6Al2Sn4Zr2Mo (6-2-4-2)	Creep and oxidation resistant engine alloy
Ti6Al2Sn4Zr6Mo (6-2-4-6)	Creep and oxidation resistant engine alloy
Ti3Al8V6Cr4Zr4Mo (Beta C)	Beta alloy with established spring applications
Ti10V2Fe3Al (10-2-3)	Beta forging alloy used for 777 landing gear
Ti15V3Cr3Sn3Al (15-3-3-3)	High strength heat treatable beta sheet alloy

Table 8.1 (continued)

Ti3Al2.5V	Medium strength alloy used for hydraulic tubing
Ti4Al4Mo2Sn (550)	Higher strength heat treatable airframe and engine alloy
Ti5.5Al3.5Sn3Zr1Nb (829)	Advanced engine alloy, creep and oxidation resistant
Ti5.8Al4Sn3.5Zr0.7Nb (834)	Advanced engine alloy, creep and oxidation resistant
Ti5Al2Sn4Mo2Zr4Cr (Ti17)	Advanced engine alloy, creep and oxidation resistant
Ti15Mo3Nb3Al0.2Si (21S)	Oxidation and corrosion resistant beta sheet alloy
Ti6Al2Zr2Sn2Mo2Cr0.25Si (6.22.22)	Airframe alloy for F22 and JSF projects
Ti4.5Al4Mo4Sn0.5Si (SP 700)	Competitor for Ti6Al4V for SPF and general use

Theme 9. COPPER ALLOYS

Copper is one of the most ancient metals. It gave the name to one of the ancient centuries. The content of copper in the earth's crust is small. Pure copper – non-magnetic metal of pink-red color, it is crystallized in the FCC (face-centered cubic) lattice. It does not have polymorphic transformations. The special features of copper are: high heat- and electrical conductivity, plasticity in the cold state, the resistivity to corrosion under normal conditions. Copper is the basis for the most important alloys - brasses and the bronze. The density of copper – 8.94 g/cm^3 , melting point is 1083°C . Pure cast copper has the ultimate strength of $150\dots200 \text{ MPa}$, tensile strain $\varepsilon=15\dots25 \%$; cold-worked copper has $\sigma_B=400\dots430 \text{ MPa}$, $\varepsilon=1\dots2 \%$. Coefficient of the temperature expansion $\alpha=16.5 \cdot 10^{-6} \text{ 1/}^\circ\text{C}$. Elastic modulus in tension equals 115 GPa .

All admixtures reduce electrical conductivity of copper and form 3 groups of the compounds:

- solid solutions with **Zn, Sb, Al, Zr, As, Fe, P**;
- low-melting eutectics with Pb and Bi;
- the compound of oxygen and sulfur with copper.

Classification and designation of copper alloys

Pure copper of grades M0 and M1 is used in the aircraft industry for manufacturing the conductors. Copper of brands M2 and M3 is utilized for manufacturing of the current-conducting parts, packing, plugs, and stoppers.

During the formation of the copper alloys the following alloying elements may be utilized: Zn, Pb, Mn, Ni, Fe, the Be, Cr. Copper alloys are divided into 2 groups: brass - the alloys of copper with zinc and bronze - the alloys of copper with other elements (among which also there can be zinc in a small quantity). According to the technological criterion brass and bronze are divided into those deformable and casting. An alloy marking is fulfilled by the large Russian letters: **Л** - for brass, **Бр** - for the bronze. The letter designation of the basic elements, which form alloy, follows after these letters. The numbers, which follow after the letters, indicate a quantity of alloying elements. The numbers are written through the dash. For deformable brasses the first 2 numbers indicate the content of copper in the alloy in the percentages, then the corresponding numbers follow and the letters, which indicate a quantity of alloying elements. The content of zinc in deformable brasses is determined by subtraction from 100 percent of a quantity of copper and remaining alloying elements. In the deformable bronze the content of basic component - copper - is not indicated, but it is determined by the difference from 100 %. Difference in the markings the cast and deformable alloys is the following: in the cast alloys the content of the alloying elements in the percentages is placed immediately after the letter, which designates its name. For the marking the following designations of the alloying elements are used: **О** - tin; **Ц** - zinc; **С** - lead; **Мц** - manganese; **Ж** - iron; **Н**

- nickel; **Φ** - phosphorus; **Б** - beryllium; **К** - silicon; **Х**- chromium; **Сy** - antimony.

Let us discuss several examples of the designation of the alloys: Л70 – deformable brass, which contains 70 % of copper and $100-70=30$ % of zinc; ЛА85-0,5 - contains 85 % of copper, 0,5 % of aluminium and $100-(85+0.5)=14,5$ % of zinc; БpO10 - deformable bronze, which contains 10 % of tin and $100-10=90$ % of copper. БpOЦC4-4-2,5 contains 4 % of tin, 4 % of zinc, 2,5 % of lead and $100-(4+4+2.5)=89.5$ % of copper; ЛАЖ60-1-1- deformable brass, which contains 60 % of copper, 1 % of aluminium, 1 % gland, zinc $100-(60+1+1)=38$ %.

ЛЦ40Mц1,5 – casting brass, which contains 40 % of zinc, 1.5 % of manganese and 58.5 % of copper; БpA10Ж3Mц2 - casting bronze, which contains aluminium – 10 %, iron – 3 %, manganese – 2 % (copper in alloy 85 %).

In the USA designation by UNS system and **Copper Development Association** (CDA) are mainly used. According to UNS (see **Appendix D**) designation consists of the prefix letter C followed by five digits.

- the **first three digits** are alloy numbers given by the CDA;
- the **last two digits** are for the modification made to the original alloy;
- wrought alloys occupy C10000 to C79999;
- cast alloys occupy C80000 to C99999.

Brasses

The content of zinc in aviation brasses varies in limits of 32...45 %. Zinc-containing copper alloys in the volume up to 10% are called pinchbecks (or tombacks), and in the volume by 10...20 % – low brass. Brass has narrow temperature solidification range and therefore they possess good casting properties. On corrosion resistance they exceed iron, carbon steel and many types of alloy steel. They are supplied in the form of rolled stock: sheets, strips, rods and in the form of castings. For preventing the cracking all semi-finished products from brass are annealed at a temperature 250...650°C for 1 hour. Aluminium, tin, nickel, manganese increase strength and corrosion resistance, silicon increases strength and casting properties, lead worsens cutting. Depending on the composition brasses are machined by cold, hot stamping, and cutting. For decreasing of hardness and increase in the plasticity the semi-finished products before the working by pressure can be subjected to recrystallization annealing.

Most frequently used marks of brasses: Л90, Л96 - possess the high plasticity, high thermal conductivity, corrosion resistance; Л59, Л60, Л62 - possesses high strength, are machined well, cheap, but worse resists corrosion; Л68 - possesses the greatest plasticity, it is utilized for stamping the parts. Special brasses are also widely used - with the increased content of the alloying elements: ЛАЖ60-1-1, ЛЖMц59-1-1, ЛC59-1, ЛЦ40C, ЛЦ40Mц3Ж, ЛЦ30A3.

By phase composition Cu-alloys containing up to 37 % of Zn belong to α -alloys group, from 37 % up to 45 % - ($\alpha+\beta$)-alloys.

Examples of alloys (designation by CDA): CZ114 – is high-strength brass having composition (Cu-57 %, Sn-0.75 %, Fe-0.75 %, Mn-1.5 %, rest is Zn) and properties - $\sigma_{yield}=250$ MPa, $\sigma_B=500$ MPa. Correspondent grade by UNS is C67500.

Application in the aircraft construction. Brasses are used for manufacturing the radiator tubes of aircraft engines, hydraulic lines, inserts, bearing cages, gears, branches, nuts, blade wheels, propeller blades.

Bronzes

The basic alloying elements of bronze are tin, aluminium, lead, silicon, beryllium, chromium, antimony, iron, nickel, manganese, zinc. Depending on the alloying elements bronze are divided into the stannous (to 20 % of Sn), the aluminium (to 11 % of Al), the lead (to 30 % Pb), the silicic (to 3.5 % of Si), the beryllium (to 2.7 % of the Be), the chromium (to 0.7 % Cr), the antimonous (to 6 % of Sb).

Bronze possess high corrosion resistance, good machinability, cutting, high antifriction qualities, good casting properties. According to the mechanical properties aluminium or beryllium bronze are not inferior to steels.

Depending on type of thermal treatment the bronze can be subjected to homogenization annealing, quenching, ageing, and work hardening.

Tin bronze (true bronze). The tin bronzes are probably the oldest alloy known, being the bronzes of the Bronze Age. They are extremely resistant to a wide variety of atmospheres, waters, and soils as evidenced by many bronze artifacts still in existence. Examples of the alloys: БрОФ6,5-0,4; БрОЦ4-3; БрОЦ4-4-2,5; БрО3Ц1.2С0.5; БрО4Ц4С1.7, C43500. They are used for manufacturing of springs, barometric boxes, membranes, antifriction parts, fittings, bearing liners, grids, elbows, contacts of electrical equipment. They are utilized in the annealed and cold-worked state. The cost of such alloys is high, since tin is expensive. At present they are replaced by plastics.

Aluminium bronze. Examples of alloys: БрА5; БрАЖН10-4-4; БрА10Ж3Мц2; БрА9Мц2. They are frost-resistant and do not give sparks with the shock. They are used for manufacturing of valves, gears, guide bushings, valves, worm gears, nipples, arms, bearings. Some alloys are suitable for the handling of alkali such as sodium or potassium hydroxide; non-oxidizing mineral acids such as sulfuric or phosphoric; and organic acids such as acetic, citric, formic, and lactic. Architectural applications are another important use of these alloys. They resist corrosion in the tropical climate, sea water, possess good casting, mechanical and technological properties. They are strengthened by tempering, annealing, tempering.

Lead bronze. Typical system of lead bronze is Cu+Ni(≈ 2 %)+Pb(7...30 %). High lead tin bronzes are free cutting and retain favorable thermal conductivity and good lubricity due to the lead content. The high lead tin bronzes are ideal for bearing applications where there could be a loss of the lubrication boundary. These alloys perform excellent in unforgiving environments where foreign matter may be

present, such as dirt and other foreign materials. The high lead alloys are able to envelope foreign matter due to its malleable nature and in doing so protects the wear surface of mating part such as a shaft.

An example of alloy is БрС30, $\sigma_B=60$ MPa. Application – protective coating on steel tubes and tapes, bearing separator. Designation by CDA is CDA938, CDA941, CDA945 and by UNS – C93400, C93500, C93600.

