AEROSPACE MATERIALS SCIENCE

LABORATORY PRACTICE

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Materials science is very important in the training of engineers who will be designers and technologists in the aerospace industry. Understanding the processes of forming the properties of materials depending on their structure, chemical composition, and treatment techniques will provide an opportunity to perform work at a high level. On the other hand, the application of acquired knowledge in the field of aviation materials science will improve the control of the quality of the released products and the ability to determine compliance with technical requirements.

The "Aerospace materials science: Laboratory Practice" study aid is written by the program (syllabus) of the "Aerospace Materials Science" subject for students under the educational programs "Aerospace and rocket systems engineering" and “Airplanes and Helicopters” specialty 134 Aviation and rocket-space technic. Besides the students of engineering specialties in the field of aviation and rocket science, the textbook will be useful for graduate students, researchers, and specialists of other technical specialties, whose activities are related to the selection of materials, etc.

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INTRODUCTION

Methodical instructions for performing laboratory works from the subject “Aerospace Materials Science” contain a complete description of 9 laboratory works performed by students of aerospace specialties while studying this subject.

In addition to the purpose of the work and the order of its execution, the description contains information on the theory in the amount necessary for the execution of the work. The theory of each laboratory work allows students to have a sufficient understanding of the range of questions that arise in this work. The independent performance of individual tasks is mandatory.

The laboratory works, covered by these guidelines, includes work on the study of the macro- and microstructure of metals, the study of the effect of plastic deformation on the structure and properties of aluminum alloys, the structure and properties of iron-carbon alloys, alloys based on non-ferrous metals, the base of heat treatment and basics of composite materials. The list of additional references for laboratory work is included at the end of the methodological instructions.

Before each laboratory work, the students have to analyze the theory of the labs according to the lecture notes, recommended references, and theoretical information outlined in the methodological instructions. During preparation for the experiment, the student chooses from the references list those sources that are available in the library or on the Internet.

The report (protocol) for each laboratory work has to correspond to the content specified in the methodological instructions and consist of the solution of the corresponding individual task and be drawn up in accordance with the accepted requirements. Before each laboratory session, the student prints out the base of the report from this book according to the curriculum and takes the necessary number of sheets to write all the results of the work. The report on the completed work is made on sheets of paper in A4 format (210x297mm). During the class, the student completes the tasks and fills in the "Results of work" section and writes the conclusions. All records are made with ink or paste of the same color, on one side of the sheet. It is necessary that all graphic constructions (graphs, drawings, tables, etc.) are performed in accordance with the appropriate scale, in pencil with the help of drawing tools. In the upper part of the title page of each report, students write a full name of the person who has done the report.

The completed sheets of the reports are collected together. In front of the collection has to be the title page. The title page indicates the name of the discipline, the full name of teacher, and the full name of the student. The teacher accepts the report on the completed work, finds out the degree of the student's understanding of the essence of the work, and assimilation of the theoretical material, and sets the appropriate assessment.

SAFETY RULES

When performing laboratory classes, you need to follow the safety rules:

- it is forbidden to store flammable substances and materials in the laboratory;
- when performing certain laboratory work, the presence of certain toxic substances (metal dust, chlorinated hydrocarbon vapor, metal hydroxides, mineral acids, ammonia, etc.) is possible in the air and workplaces. Therefore, everyone who are working in the laboratory is obliged to carefully observe the rules of personal hygiene;
- it is strictly forbidden to store any food, eat, drink it in laboratory rooms;
- unauthorized connection of equipment (microscopes, furnaces, hardness testers, etc.) to the electrical system without checking the connection equipment by a teacher or assistant (engineer) is prohibited;
- do not use any equipment with visible damages;
- loading samples into heated furnaces should be carried out only by special devices with long handles - holders. The holders must always be dry, especially when do hardening of samples in salt tanks;
- persons who are not directly involved in the performance of any treatment operations must be at a safe distance from furnaces and quenching tanks;
- it is forbidden to take any spacemans by hand without the permission of the teacher or engineer (especially samples that are near thermal furnaces);
- the use of various substances and compounds during laboratory works is allowed only after studying their properties;
- it is forbidden to carry out chemical etching of samples outside the ventilated box;
- carry out the study of the macrohardness of samples using a Rockwell, Brinell or Vickers hardness tester in accordance with the instructions and under the supervision of an engineer.

Additional safety information for each job is provided by a teacher or engineer at the beginning of each lesson.

LAB NO. 1

INVESTIGATION OF MATERIALS STRUCTURE

Main goal: to learn the microstructural and macrostructural investigation methods of materials structure.

Equipment and materials:

1. Specimens.
2. Optical MIM 7 or MIM 6 microscopes.

Theoretical information

Microstructural analysis

Microstructural analysis (microanalysis) is the study of internal structure of metals (microstructure) using an optical microscope with magnification from 50 to 2000 times.

Microanalysis makes it possible to study the shape and size of individual grains and phase inclusions which form metal, to detect changes in the internal structure that occur under the influence of various factors during thermal or thermochemical treatment, as well as to detect nonmetallic inclusions and micro defects located in the metal [1].

For microanalysis, we have to prepare specimens by a special technique. The preparation process consists of: (i) cutting a part of the material, (ii) grinding, (iii) polishing, and (iv) etching of the outer surface. After that, it can be investigated using an optical microscope. The specimen prepared by such a technique is called by **cross-section**.

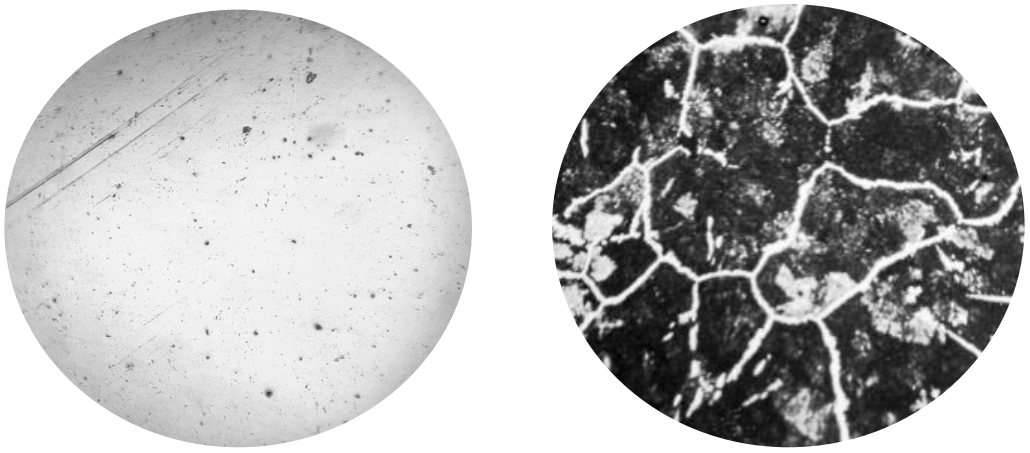
The cross-section preparation technique. The specimen is always cut from the part of the workpiece, which is of particular interest for a study. To conduct the study, the most convenient is a cross-section area of about 10 – 15 mm^2 and a height of 10 – 15 mm with the shape of a cylinder, square, parallelepiped, etc. In practice, it is necessary to make specimens of a larger or smaller size.

Cutting the specimen from the workpiece or part is carried out on metal cutting machines, mechanical or manual saw. During cutting, it is necessary to avoid significant heating of the specimen, which can cause substantial changes in the metal structure. After cutting, use a grinding wheel to align the surface, which is intended for microanalysis.

In case, if the specimens are small or have a complex surface structure, for convenience, during the preparation special holders or materials with a low melting points (sulfur, epoxy resin, plastic, etc.) are used.

In the next step, the flat surface of the specimen is ground on grinding paper with a different granularity of the abrasive. At first, grinding is carried out on special abrasive wheels or on high-strength abrasive paper. In order to prevent the thermal impact on the internal structure of the specimen cut during grinding on abrasive wheels, intensive cooling should be applied. After rough grinding, the specimen is cleaned from particles of separated metal, abrasive, and grinded on a ground paper with the size of abrasive particles from 125 to 25 μm and smaller. Grinding is finished if all scratches from the previous step are fully disappeared. When switching from one-grain size paper to another one, it is necessary to clean the specimen from the abrasive and change the direction of grinding by 90°. In the case of manual preparation, grinding paper is recommended to be placed on a glass or other solid and flat substrate.

The next step is mechanical polishing. It is carried out on a polishing machine with rotating circles, which are covered with a polishing cloth (cloth, felt, cotton cloth, etc.) depending on the specimen composition. The polishing cloth should be periodically moistened with a polishing liquid consisting of water and abrasive (Cr_2O_3, Al_2O_3, CeO, etc.). The polishing is continued for 5 – 10 minutes and is considered to be complete when all scratches are removed from the surface and the surface has a mirror luster. After the polishing process, we can observe: non-metallic inclusions and surface defects (pores, cracks, etc.) on the cross-section (figure 1.1 *a*). If the process of cross-section preparing was not carried out correctly, then there will be scratches from the abrasive on the surface of the cross-section. In most cases, there are several such scratches, and they are oriented in one direction. To eliminate these scratches, it is necessary to re-grind or re-polish the cross-section.



a *b*

Figure 1.1 – Real microstructures of the cross-section after polishing (*a*) and after etching (*b*)

To detect the microstructure of metals or alloys do the last step of specimen preparation – etching. This step allows you to determine the number, size, shape, possible location and quantitative ratio of phases and structural components in the

specimen (figure 1.1 *b*). The etching of specimens depends on the chemical composition, method of treatment, and the purpose of the study. Such treatment is carried out by chemical reagents, among which the weakest alcohol solutions of acids or alkalis and mixtures of various acids. For example, iron-carbon alloys are etched in a 3 – 5 % solution of nitric acid in ethanol.

The scheme of interaction of metal with acids or alkalis. The structure of the surface of the cross-section is heterogeneous. Since it has some different electrical energy potentials. Plots of the domestic cross-section with a lower potential act as anodes and dissolve. Greater grain boundaries are more intensively etched, which are imperfect buds, as well as more impurities than the grain itself, and this contributes to the maintenance of microcrystalline elements. After etching the hollows on the grain boundary are formed, which look like micro-relief. When considering the cross-section in an optical microscope, micro relief will form a combination of light and shadow (deeper etched areas give more structural details and look darker).

Structure of the metallographic microscope. For investigation and photographic capture of metals and alloys, the metallographic optical microscope (MIM-6, MIM-7, etc.) is used (figure 1.2 *a*). The metallographic microscope consists of the following main units and assemblies [3]:

1. Optical system (own microscope), which includes objective 10, eyepiece 11, series of auxiliary optical elements – mirrors, prisms and devices for installation and focusing of light (figure 1.2*b*).

2. Lighting system consisting of an artificial powerful light source, several lenses, filters and diaphragms.

3. The mechanical part, which includes a tube carrier, mechanisms of movement of the tube and a table of contents.

Cross-section 13 is placed on a table of objects 12 of microscope with a polished surface down, which is illuminated by light rays from below. Rays of light pass through the lens almost parallel to the optical axis of the microscope, reflected from the surface of the cross-section and fall again into the objective. The objective generates a real, reverse, enlarged image, which, with the aid of an achromatic lens 16 is transferred to a plane close to the focus of the eyepiece 8. The eyepiece is located relative to the intermediate image as a magnifying glass and only enlarges it. As a result, the residual image is imaginary, reversed and enlarged.

The light system of the microscope includes a powerful lamp 25, a collecting lens 24, which directs the light flux through the mirror 23, and color filters into the plane of the aperture diaphragm 21. Then the light passes through the lenses 19, 20, the field diaphragm 17, being refracted in the pentaprism 16, falls on the changing lenses 14 – 15. The next light flux passes through the plane-parallel reflective plate 7, the lens 10

and is reflected from the cross-section. The total flux is only about 2/3 of the total luminous flux of the lamp. Reflected from the cross-section located in the focal plane of the lens, the rays again pass through the lens, the plane-parallel plate 9 (7), and the achromatic lens 5, and after the reflection from the mirror 4 enter the eyepiece 8.

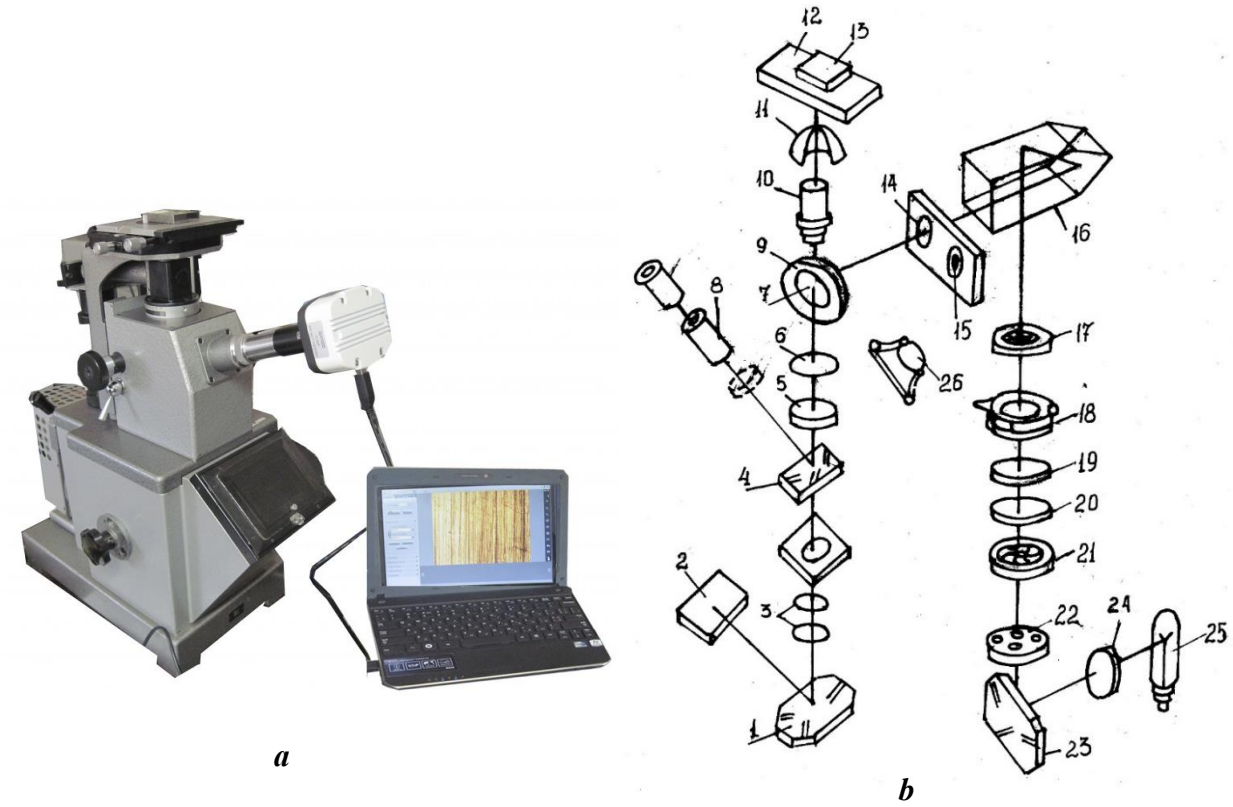


Figure 1.2 – Metallographic microscope MIM–7:
a – view of microscope connected to PC [2]; *b* – optical circuit of a microscope [1]

For the camera/shooting mode of the microscope, the formed image is transferred to the camera (video output). To do this, mirror 4 is placed together with the visual control tube and the rays pass through the three lenses 3 located in the same disk. After reflection from the mirror 1, the light rays enter the matte glass or camera 2. For photography, photo and video cameras with a system for monitoring, recording and digital image processing 2 are used.

For the study of relief structures, it is necessary to apply the method of oblique illumination. In this case, for the transmission of the image, mainly rays are used that do not parallel to the optical axis of the microscope. The ductility of the grinding is achieved by displacing the aperture diaphragm and the lamp from the optical axis. For the best determination of individual elements of the structure, it may be useful to change the angle of incidence of light on the grinding, for which it is necessary to turn the frame of the aperture diaphragm. Light filters are used for visual observation and photographing – they make the light more monochromatic. To extinguish all the colors for which the lens does not have a correction, use a yellow-green filter, and to darken the contrast of

the image on the plate, a blue filter is used.

The overall magnification in the microscope is determined by the magnification in the objective to magnify the eyepiece. Modern microscopes have a maximum magnification of 4165 times, but a useful magnification, which depends on the resolution of the eye and the microscope, is much smaller. The formula 1.1 is used for the calculation of overall microscope magnification:

$$V_{\text{overall}} = V_{\text{objective}} \cdot V_{\text{eyepiece}} = \frac{250\ L}{F_{\text{objective}} \cdot F_{\text{eyepiece}}} \quad (1.1)$$

where L is an optical length of the tube, m; $F_{\text{objective}}$, F_{eyepiece} are the focus distances of the objective and eyepiece, respectively; $V_{\text{objective}}$, V_{eyepiece} are the magnifications of objective and eyepiece, respectively.