Silicon bronzes. Solubility of Si in copper is very poor (2...4 %). Examples of the alloys: БрКМц3-1; БрКН1-3, C65600. The heat resistance of these alloys reaches 500°C. They are more inexpensive than tin brass. They are used for manufacturing of flat and circular springs, wire for welding, fasteners (bolts, nuts, rivets, studs). They are machined by pressure, cutting, welding.

Beryllium bronze. Examples of the alloy: БрБ2. Their cost is high; therefore frequently beryllium is replaced by manganese. They are used for manufacturing of the membranes, springs, contacts, and silphons, non-sparking tools. They are strengthened by quenching and ageing (temperature of quenching 760...780°C, the temperature of ageing 300...350°C). After the heat treatment of the alloy БрБ2 has the ultimate strength 450 MPa and tensile strain 40 %.

Chromium bronze. Examples of the alloy: БрХ0,5. It is alloyed well with steel and is used for obtaining the bimetals. Its coefficient of friction is high. It is used for manufacturing of brake drums, clutch plates, bearings; it is well forged and rolled. It possesses high corrosion resistance and electrical conductivity - it is used during the welding and for the collectors of electric motors. An alloy C18150 (Cu+1 %Cr+0.1 %Zr) after drawing and ageing can operate up to the temperature 500°C and used for bearings manufacturing.

Antimony bronze. Examples: БрСyН6-2 (Cr+6 %Sb+2 %Ni), БрСyН7-2, БрСy3Н3Ц3С2Ф alloys are used for corrosion resistant to fuel bearing, pumps, bushings and jewelry.

Phosphorus bronze. Distinctive features of this bronze type are high wear and chemical resistance. Typically they contain 3.5...10 % of phosphorus. Examples: C51000 (8 %P), C51100 (4 %P), C52100. Application: springs, bolts, ship propellers, musical instruments.

Cupronickel alloys

Alloys on the basis of copper and by the basic alloying element - nickel are related to these alloys. The additional alloying elements are: manganese, aluminium, iron, zinc, cobalt, lead, chromium, magnesium, lithium. Industrial cupronickel alloys are divided into the structural and the electrotechnical.

Structural alloys. They include the cupronickel, German silver and Cunial.

Cupronickel - alloy on the basis of copper and nickel (sometimes with additional alloying elements - iron and manganese). Frequently the alloys МНЖКМц30-1-1, МН19, C70600, C71640 are used. They are machined well by pressure in hot and cold states. They possess high corrosion resistance in sea water and organic

acids. It is used for manufacturing of thermostats, condenser tubes of heat exchangers. Thermocouples and resistors whose resistance is stable across changes in temperature contain 55 % copper – 45 % nickel alloy. Cylinder cores, cylinder locks and locking systems are made of wear-resistant cupronickel.

German silver (Nickel silver). It is based on the system of **Cu+Ni (up to 20 %)+Zn(up to 20%)**. It possesses high strength and corrosion resistance. Frequently alloys MHL15-20, MHL16-29-1,8 are used. It is used for manufacturing of electric contacts, parts of precision instruments. Example of UNS designation is C76200.

Cunial (copper-based alloy). It is based on the system **Cu+Ni+Al**. The most frequently used alloys are Cunial A MHA13-3, Cunial B MHA6-1.5. They are used for heavy-duty springs, parts of electrical engineering. They are strengthened by heat treatment - quenching and ageing. Cunial is machined by pressure. It has high corrosion resistance.

Theme 10. CORROSION-RESISTANT, HIGH-TEMPERATURE AND HEAT RESISTANT STEELS AND ALLOYS

The destruction of metals under the action of environment is called **corrosion**. Frequently in this case metals are covered with the products of corrosion. As a result of the effect of environment the mechanical properties of metals sharply deteriorate, sometimes even in the absence of the visible change in the exterior view of surface.

Steels, which possess high corrosion resistance in the atmospheric conditions, fresh and sea water, the solutions of salts, alkalies, some acids at room and elevated temperatures, are called corrosion-resistant (or stainless).

From the chemistry point of view two types of corrosion may be distinguished:

- chemical corrosion, which takes place under the influence of metal of gases and nonelectrolytes (gas corrosion);
- electrochemical corrosion, caused by the action of electrolytes.

Gas corrosion causes deterioration of turbine blades, exhaust nozzles, reinforcing rods of furnaces. The composition of atmosphere influences on alloys corrosion: for steel articles sulphuric gas SO_2 , hydrogen sulphid H_2S , chlorine Cl_2 and chlorine hydrogen HCl are mostly dangerous.

The electrochemical corrosion includes atmospheric and soil corrosion.

Classification of operational corrosion types

Corrosion manifests in many different forms. Concentration cell corrosion, or **crevice corrosion**, is the most common type found on airplanes, occurring whenever water is trapped between two surfaces, such as under loose paint, within a delaminated bond-line, or in an unsealed joint. It can quickly develop into pitting or exfoliation corrosion, depending on the alloy, form, and temper of the material being attacked.

All forms of concentration cell corrosion can be very aggressive, and all result from environmental differences at the surface of a metal. The most common form is oxygen differential **cell corrosion**. This occurs because moisture has a lower oxygen content when it lies in a crevice than when it lies on a surface. The lower oxygen content in the crevice forms an anode at the metal surface. The metal surface in contact with the portion of the moisture film exposed to air forms a cathode. As shown in Figure 3, chloride ions (Cl) migrate to the anode and create an acidic and corrosive condition. The most effective way to eliminate this kind of corrosion is to keep water out of the joint.

Two of the most destructive forms of corrosion are **stress corrosion cracking** (SCC), also known as environmental assisted stress corrosion, and exfoliation corrosion. SCC occurs rapidly and follows the grain boundaries in aluminium alloys. Exfoliation corrosion also follows grain boundaries. It occurs

in multiple planes, causing a leaf-like separation of the metal grain structure. Both forms of corrosion cause a loss of load-carrying capability. The most effective way to control this kind of corrosion is to use materials that are not susceptible to SCC at design stress levels or have a grain structure that is not susceptible to exfoliation.

Pitting corrosion results in a local loss of material. Although very little metal is removed, the pits can act as stress risers that lead to fatigue failure if located in a critical load path.

Galvanic corrosion occurs when two metals with different electrical potentials are electrically connected in the presence of an electrolyte. This can occur at a macro scale, such as an aluminium-nickel-bronze bushing in an aluminium fitting, or on a micro scale, such as an aluminium-copper intermetallic at the surface of an aluminium alloy.

Clad aluminium sheet and plate are used where weight and function permit, such as for fuselage skins. Corrosion-resistant aluminium alloys and tempers are used to increase resistance to exfoliation corrosion and SCC. An example of such a change is the replacement of 7150-T651 aluminium plate on upper wing skins with 7055-T7751 plate, which is not as susceptible to corrosion. Major structural forgings are shot peened to improve the fatigue life of aluminium and steel parts and to reduce susceptibility to SCC. Corrosion-resistant titanium alloys are considered for use in severe corrosion environments, such as floor structure under entryways, galleys, and lavatories. Corrosion-resistant steels are used wherever possible, but a number of highly loaded structural parts, such as landing gear and flap tracks, are made of high-strength, low-alloy steel. Magnesium alloys are no longer used for primary structure. Fiber-reinforced plastics are corrosion resistant, but plastics reinforced with carbon fibers can induce galvanic corrosion in attached aluminium structure.

For example, graphite fibers, which are used to reinforce some plastic structure, present a particularly challenging galvanic corrosion combination. The fibers are good electrical conductors and they produce a large galvanic potential with the aluminium alloys used in airplane structure. The only practical, effective method of preventing corrosion is to keep moisture from simultaneously contacting aluminium structure and carbon fibers by finishing, sealing, using durable isolating materials such as fiberglass, and providing drainage. Figure 15 shows the 777 carbon fiber-reinforced plastic (CFRP) floor beam design and corrosion-protection methods. An aluminium splice channel is used to avoid attaching the floor beam directly to the primary structural frame.

Fig. 10.1 illustrates some typical sources of the corrosion that affects airplanes. As shown in Fig. 10.2, three conditions must exist simultaneously for corrosion to take place: the presence of an anode and a cathode. This occurs when two dissimilar metals or two regions of differential electrolyte concentration create a difference in electrical potential. A connector between the anode and cathode is an electrolyte such as water.

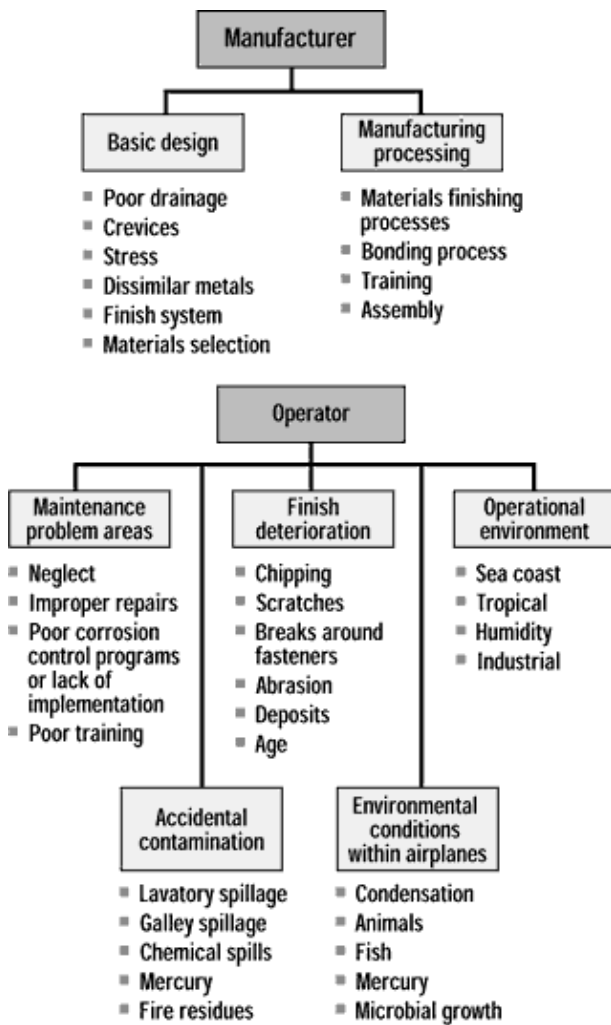


Fig. 10.1. Typical causes and sources of corrosion

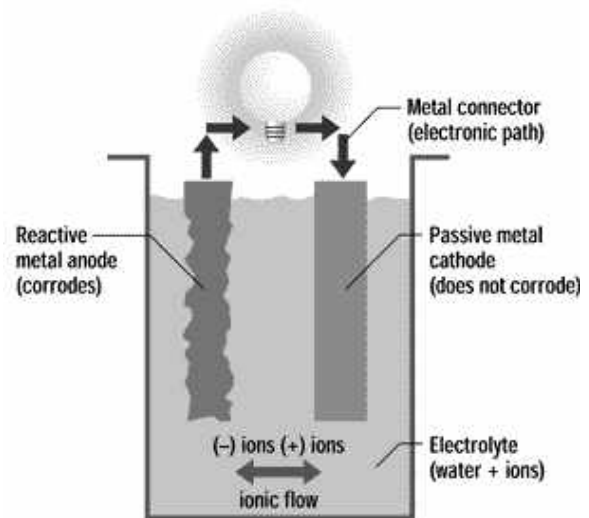


Fig. 10.2. Corrosion cell

Eliminating these three conditions in airplanes is restricted by practicality, functionality, and feasibility.