The resolution of the microscope can be determining under as the minimum distance between 2 distinct points of a specimen where they can still be seen by the observer or microscope camera as separate entities.

The second important feature of the lens is the depth of field. This characteristic is determined by how much bulky parts of the specimen (that is, what depth) can be seen in the same microscope's sharpening of the sharpness. It can be shown that the depth of field is proportional to $1/A^2$, therefore, for the study of rough surfaces, it is necessary to use a lens with a small aperture, that is, a lens with a small magnification.

The qualitative image of the microstructure is provided when the total magnification in the optical system does not exceed its useful magnification. Using an optical microscope, it is not possible to investigate objects whose size is less than $5 \cdot 10^{-8}$ m^{-1}, which would not be used for a large magnification. That is connected with the wave nature of "white" light. In this case use electronic microscopes, which supply the resolution of the system up to $(2 – 5) \cdot 10^{-8}$ m^{-1}, that is, at the boundary of the interatomic distances.

Macrostructural analysis

Macrostructural analysis (macroanalysis) consists in studying the structure of metals and alloys without or with a slight magnify of up to 30 times. This allows us to study the large sections of metals, to draw conclusions about their structure and the presence of certain defects, as well as select places for further investigation. The structure of metals and alloys, defined in this way, is called the macrostructure.

Using macroanalysis you can determine:

– violation of continuity of metals;
– shrinkage inconsistency, central porosity, subcortical blisters, fistulas;

– the structure of cast and deformed metals;
– chemical heterogeneity;
– liquation;
– a kind of break;
– the structure of metal after welding and different types of heat and thermochemical treatment.

In the same case of microstructural analysis, we must prepare specimens to investigate macrostructure. The process of preparation consists of cutting a part of the material, some grinding, and etching the surface. The above-mentioned stages of preparation are the same as in the case of cross-section preparation. However, at the grinding stage, we only need to bring the examined surface to a completely flat state, and at the etching stage, much more aggressive environments are used.

Chemical heterogeneity. The disadvantages of the ingot include its chemical heterogeneity (liquation). There are two types of liquation: a macroscopic one that can be detected without magnification; and a microscopic one, which is detected by special methods of analysis (metallography, X-ray analysis, etc.).

Macroscopic liquation includes normal zonal, reverse zonal, and liquation through density. For normal zonal normalization typical heterogeneity of ingot zones. It is most typically in the central part of the ingot. In the case of reverse zonal etching, areas with a high concentration of impurities are located on the outer surface. Liquation through density is due to the different specific gravity of solids and liquid phases.

Microscopic liquation includes dendritic and intracrystalline etching. The first sections of the dendrite are saturated with refractory components, and the remains of the liquid are rich in low-melting impurities, which solidify the latter and thus form a dendrite.

Liquation causes the formation of various defects in cast metals and alloys, impedes their processing, and reduces properties.

Macro analysis of cast metal. Etching of the macro cross-section is carried out in a 15 % aqueous solution of ammonium persulfate at a temperature of 80 – 90 ºC for 5 – 10 minutes. Cast metal (figure 1.3) is characterized by great heterogeneity of grains in shape and size, the presence of discontinuities, and heterogeneity in chemical composition. These features of the structure of the cast metal worsen its properties and belong to the disadvantages caused by the features of crystallization.

The results of the macro analysis show that four zones can be distinguished in the structure of the metal ingot (figure 1.3):

1) zone of small unoriented crystals;
2) zone of oriented columnar crystals;
3) zone of large unoriented crystals;

4) shrink cavity.

The heterogeneity of the structure of the metal ingot is associated with changes in cooling conditions during crystallization. Crystallization can occur with certain supercooling of the melt. The amount of supercooling is characterized by the degree of supercooling ΔT, which, in turn, is defined as the difference between the theoretical (equilibrium) and actual crystallization temperatures.

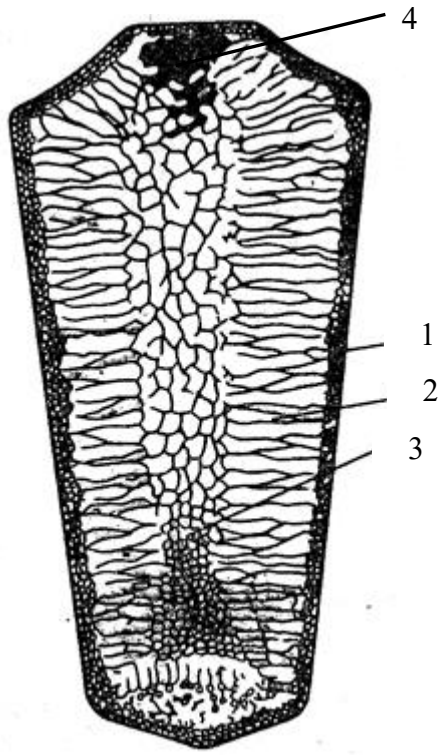


Figure 1.3 – Scheme of the structure of a metal ingot [3]:
1 - zone of small non-oriented crystals; 2 - zone of oriented columnar crystals;
3 - zone of large non-oriented crystals; 4 - shrink cavity

Macrostructure of the weld. To investigate the structure of weld steel, do the similar preparation as for the cast iron. In the macrostructure of the weld, there are two zones – the welded and base metals (figure 1.4). The structure of the welded metal is characterized by the presence of columnar crystals, the size of which, unlike the size of the crystals of cast metal, is rather small. This difference is caused by the high rate of crystallization of the welded metal. The macroscopic analysis can also reveal a heat affected zone (HAZ), non-humidity, cracks, and slag impurities.

The macrostructure of deformed metal is formed during plastic deformation in hot or cold states. As a result of rolling, forging, stamping or drawing, some defects that were in the metal are eliminated. Dendrites, grains and nonmetallic inclusions are deformed and pulled in the direction of the processing. As a result, a typical band-shaped (fibrous) rolled metal structure is formed (figure 1.5). The fibrous structure of the metal causes the anisotropy of its properties (the difference in properties along and across the

fibers). The plasticity, durability, and ductility of the specimens cut along the fibers are higher than the specimens cut across the length. Responsible products with significant dynamic loads (crankshafts, gears, rods, hooks) are manufactured in such a way that the

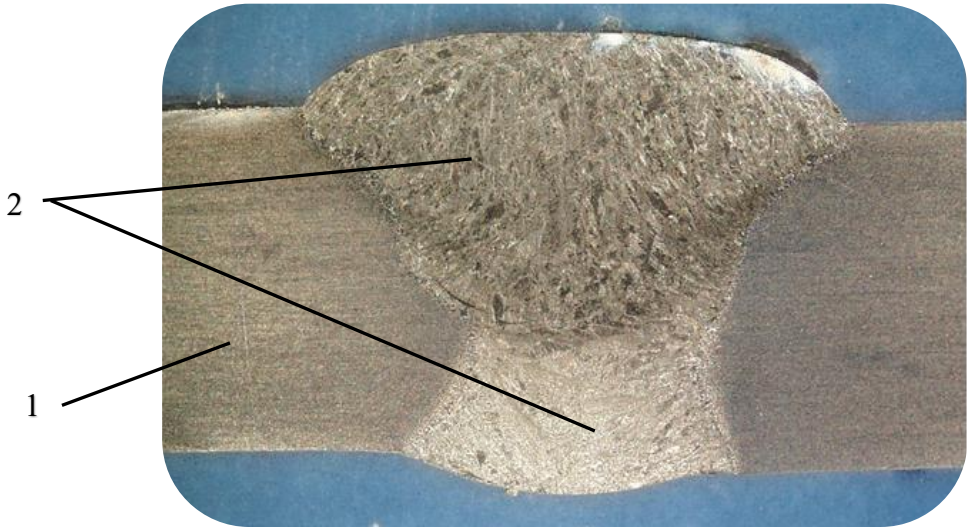


Figure 1.4 – Image of the macrostructure of a two-pass weld: 1 - base metal; 2 – weld metal.

fibers in the products are not cut, but conform to the configuration of the product.

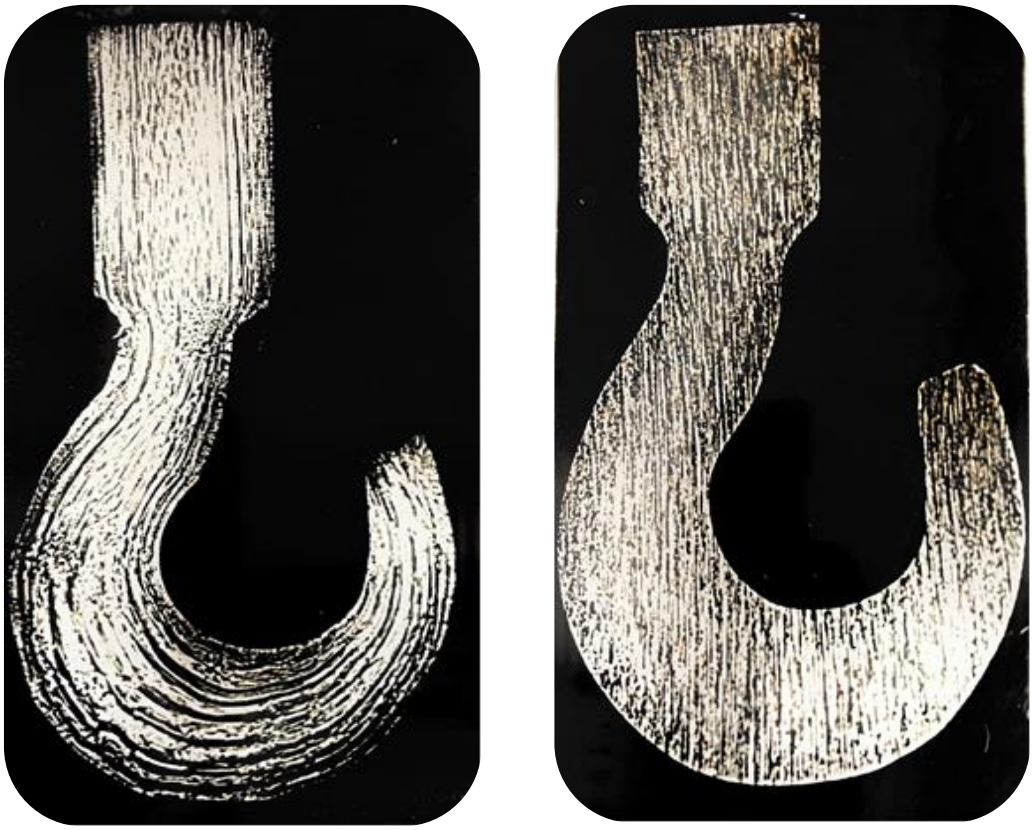
The fracturing method. The fracturing method studies the surface that occurs when the metal specimens are destroyed. With this method, it is possible to find out the shape and size of the grains, the kind of breakage, and the nature of the destruction. There are such types of fractures: ductile and brittle. The **ductile fracture** is formed by elongated, sharpened grains, which shows a significant degree of plastic deformation before destruction. The shape and size of metal grains can't be detected from a ductile fracture.

For a **brittle fracture** is characterized by the presence of brilliant areas (facets). In this case, surface without noticeable plastic deformation is formed. The shape and size of the grains do not change, which makes it possible to draw conclusions about their initial size. The brittle variant of failure is the most dangerous, as it occurs most often at a stress lower than the yield point of the material. Brittle fractures are divided into intracrystalline and transcrystalline. The destruction occurs along the grain boundaries of the metal due to **intracrystalline fracture**. This is due to the presence of non-metallic compounds in grain boundaries-sulfides, carbides, nitrides, etc. In **transcrystalline fracture**, the fracture occurs through the grain. In most cases, transcrystalline fracture occurs along slip planes of crystalline structure.

The appearance of the fracture also depends on the conditions of the test – temperature, loading rate, the nature of the stressed state, etc.

The following are the main types of brittle fractures. The **naphthalic** fracture is

transcrystalline with a large grain and selective brilliance. This fracture shows a high brittleness and is typical for doped instrumental steels. The main reason for this phenomenon is overheating during heat treatment, which causes an increase in the texture / preferential orientation of grains in a particular direction. A **crumbling** fracture is called rocky if destruction occurs within the limits of large grains. The reason for such destruction is the impurities that, when overheating the metal, concentrate on the grain boundary or in the boundary zones. For properly processed steel will be characterized by a **porcelain-shaped fracture** – fine-grained with a matte tinge (figure A.2).



a *b*

Figure 1.5 – Image of the macrostructure of the deformed metal: a forged hook (*a*) and a hook cut from a sheet of rolled metal (*b*) [3]

More often there are **mixed fractures**, in the macrostructure of which there are areas of ductile and brittle fracture.

In the case of brittle, metal destruction occurs after prolonged exposure to cyclic loads. Structure of break material in this case consists of three zones: the zone of origin of the crack; the zone of crack propagation during cyclic loading – fatigue zone; the bulk fracture. The first zone is flat, for the second is typically concentric furrows or arcs and portions of the porcelain fracture. The third zone of the bulk can be ductile or brittle.

The order of work execution

1. To study the structure of a metallographic microscope and learn how to use it.

2. To study how to prepare a cross-section and schematically draw its microstructure before and after etching (Appendix A, figure A.1).
3. To draw the structure of cast metal (figure1.2), two macrostructures of two specimens after plastic deformation (figure 1.4) and weld metal (Appendix A, figure A.2 *a*). Explain the drawings and indicate the technology of manufacturing products.
4. Draw and explore typical fractures (Appendix A, figure A.2 *b*). Perform a comparative analysis of fractures.

Check Questions

1. Give the definition of microanalysis.
2. How to prepare a cross-section?
3. Which main systems does a MIM-7 microscope have?
4. How to calculate the overall magnification in the microscope?
5. What can you find in the microstructure before etching?
6. What can you find in the microstructure after etching?
7. What is the essence of the fracturing method?
8. Which types of fractures do you know?

The result of the work

LAB NO. 2

PLASTIC DEFORMATION AND RECRYSTALLIZATION OF METALS

Main goal: to study the influence of plastic deformation and recrystallization on the structure and mechanical properties of metals.

Equipment and materials:

1. 5 aluminum plates.
2. A mixture of acids: HCl – 40 %, HF – 20 %, HNO_3 – 15 %, H_2O – 25 %.
3. Caliper or ruler.
4. Clamps.
5. Metallurgical furnace.

Theoretical information

Deformation is called a change in the shape and size of the solid because of the action of external or other forces, under the influence of which in the metal there are internal forces of interaction that act on each of its parts. These forces per unit area are called stress.

Deformations are divided into elastic and plastic. Deformations that disappear after the removal of the forces caused by them are called **elastic**. They are related to the elastic deformation of the crystal lattice and, of course, are small. Deformations that are partially (after removing the elastic deformation) are preserved after the removal of applied forces, called residual, or **plastic deformation**. It is associated with the irreversible movement of some part of crystal compared to another one.

To obtain residual form changes, it is necessary to create stresses in the metal that exceed their values at which elastic deformations occur. For example, carbon steel with a carbon concentration of 0.35 % has an elastic limit of 280 MN/m^2; a yield strength of 320 MN/m^2 and a tensile strength of 560 MN/m^2. However, such deformation will be obtained by plastic elongation of the specimen if the external stress on the metal exceeds the elastic limit and are not lower than 320 MN/m^2.

Plastic deformation of polycrystalline metal is conducted by the displacement of one part relative to another. The shear has two mechanisms: slipping and twinning.

The twinning deformation occurs since the part of the crystal (double) occupies a position, mirror-symmetric undeformed part (figure 2.1 *a*). On the surface of a single crystal or a grain, the double has the appearance of a more etched area, which is bounded by two parallel lines.

Twinning in comparison with slipping has a secondary significance. Slipping occurs due to displacement of dislocations, first of all, in the planes of the slightest shear, that is, on the densest packed and spaced apart planes, where the displacement of

dislocations requires the least effort (figure 2.1 *b*). The movement of dislocations causes the displacement of one part of the grain relative to another, which leads to the formation of a ledge on the surface of the crystal. The cavities formed due to the output of few dozen dislocations are called slip lines and can be seen with a microscope.

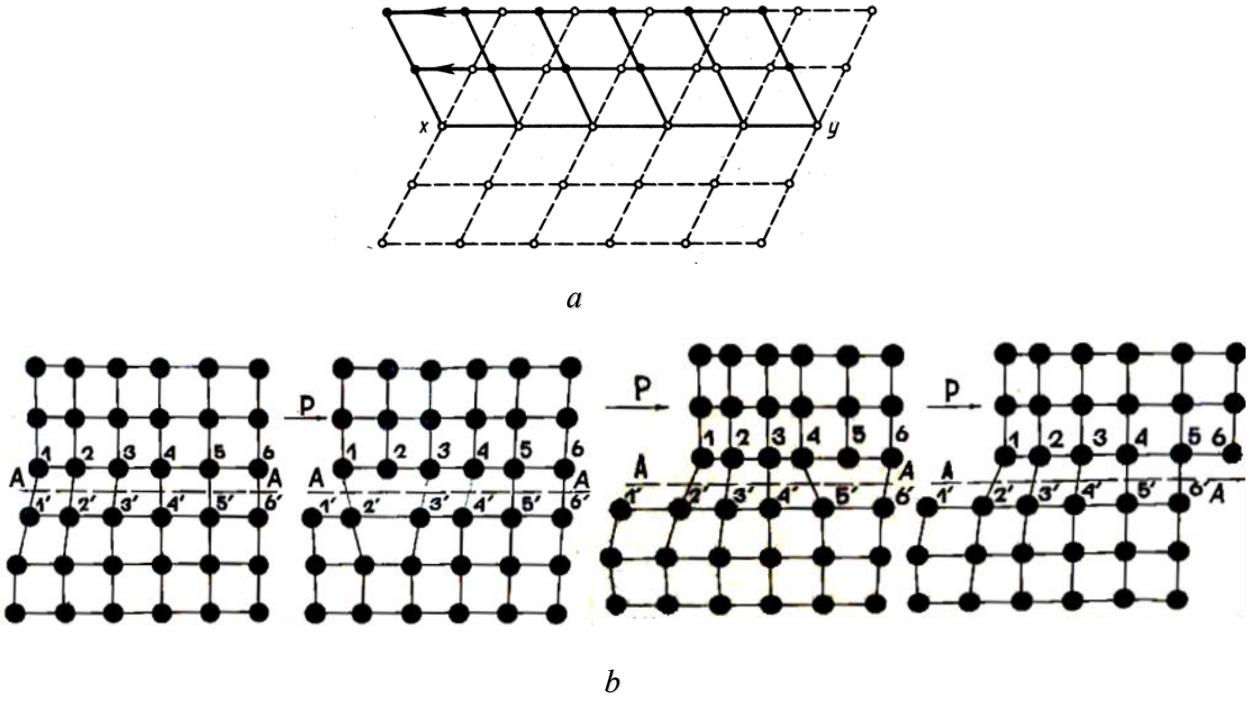


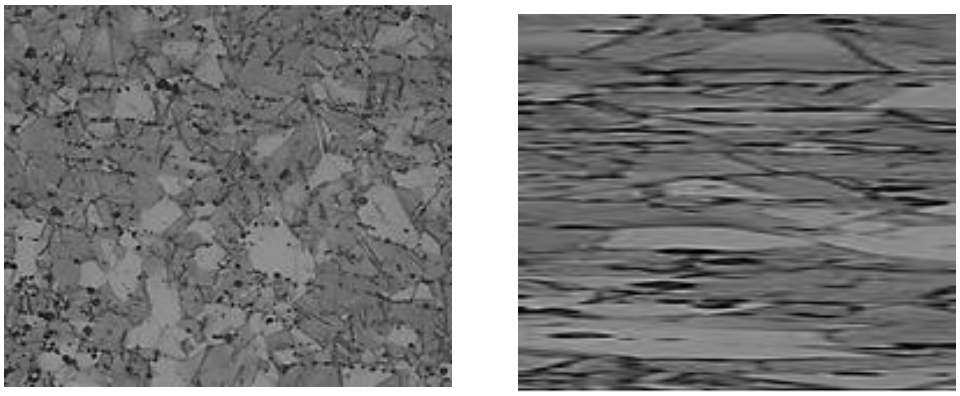
Figure 2.1 – Plastic deformation of crystal [1]: twinning (*a*) and slipping (*b*) mechanism

At higher degree of deformation of the slide begins to occur on other directions. This process is called multiple slipping. At this stage of deformation, the density of dislocations increases, which leads to an increase in the resistance of their movement and even to the loss of metal ability to plastic deformation.

Due to the deformation of polycrystalline metal, first of all will deform the grains in which the planes of the lightest shear are located most favorably to the acting external force at the angle of 45°, after that will deform the grains with another plane's orientation. This leads to the fact that with an increase in the degree of deformation all grains will deform in the direction of influence of external forces. In its shape, deformed grains are like fibers, so this structure is called **fibrous** (figure 2.2 *b*).

Plastic deformation leads to a significant change in the mechanical, physical and chemical properties of the metal. The combination of phenomena associated with increased strength and hardness and a decrease in the plasticity and ductility of the metal in the course of plastic deformation is called **cold hardening.**

In addition, the physical and chemical properties of the metal are changing (electrical resistance, magnetic properties, thermal conductivity and corrosion resistance).



a *b*

Figure 2.2 – Image of microstructures of deformed metal, x200: *a* – initial state of metal before deformation; *b* - a large degree of deformation

The deformed metal is in a nonequilibrium, thermodynamically unstable state due to the increase of the free energy in the form of stress fields of dislocations and other structural imperfections. Therefore, processes of transition to a more equilibrium state occur independently in it. The rate of such processes increases with increasing temperature.

The process of transition from a deformed nonequilibrium state to equilibrium takes place in two stages. At relatively low temperatures (below 0.3 temperature of melting point T_{melt}), a **return** is taking place, and at higher temperatures, **recrystallization** occurs. There is a partial removal of mechanical strengthening (by 20 – 30 %) due to return. For low-carbon deformed steel, the return temperature is 270 – 400 °C. Due to return the size and shape of the grains do not exchange. But at the same time will exchange the properties, and that is result of decreasing in the number of point defects and the annihilation of part of the dislocations and their alignment in the walls (polygonization).

For an increasing heating temperature to a certain value, there is a change in the crystalline structure of cold-deformed metal. At this case there is the formation of new centers of crystallization and growing grains. Such a phenomenon is called **recrystallization**. Emergence of new grains arises in areas with the highest density of dislocations – usually on the boundaries of deformed grains.

The temperature of the beginning of recrystallization depends on the degree of deformation. At the higher deformation degree, the lower the temperature of recrystallization. The temperature of the recrystallization beginning also depends on the purity of the metal, the complexity of the alloy, and melting temperature: $T_{rec} = \alpha\ T_{melt}$. Coefficient α equal to 0.1 – 0.2 for very pure metals, for metals of technical purity it is equal to 0.35 – 0.40, and for alloys can reach up to 0.7 – 0.8. To calculate the critical temperature of the beginning of recrystallization, it is necessary to consider that its dimension is taken in kelvin (K).

The size of the grains obtained because of recrystallization depends on the degree of the previous deformation and the temperature of the heating. At the deformation higher degree, the smaller the grain size (figure 2.3). At small (critical) deformation degrees (approximately 3 – 10 %), the grains will growth very large. Due to increasing degree of deformation, the grain size decreases. Grain sizes increase if the temperature of the recrystallization increases.

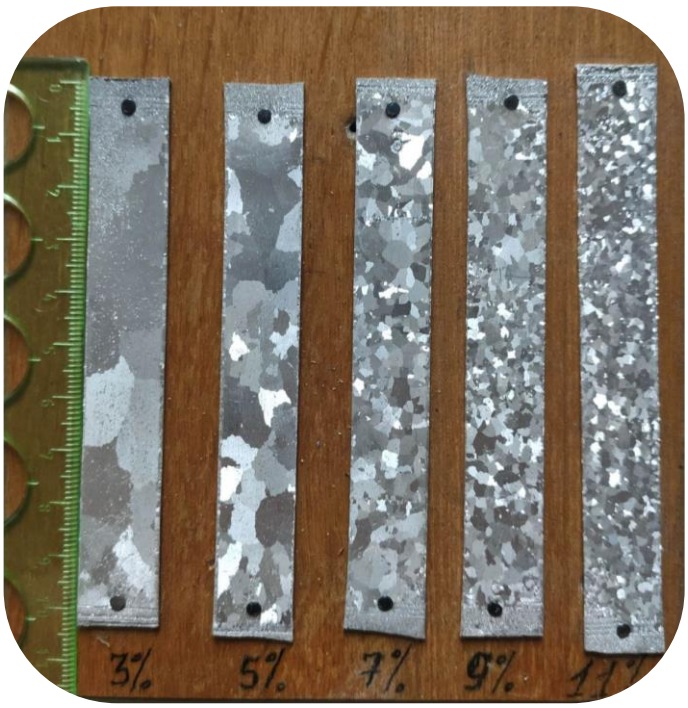


Figure 2.3 – Image of macrostructure of deformed meta Al plates at 3-11% of deformation

The process of increasing only some grains due to smaller adjacent grains is called collective recrystallization. Some of the properties of metals, in particular, the impact strength depends on the size of the grains. The ductility of the metal increases due to of decreasing in the grains size.

The order of work execution

1. Deform aluminum plates by stretching them to 3, 5, 7, 9, 11 %.
2. Proceed to the recrystallization annealing of deformed specimens.
3. To do the etching the specimens in a 10 – 15 % aqueous solution of NaOH followed in the reagent composition: HCl – 40 %, HF – 20 %, HNO_3 – 15 %, H_2O – 25 %.
4. Investigate the macrostructure of specimens. Draw schematically macrostructure of specimens after 3, 5, 7, 9, 11 % deformation and recrystallization.
5. Find the grains size on recrystallized specimens in different directions (write to Table 2.1) compare with reference values.

6. Calculate average size of grains for each specimen.
7. Draw the graph of grain size dependence on the degree of deformation.

In the case of distance mode of education, all the necessary data for completing the tasks are presented in Appendix B.

Check Questions

1. Give the definition of the deformation.
2. Which difference between elastic and plastic deformation?
3. Which two varieties of shifting grains?
4. Which mechanism of slipping?
5. How structure after deformation is called?
6. Give the definition of the return.
7. What is the essence of recrystallization?
8. From which factors the temperature of recrystallization depends on?
9. Decide coefficient α for very pure metals, for metals of technical purity, and for alloys.
10. How the size of the grain depends on the degree of deformation after recrystallization?

The result of the work

The structure of deformed Al plates

3 %	5 %	7 %	9 %	11 %

Table 2.1 – Measurement results

% of deformation		3 %	5 %	7 %	9 %	11 %
Size of one gain in different directions, mm	Grain 1					
	Grain 2					
	Grain 3					
Average grain size, mm						

Graphs

LAB NO. 3

STEELS AND WHITE CAST IRONS

Main goal: study the structure of steels and white cast irons.

Equipment and materials:

1. Specimens of different steels and cast irons.
2. Optical microscopes MIM 7 or MIM 6.

Theoretical information

Iron-carbon alloys containing up to 0.02 % of C are called **technical iron** (figure 3.1). If the carbon content ranges from 0.02 % C to 2.14 % C such alloys are called **steels**, and above than 2.14 % of C till to 6.67 % of C – **casts irons**.

Technical iron, with concentration of carbon less than 0.0002 %, at room temperature has a ferrite structure.

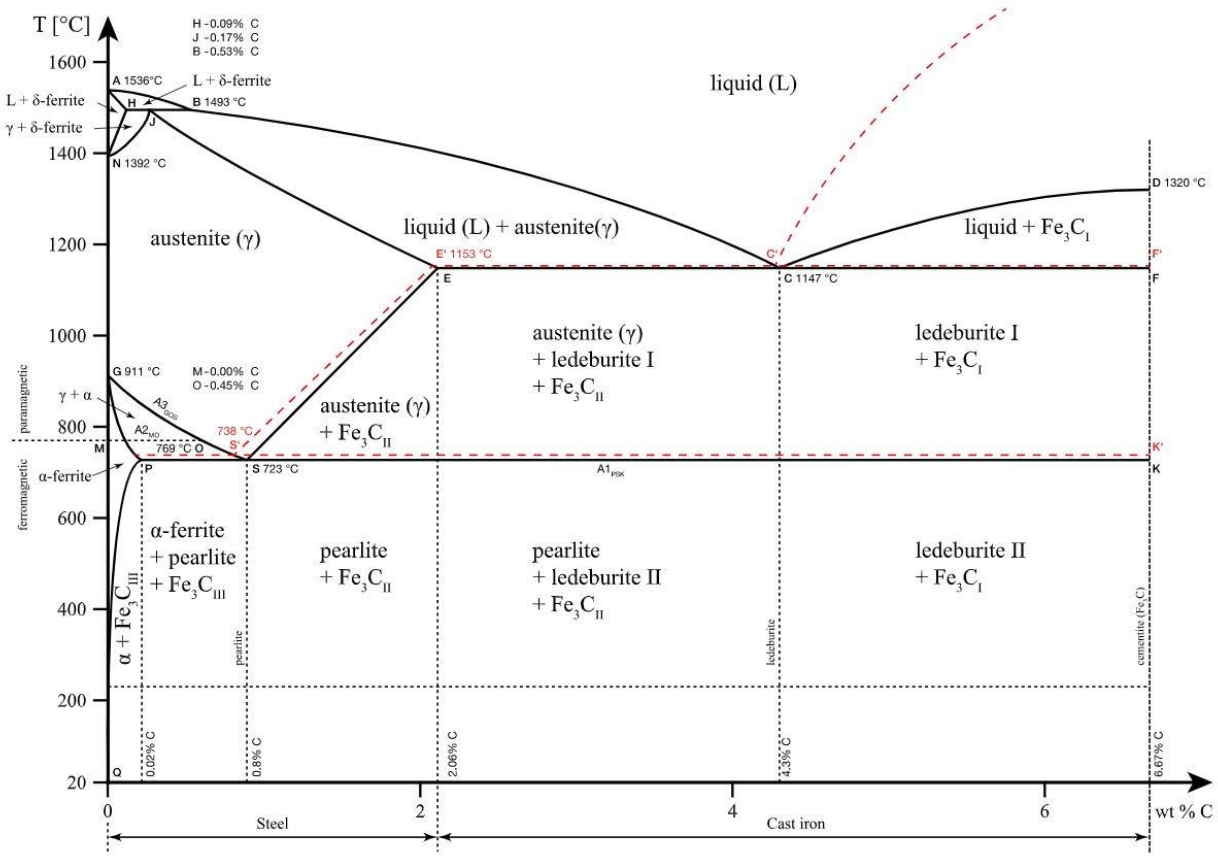


Figure 3.1 – Diagram state of Fe-Fe_3C [4]

With an increase in carbon content up to 0.02 % of C, the structure of alloys consists of the ferrite grains and tertiary cementite on the grain boundaries (figure 3.2). Due to increasing the tertiary cementite on the structure, reduce the plasticity of alloy. Cementite, like ferrite, after etching with a solution of nitric acid in the alcohol stays light color, only the grain boundaries are black color. Microslip etching with sodium picrate to increase the contrast between the cementite and the ferrite, which gives the

cementite a dark color.

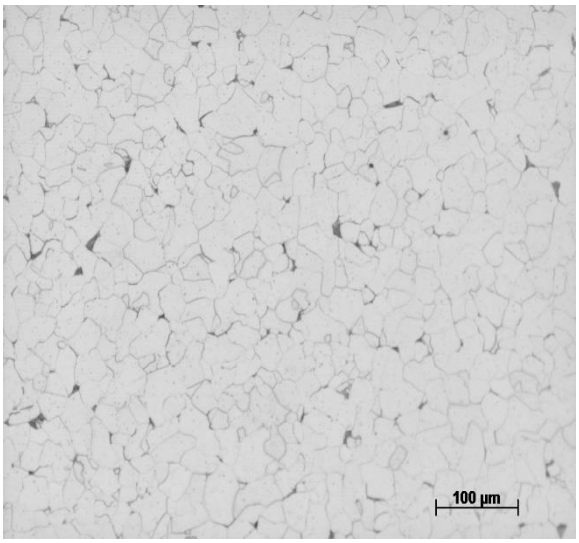
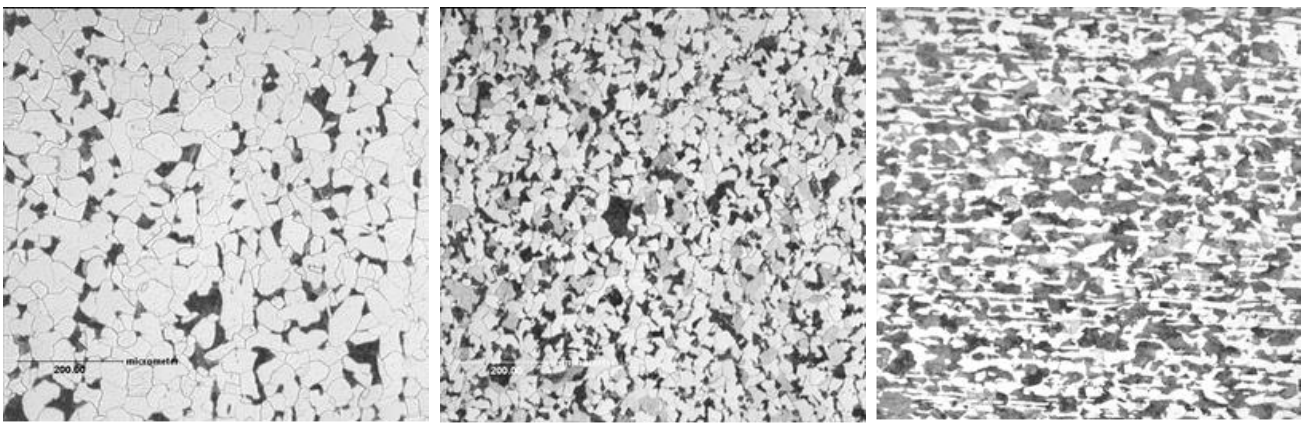


Figure 3.2 – Microstructure of technical pure iron

Steels

Depending on the carbon concentration, steels are divided into:

1) pre-eutectoid, having up to 0.8 % of C. The structure of these steels consists of light grains of ferrite and dark perlite (figure 3.3). With a large magnification, the perlite looks like a set of bright plates of ferrite and cementite, which alternate and have dark boundaries. With a slight magnification (100 – 200 times), the boundaries of such plates merge, giving perlite a dark color. Along with the increase in carbon content, the amount of perlite increases, and ferrite decreases.