Dissimilar metal contact cannot always be avoided because of weight, cost, and functional issues, but the potential for corrosion can be minimized by using surface treatments, plating, painting, and sealing. Water cannot be avoided, but it can be controlled with drain paths, drain holes, sealants, and corrosion-inhibiting compounds. Controlling the presence of water is usually the most effective means of preventing corrosion.

The mechanism of electrochemical corrosion encloses formation of galvanic couple of two different metals in the medium of electrolyte. Therefore during the selection of the together working metals it is necessary to carefully select pairs, since the metal, which protrudes as the anode fails. In the sea water and the atmospheric moisture in the ascending order of electrochemical potential metallic number can be represented in the form of the sequence (Table 10.1).

With the contact of two metals first fails that, which is arranged to the left. The cathode protection of steels from the corrosion is based on this principle. Usually to

the surface of steel a layer of chromium, nickel or tin may be applied. A disadvantage of this method of corrosion protection - during the least disturbance of protective layer metal begins to fail intensively.

Table 10.1. Series of elements electrochemical potentials

Element	Mg	Al	Zn	Cr	Fe	Co	Ni
E0, V	-2,37	-1,66	-0,76	-0,74	-0,44	-0,28	-0,25
Element	Sn	Pb	H	Cu	Hg	Ag	Au
E0, V	-0,14	-0,13	0	+0,34	+0,79	+0,80	+1,50

The criterion of corrosion is corrosion rate (mm/year). In the Russia, USA and Germany five-grade system of corrosion degree estimation.

Corrosion fatigue is a phenomenon caused by corrosion. It means accumulation of micro-damages under cyclic stress and chemically-active environment. Appearance and developing of fatigue cracks is accompanied with inside corrosive medium penetration. This kind of deterioration can be observed in steels, aluminium, titanium, copper alloys etc. Moreover corrosion-fatigue failure can occur at stress less than fatigue limit.

Steels, stable against the gas corrosion at temperatures higher than 550°C, are called **scale-resistant** steel or **high-temperature** (oxidation-resistant) steel.

An increase in the resistance of steel to the corrosion is achieved by the introduction into it of the elements, which form protective films on the surface of steel.

Chromium is the basic alloying element of corrosion-resistant (stainless) steels. It is established that in the stainless steel there must be not less than 12.5 % of chromium otherwise shielding effect is not observed. Chromium creates on the surface of steel the shielding oxide film Cr_2O_3 . Nickel is introduced to high-chromium steels for an improvement in their anticorrosive properties.

According to the chemical composition corrosion-resistant steels are divided into the chromium and the chrome-nickel. Chromium steels contain not less than 13 % chromium and, in turn, they are divided into the martensite (20X13, 30X13, 40X13 - they contain 0.12...0.14 % of carbon and 12...14 % of chromium), the martensite-ferrite (12X13) and the ferrite (12X17, 15X28, 15X25T - contain carbon less than 0.12 %, chromium – 28 %). Steels 12X13 and 20X13 are welded well and in the annealed state possess high plasticity. They are machined with cold pressing. They are subjected to oil quenching at temperatures of 1000...1100°C and to high-temperature tempering. Steels 30X13 and 40X13 are related to the class of those improved. They are quenched at temperatures of 1000...1050°C and are tempered at temperatures 180...200°C. After this heat treatment they gain high hardness and corrosion resistance. Chromium steel is used for the parts of fuel equipment, the aircraft instruments, the parts of aircraft engines, fire walls, and parts of armament. Steels of ferrite class, which can work in the more aggressive media and at higher temperatures, possess higher corrosion resistance. A drawback in the ferrite alloys

is the fact that during heating (for example, during the welding) they gain the coarse-grained structure, which is not corrected by heat treatment.

High-temperature (oxidation-resistant) steels

An increase in the heat resistance of steel consists of alloying with chromium, aluminium and silicon. In this case on the surface of steel the oxide films of Cr_2O_3 , SiO_2 , and Al_2O_3 are formed. These films shield metal from the oxidation. During the introduction into steel of 5...8 % chromium the heat resistance of steel is increased to 700-750°C. Addition of 5...8 % chromium increases heat resistance up to 1100°C. Heat resistance of steel may be increased up to 1300°C by alloying of steel with 25 % aluminium and silicon.

Austenitic steels are not strengthened with heat treatment. They are welded well, possess sufficient plasticity in the hardened state. High-temperature (oxidation-resistant) steels are used for manufacturing combustion chambers, flame tubes, afterburners, gas-turbine blades, disks of compressors, unit-cast rotors. These steels are supplied in the form of sheet blanks and cast. Standard trademarks of steels used: 20X23H18, 12X17, 15X25T, 36X18H25C2, etc.

Heat-resistant steels

Frequently the parts of modern aircraft engines and flight vehicles during the work are heated to temperatures of 700...1000°C. Heat resistance is the ability of material at high temperatures to resist beginning and development of plastic deformation and destruction under the effect of prolonged mechanical loads. The strength of metal is determined by the time of loading and by the temperature of operation. The greater the temperature and the duration of the effect of load, the more rapidly the plastic strain is developed and the more rapidly the structural failure begins. During the analysis of the heat resistance of materials special attention is paid to the phenomenon of **creep**.

Creep is the property of materials to be deformed at high temperatures under the action of **constant** load. The phenomenon of creep is observed if operating stresses in the part exceed elastic limit of material, and operating temperature higher than recrystallization temperature. Heat resistance is characterized by creep limit and by stress-rupture strength. Creep limit - stress, to which corresponds permitted for the normal operation of construction rate or the value of strain in the prescribed temperature and the duration of the effect of load. For example expression

$$\sigma_{\varepsilon/\tau}^t = \sigma_{0,2/100}^{800} = 160 \text{ MPa}$$

designates for the nickel alloy ЭИ437Б, what for 100 hours of work a part is deformed to 0.2 % at operating temperature 800°C, while constant stresses in

160 MPa are applied to the part.

Long-term (stress-rupture) strength is a stress, which corresponds to structural failure with the given temperature and duration of the effect of load. The recording

$$\sigma_r^t = \sigma_{200}^{800} = 250 \text{ MPa}$$

designates for the alloy ЭИ437Б, that the part fails under the influence on it of stresses 250 MPa for 200 hours of work at operating temperature 800°C.

To determine numerical values of mentioned creep characteristics creep test has to be conducted. Its principal scheme is shown on Fig. 10.3.

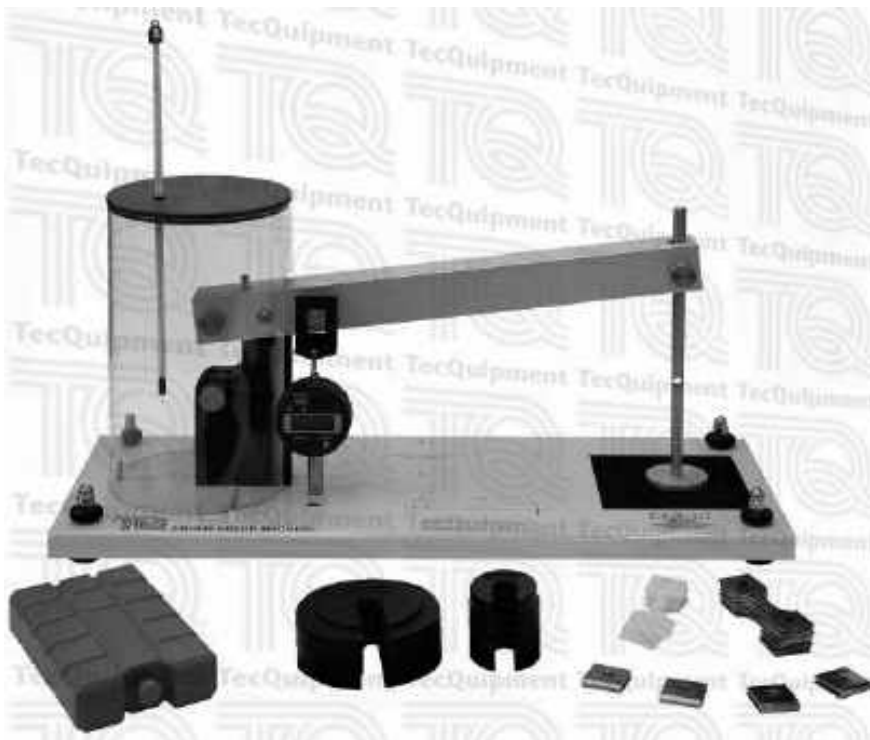


Fig. 10.3. Principal scheme of creep test

To determine creep properties, material is subjected to prolonged constant tension or compression loading at constant temperature. Deformation is recorded at specified time intervals and a creep vs. time diagram is plotted. Slope of curve at any point is creep rate. If failure occurs, it terminates test and time for rupture is recorded. If specimen does not fracture within test period, creep recovery may be measured. To determine stress relaxation of material, specimen is deformed a given amount and decrease in stress over prolonged period of exposure at constant temperature is recorded. Standard creep testing procedures are detailed in ASTM E-139, ASTM D-2990 and D-2991 (plastics) and ASTM D-2294 (adhesives). The most commonly used expression for relating creep rate $\dot{\epsilon}$ to stress σ and absolute temperature T has the form

$$\varepsilon = A\sigma^n e^{-E/RT},$$

where **A** and **n** are constants, **E** is the activation energy for creep in the metal and **R** is the universal gas constant.

The equation shows that the creep rate is increased by raising either the stress or the temperature.

It is obvious, that the heat resistance of materials depends on their tendency toward creep. For manufacturing the parts of aircraft engines (turbine blades, turbine disks, and turbine casings) steels with the carbide (40X15H7Г7Ф2MC, 37X12H8Г8MФБ) and inter-metal hardening (10X11H20T3P, 10X11H23T3MP) are used.

With the advent of jet aviation nickel became one of the basic materials for the high-temperature alloys.

Globally methods of materials protection from corrosion can be divided into the following main groups:

- application of protective coatings (metal and non-metal);
- changing of electrochemical potential of a material under protection refer ambient atmosphere;
- modification of corrosion medium.

High-temperature and heat-resistant nickel alloys

Industrial nickel alloys are divided into the heat-resistant (oxidation-resistant), the high-temperature, the corrosion-resistant and steels with the special properties. Nickel alloys are marked or by special letters with the ordinal number (for example, ЭИ435) or as steels - X20H77ТЮ.

For the production of high-temperature alloys the metal with the high melting point is usually selected. Nickel forms on its surface the protective film of **NiO**. The nickel-chromium system is the basis of industrial oxidation-resistant nickel steels and alloys. They are frequently called Nichromes. The content of chromium in the nickel alloy forms 20...40 %. Oxidation-resistant Nichromes X10H90, X20H80, X30H70, X40H60 are used at temperatures to 1200°C. High-temperature nickel alloys are strengthened by and ageing. Quenching temperature equals 1100...1200°C (heating carries out during 2...12 hours in the vacuum ovens or the furnaces with the protective medium). Cooling is conducted in air. Ageing is conducted at temperatures 750...950°C.

High-temperature nickel alloys are divided into the deformable, casting and dispersive-strengthened (or age-hardened). The high-temperature deformable nickel alloys are called **Nimonic**. They are alloyed with chromium, titanium, aluminium. The marks most widely are used: ЭИ437 (it contains 20 % of chromium, 2.5 % of titanium, 0.75 % of aluminium), ЭИ617, ЭП742.

For manufacturing hollow blades of turbines, turbine disks high-temperature cast alloys are used. The most spread cast nickel alloys - ЖС,

ЖСЗ, ЖС6, ЖС6К, ЖС6КП, ЖС6У, ЖС6Ф. The basic alloying elements of these alloys are: molybdenum, chromium, tungsten, aluminium, titanium, niobium, vanadium, cobalt. Operating temperatures of these alloys achieve 900...1050°C. Nickel alloys are widely used in the cast form and they frequently undergo aluminizing.

The precipitation-hardened (age-hardened) alloys ВДУ-1, ВДУ-2, ВДУ-3 can be obtained by the methods of powder metallurgy. They consist of metallic matrix and dispersed oxides. Operating temperature for these alloys composes 1100...1200°C.

It's necessary to note that to the high-temperature alloys can be attributed also titanium high-temperature alloys, alloys on the basis of refractory metals. These alloys are examined in the appropriate lectures.

Theme 11. REFRACTORY METALS AND ALLOYS

Metals with the melting point higher than 1800°C are called refractory metals. They include the tungsten, molybdenum, chromium, tantalum, niobium, rhenium, hafnium, vanadium, zirconium, osmium, iridium, ruthenium.

Interest in the refractory metals and the alloys on their basis appeared in connection with the building of rockets, spacecrafts, nuclear reactors, and the development of power plants. The parts of these devices work in the range of temperatures of 1500-2000°C.

The physical properties of some refractory metals are given in the Table 11.1. Such elements as **Cr**, **Zr**, **Hf** have polymorphic transformations. To deficiencies in the refractory metals one should relate: their cold-shortness (especially it is expressed in chromium, molybdenum and tungsten), tendency toward oxidation. Therefore it is possible to use them only in the presence of protective coatings

Refractory metals are alloyed for decreasing the tendency toward brittle failure with a temperature decrease and for increasing the strength and high-temperature characteristics. The basic alloying elements for the tungsten, molybdenum and niobium are rhenium, carbon, zirconium, lanthanum, titanium, boron.

All high-melting materials are characterized by a good plasticity. Niobium is welded well.

At present the heat treatment of high-melting alloys does not find wide application in the industry. This is connected with the absence of special equipment for the quenching with rapid rate of cooling and guarantee of high temperature of the transition of alloy from viscous state to brittle.

Tungsten and its alloys

Density of tungsten is 19.3 g/cm³ (i.e. "heavy stone" from the Sweden language), elasticity modulus is 350 GPa. Tungsten is obtained by the methods of powder metallurgy: it is restored by hydrogen trioxide of tungsten **WO₃**. Then powder-like **W** is pressed and sintered into 2 stages - at a temperature of 1150...1300°C and 3000°C. Half-finished product may be hammered, stretched, rolled. For increasing the purity the obtained tungsten is re-melted in the electric-arc furnaces. In this case improbably plastic tungsten is obtained. Tungsten and tungsten alloys can be pressed and sintered into bars and subsequently fabricated into wrought bar, sheet, or wire, forgings. Many tungsten products are intricate and require machining or molding and sintering to near-net shape and cannot be fabricated from standard mill products.

At normal conditions pure tungsten is quite chemically resistant to chlorine, sulphuric, nitrogen, fluoric, aqua regia acids up to 100°C. Can be dissolved in alkalis at heating.

Table 11.1 – Properties of some refractory metals

Physical-mechanical characteristics	Refractory metals								
	W	Re	Ta	Mo	Nb	Cr	V		
Melting point, °C	3410	3180	3000	2625	2470	1903	1900		
Density, g/cm ³	19.3	21.0	16.6	10.2	8.6	7.2	6.1		
Recrystallization temperature, °C	1450	1300	1250	1100	1050	850	800		
The type of lattice	BCC	CPH	BCC	BCC	BCC	BCC, higher 1840°C FCC	BCC		
The temperature of the beginning of intense oxidation, °C	600...700	365	400	540	400	1050	600...700		
The melting point of oxide, °C	1500	296	1470	793	1440	2265	675		
The module of elasticity E, GPa	415	476	190	330	100	290	135		
The threshold of cold-shortness, °C	-200	-196	-196	-100	-196	-60	-110		
Linear expansion coefficient, 1/°C	4,3	4.6...12.4	6.6	5.5	7.2	6.2	6.5		
Long-term strength $\sigma_{24/1}^{1000}$, MPa	96	–	48...64	48...64	45	32...48	–		
Percentage of element in earth crust refer to copper (copper %=100)	92	0.001	3	21	34	290	–		

Note. In the table the types of crystal lattices are designated: BCC - body-centered cubic, FCC - face-centered cubic, CPH - close-packed hexagonal

Powder tungsten is obtained by hydrogen reduction in tubular electrical furnaces at 700...850°C. Then it is formed by pressure 3 ...5 tons/cm² and electrically heated up to 3000°C in hydrogen medium. As a result ductile tungsten rods are obtained and processed by forging, drawing and rolling.

The basic alloying elements are: rhenium (to 30 %), niobium (to 0.6...0.9%), zirconium (to 0.12 %), dioxide of thorium **ThO₂** (to 2 %), carbide of tantalum **TaC** (to 0.4 %). Strengthening is manufactured due to the solid solutions of the alloying elements and dispersed particles of high-melting oxides and carbides. Tungsten carbide accounts for about 65% of tungsten consumption. It is combined with cobalt as a binder to form the so-called **cemented carbides**.

During the operation at high temperatures the alloys of tungsten are shielded by coatings **Al₂O₃**, **ZnO₂** and by alloy (**Hf+Ta**), which can be applied by plasma spraying with the help of plasmatoms. During alloying of tungsten with the nonmetals carbides (**W₂C**, **WC**), nitrides (**WN**, **WN₂**), borides (**W₂B**, **WB**, **W₂B₅**), silicides (**W₃Si₂**, **WSi₂**) are formed. They have a melting point from 2300 to 2750°C, they possess large hardness, good cutting properties, and they are resistant to oxidation.

The typical representative of tungsten alloys - alloy BB-2. It consists of tungsten and (0.3...2) % of niobium. Ultimate strength at a temperature of 1000°C is 240 MPa. Stress-rupture strength for 500 hours of loading at a temperature of 1500°C is 50 MPa. Another designations tungsten alloys are: American - AMS-7897 (90 %W+6 %Ni+4 %Cu), ASTM-B-777-87: Class 1; United Kingdom – Elkanite 10W3 (72 %W+Cu), Elkanite 20S (W+27 %Ag), Mallory 1000 (90 %W+Ni+Cu).

Application of alloys. At present tungsten alloys are used in the electroslag, radio engineering, electric vacuum industry. Among the elements of aircraft engines from the tungsten alloys the parts of compressors, insets in nozzle throats of engines are manufactured. The inserts in nozzle throats of liquid propellant rocket engines are made of the tungsten, impregnated with silver (so-called "weeping metal").

Special attention is paid to tungsten alloys as to material for manufacturing of the cutting and drill tool (cutters, milling cutters, and drills), drawings, wire and roller.

Non-aviation application of tungsten is damping weights for computer disk drive heads, balancing weights for ailerons in commercial aircraft, helicopter rotors, and for guided missiles, kinetic energy penetrators for defeating heavy armor, Radiation shielding, radio isotope containers, gyroscope components

Pure tungsten is used for manufacturing hot wires of electric lamps, cathodes and anodes of X-ray tubes, parts of electrical amplifiers, rectifiers, for the welding electrodes and manufacturing thermocouples, which make it possible to measure temperature in the range of 1200...2000°C.

Molybdenum and its alloys

The most valuable property of molybdenum is its ability to retain mechanical properties the temperature up to 1000°C. The production of molybdenum is connected with the difficulties, depended on its high melting point and oxidizability with the formation of low-melting and volatile oxide MoO_3 .

Molybdenum is obtained by the method of powder metallurgy. For increasing the purity molybdenum is remelted in the electric-arc furnaces. Remelted molybdenum easily yields to forging, stamping, rolling. It is supplied in the form of sheets with thickness to 0.1 mm, wire, tubes with the diameter of 1.2 mm and with the wall thickness of 0.1 mm, and sheets.

Molybdenum forms carbides, borides, silicides. Basic alloying elements are: boron, silicon - for increasing the hardness; aluminium, chromium, cobalt, iron, nickel, tantalum, silicon - for increasing the ductility; zirconium, titanium, niobium - for increasing the cold resistance. As a rule, the mass the alloying element is not more than 1 %. In a considerable quantity it is possible to alloy molybdenum only by tungsten and by tantalum - to 20 %. In the alloys of the type BM-3 besides the above-indicated alloying elements the strengthening is achieved by the introduction of the particles of carbides of titanium, zirconium, tantalum and hafnium. Industrial molybdenum alloys are divided into those strengthened by work hardening and strengthened by heat treatment. For stress relaxation in the semi-finished products and the finished articles it is used annealing and the polygonization at temperatures of 800...1200°C in the course of 15 minutes.