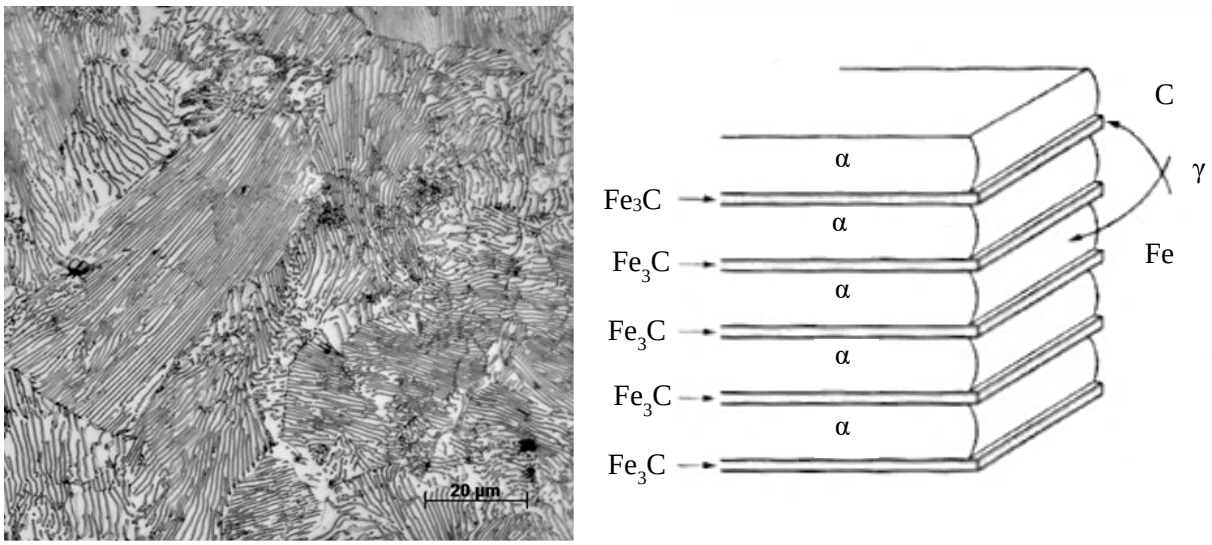


a *b* *c*

Figure 3.3 – Microstructures of pre-eutectoid steels containing, x300:
0.15 % C (*a*), 0.35 % C (*b*), 0.45 % C (*c*)

2) eutectoid, containing 0.8 % of C. The steel structure is only perlite (figure 3.4).

3) post-eutectoid steels, having more than 0.8 % of C. The structure of these steels – dark perlite grains, on the grain boundary light grid cementite (figure 3.5).



a *b*

Figure 3.4 – Structure of eutectoid steel with 0.8 % C concentration:
a – real microstructure; *b* – schematic structure of pearlite colonies

Steel properties, like the structure, depends on the carbon content. The structure of steels forms two phases: plastic and soft ferrite (HB 80 – 100) and brittle, hard cementite (HB 800).

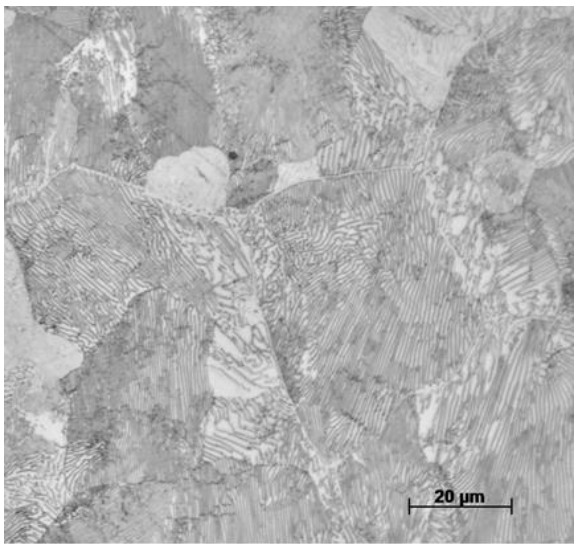


Figure 3.5 – Microstructure of post-eutectoid steel with 1.0 % C concentration

With increasing carbon content in steel, the amount of cementite increases, and ferrite decreases, which leads to increased hardness and reduced plasticity and ductility (figure 3.6). Cementite particles increase the resistance to the displacement of dislocations, that is, increase the strength. However, with a carbon content of more than 0.8 – 1.0 %, the strength limit decreases, which is explained by formation of grid of very brittle secondary cementite around perlite grains. When testing tension in this grid, high

tensions arise and the specimen breaks down with very small internal stresses.

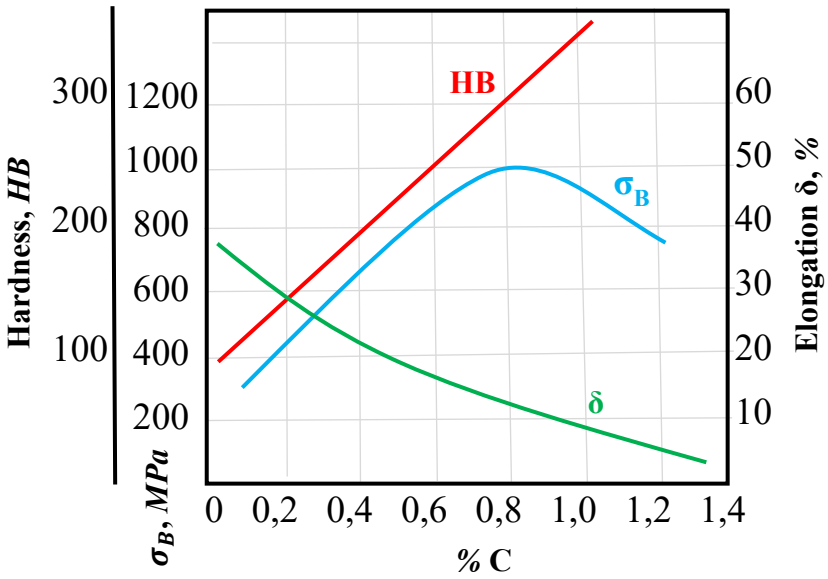


Figure 3.6 – The dependence of the mechanical properties of steels from the carbon content [3]: σ_B – tensile strength; δ – elongation; HB – hardness

Microstructural analysis allows more or less precisely to determine the carbon content in steels. If you do not take into account the extremely low carbon content in the ferrite, it can be assumed that in pre-eutectoid steels all carbon is contained in perlite. We can calculate the carbon concentration in the pre-eutectoid steels using the microstructural images and next formula:

$$\% \, \mathrm{C} = \frac{S_{perlite} \, \% \cdot \, 0.8 \, \%}{100 \, \%}$$

where $S_{perlite}$ % is the area occupied by perlite, 0.8 % that is the content of carbon on perlite.

We can use next formula to calculate carbon content in post-eutectoid steels:

$$\% \, \mathrm{C} = \frac{S_{perlite} \, \% \cdot \, 0.8 \, \% + S_{cementite} \, \% \cdot 6.67 \, \%}{100 \, \%}$$

where $S_{cementite}$ % is the area occupied by secondary cementite, $S_{perlite}$ % is the area occupied by perlite, 0.8 % is the content of carbon on perlite, 6.67 % is the content of carbon on cementite.

By designation, carbon steels are divided into two main groups: structural and instrumental (tool steels).

Structural carbon steels (carbon content from 0.002 % up to 0.7 – 0.85 %) are

widely used in industry. Low-carbon steels with concentration of 0.05 – 0.1 % of C is used for stamped and welded products (tanks, boilers, car body parts, wheel drives, etc.). Mechanical properties after normalization: $\sigma_{tensile}$ = 340 MPa, σ_{yield} = (200 – 210) MPa, δ = (31 – 33) %.

Steel with concentration of carbon from 0.15 to 0.25 % use without heat treatment or in normalized state for production of cemented products (shafts, gears, cams, etc.). Steel with such carbon concentration is used for production structural channels and beams ($\sigma_{tensile}$ = (380 – 460) MPa; σ_{yield} = (230 – 280) MPa; δ = (23 – 27) %).

Most of the details in machine building (axles, shafts, gears, bushes, bolts, etc.) are made of medium carbon steels with concentration of carbon from 0.3 to 0.55 % ($\sigma_{tensile}$ = (500 – 610) MPa; σ_{yield} = (300 – 360) MPa; δ = (16 – 21) %).

Construction steels with high carbon concentration from 0.6 up to 0.85 % are used after hardening and average tempering ($\sigma_{tensile}$ = 800 MPa; (40 – 45) HRC) mainly for spring production.

Steel with concentration of carbon from 0.7 to 1.3 % are used for manufacturing of a cutting and stamping tools (chisels, cutters, drills, dies, punches, matrices, etc.), so it calls **instrumental steels**. Such carbon steels in annealed state are characterized by low hardness (1660 – 1920) HB and satisfactory ability to processing by cutting and pressure. After hardening and low tempering, the hardness increases to (60 – 65) HRC, strength σ = (250 – 350) MPa.

Stainless steels

Stainless steels are a group of ferrous alloys that contains a minimum chromium in its contents 11 %, an element that prevents the iron from rusting and also provides heat-resistant properties. Diverse types of stainless steels include the carbon (from 0.03 % up to 1.00 % and more), nitrogen, aluminum, silicon, sulfur, titanium, nickel, copper, selenium, niobium, and molybdenum. Specific types of stainless steels are often named by their AISI three-digit number, e.g., 304 stainless. The ISO 15510 standard lists the chemical compositions of stainless steels of the specifications in existing ISO, ASTM, EN, JIS and GB (Chinese) standards.

Resistance of stainless steels to rusting is a result of presence of chromium in the alloy, which forms a passive film on surface of detail that protects the underlying material from corrosion attack and can self-heal in the presence of oxygen. Corrosion resistance can be increased further by:

- increasing chromium content to more than 11 %.
- add nickel at least 8 %.
- add molybdenum (which also improves resistance to pitting corrosion).

The addition of nitrogen also improves resistance to pitting corrosion and increases mechanical strength. Thus, there are numerous grades of stainless steels with

varying chromium and molybdenum contents to suit the environment the alloy has to endure.

Resistance to corrosion and staining, minimal maintenance, and familiar luster make stainless steel an ideal material for many applications where both the strength of steel and corrosion resistance are required. Moreover, stainless steel can be rolled into sheets, plates, bars, wire, and tubing. These can be used in cookware, cutlery, surgical instruments, major appliances, vehicles, construction material in large buildings, industrial equipment (e.g., in paper mills, chemical plants, water treatment), and storage tanks and tankers for chemicals and food products. In aerospace stainless steels are used in manufacturing of actuators, landing gear components, plane control rods, exhaust components, fasteners. The material's corrosion resistance, the ease with which it can be steam-cleaned and sterilized, and the absence of the need for surface coatings have prompted the use of stainless steel in kitchens and food processing plants.

There are five main families of stainless steels, which are primarily classified by their crystalline structure:

- austenitic,
- ferritic,
- martensitic,
- duplex,
- precipitation hardenable.

Precipitation hardenable stainless steels have corrosion resistance comparable to austenitic varieties, but can be precipitation hardened to even higher strengths than other martensitic grades. There are three types of precipitation hardening stainless steels:

Martensitic 17 – 4 PH (AISI 630 EN 1.4542) contains about 17 % Cr; 4 % Ni; 4 % Cu and 0.3 % Nb.

Solution treatment at about 1040 °C followed by hardening results in a relatively ductile martensitic structure. Subsequent aging treatment at 475 °C precipitates Nb and Cu-rich phases that increase the strength up to above 1000 MPa yield strength. This outstanding strength level is used in high-tech applications such as aerospace (usually after remelting to eliminate non-metallic inclusions, which increases fatigue life). Another major advantage of this steel is that aging, unlike tempering treatments, is carried out at a temperature that can be applied to (nearly) finished parts without distortion and discoloration.

Semi-austenitic 17 – 7 PH (AISI 631 EN 1.4568) contains about 17 % Cr; 7.2 % Ni; and 1.2 % Al.

Typical heat treatment involves solution treatment and hardening. At this point, the structure remains austenitic. Martensitic transformation is then obtained either by a

cryogenic treatment at −75 °C or by severe cold work (over 70 % deformation, usually by cold rolling or wire drawing). Aging at 510 °C – which precipitates the Ni_3Al intermetallic phase is carried out as above on nearly finished parts. Yield stress levels above 1400 MPa are then reached.

Austenitic A286 (ASTM 660 EN 1.4980) contains about Cr 15 %; Ni 25 %; Ti 2.1 %; Mo 1.2 %; V 1.3 %, and B 0.005 %.

The structure remains austenitic at all temperatures. Typical heat treatment involves solution treatment and hardening, followed by aging at 715 °C. Aging forms Ni_3Ti precipitates and increases the yield strength to about 650 MPa at room temperature. Unlike the above grades, the mechanical properties and creep resistance of this steel remain particularly good at temperatures up to 700 °C. As a result, A286 is classified as an Fe-based superalloy, used in jet engines, gas turbines, and turbo parts.

Unlike carbon steels, stainless steels do not suffer uniform corrosion when exposed to wet environments. Unprotected carbon steel rusts readily when exposed to a combination of air and moisture. The resulting iron oxide surface layer is porous and brittle. In addition, as iron oxide occupies a larger volume than the original steel, this layer expands and tends to flake and fall away, exposing the underlying steel to further attack. In comparison, stainless steels contain sufficient chromium to undergo passivation, spontaneously forming a microscopically thin inert surface film of chromium oxide by reaction with the oxygen in the air and even the small amount of dissolved oxygen in the water. This passive film prevents further corrosion by blocking oxygen diffusion to the steel surface and thus prevents corrosion from spreading into the bulk of the metal. This film is self-repairing, even when cracked or temporarily disturbed by an upset condition in the environment that exceeds the inherent corrosion resistance of that grade.

The resistance of this film to corrosion depends upon the chemical composition of the stainless steel, chiefly the chromium content. It is customary to distinguish between four forms of corrosion: uniform, localized (pitting), galvanic, and SCC (stress corrosion cracking). Any of these forms of corrosion can occur when the grade of stainless steel is not suited for the working environment.

Heat resistance stainless steels. Stainless steels are most used for their corrosion resistance. The second most common reason stainless steels are used is for their high temperature properties; stainless steels can be found in applications where high temperature oxidation resistance is necessary, and in other applications where high temperature strength is required. The high chromium content which is so beneficial to the wet corrosion resistance of stainless steels is also highly beneficial to their high temperature strength and resistance to scaling (oxidation) at elevated temperatures.

Different to the conventional ferritic, austenitic and nickel-based alloys with these

particular steels the focus is doubtless on stresses due to high temperatures, as previously mentioned. The most important criteria are:

- High fatigue strength/creep resistance in the designed temperature range;
- High temperature corrosion resistance;
- Scaling resistance by creation of an oxide layer;
- Special characteristic against stress caused by continuously changing temperatures and the resulting risk for embrittlement (depending on the used material);
- Stable microstructure
- High mechanical strength.

Resistance to oxidation, or scaling, depends on the chromium content in the same way as the corrosion resistance is, as shown in the graph below (figure 3.7). Most austenitic steels, with chromium contents of at least 18 %, can be used at temperatures up to 870 °C and Grades 309, 310 and 2111HTR (UNS S30815) even higher. Most martensitic and ferritic steels have lower resistance to oxidation and hence lower useful operating temperatures (figure 3.8). An exception to this is the ferritic Grade 446 – it has approximately 24 % chromium, and can be used to resist scaling at temperatures up to 1100 °C.

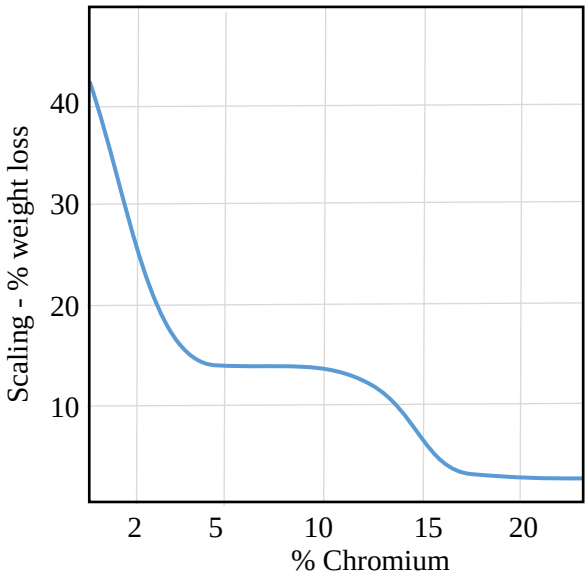


Figure 3.7 – Effect of Chromium Content on scaling resistance of Chromium-Iron alloys [5]

Because of its extreme versatility, stainless steel can be used for virtually any metallic part found on an aircraft. However, practical considerations such as cost, and weight mean that aluminum is often (but not always) the first choice for many airpline parts. However, we still see that airplane manufacturers are increasingly relying on stainless steel for certain parts that have higher performance requirements.

For example, the fuel tanks on many airplanes are made from stainless steel. This

makes sense, as not only are fuel tanks exposed to extremely corrosive materials, but also have to be able to withstand high temperatures and protect from structural damage.

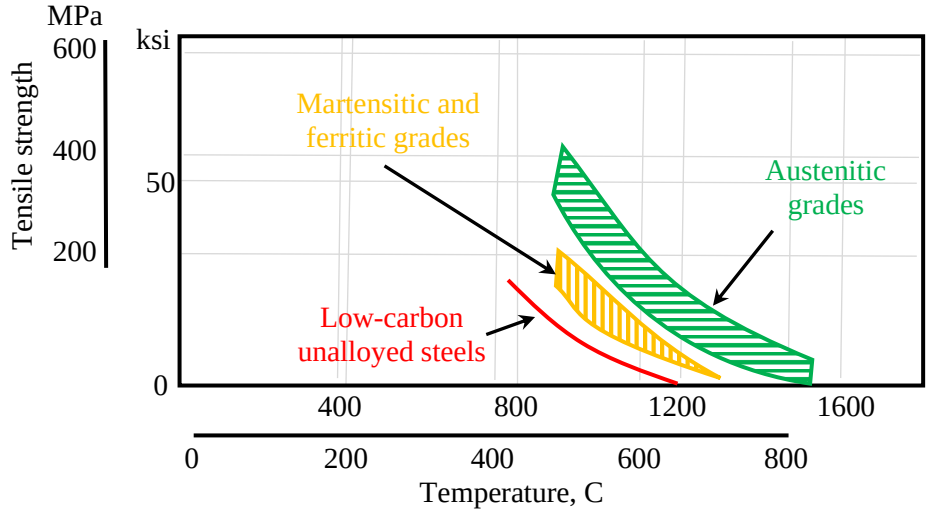


Figure 3.8 – General hot-strength characteristics of austenitic, ferritic and martensitic stainless steels [6]

This same principle extends to exhaust components, engine parts, and other crucial systems related to the airplane's power source.

Other parts that will likely be made from stainless steel are key structural components, such as fasteners. These are what hold together the airplane, and can be found in the landing gear, the wings, the engines, and the cockpit. In engineering, the fasteners are often the weakest link of any structure, and particularly in an airplane, you can't afford anything less than the most reliable options available.

Of course, not every aircraft is an airplane. The aerospace industry is becoming more diversified over time and includes the latest rocket ships being designed by new private companies trying to make space travel more accessible and affordable. Modern aerospace vehicles are much more likely to be built with stainless steel airframes or fuselages. While more expensive, they are also much stronger than aluminum, and depending on the grade used, can still offer an excellent strength to weight ratio.

You can find a number of different stainless-steel grades and alloys in modern aircraft. This starts with what is likely the most popular stainless steel, 304. This austenitic stainless steel is known to be weldable, formable, and machinable with good corrosion resistance. Applications you are likely to find it in include aircraft tubing, wiring, sheet metal and more.

Another high performance alloy found in aircraft is 321. Because it is alloyed with titanium, this grade is especially resistant to intergranular corrosion. This alloy can withstand temperatures in the 420 to 820 °C range and still maintain its stability. Common uses in the aircraft industry include jet engines, exhaust ducts, flanges, piston engine exhaust manifolds, afterburners, flash boilers, and more.

Alloy 316 is also popular. This particular grade is especially renowned for its corrosion resistance in marine environments. Besides austenitic steel 430 is corrosion and heat resistant, and ideal for decorative trim. A martensitic alloy 410, is popular for parts that have to withstand high stress with good corrosion resistance and strength. Precipitation hardening stainless steels such as 13 – 8, 15 – 5, 17 – 4, and 17 – 7 grades have levels of corrosion resistance comparable to austenitic varieties, but after undergoing precipitation hardening can achieve even higher strengths than many martensitic grades. These are especially attractive when high performance metals are necessary.

White cast irons

Alloys of iron with carbon and other elements that contain more than 2.14 % C are called **cast irons**. Carbon in cast iron (depending on the chemical composition and cooling rate) can be either in a bound state - in the form of cementite (with rapid cooling), or a free state - in the form of graphite (with slow cooling). Due to the white color of the fracture, cast iron in which carbon is mainly in the form of carbides is called white. Phase transformations in white unalloyed cast irons occur in accordance with the metastable state diagram of Fe-Fe_3C.

According to the structure, white cast irons are divided into pre-eutectic, eutectic and post-eutectic. It should be recalled that the carbon content in the eutectic for the Fe-Fe_3C system is determined by the abscissa point C on the state diagram (figure 3.1) and for unalloyed white cast irons it is 4.3 % C. At a temperature of 1147 ^oC, a mixture of two hard phases is formed from a liquid of eutectic composition: austenite and cementite. This eutectic mixture is called ledeburite. The shape of the ledeburite grains vaguely resembles a honeycomb (Fig. 3.9): hard cementite on the outside, soft austenite on the inside.

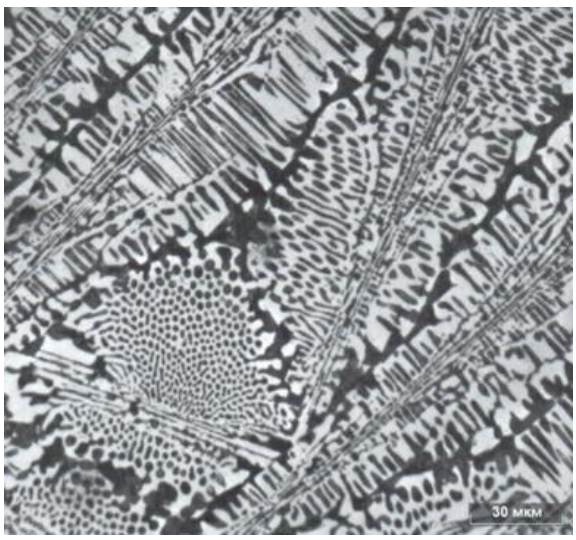


Figure 3.9 – Structure of eutectic cast iron with 4.3% C concentration

In pre-eutectic white cast irons, the carbon content does not reach 4.3 % (figure 3.1). Crystallization of pre-eutectic cast irons begins with the release of austenite. As the temperature decreases, the amount of crystallized austenite increases, the iron content in the liquid phase decreases, and carbon, accordingly, increases (along the liquidus line BC of the state diagram) and at a temperature of 1147°C reaches 4.3 % (point C). Therefore, the primary crystallization of the alloy ends with a eutectic transformation with the formation of ledeburite. The structure of pre-eutectic cast iron immediately after completion of crystallization (at 1147 °C) is dendrites of primary austenite, between which are located ledeburite colonies. At the moment of completion of crystallization, both primary austenite and austenite, which is part of ledeburite, contain the maximum amount of carbon, which corresponds to the abscissa of the state diagram (>2.14 %C). Upon further cooling, the same processes occur with austenite as in pre-eutectoid carbon steel (separation of secondary cementite, eutectoid pearlite transformation, separation of tertiary cementite from ferrite). Therefore, the structure of pre-eutectic white cast irons at room temperature consists of large dark pearlite grains of dendritic form (transformed primary austenite), light secondary cementite that surrounds these grains, and ledeburite, which has a spotted (honeycomb) structure - dark small pearlite grains (transformed austenite, which was a part of ledeburite) on the background of light cementite (figure 3.10).

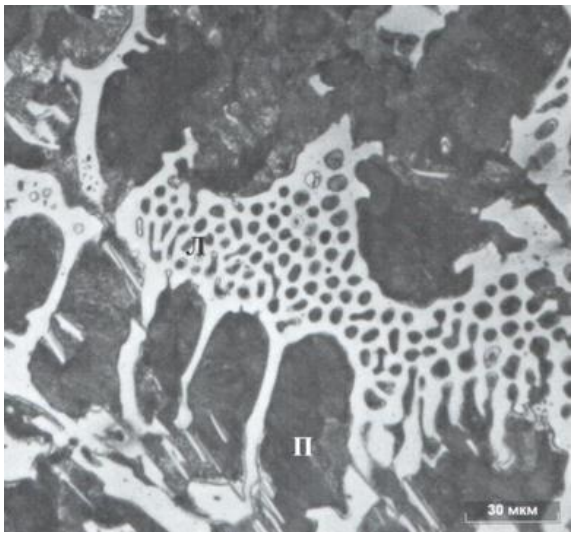


Figure 3.10 – Microstructure of pre-eutectic cast iron

The post-eutectic white cast irons contain from 4.3 to 6.67 % carbon. Their crystallization begins with the separation of primary cementite crystals and ends with the formation of ledeburite. Therefore, in addition to ledeburite, the structure contains large light plates (on a needle cut) of primary cementite (figure 3.11). It should not be forgotten that upon further cooling after the completion of crystallization, austenite undergoes transformations in accordance with the state diagram of the iron-cementite

system (figure 3.1).

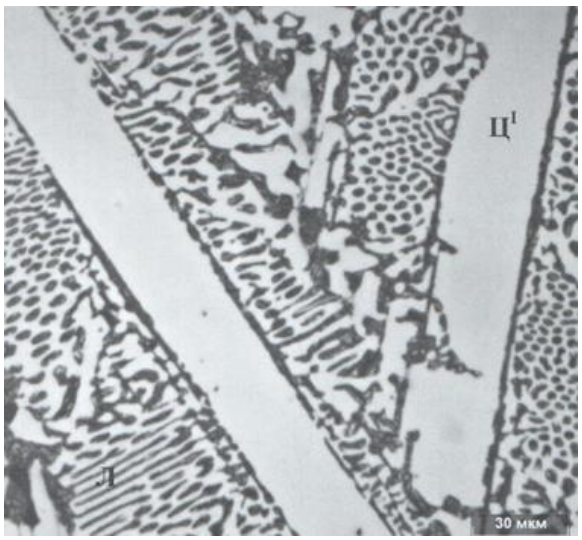


Figure 3.11 – Microstructure of post-eutectic cast iron

Due to the large amount of cementite, white cast iron is extremely hard and brittle (HB 4500 – 5500). However, due to their high hardness, white cast iron is a good wear-resistant material. Due to unsatisfactory workability by cutting (due to high hardness), blanks from white cast iron for the manufacture of machine parts are obtained by casting. Cast iron castings with a bleached layer are also used. On the surface, they have the structure of white cast iron, and in the core-gray with lamellar graphite. This structure is favorable for parts that work under conditions of high pressure and intensive wear (rolled rolls, balls of ball mills, trolley wheels, etc.). To obtain ductile iron, castings from white iron are subjected to graphitizing annealing.

The order of work execution

1. Draw the binary diagram state Fe-Fe_3C and structures of steels and cast irons (Appendix C), write under each structure the carbon content and the structural elements.
2. Explore the structure of steels and determine the carbon content.
3. Explore, draw and explain cast iron microstructures. Specify the chemical composition and structure.

Check Questions

1. Give the definition of the steel.
2. Give the definition of the cast iron.
3. What concentration of the carbon can be in technical iron?
4. Which types of steels do you know depending on the carbon concentration?
5. How mechanical properties of steels depend on carbon concentration?

6. How to calculate carbon concentration using microanalysis?
7. Determine the sphere of application of structural carbon steels with concentration of carbon up to 0.25 %.
8. Determine the sphere of application medium carbon structural steels?
9. Determine the sphere of application of carbon steels with concentration of carbon from 0.55 % to 0.85 %?
10. Determine the sphere of application of carbon steels with concentration of carbon from 0.7 % to 1.3 %?
11. How cast irons are divided by depending on the carbon concentration? Which structures do these categories have?
12. Why white cast metals are useless?

The result of the work

LAB NO. 4

HEAT TREATMENT OF STEELS

Main goal: to study the structure and properties of steels after hardening and tempering.

Equipment and materials:

1. Specimens of steels with concentrations of carbon: 0.2 %, 0.45 % and 0.8 %.
2. Optical MIM 7 or MIM 6 microscopes.
3. Metallurgical furnace.
4. Rockwell macrohardness tester (HRC).

Theoretical information

Heat treatment (HT) is called technological processes, which consist of heating, isothermal espousing and cooling of metal parts in order to change their structure and properties (figure 4.1). The most common types of heat treatment of steels are annealing, normalization, hardening (quenching) and tempering.

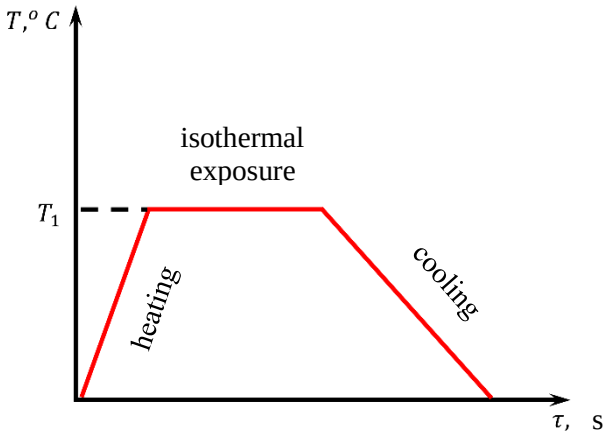


Figure 4.1 – Process of heat treatment

In general, the heat treatment of metal details is carried out in three steps: the precursive, the main and final heat treatment (figure 4.2). During the precursive heat treatment usually do annealing or normalization, the main heat treatment – hardening and final heat treatment – tempering.

Annealing consists of heating metal detail to a specific temperature and then cooling at the rate that will produce a refined microstructure (figure 4.3), either fully or partially separating the constituents. The rate of cooling due to annealing is generally slow, so mainly together cooling of details and furnace occur. Annealing is most often used to soften metal for cold working, to improve processing, or to enhance properties like electrical conductivity.

In ferrous alloys, annealing is usually accomplished by heating the metal beyond the upper critical temperature and then cooling very slowly, resulting in the formation

of fine structure. In both pure metals and many alloys produced by cold working, annealing, is used to remove the hardness. The metal is heated to a temperature at which recrystallization can occur, thereby repairing the defects caused by plastic deformation. In these metals, the rate of cooling will usually have small effect. Most non-ferrous alloys that are heat-treatable are also annealed to relieve the hardness of cold working. These may be slowly cooled to allow full precipitation of the constituents and produce a refined microstructure.