More molybdenum is consumed annually than any other refractory metal. Molybdenum ingots, produced by melting of powder metallurgy electrodes, are extruded, rolled into sheet and rod, and subsequently drawn to other mill product shapes, such as wire and tubing. These materials can then be stamped into simple shapes. Molybdenum is also machined with ordinary tools and can be gas tungsten arc and electron beam welded, or brazed.

Molybdenum has outstanding electrical and heat-conducting capabilities and relatively high tensile strength. Thermal conductivity is approximately 50 % higher than that of steel, iron or nickel alloys. It consequently finds wide usage as heatsinks. Its electrical conductivity is the highest of all refractory metals, about one third that of copper, but higher than nickel, platinum, or mercury. The coefficient of thermal expansion of molybdenum plots almost linearly with temperature over a wide range. This characteristic, in combination will raise heat-conducting capabilities, accounts for its use in bimetal thermocouples. Methods of doping molybdenum powder with potassium aluminosilicate to obtain a non-sag microstructure comparable to that of tungsten also have been developed.

The major use for molybdenum is as an alloying agent for alloy and tool steels, stainless steels, and nickel-base or cobalt-base super-alloys to increase hot strength, toughness and corrosion resistance.

In the electrical and electronic industries, molybdenum is used in cathodes, cathode supports for radar devices, current leads for thorium cathodes, magnetron

end hats, and mandrels for winding tungsten filaments.

Molybdenum is important in the missile industry, where it is used for high-temperature structural parts, such as nozzles, leading edges of control surfaces, support vanes, struts, reentry cones, heat-radiation shields, heat sinks, turbine wheels, and pumps.

The alloys **Mo-0,5Ti**; **Mo-50Re**; ЦМ-2А; BM-1; BM-2, BM-3, MP-47ВП, ТСМ3 found the most complete application in the aircraft structures.

An example of the composition of alloy BM-1: 0.4 % **Ti**, 0.08...0.25 % **Zr**, 0.01 % **C**, 0.6 % **Nb**). This alloy has ultimate strength at normal temperature of 800 MPa, at temperatures of 1800°C...100 MPa. The threshold of the brittleness of alloy MP-47ВП (47 % of rhenium) is approximately -247°C. Mo-based alloy ЦМ3 has $\sigma^{1200} = 500$ MPa, $\sigma_{100}^{1200} = 180$ MPa.

Application. In the aircraft structures molybdenum alloys are used with the protective coatings. Without the protective coatings molybdenum can be used in the single use apparatuses and in vacuum. At a temperature up to 1100°C for the protective coatings one or several layers of metals (nickel, chromium, platinum) may be used. Period of the service of such coatings is about 1000 hours.

At temperatures of 1100...1500°C the coatings from oxides **Zr₂O₃**, **Al₂O₃**, **Cr₂O₃** with the glassy matrix are used. At temperatures of 1200-1300°C the period of the service of coating is approximately several hundred hours. At temperatures of 1500...1800°C coating on the basis of **MoSi₂** withstands up to 30 hours.

From the molybdenum alloys the engine nozzles of flight vehicles, ring of the combustion chambers of the engines of supersonic flight vehicles are manufactured. Molybdenum is used for manufacturing the edges of tail assembly and nose cones of the streamlined housings of the flight vehicles. Molybdenum is considered as promising material for manufacturing the fuel elements of nuclear reactors. Also molybdenum alloys are used for die inserts for casting aluminium, magnesium, zinc, and iron, heat shields for furnaces, structural parts, and heating elements.

Niobium and its alloys

Pure niobium is low-strength, but very plastic metal. It yields to forging, stamping, rolling, and dragging. It is supplied in the form of sheets, wire, tubes. Niobium is machined well, it possesses corrosion resistance, steady to the action of acids, and it is well welded. By its significance and accessibility it is close to molybdenum. Deficiencies in niobium: rapid oxidizability in the air and the high rate of diffusion of new impurities when heating. Almost all refractory metals increase the temperature of recrystallization and melting of niobium. Niobium is alloyed by these elements: by molybdenum, by tungsten, by vanadium, by titanium, by tantalum, by aluminium, by chromium, by zinc, by silicon, by boron. According to the structure niobium alloys are divided into the solid solutions and the heterogene-

ous-phase alloys. Niobium alloys are strengthened by work hardening and are annealed at temperatures of 1100...1300°C for 1 hour. Most widely the alloys of system **Nb+Mo** (example - alloy BH-2, it contains 4.5 % of molybdenum, the rest - niobium) and the of system **Nb+Mo+Zr+C** (alloys BH-3, BH-4, BH-5A) are used. Example of the composition of alloy BH-5A: molybdenum 6 %, zinc 0.7 %, carbon 0.1 %, rest - niobium.

As the strengtheners carbides **ZrC**, **MoC** also may be used.

Niobium practically does not interact with uranium at a temperature to 1100°C, it has high thermal conductivity, it possesses a good resistance to molten metals, and it is consistent with the structural materials. These properties make it possible to utilize niobium in nuclear power engineering. The tubes of heat exchangers and fuel elements are manufactured from niobium. Niobium is considered as promising material for the parts of nuclear engines of flight vehicles and for onboard power engineering with the nuclear propellant.

Niobium alloys were utilized for heat shielding of the front edges of the tail assembly of space vehicle "Asset", and also, for the parts of the engine nozzle of rocket "Apollo". Firms General Electric and Pratt&Whitney widely use niobium for manufacturing the parts of turbines, which work at temperatures of 1100-1500°C. Here are some examples of the niobium alloys: BH-2, BH-3, PH-6, F-48, F-50, D-31, and D-43. Alloy BH-2A cold-worked at a temperature of 20°C has a limit of strength 900 MPa, at a temperature 1200°C - 260 MPa, stress-rupture strength after 100 hours of loading and at temperature of 1200°C is 30 MPa. An example of the composition of alloy BH-4: molybdenum - (8.5...10.5 %), zirconium - (1...2 %), carbon (0.25...0.4 %), the rest – niobium.

Rhenium alloys

Among the elements, rhenium has the highest melting point, except for tungsten and carbon. Its density is exceeded only by osmium, iridium, and platinum. A ductile-to-brittle transition temperature does not exist in pure rhenium. Rhenium is the only refractory metal that does not form carbides.

Rhenium has a high electrical resistivity over a wide temperature range. This characteristic, combined with a low vapor pressure, makes it ideally suited for filament applications; additionally, it maintains ductility and is not affected by the oxidation/reduction cycle experienced in these applications, as is tungsten. One of the largest applications for rhenium is for mass spectrometer filaments, where it is available in commercial (99.99 %) and zone-refined (99.995 %) purities.

Rhenium is not attacked by molten copper, silver, tin, or zinc. It dissolves readily in molten iron and nickel, but is stable in the presence of aluminium. Rhenium has a significant hardening effect on platinum. At elevated temperature, rhenium resists attack in hydrogen and inert atmospheres. It is resistant to hydrochloric acid and seawater corrosion and to the mechanical effects of electrical erosion.

Rhenium is a beneficial alloying addition with other refractory metals. Rhe-

nium greatly enhances the ductility and tensile strength of refractory metals and their alloys. Rhenium alloys are used in nuclear reactors, semiconductors, electronic tube components, thermocouples, gyroscopes, miniature rockets, electrical contacts, thermionic converters, and other commercial and aerospace applications. Tungsten-rhenium alloys, applied by vapor deposition, are used to coat the surface of molybdenum targets in x-ray tube manufacture. Other rhenium alloys (with tungsten or molybdenum) are used for filaments, grid heaters, cathode cups, and igniter wires in photoflash bulbs.

According to GOST system commercially pure rhenium is designated as Re-0, Re-1. An examples of Re alloys are: BP-27BП, BP273П, MP47BП (Mo+47 %Re), MP473BП, BAP-5, BP5, BP20 (W+(5...27) %Re).

Mentioned alloys are quite ductile, keep shape and properties at elevated temperature.

Application of rhenium-containing alloys: cathodes, heating filament, amplifying generators, gyroscope, thermocouples, heat protective screens of landing spacecrafts (with measuring range up to 2600°C) .

Hafnium alloys

Hafnium properties are very close to zirconium ones. The most significant hafnium ores are located in Australia and South Africa. The most well-known is hafnium dioxide. Visually hafnium is very similar to steel. Density of hafnium is 13.2 g/cm³, melting point is 2227°C. Hafnium possesses high corrosion resistance to hot water, steam, alkali, chloric and nitrogen acids, high radiation resistance. Pure Hf is very ductile and can be processed with hot and cold forming, forging, rolling and welding.

Hafnium is supplied as powder, sponge, rods, castings, wire, sheets, tubes, foil etc.

Commercially pure Hf in quantity of 1...2 % is used as alloying element (for example with Zr, Ti, Ta, Ni, Co, W, Mo, Re and light alloys).

Hafnium containing alloys are used for manufacturing turbine blades, valves, nozzles, cases of rockets, fire-proof crucibles and screens, cutting tools for steels, as protective coating of exhaust nozzle, for sitalls and glasses, nuclear industry (heat releasing rods). Hf is a unique metal which can be used as solder for welding of low-carbon steels.

Theme 12. STEELS AND ALLOYS WITH SPECIAL PROPERTIES

Steels with special properties are developed to get definite physical and mechanical properties. These steels can be classified as following:

- steels for building structures;
- steels for ship-building;
- steels for railways;
- steels precision super-conductive;
- steels precision magnetic-soft;
- steel precision magnetic hard;
- steels precision with definite coefficient of thermal linear expansion;
- steels precision for thermo-bimetals;
- steels precision with known elastic properties;
- steels precision with high electrical resistance.

Steels with special electrical and magnetic properties are considered in the course “Electrical and radio materials”.

Alloys with special thermal and elastic properties

Instrument making industry demands so-called **precision** alloys (i.e. their chemical composition is strongly kept) with:

1. Definite linear expansion coefficients (LEC): equal to glass LEC, close to zero; large LEC.

2. Definite magnetic properties.

3. Definite electric properties.

4. Definite elastic modulus.

Generally $\alpha_{t_1} < \alpha_{t_2}$ if $t_1 < t_2$ (Fig.12.1).

Thermal expansion is increasing spacing between atoms of crystalline lattice at heating and contraction at cooling. Thermal linear expansion coefficients for several metals are shown in Table 12.1.

Table 12.1. Dependence of LEC on temperature

Metal	$\alpha \cdot 10^6, 1/K$				
	0°C	100°C	200°C	600°C	800°C
Iron	11.3	12.2	12.7	14.5	14.8
Copper	16.7	17.0	17.4	18.8	19.6
Aluminium	22.8	23.7	24.5	27.9	–
Nickel	13.4	13.6	14.0	15.6	16.1
Cobalt	12.0	12.5	13.0	–	–
Platinum	8.9	9.1	9.2	9.7	9.9

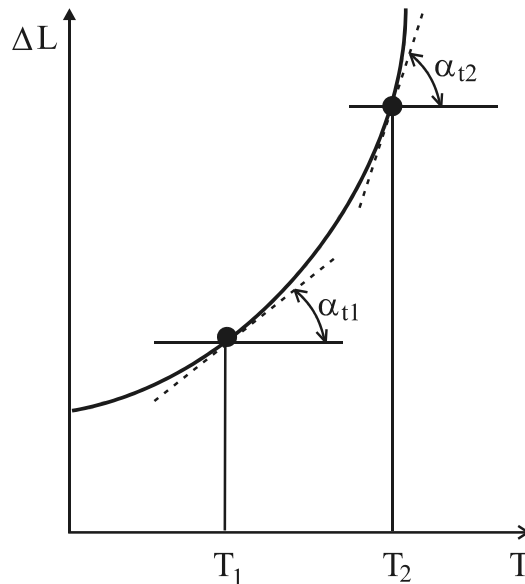


Fig. 12.1. Linear dependence of expansion on temperature $\alpha=a+b\cdot T$

LEC of an alloy depends on alloying elements quantity:

– if an alloy represents mechanical mixture its $\alpha_2 = \alpha_1 + \alpha_2 + \dots$ of components;

– if an alloy represents solid solution its $\alpha_1 < \alpha_2 < \alpha_2$ of components.

Two anomalous systems Fe-Ni and Fe-Pt disobeys general laws (Fig. 12.2, Table 12.2).

Alloys of Fe +Ni are divided by ferromagnetic and non-magnetic.

Ferromagnetic alloys are divided into three groups:

– with minimal CTE $\alpha < 3.5 \cdot 10^{-6}$, 1/K;

– with low CTE – $(4 \dots 6) \cdot 10^{-6}$, 1/K;

– with average CTE – $(7 \dots 12) \cdot 10^{-6}$, 1/K.

An example – alloys 18XTΦ and 18XMTΦ.

Pure Fe has LEC $\alpha = 11.6 \cdot 10^{-6}$, 1/K at $T = 20^\circ\text{C}$.

Fe+25 %Ni $\alpha = 20.0 \cdot 10^{-6}$, 1/K at $T = 20^\circ\text{C}$.

Fe+36 %Ni $\alpha = 1.5 \cdot 10^{-6}$, 1/K at $T = 20^\circ\text{C}$.

Percentage of C is less than 0.05 % because C changes parameters of crystalline lattice.

Alloys of iron and nickel are known as Invar and are used for high precision instruments production (see Fig. 12.2).

Fe+42 %Ni has $\alpha = 7.5 \cdot 10^{-6} = \text{const value}$, 1/K at $T = 20 \dots 200^\circ\text{C}$.

Table 12.2. Iron-Nickel alloys properties

Alloy	Composition	$\alpha \cdot 10^6$, 1/K	T range, °C
Invar	Ni 36 %+ Fe	1.5	20...100
Superinvar	Ni (30...35) %+(4...6) %Co+Fe	1.0	20...60
Platynite	Ni 48 %+ Fe	9.0	20...300

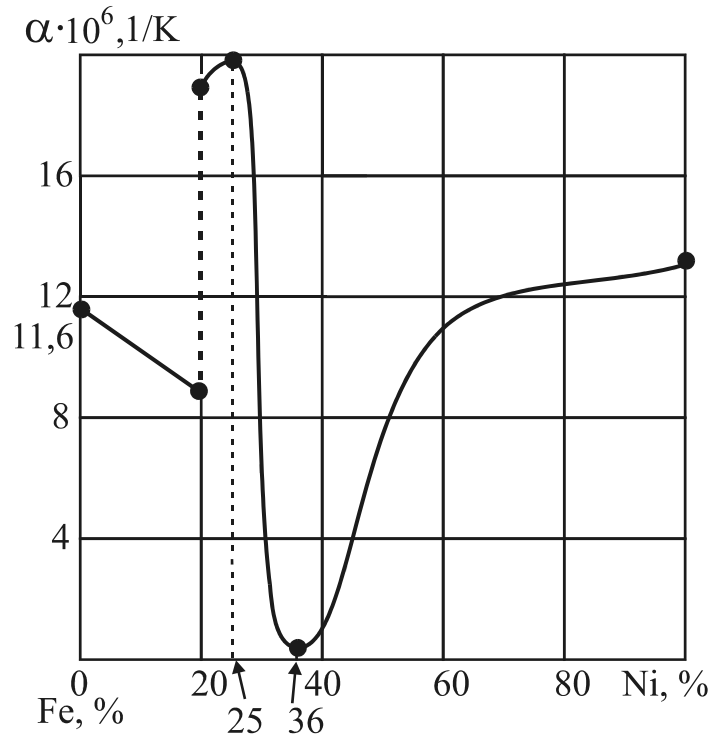


Fig. 12.2. Linear expansion coefficient of Fe-Ni alloys

Platynite has LEC like glass and is used for platinum articles sealing. The alloy with Ni(29 %)+ Co(18 %) +Fe is known as Covar, has $\alpha=5 \cdot 10^{-6}$, 1/K and is used for molybdenum glass sealing.

For springs, tuning forks it is necessary to have temperature independent elasticity modulus (E, G) (Table 12.3, 12.4). For this purpose Elinvar alloy (36 %Ni+8 %Cr+Fe) is used (Fig. 12.3). Their elasticity modulus gradient is very small:

$$\Delta E(T)=(18 \dots 23) \cdot 10^{-6}, 1/K.$$

Table 12.3. Composition of alloys with constant modulus

Alloy	Composition
Elinvar 1	0.4 %C+(7.3...8.3) %Cr+(36.5...38.5) %Ni+(0.3...0.8) %Mn+Fe
Elinvar 2	(0.7...0.8) %C+(7...8.9) %Cr+(33...35) % Ni+(2...4) %W+ +(2...3) % Mn+Fe
Ni-Span-C	0.06 %C+(5.1...5.7) %Cr+(41...43) %Ni+(2...2.6) %Ti+ +(0.4...0.8) % Al+(0.3...0.6) %Mn+Fe

Examples: 36HX11, 42HXTЮ, 36 HXTЮ

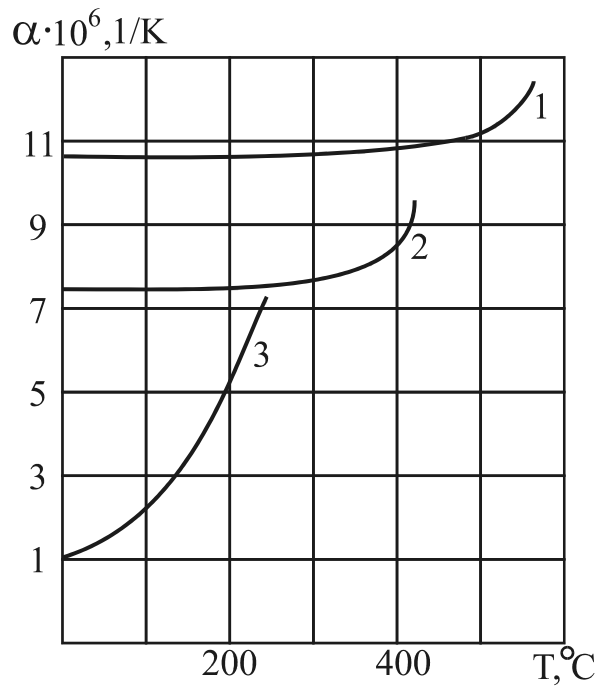


Fig. 12.3. LEC of Elinvar depending on Ni quantity

Table 12.4. Properties of Elinvar and Ni-Span-C alloys

Property	Elinvar	Ni-Span-C
E , GPa	160...170	180
$\alpha \cdot 10^6$, 1/K	7...8	7...8
Ω , Ohm·mm ² /m	0.9	0.9
σ_B , MPa	700...900	700...1400
ε_{max} , %	15...20	40...70

Alloys of this group are used for high precision devices like clocks. They can ensure accuracy for clock up to 0.5 sec per day. Ferrite Fe-Cr alloys 18ХТФ и 18ХМТФ are used for soldering with glass.

Appendix A

Correspondence in designation of different countries (unions) standards

Country	Standard
Australia	AS
Austria	ONORM (ON)
Belgium	NBN
Bulgaria	BDS
United Kingdom, UK Great Britain, GB	BS
Hungary	MSZ
Germany	DIN, WerkstoffNumber (WN, W.Nr.)
Greece	ELOT
European	EU, EN (Euronorm)
Spain	UNE
Italy	UNI
Canada	CSA
China	GB
Norway	NS
Poland	PN
Russia, Ukraine	GOST (DSTU)
Romania	STAS
Slovak	CSA
United States, US	AISI, ANSI, AMS, ASI, API, ASME, ASTM, AWS, SAE, UNS
Turkey	TSE
France	AFNOR NF
Finland	SFS
Czech Republic	CSN
Switzerland	SNV
Sweden	SS
Japan	JIS
International standard	ISO

Appendix B

Steels designation by European Norms

Table B.1. Steels enumeration (group 1) by EN 10027 (part 1)

First letter (steel applica- tion)	Property (designated by numbers)	Auxiliary symbols				
		Subgroup 1			Subgroup 2	
Structural steels S – G – means steel casting, forwards de- signation if ne- cessary	For example, S355JO. 355 means minimal guar- anteed yield- ing strength in N/mm ² (three digits)	Work of im- pact at brea- kage			Tem- pera- ture, °C	C – with elevated ductility in cold state D – for deposition of coating in hot state E – for enameling F – for forging and forming L – for operation at low temperature M – thermo- mechanically strengthened N – after normali- zation O – for offshore structures Q – after thermal treatment S – for shipbuilding T – for tubes W – resistant to atmospheric corro- sion
		27	40	60		
		JR	KR	L R	+20	
		J O	KO	L O	0	
		J2	K2	L2	-20	
		J3	K3	L3	-30	
		J4	K4	L4	-40	
		J5	K5	L5	-50	
		J6	K6	L6	-60	
		M – thermo- mechanically streng- thened N – after normaliza- tion Q – after thermal treatment G – other properties*				

Table B.1 (continued)