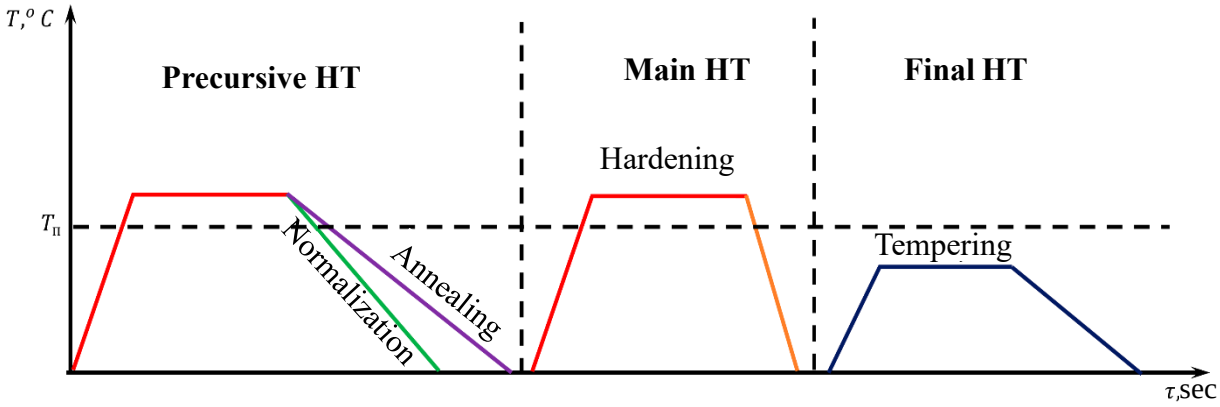


Figure 4.2 – Types of heat treatment

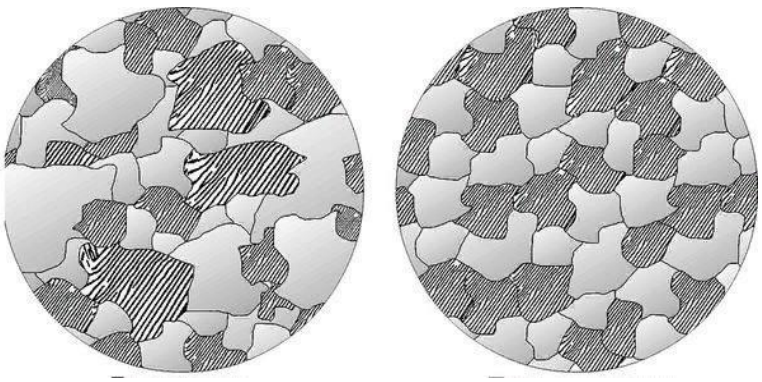


Figure 4.3 – Influence of annealing onto the structure

Normalization is technique used to provide uniformity in grain size and composition (equiaxing) throughout an alloy. The term is often used for ferrous alloys that have been austenized and then cooled on air. Normalization not only produces pearlite, but also Martensite and sometimes bainite, which gives harder and stronger steel, but with less ductility for the same composition than full annealing.

Hardening is called a set of actions of heating the steel to the austenitic state (above phase transformation temperature), isothermal exposure and subsequent cooling with a critical rate. The purpose of this is to obtain a supersaturated solid solution in α-iron named Martensite, which has the highest hardness. The critical rate of hardening is

called the minimum cooling rate at which austenite transforms into Martensite. To determine the critical rate of hardening rate draw tangent to the C-shaped curve in the diagram of the isothermal transformation of supercooled austenite (figure 4.4). In some cases, the purpose of hardening is to obtain bainite structures.

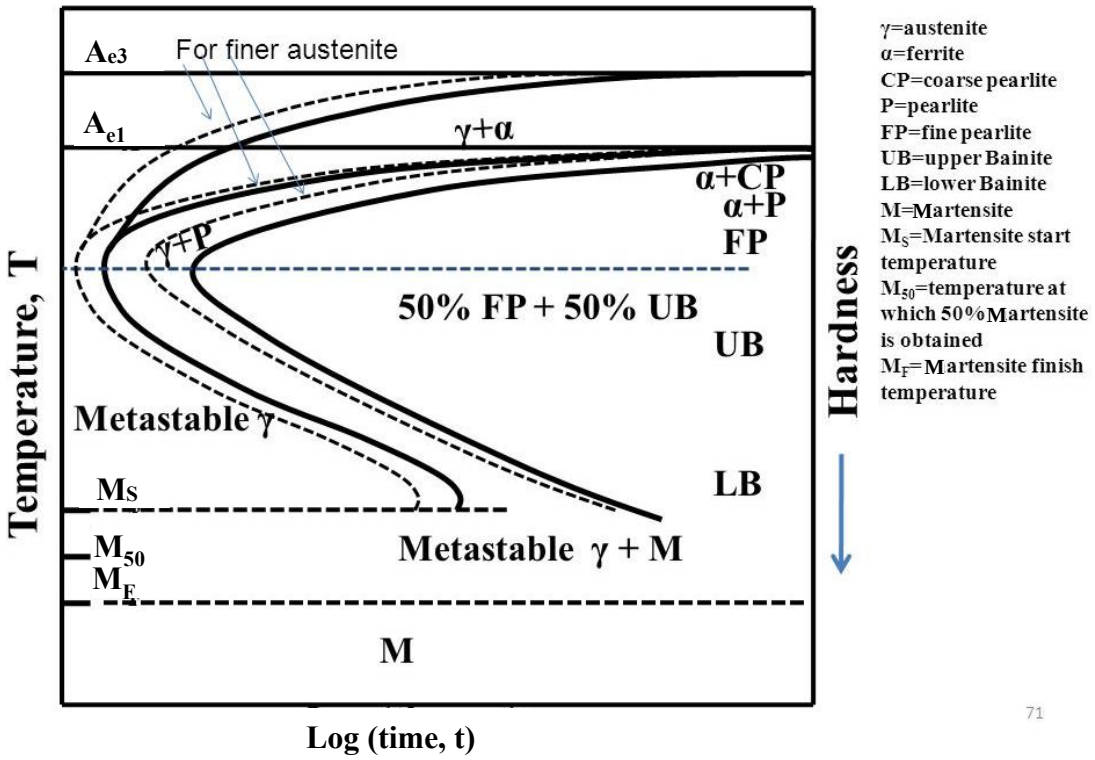


Figure 4.4 – Diagram of isothermal transformation of supercooled austenite of plain carbon post-eutectoid steel [7]

The mechanical properties of steel after the hardening are determined by the chemical composition of the steel, the temperature of the heating under hardening and the cooling rate.

The temperature of the heating under hardening is determined by the steel composition. For carbon steels the state diagram of $Fe-Fe_3C$ system, can determine it (figure 4.5).

Depending on the heating temperature the hardening divided on complete and incomplete. The complete hardening is called heating to the temperatures of a single-phase austenitic area. Incomplete hardening – heating to inter critical temperatures, in which, depending on the content of carbon in the steel, along with austenite, excess phase is stored – ferrite or secondary cementite.

Pre-eutectoid steels mainly do complete hardening (figure 4.5). The optimum temperature of the heating is 30 – 50 °C above temperature A_3. Incomplete hardening of pre-eutectoid steels is not recommended, because the presence of excess ferrite in the structure of hardened steel significantly decreases its hardness. Strong overheating of pre-eutectoid steels, to temperatures significantly higher than the critical point A_3,

contributes to the growth of austenitic grains, which increases the tendency to deform and crack formation during hardening. The structure of such steels in the tempered state will consist of a coarse-grained Martensite, which has a reduced impact strength.

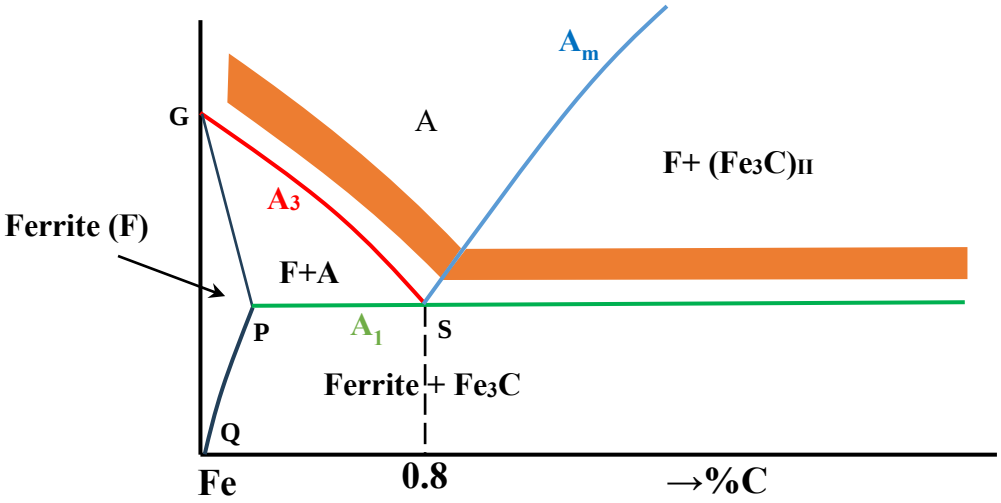


Figure 4.5 – Optimum temperature of hardening of carbon steels with different concentrations of carbon [3]

Post-eutectoid steels mainly do incomplete hardening (figure 4.5). The optimum temperature of heating is 30 – 50 °C above temperature A_1. The incomplete hardening of post-eutectoid steels allows to store in the structure secondary cementite, which ones increases wear resistance alloys without reducing the hardness. The alignment of post-eutectoid steels at temperatures well above the point of A_{cm} is accompanied by the formation of a structure of a coarse-grained Martensite with the large amount of residual austenite. The presence of the latter leads to a decrease in the hardness of hardened steel, and the strength of Martensite reduces its impact strength. Overheating of post-eutectoid steels above point A_{cm} (line SE) will lead to the dissolution of secondary cementite, grain aggregation, increase of hardening stresses and decarbonization steel from the surface. In the structure of steel, along with large-grained Martensite, an exceptionally large amount of residual austenite will be observed. Hardness and wear resistance of steels, with such structure, will be low. The optimal temperature intervals for the heating of carbon steels under hardening are given in figure 4.5.

The rate of heating of steels under hardening in electric air furnaces is approximately 1 minute per 1 mm cross-section. The shutter rate, as a rule, is equal to 1/5 of the heating time.

The nature of the structures formed during the hardening, as well as their hardness, depend on the cooling rate. At low cooling rates (figure 4.6), the conversion of austenite occurs at a slight overcooling relative to the temperature of the point A_1 (the temperature of the transformation of austenite into perlite by the diagram of the state of the cementite). As a result of this, the mechanical mixture of ferrite and cementite, called

perlite, whose hardness is 180 – 250 HB, is formed (figure 4.7). The increase in the cooling rate leads to a lowering of the conversion temperature of the supercooled austenite. In this case, the dispersion of the formed ferrite-cementite mixture increases, so as a result strength and hardness of alloy increases. This structure is called sorbite and has a hardness of 250 – 350 HB. With the further reduction of the decay temperature of the supercooled austenite, the dispersion of the products of decomposition increases as the resulting ferrite-cementite mixture becomes impossible to differentiate under a microscope. This structure is called troostite. The troostite has the highest hardness of ferrite + cementite mixtures, which equals 400 – 450 HB.

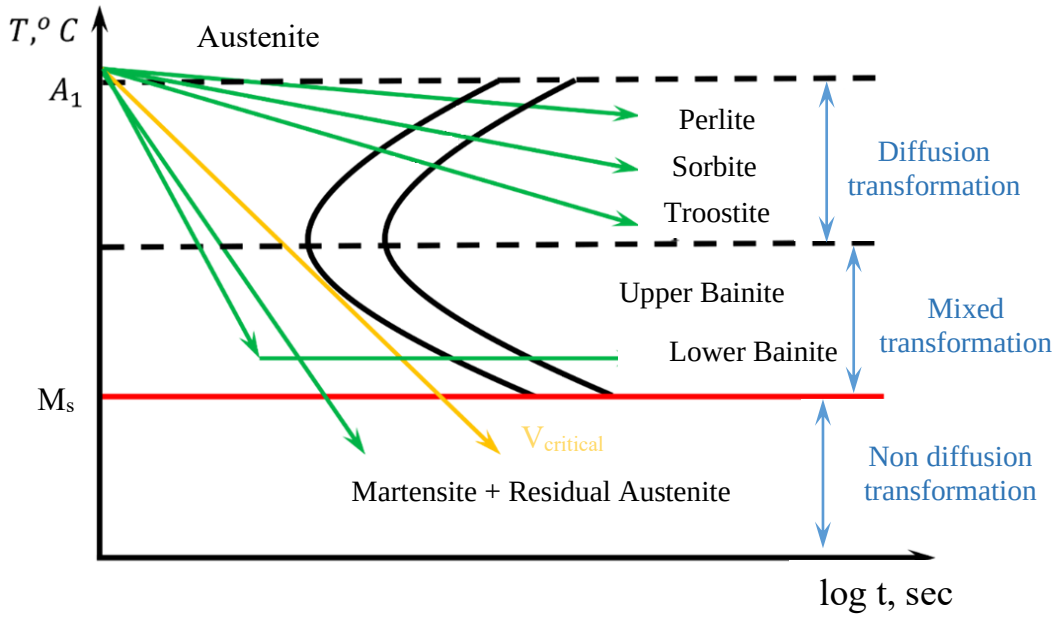


Figure 4.6 – Diagram of isothermal transformation of supercooled austenite of plain carbon eutectoid steel

At high cooling rates in the case of suppression of diffusion processes, austenite is supercooled to lower temperatures and undergoes a non-diffusion transformation with the formation of the **Martensite** – supersaturated solid carbon solution in α-iron. Martensite has the same carbon concentration as in the original austenite. As a result, the crystalline solid state lattice is distorted, and the Martensite formed tetragonal structure (figure 4.8). The higher the amount of carbon in the austenite, the greater the tetragonality and the hardness of Martensite. At the same time, a sufficiently high hardness of Martensite is already achieved in steels with a carbon content of 0.3 – 0.95 % and increases due to increasing concentration of carbon.

From the concentration of 0.7 – 0.8 % carbon hardness of the hardened steels practically does not change. This is due to the fact that in hardened steels with a carbon concentration more than 0.5 % due to large structural and thermal stresses, not all austenite is converted into Martensite. So, part of austenite remains in the form of

residual austenite, which is clamped between the needles of Martensite. In this case, the amount of residual austenite in the structure of the tempered steel increases with the increase in the amount of carbon concentration.

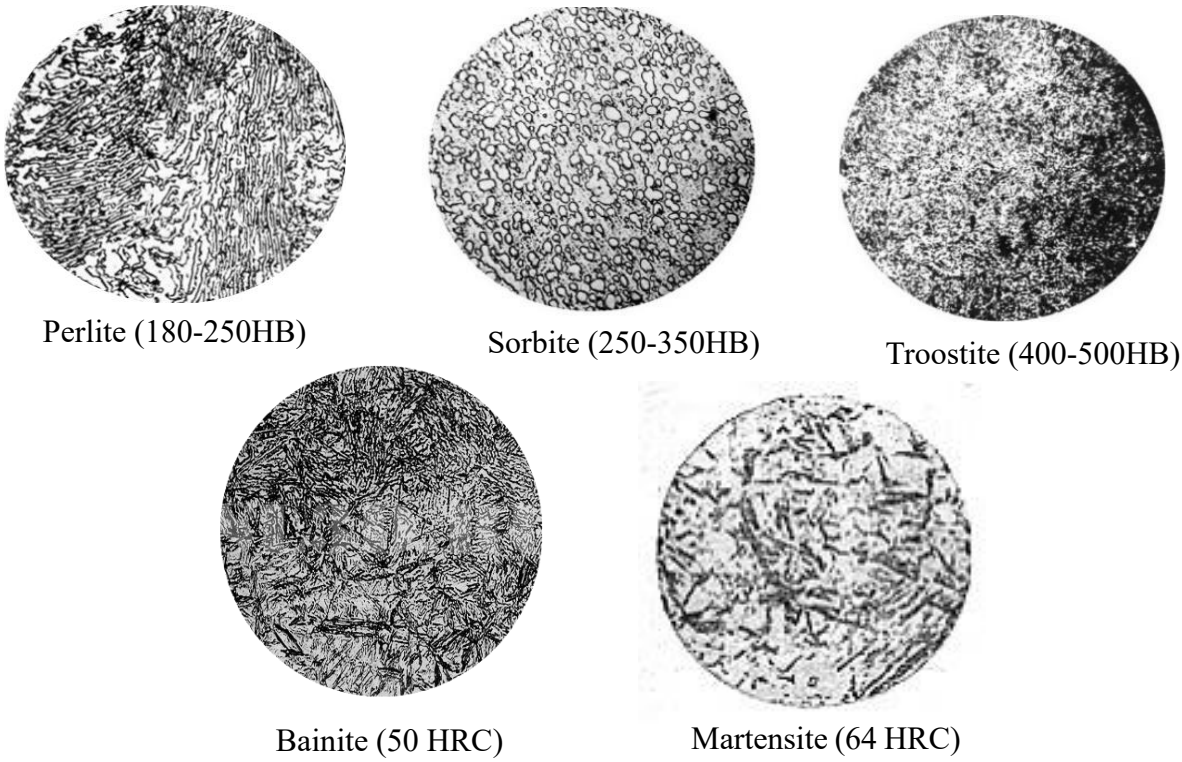


Figure 4.7 – Microstructure of hardened steel (0.8 % C) with different duration

As fluid for hardening most often are used water, aqueous solutions of salts, alkalis, mineral oils etc. Different fluids have different thermal conductivity so as a result different colling rate. The choice of fluid is based on the intensity of their cooling in the

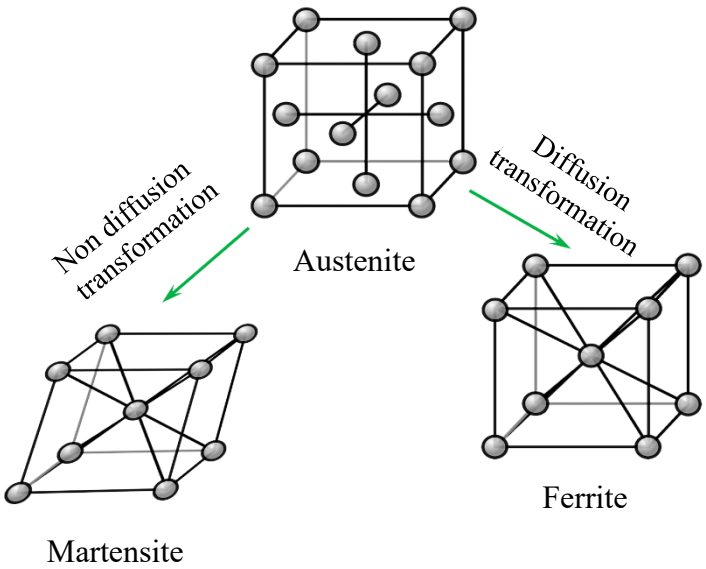


Figure 4.8 – Distortion of crystalline lattice due to hardening with high colling rate

intervals of stability of the supercooled austenite and the martensitic transformation.

The stainless steel is accompanied by a significant increase in the volume, which in the conditions of high rate and conversion inhomogeneity of the hardened part volume causes significant internal stresses. High internal stresses can lead to distortion of products (parts) and the formation of cracks in the process of hardening. In addition, residual high internal stresses over time under operating conditions can cause deformation of parts.

The **tempering** is called the process, which consists of heating the hardened steels to temperatures below A_1, isothermal exposure and subsequent cooling (most often on the air) (figure 4.2). Tempering is a final operation of heat treatment. Tempering have affected not only for eliminating internal stresses, but for obtaining a more equilibrium structure. As a result of tempering is form complex of mechanical properties (hardness, plasticity and ductility).

In practice, there are three types of tempering of hardened steels (figure 4.9): low tempering (100 – 200 °C), middle tempering (350 – 500 °C), high tempering (500 – 600 °C).

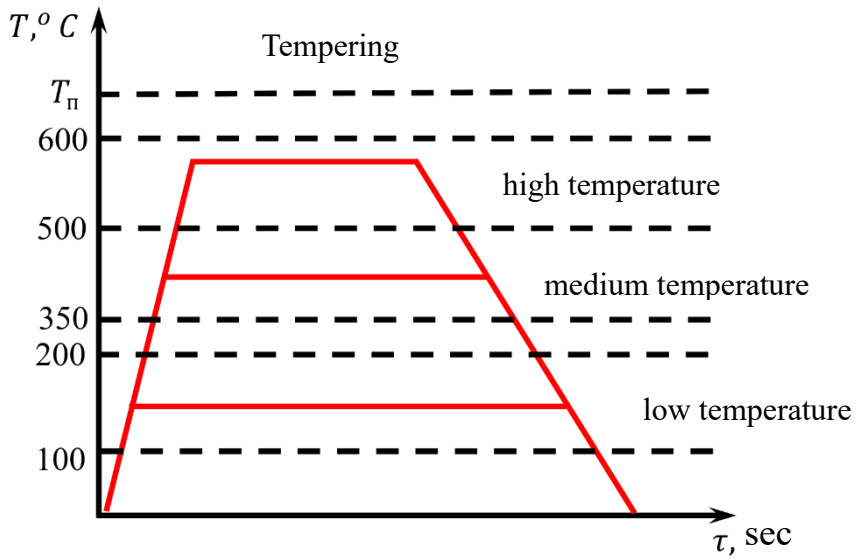


Figure 4.9 – Types of tempering

The hardened steel (0.5 – 1.3 % of C) after a low tempering retains a high hardness of 58 – 63 HRC and therefore has high strength and wear resistance. Incomplete hardening and low tempering are often used for heat treatment of cutting tool.

The middle tempering reduces the hardness of the hardened steel to 40 – 50 HRC and provides a high limit of elasticity, endurance and relaxation stability. Complete hardening and middle tempering use mainly for the treatment of springs.

The high tempering significantly reduces the hardness of the hardened steel to 28 – 32 HRC, but provides the best correlation between ductility and strength. That is a result formation more equilibrium and fine grain structure. Thermal treatment, which

consists of complete hardening steel with a subsequent high tempering, is called improvement of steel. Complete hardening and middle tempering are used mainly for heat treatment of the medium carbon structural steels (shafts, axles, gears).

The order of work execution

Task 1. *Influence of temperature of hardening on microstructure and hardness of carbon steel.*

The order of the task 1:

1. Load specimens of a pre-eutectoid steel (0.45 % or 0.5 % of C) to the furnaces, which are heated to temperatures of 650, 750, 800, 850 and 900 ºC;
2. Hold specimens on furnace at that temperature for 15 minutes to isothermal exposure;
3. Cool specimens in water;
4. Measure hardness of hardened specimens by Rockwell (HRC), record results to Table 4.1;
5. Draw the graph of dependence of hardness on heating temperature. The hardness (ordinate axis) – heating temperature (axis abscissa);
6. Using the binary diagram state of Fe-Fe_3C system, analyze the microstructures of steels, depending on the hardening temperature.

Task 2. *Investigation of influence of cooling rate on microstructure and hardness of carbon steel.*

The order of the task 2:

1. Load three specimens of steel with carbon concentration 0.8 % into the furnace, which is heated to a temperature of 850 ºC;
2. Hold specimens on furnace at that temperature for 15 minutes to isothermal exposure;
3. Cool one specimen in water, another one in oil and last one in air;
4. Measure the hardness of the cooled specimens by Rockwell (HRC), the results are record to Table 4.2;
5. Draw the histogram in coordinates the hardness (ordinate axis) – the cooling medium (abscissa axis).

Task 3. *Influence of carbon content in the steel on hardness of steels after hardening.*

The order of the task:

1. Specimens of steels (0.2 %, 0.45 % and 0.8 % of C) load into the furnace, which is heated to 850 ºC;

2. Hold specimens on furnace at that temperature for 15 minutes to isothermal exposure;
3. Cool specimens in water;
4. Measure the hardness of hardened specimens and record results to Table 4.3;
5. Draw a graph of the dependence of hardness on the contents of carbon in a steel. The hardness (ordinates axis), the carbon concentration in the steel (abscissa axis).

Task 4. *Influence of temperature of tempering on hardness of hardened carbon steel.*

The order of the task:

1. Select 7 hardened steel specimens with a carbon concentration of 0.8 %;
2. Load one specimen at a time into the furnace heated to temperatures 100, 200, 300, 400, 500 and 600 ºC;
3. Hold specimens on furnace at that temperature for 60 minutes;
4. Cool specimens in air;
5. Measure specimens hardness after tempering, the results write to Table 4.4;
6. Draw the graph of dependence of hardness on the temperature of the tempering. The hardness (ordinate axis), temperature (abscissa axis).

In the case of distance mode of education, all the necessary data for completing the tasks are presented in Appendix D.

Check Questions

1. Give the definition of heat treatment.
2. Which types of heat treatment do you know?
3. What is annealing?
4. Give the definition of normalization.
5. What is hardening?
6. How to do tempering?
7. Which difference between complete and incomplete hardening?
8. Which types of hardening use for pre- and post-eutectoid steels?
9. Which types of structures can form during the process of hardening with different degree of supercooling (rate of cooling)?
10. Which types of the tempering of hardened steel do you know?
11. How dose change the structure of complete hardened pre eutectoid steel after middle tempering?
12. How does change the mechanical properties of incomplete hardened tools steel after low tempering?

The result of the work

Table 4.1 – Measurement results of task 1

Heating temperature, ^{o}C	Hardness after quenching by Rockwell HRC
650	
750	
850	

Table 4.2 – Measurement results of task 2

Cooling medium	Hardness after quenching, HRC
Air (room temp.)	
Water (room temp.)	
Oil (room temp.)	

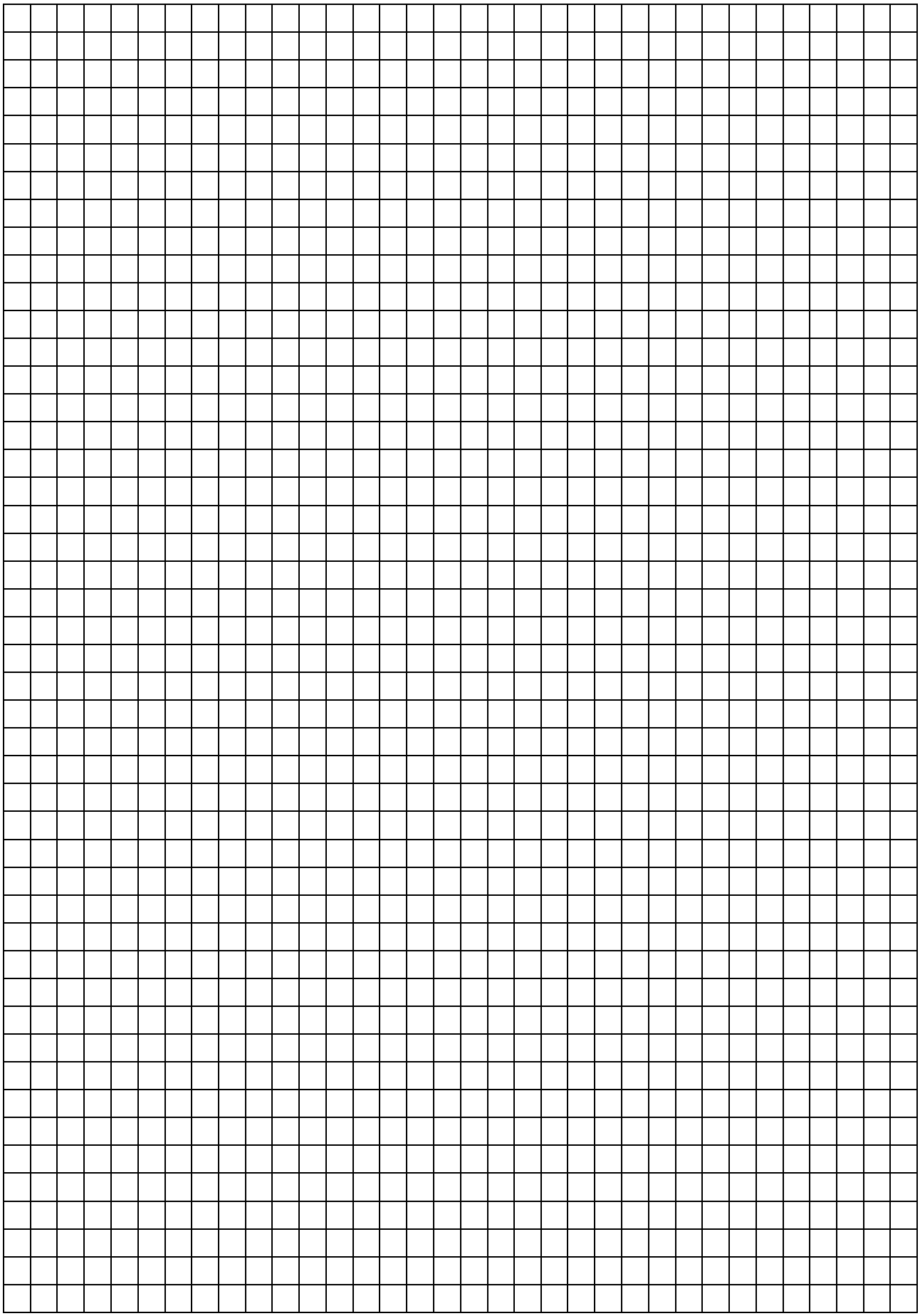
Table 4.3 – Measurement results of task 3

Concentration of carbon, %	Hardness after quenching, HRC
0.2	
0.45	
0.8	

Table 4.4 – Measurement results of task 4

Tempering temperature, ^{0}C	Hardness after quenching, HRC
100	
200	
300	
400	
500	
600	

Graphs



LAB NO. 5

WELD STRUCTURE

Main goal: to study the structures of the welded joint and the heat affected zone.

Equipment and materials:

1. Specimens of weld metal.
2. Optical MIM 7 or MIM 6 microscopes.

Theoretical information

Welding of metals is the process of obtaining integral joints of metal products when establishing interatomic bonds between welded parts during their local heating, plastic deformation or during their joint action. The most common are arc welding methods, which in comparison with other methods have a number of advantages – high heat density, versatility, simple and inexpensive equipment, stability. The formation of welded joints occurs in this case when heated in a narrow crystallization zone with the formation of a weld. The metal of the welded joint zone is characterized by the same set of properties as the welded metal: strength, ductility, corrosion resistance, etc. The quality of the weld is dependents on the chemical composition of the steel, physical properties and heat treatment of the steel before welding. Carbon structural steels containing up to 0.25 % carbon are well welded in all welding methods. Increasing the carbon content in steel by more than 0.3 % leads to self-hardening in heat affected zone (HAZ) of the base metal and it becomes more brittle. Therefore, steels with high carbon content in most cases are welded with preheating, and sometimes with subsequent heat treatment – normalization or annealing.

In arc welding, the heat transfers from the welding zone to the base metal. In this case, in the zone of weld formation, sections consisting of unmelted metal and weld metal can be distinguished. The part of the metal that melts and crystallizes in the process of welding is called the weld metal. The weld metal is the product of liquid mixing of deposited (filler) and molten base metal, taking into account the changes caused by the processes accompanying welding (evaporation, oxidation, etc.).

The metal of single pass welding has the structure of cast steel: coarse-grained, dendritic, in most cases it is in the form of columnar crystals (figure 1.3). The columnar crystals are directed from the zone of incomplete melting to the depth of the weld. The study of the structure of columnar crystals allows us to establish that each of them consists of separate dendrites. Dendrites within a columnar crystal have the same orientation, but may have different branching, and there is no clear boundary between such dendrites. The group of dendrites, which has a clear boundary, is a columnar crystal.

The structure of the columnar crystal of the weld metal is a section with uniformly distributed perlite framed by a ferrite grid.

In the case where the weld consists of several passes, then in the heat affected zone on the previous passes there are areas where recrystallization takes place. When the weld metal is reheated above 900 ºC and rapidly cooled, the columnar structure turns into a fine-grained with equilibrium shape. Therefore, in multi-pass arc welding, the structure of the first and subsequent layers is fine-grained and equilibriumed. But the last layer remains columnar grains, which has reduced mechanical properties.

The zone of the base metal, in which changes in structure and properties occur as a result of heating and cooling due to welding, is called the heat affected zone. In HAZ it is possible to allocate the following zones (figure 5.1):

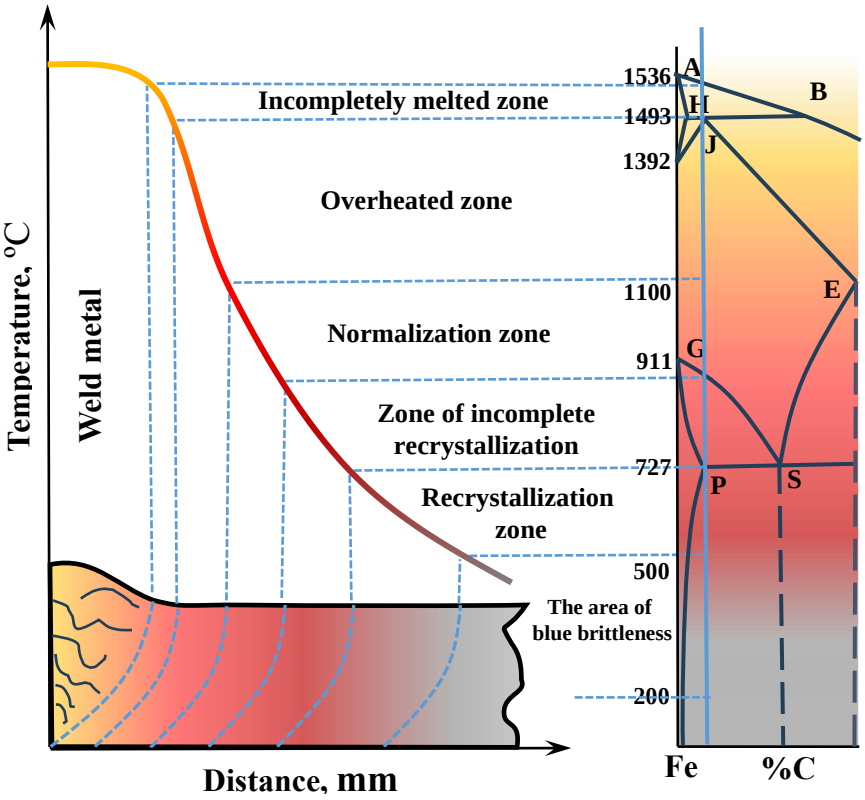


Figure 5.1 – Distribution of areas of HAZ for low carbon steel [1]

1**. Incompletely melted zone.** It includes a narrow strip of base metal, which is heated during welding to the temperature range between the start and end temperatures of steel melting. The liquidus-solidus temperature interval in low-carbon steels is small (30 – 40 ºC), so the area of incomplete melting area has mainly small width: for ARC 0.08 – 0.1 mm and for gas and electroslag welding 0.15 – 0.20 mm. Due to the small width, it is difficult to distinguish this zone from the others.