First letter (steel applica- tion)	Property (designated by numbers)	Auxiliary symbols	
		Subgroup 1	Subgroup 2
Steels for boilers and high pressure vessels P – G – means steel casting, forwards designation if necessary	For example, P265B. 265 means minimal guaranteed yielding strength in N/mm^2 (three digits)	M – thermo-mechanically strengthened N – after normalization Q – after thermal treatment B – for pressure vessels with compressed gas S – ordinary pressure vessels G – other properties*	H – high temperature L – low temperature R – room temperature X – high or low temperature
Steels for tubes L –	For example, L360Q. 360 means minimal guaranteed yielding strength in N/mm^2 (three digits)	M – thermo-mechanically strengthened N – after normalization Q – after thermal treatment G – other properties*	Letter and number if necessary
Steels for machine-building E –	For example, E295. 295 means minimal guaranteed yielding strength in N/mm^2 (three digits)	G – other properties*	–
Reinforcing steels B –	For example, B500N. 500 means minimal guaranteed yielding strength in N/mm^2 (three digits)	N – after normal drawing H – after high drawing G – other properties*	–

Table B.1 (continued)

First letter (steel appli- cation)	Property (designated by numbers)	Auxiliary symbols	
		Subgroup 1	Subgroup 2
Steels for pre-stressed structures Y –	For example, Y1770C. 1770 means minimal guar- anteed ultimate strength in N/mm ² (four digits)	C – cold-drawn wire H – hot-rolled or pre-stressed bars Q – thermally strengthened wire S – thin rope G – other proper- ties*	–
Rail steels R –	For example, R0880Mn. 880 means minimal guar- anteed ultimate strength in N/mm ² (four digits, zero can be the first)	Mn – high contents of manganese Cr – alloyed with chromium G – other proper- ties*	Q – thermally strengthened wire
Cold-rolled sheets from high-strength steels for cold forming H – if yield strength is controlled HT – if ulti- mate strength is controlled	For example, H420M. 420 means minimal guar- anteed yield strength in N/mm ² (three digits) HT420M 420 means minimal guar- anteed ultimate strength in N/mm ² (three digits forwarded with HT)	M – thermo- mechanically strengthened or cold-rolled B – quenched in furnace P – alloyed with phosphorus X – double-phase Y – with low con- tents of interstitial elements (C and N) G – other proper- ties*	–

Table B.1 (continued)

First letter (steel applica- tion)	Property (designated by numbers)	Auxiliary symbols	
		Subgroup 1	Subgroup 2
Rolled sheets for cold forming D –	For example, DC12EK C – cold-rolled D – hot-rolled X – state of rolled metal (two letters or numbers)	D – for deposition coatings in hot state EK – for enameling DK – for primerless enameling G – other properties*	–
Packageing sheets and tapes T – If yielding strength is con- trolled TH – if hard- ness is con- trolled	For example, T660 660 means minimal guar- anteed yield strength in N/mm ² for dou- ble cobbing (three digits) TH52 52 means av- erage hardness (TH and then two numbers)	No other symbols	No other symbols

Table B.1 (continued)

First letter (steel applica- tion)	Property (designated by numbers)	Auxiliary symbols	
		Subgroup 1	Subgroup 2
Electrotechnical steels M –	For example, M400-50A. 400 means al- lowable losses on remagneti- zation in W/kg multiplied by 1000 (three di- gits)	For magnetic induc- tion from 1.5 T (at 50 Hz) A – with non- oriented grains D – non-alloyed with- out final annealing E – alloyed without final annealing N – with normal losses on remagne- tization For magnetic induc tion from 1.7 T (at 50 Hz) S – oriented grains with limited losses on remagnetization P – oriented grains with low losses on remagnetization	No other symbols

* – with one or two digits if necessary

Table B.2 Steels enumeration (group 2) by EN 10027 (part 1)

First letter (steel type)	Property designated by numbers	Auxiliary symbols										
<p>Non-alloyed steels with average contents of manganese less than 1 % (excluding automatic steels)</p> <p>C –</p> <p>G – means steel casting*</p>	<p>For example C35E4</p> <p>First letter: average carbon contents in hundreds of percent (up to three numbers)</p> <p>35 means 0.35 % C</p>	<p>E – allowable maximum concentration of sulphur in hundreds of percents</p> <p>R – defined range of sulphur quantity in hundreds of percents</p> <p>D – for drawn</p> <p>C – with elevated ductility in cold state</p> <p>S – for springs</p> <p>T – tool steel</p> <p>W – for welding wire</p> <p>G – other properties, if necessary with one or two numbers</p>										
<p>Non-alloyed steels with average contents of manganese more than 1 %, non-alloyed automatic steels, alloyed steels (excluding fast-cutting steels) with contents of each alloying elements up to 5 %</p> <p>No letter</p> <p>G – means steel casting*</p>	<p>For example 28Mn6</p> <p>First letter: average carbon contents in hundreds of percent (up to three numbers)</p> <p>28 means 0.28 %C, 1.5=6/4 % Mn</p>	<p>Alloying elements: Letters – symbols of chemical elements; Numbers (separated by dash) – correspond to average contents of the element multiplied by coefficients shown below</p> <table border="1"> <thead> <tr> <th>Element</th> <th>Coefficient</th> </tr> </thead> <tbody> <tr> <td>Cr, Co, Mn, Ni, Si, W</td> <td>4</td> </tr> <tr> <td>Al, Be, Cu, Mo, Nb, Pb, Ta, V, Zr</td> <td>10</td> </tr> <tr> <td>Ce, N, P, S</td> <td>100</td> </tr> <tr> <td>B</td> <td>1000</td> </tr> </tbody> </table>	Element	Coefficient	Cr, Co, Mn, Ni, Si, W	4	Al, Be, Cu, Mo, Nb, Pb, Ta, V, Zr	10	Ce, N, P, S	100	B	1000
Element	Coefficient											
Cr, Co, Mn, Ni, Si, W	4											
Al, Be, Cu, Mo, Nb, Pb, Ta, V, Zr	10											
Ce, N, P, S	100											
B	1000											

Table B.2 (continued)

First letter (steel type)	Property designated by numbers	Auxiliary symbols
Alloyed steels (excluding fast-cutting steels) with average contents at least of one alloying element more than 5 % X – G – means steel casting*	For example X5CrNi18-10 First letter: average carbon contents in hundreds of percent (up to three numbers) 5 means 0.05 % C, 18 % Cr, 10 % Ni	Alloying elements: Letters – symbols of chemical elements arranged by decreasing of alloying elements contents (if contents is the same – in alphabetical order) Numbers (separated by dash) – correspond to average contents of the element
Fast-cutting steels HS –	For example HS2-9-1-8 Numbers separated by dashes mean contents of alloying elements in following accordance: W-Mo-V-Co	No other symbols

* – stays first if necessary

Table B.3. Steel enumeration by EN 10027 (part 2)

Steel		Ordinary number
Plain-carbon	Ordinary quality	1.00XX
	Qualitative	1.01XX-1.09XX
	High-quality	1.10XX-1.13XX
	Tool	1.15XX-1.18XX
Alloyed	Tool	1.20XX-1.28XX
	Fast-cutting	1.32XX-1.33XX
	Wear-resistant	1.34XX
	Bearing	1.35XX
	With special properties	1.36XX-1.39XX
	Corrosion-resistant	1.40XX-1.45XX
	High-temperature, heat-resistant	1.46XX-1.49XX
	High-quality	1.50XX-1.85XX
Welding	1.87XX-1.89XX	

Appendix C

Unified numbering system (UNS) of ferrous metals and alloys designation

Table C.1. Designation of ferrous alloys according to UNS

Designation	Alloys
D00001-D99999	Steels with specified mechanical properties
D40450-D40900	Carbon Steels
D50400-D52101	Alloy Steels Casting
F00001-F99999	Cast irons
F 10001-F15501	Cast Iron, Gray
F 10090-F10920	Cast Iron Welding Filler Metal
F 20000-F22400	Cast Iron, Malleable
F 22830-F26230	Cast Iron, Pearlitic Malleable
F 30000-F36200	Cast Iron, Ductile (Nodular)
F 41000-F41007	Cast Iron, Gray, Austenitic
F 43000- F43030	Cast Iron, Ductile (Nodular), Austenitic
F45000 F 45009	Cast Iron, White
F47001-F47006	Cast Iron, Corrosion
G00001-G99999	AISI and SAE carbon and alloy steels (except tool steels)
G10050-G10950	Carbon Steel
G15130-G15900	Carbon Steel
G11080-G11510	Resulfurized Carbon Steel
G12110-G12150	Rephosphorized and Resulfurized Carbon Steel
G13300-G13450	Mn Alloy Steel
G40120-G48200	Mo Alloy Steel, Cr-Mo Alloy Steel, Ni-Cr-Mo Alloy Steel, Ni-Mo Alloy Steel
G81150-G88220	Ni-Cr-Mo Alloy Steel
G50150-G52986	Cr Alloy Steel, Cr-B Alloy Steel
G61180-G61500	Cr-V Alloy Steel
G92540-G98500	Cr-Si Alloy Steel, Si-Mn Alloy Steel, Cr-S-Mn Alloy Steel, Ni-Cr-Mo Alloy Steel, Ni-Cr-Mo-B Alloy Steel
H00001-H99999	AISI and SAE H-steels
H10380-H15621	H-Carbon Steel, C-Mn H-Alloy Steel, C-B H Carbon Steel, Mn H-Carbon Steel, B- Mn H -Carbon Steel
H40270-H48200	C-Mo H-Alloy Steel, Cr-Mo H-Alloy Steel Ni-Mo H-Alloy Steel
H50401-H51601	C-Cr-B H-Alloy Steel, C-Cr H-Alloy Steel
H61180-H61500	Cr-V H-Alloy Steel
H81451-H94301	Ni-Cr-Mo H-Alloy Steel

Table C.1 (continued)

Designation	Alloys
J00001-J99999	Cast steels (except tool steels)
J01700-J05003	Carbon Steel Casting
J11442-J84090	Alloy Steel Casting
J91100-J92001	Austenitic Manganese Steel Casting, Alloy Steel Casting
J92110-J93000	Alloy Steel Casting Precipitation Hardening, Alloy Steel Casting, Cast Cr-Ni-Mo Stainless Steel, Cast Cr-Ni Stainless Steel, Cast Cr-Mn-Ni-Si-N Stainless Steel
J93001-J95705	Stainless Steel Casting, Cast Cr-Ni-Mo Stainless Steel, Alloy Steel Casting, Maraging Cast Ferritic-Austenitic Stainless Steel, Duplex Alloy Steel Casting, Alloy Steel Casting
K00001-K99999	Miscellaneous steels and ferrous alloys
K00040-K08500	Carbon Steel, Carbon Steel with Special Magnetic Properties, Steel Welding Rod, Enameling Steel
K10614-K52440	Alloy Steel, Alloy Steel Electrode and Welding Wire, High-Strength Low-Alloy Steel
K90901-K95000	Alloy Steel, Superstrength; Ferritic Cr-Mo-V Steel; Manganese Steel, Nonmagnetic; Ni-Co Steel Welding Wire; Iron, Electrical Heating Element Alloy; Iron Thermostat Alloy; Martensitic Age-Hardenable Alloy; Maraging Alloy; Fe-Co Soft Magnetic Alloy; Nickel Steel; Invar; Iron, Nickel Sealing Alloy; etc.
S00001-S99999	Heat and corrosion resistant steels (stainless), valve steels, iron-base "super alloys"
S13800-S17780	Precipitation Hardenable Cr-Ni-Al-Mo-(Cu, Ti) Stainless Steels
S20100-S39000	Austenitic Cr-Mn-Ni (Si,Mo,Cu,Al) Stainless Steel; Thermal Spray Wire; Austenitic Cr-Mn-Ni Stainless Steel and Welding Filler Metal; Austenitic Cr-Ni Heat Resisting Steel and Welding Filler Metal; Precipitation Hardenable Cr-Ni-(Si, Ti, Mo, Al) Stainless Steel, etc.
S40300-S46800	Martensitic Cr Stainless Steel; Ferritic Cr Stainless Steel with Ti or Ni or Mo; Martensitic Cr-Ni-Mo Stainless Steel; Hardenable Cr Stainless Steel
S50100-S50500	Cr Heat Resisting Steels and Filler Metal
S63005-S64007	Valve Steel
S65006-S65007	Valve Steel
S65150-S67956	Iron Base Super alloy

Table C.1 (continued)

Designation	Alloys
T00001-T99999	Tool steels, wrought and cast
T11301-T12015	High-Speed Tool Steels
T20810-T20843	Hot-Work Tool Steels
T30102-T 30407	Cold Work Tool Steels
T31501-S31507	Oil-Hardening Steels
T41901-T41907	Shock-Resisting Tool Steels
T51602-T51621	Mold Steels
T60601-T60602	C-W Tool Steels
T61202-T61206	Low-Alloy Tool Steels
T72301-T72305	Water Hardening Tool Steels
T74000-T75008	Cr-Steels Solid Welding Wire for Machinable Surfaces and Tool and Die Surfaces
T87510-T87520	Thermal Spray Wire
T90102-T91907	Cast Tool Steels

Appendix D

Designation of non-ferrous metals and alloys according to Unified Numbering System (UNS)

Table D.1. Designation of non-ferrous alloys according to UNS

Designation	Alloys
A00001-A99999	Aluminium and aluminium alloys
A01001-A63562	Aluminium Foundry Alloys, Ingot or Casting
A82014-A87475	Wrought Aluminium Alloys Clad with Wrought Aluminium Alloys, Non- or Heat Treatable
A91030- A91450	Wrought Aluminium Alloys, Non- Heat Treatable
A93002-A95954	Wrought Aluminium Alloys, Non- Heat Treatable
A98001-A98280	Wrought Aluminium Alloys, Non- Heat Treatable
A92001-A92618	Wrought Aluminium Alloys, Heat Treatable
A96002-A97472	Wrought Aluminium Alloys, Heat Treatable
C00001-C99999	Copper and copper alloys
Wrought Alloys	
C10100-C15760	Pure and Low Alloyed Copper (>99 % Cu)
C16200-C16500	Cadmium Copper
C17000-C17700	Copper-Beryllium Alloy (Beryllium Bronzes)
C18000-C19900	Copper and High Copper Alloys (> 96 % Cu)
C20500-C29800	Brasses (Cu-Zn)
C31000-C35600	Leaded Brasses (Cu-Zn-Pb)
C40400-C49080	Tin Brasses (Cu-Zn-Sn-Pb)
C50100-C52900	Phosphor bronzes (Cu-Sn-P)
C53200-C54800	Leaded Phosphor Bronzes
C55180-C56000	Cu-Ag-P and Cu-P Brazing Filler Metal
C60600-C64400	Aluminium Bronzes
C64700-C66100	Silicon Bronzes
C66200-C66420	Copper Alloys
C66700-C67820	Manganese Bronzes
C68000-C69950	Silicon Brasses and Other Copper-Zinc Alloys
C70100-C72950	Copper-Nickel Alloys
C73150-C79900	Nickel Silvers and Leaded Nickel Silvers
Cast alloys	
C80100-C81200	Cast Coppers (>99 % Cu)
C81300-C82800	Cast Chromium Copper and Beryllium Copper Alloys (>96 % Cu)
C83300-C85800	Cast Red, Yellow and Leaded Brasses
C86100-C86800	Cast Manganese Bronzes and Leaded Manganese Bronzes

Table D.1 (continued)

C87300-C87900	Cast Silicon Brasses and Bronzes
C89320-C89940	Cast Cu-Sn-Bi-(Se, Zn, Ni) Alloys
C90200-C94500	Tin Bronzes and Lead Tin Bronzes
C94700-C94900	Cast Nickel-Tin Bronzes
C95200-C95810	Cast Aluminium Bronzes
C96200-C96800	Cast Copper-Nickel Alloys
C97300-C97800	Cast Nickel-Silver Alloys
C98200-C98840	Cast Lead Copper Alloys
C99300-C99750	Cast Copper Alloys
E00001-E99999	Rare earth and rare earth-like metals and alloys
E00000-E00999	Actinium
EO1000-E20999	Cerium
E21000-E45999	Mixed rare earths
E46000-E47999	Dysprosium
E48000-E49999	Erbium
E50000-E51999	Europium
E52000-E55999	Gadolinium
E56000-E57999	Holmium
E58000-E67999	Lanthanum
E68000-E68999	Lutetium
E69000-E73999	Neodymium
E74000-E77999	Praseodymium
E78000-E78999	Promethium
E79000-E82999	Samarium
E83000-E84999	Scandium
E85000-E86999	Terbium
E87000-E87999	Thulium
E88000-E89999	Ytterbium
E90000-E99999	Yttrium
L00001-L99999	Low-melting metals and alloys
L00001-L00999	Bismuth
L01001-L01999	Cadmium
L02001-L02999	Cesium
L03001-L03999	Gallium
L04001-L04999	Indium
L06001-L06999	Lithium
L07001-L07999	Mercury
L08001-L08999	Potassium
L09001-L09999	Rubidium
L10001-L10999	Selenium
L11001-L11999	Sodium

Table D.1 (continued)

L13001-L13999	Tin
L50001-L59999	Lead
M00001-M99999	Miscellaneous nonferrous metals and alloys
M00001-M00999	Antimony
M01001-M01999	Arsenic
M02001-M02999	Barium
M03001-M03999	Calcium
M04001-M04999	Germanium
M05001-M05999	Plutonium
M06001-M06999	Strontium
M07001-M07999	Tellurium
M08001-M08999	Uranium
M10001-M19999	Magnesium
M20001-M29999	Manganese
M30001-M39999	Silicon
P00001-P99999	Precious metals and alloys
P00001-P00999	Gold
P01001-P01999	Iridium
P02001-P02999	Osmium
P03001-P03999	Palladium
P04001-P04999	Platinum
P05001-P05999	Rhodium
P06001-P06999	Ruthenium
P07001-P07999	Silver
R00001-R99999	Reactive and refractory metals and alloys
R01001-R01999	Boron
R02001.R02999	Hafnium
R03001-R03999	Molybdenum
R04001.R04999	Niobium (Columbium)
R05001-R05999	Tantalum
R06001-R06999	Thorium
R07001.R07999	Tungsten
R08001-R08999	Vanadium
R10001.R19999	Beryllium
R20001-R29999	Chromium
R30001.R39999	Cobalt
R40001.R49999	Rhenium
R50001-R59999	Titanium
R60001-R69999	Zirconium
W00001-W99999	Welding filler metals, classified by weld deposit composition
W60000-W69999	Copper base alloys
W70000-W79999	Surfacing alloys
W80000-W89999	Nickel base alloys
Z00001-Z99999	Zinc and zinc alloys

Appendix E

Specific cost of structural metals and alloys

Material	Specific cost, hrn/kg (or \$/kg)	Material	Specific cost, hrn/kg (or \$/kg)
Aluminium (Д16, АМг, АМц, В95, АК-12)	26...35 (rods) 15...20 (ingot)	Platinum	12500 \$/kg
Plate 2024 Т351	0.53...0.59	Solder (ПОС10, ПОС30)	50...75 (rod), 15...60 (sheet)
6061 Т651	0.33...0.35	Rhenium (Re0, Re1)	4800 \$/kg (sheet), 1600 \$/kg (powder)
7075 Т651	0.56...0.62	Rhodium	20000 \$/kg
Sheet 2024 Т3	0.51...0.65	Silver	120 \$/kg
3003 Н14	0.27...0.3	Lead (С1)	10...20
6061 Т6	0.36...0.4	Steel 12Х18Н10Т	30...45
Beryllium	200 \$/kg	Stainless 304	23 \$/kg
Bronze (БРХ1)	24 (ingot, sheet) 50 (rolled)	Round bar 304	0.31...0.73 \$/kg
Hafnium	2500 \$/kg,	Square bar 303	0.56...10 \$/kg
ПЧ	3500 \$/kg	Ст.3-45, 20Х, 40Х	3,5...5,5
Vanadium (ВНМ)	750 \$ (sheet)	Hot rolled (plate)	0.6...0.7 \$/kg
Tungsten (ВТ, ВА, ВЛ, ЭВН)	350...750 (rod) 300 \$/kg (sheet) 500 (wire)	Cold rolled (sheet)	0.75...0.9 \$/kg
Gold	12500 \$/kg	Tantalum (ТВЧ)	500 \$ (rod) 600 \$ (sheet)
Cobalt (К1, К1АУ)	350...400	Titanium (ВТ0, ВТ6, ВТ20)	300...400 (sheet), 150...250 (rod)
Brass	45...55	Chromium (Х99)	35...60
Lithium	60...70 \$/kg	Zinc (Ц0П10)	50...60 (rod)
Magnesium (МЛ)	15...20 (rod)	Zirconium (ZR0)	450..500 (rod), 400 \$ (sheet)
Manganese (МН965)	15...25		
Copper (М1, М2, С3)	55...65		
Nichrome (Х20Н80)	135...210		
Tin (О-1, О1ПЧ)	100...130 (rod)		
Molybdenum (МЧ, МВ-50)	200 \$/kg (rod), 300...400 \$/kg (sheet), 600 \$/kg (wire)		
Nickel (НП1, НП2)	100...150 (sheet), 150...200 (rod)		
Niobium (НВЧ)	200 \$/kg (rod), 260 \$/kg (sheet)		

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КОНСТРУКЦІЙНІ МАТЕРІАЛИ**

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