2. **Overheated zone.** The metal, which is located in this area, is heated to temperatures close to the melting point (1100 – 1200 ºC). As a result of overheating, the

metal has a large-crystalline structure, and further accelerated cooling leads to formation of Widmannstetter structure (figure 5.2). As the distance from the weld metal zone is increases, the degree of overheating decreases, which leads to decreasing of grain size.

In these two areas (incompletely melted and overheated zones), as a result of heating and cooling, the structure and properties of the base metal change most sharply of plasticity and toughness decreases, hot cracks are formed. The metal of this zone has the highest brittleness and is the weakest point of the welded joint.

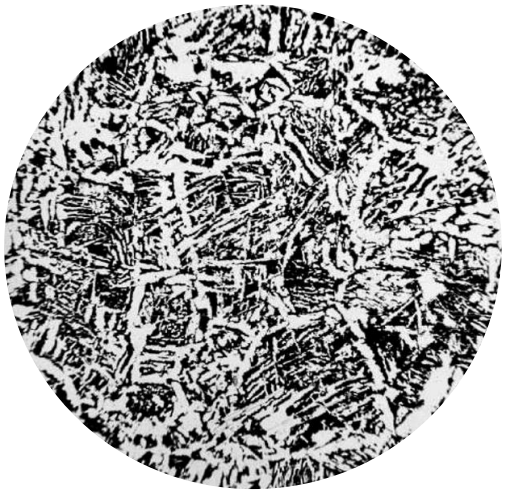


Figure 5.2 – The microstructure of overheated zone

3. **Normalized zone.** The metal of this area is heated to a temperature corresponding to the critical point A_3 (line GS on diagram state, 900 – 1100 ºC). Normalization zone presents on HAZ of weld metal only in the case when the welded steel had an initial coarse-grained structure. Due to the recrystallization processes, the final structure of this section has small equilibrium grains of ferrite and perlite (figure 5.3). This structure is characterized by rather high mechanical properties

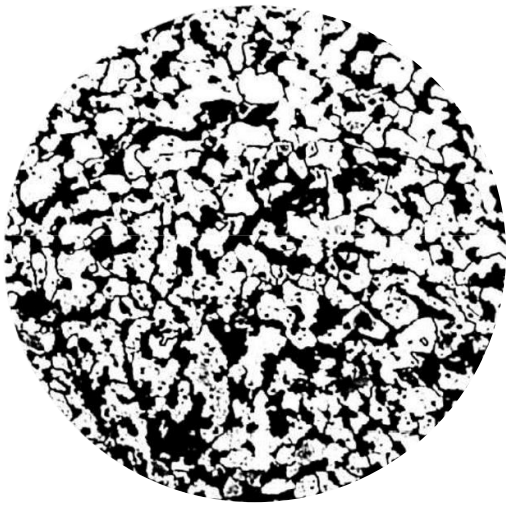


Figure 5.3 – The microstructure of normalization zone

(strength, ductility).

4. **Zone of incomplete recrystallization**. The metal in this zone is heated to a temperature from 723 up to 900 °C (from A_{c1}, located on the line PS on diagram state, to A_{c3}, located on the line GS on diagram state). Its structure is extremely peculiar. Here, along with the old, larger grains of ferrite that have not undergone recrystallization, and new, much smaller grains of ferrite and perlite that have undergone recrystallization are located (figure 5.4). Due to the rather sharp difference in grain sizes, this zone has relatively low mechanical properties.

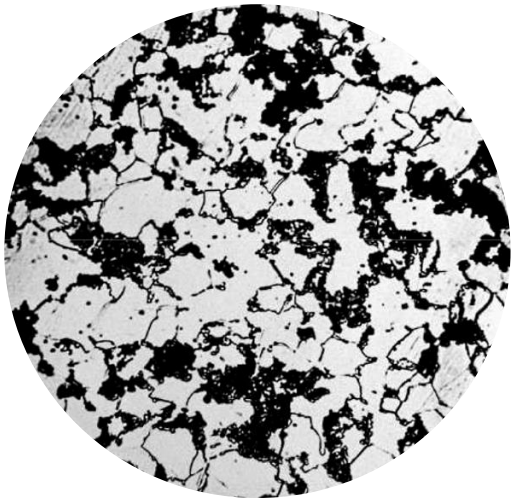


Figure 5.4 – The microstructure of incomplete recrystallization area

5. **Recrystallization zone.** Such zone presents on HAZ of weld metal only if welded steel was cold deformed before process of welding. For hot-formed or annealed steel before welding, the part of the metal that was heated to temperatures below A_{c1} does not change its structure. If the metal was cold deformed before welding (as a result of cold rolling, stamping, bending, etc.), during welding structural transformations will be observed. In this case, recrystallization takes place, which leads to significant grain growth. Recrystallized structure in the welded joint is observed in the zones that are heated above the recrystallization temperature (450 – 725 °C). The recrystallization zone is characterized by equilibrium enlarged grains of ferrite and perlite (figure 5.5). The grain size will depend on the degree of plastic deformation metal before welding. Such structure can be distinguished from the initial structure by the absence of grains of fibrous shape. In cast and hot-deformed steels, the recrystallization site is absent.

6. **The zone of blue brittleness**. The structure of this section is metallographically indistinguishable from the structure of the initial metal. In the process of welding, the metal of this zone is heated to temperatures 200 – 400 °C, at which the blue color of variability appears. Heating to such temperatures causes an increase in the strength of some steels, as well as a decrease in ductility and toughness. This is most likely due to the formation of submicroscopic particles from the solid solution along the grain

boundaries.

According to the structural changes during welding, a conclusion is made about the properties of the weld joint, which should be taken into account when choosing the welding technology.

Figure 5.5 – The microstructure of recrystallization area

The order of work execution

1. To study the structure of the welded joint and the heat affected zone formed during single-pass arc welding. Use a microscope with magnification 100 times.
2. Draw the structure of the welded joint and HAZ, indicate all zones of the heat affected zone (Appendix E).

Check Questions

1. Give the definition of welding.
2. What is the structure of the weld metal in a single-pass welded joint?
3. Describe the structure of the multi-pass weld metal.
4. Describe the structure of the:
   4.1. Incompletely melted zone;
   4.2. Overheated zone;
   4.3. Normalization zone;
   4.4. Zone of incomplete recrystallization;
   4.5. Recrystallization zone;
   4.6. The zone of blue brittleness.

The result of the work

LAB NO. 6

COPPER-BASED ALLOYS

Main goal: to study the structure and properties of copper-based alloys.

Equipment and materials:

1. Specimens of copper-based alloys.
2. Optical MIM 7 or MIM 6 microscopes.

Theoretical information

Copper is a red metal with a density of 8.94 g/cm^3. Crystal lattice – FCC with a period of 0.3615 nm. Melting point – 1083 ºC. In terms of electrical conductivity, copper is second only to silver. The electrical resistance at 20ºC is $1.68 \cdot 10^{-8}$ Ohms · m. A small number of impurities significantly reduces the electrical conductivity. The mechanical properties of pure copper are as follows: $\sigma_B = 220 – 240$ MPa; $\delta = 60$ %; hardness 35 HB; shear modulus $4.24 \cdot 10^4$ MPa. The most important groups of industrial alloys are brasses and bronzes.

Brass is the copper alloys, in which the main alloying element is zinc. The chemical composition of brass is divided into double (Cu-Zn) and multicomponent, which contain in addition to zinc other alloying elements (aluminum, lead, tin, silicon, etc.).

According to DSTU and GOST standards, brass is marked with the letter «Л» and number that shows the average copper content on % (for example: Л68, Л96). If the brass is alloyed in addition by other elements, then after the letter «Л» put the latter which corresponds to these elements: «С» – lead, «О» – tin, «Ж» – iron, «А» – aluminum, «К» – silicon, «Мц» – manganese, «Н» – nickel, etc. The number after the letters indicate the average content of each alloying element in brass, except zinc. For example, ЛАЖ 60-1-1 that is brass, which contains 60 % Cu, 1 % Al and 1 % Fe, the rest is Zn (38 %).

The structure and properties of brass are determined by the Cu-Zn state diagram (figure 6.1). In the solid state, the solubility of zinc in copper is quite high and reaches 39 % at a temperature of 454 ºC with the formation of α-solid solution, which has a face-centered cubic lattice. When the temperature decreases, the solubility of zinc in copper decreases and at room temperature the solubility is equal to 35 %. As the zinc content in the alloy's increases, five peritectic transformations take place. As a result of phases – chemical compounds are formed: β (CuZn), γ (Cu_5Zn_8), δ ($CuZn_3$) and others. At high temperatures, the β-phase has a disordered arrangement of copper and zinc atoms in the lattice of the compound CuZn and is characterized by high plasticity. At temperatures

below 454 – 468 °C, the β-phase becomes ordered and is denoted by β'. The appearance of an ordered β'-phase in the structure leads to a decrease in ductility (with a zinc content of more than 39 %). With a complete change of the β-phase to the β'-phase leads to a decrease in the tensile strength observed in alloys with more than 47– 50 % Zn concentration (figure 6.2). As a result, alloys containing up to 47 % Zn are particularly useful. Single-phase β-alloys with a zinc content ~ 50 % are used as the basis of alloys with the effect of shape memory and elasticity.

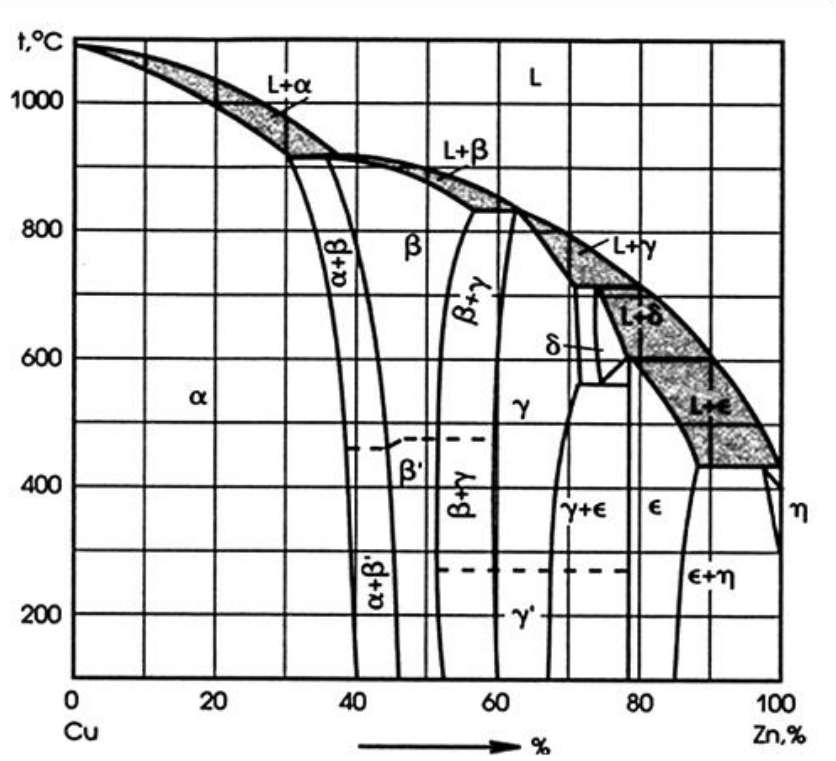


Figure 6.1 – Cu-Zn state diagram [8]

Brasses depending on the structure are divided into two groups: single-phase (α) brasses and two-phase (α + β) brasses (figure 6.3). Brasses are single-phase in zinc concentration on brass up to 39 %. In the cast state, single-phase brass has a dendritic structure in which the central areas are light, enriched in copper, and the peripheral, dark areas are enriched in zinc. After deformation and annealing, the chemical composition of the α-solid solution more equilibrium and the grains are obtained in a polyhedral shape. In the case of recrystallization after deformation, a typical polyhedral structure with a large number of annealing doubles is obtained. The structure of two-phase brasses contains β'-phase crystals along with the grains of the α-solid solution.

The mechanical properties of brasses depend on their structure and zinc content (figure 6.2). Single-phase brasses have high ductility, it is the highest in alloys with 30 – 32 % Zn. Brass with a lower zinc content (10 – 20 % Zn) are inferior to brass Л68 and Л70 in ductility, but exceed them in electrical and thermal conductivity, corrosion

resistance. Single-phase α-brass is easily subjected to hot and cold pressure treatment. Cold deformation leads to a significant increase in the strength of brass while sharply decreases its ductility. Annealing of deformed brass at temperatures above 400 °C removes deformation defects. Two-phase brass (40 – 41 % Zn) have lower ductility, but higher wear resistance and strength. Such properties exchanging due to formation of β`– solid phase. As usual these brasses are subjected to hot pressure treatment.

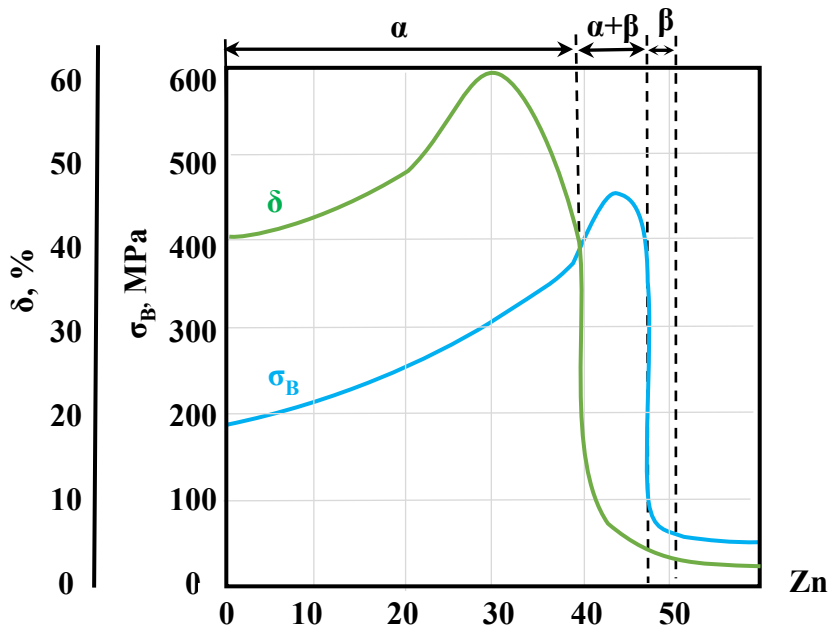
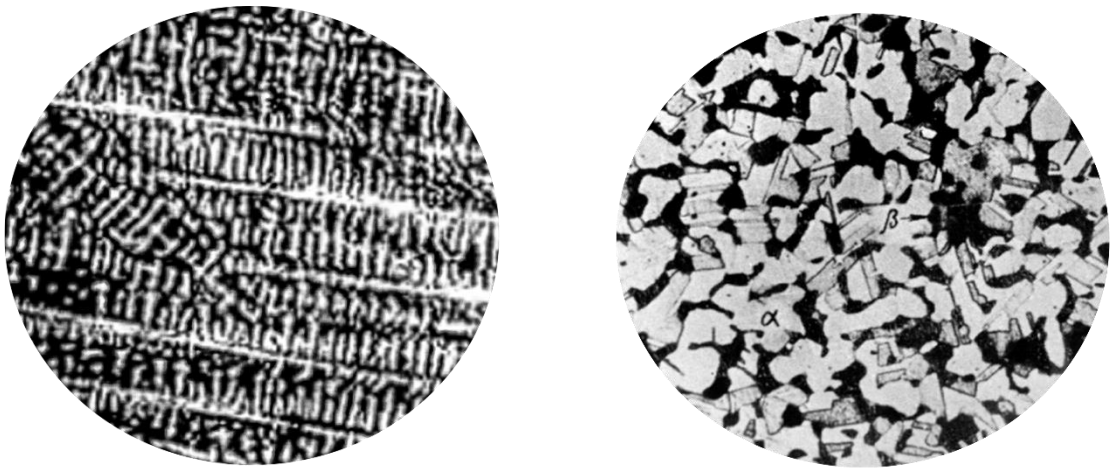


Figure 6.2 – Dependence of mechanical characteristics on concentration of Zn [8]



a ***b***

Figure 6.3 – The microstructure of dendritic single α-phase (*a*) brasses and two (α + β)-phase (*b*) brasses

The properties of brass are significantly depend on impurities and additional alloying. The most harmful impurities are bismuth and lead, which form in the alloys fusible eutectics along the grain boundaries, which leads to the red brittleness of the

alloys. In addition, bismuth, as a brittle metal, causes the phenomenon of cold brittleness in copper alloys.

In two-phase brasses, the harmful effect of lead is weakened as a result of the phase α⇔β transformation during heating and cooling. Lead is found in the middle of the α-phase grains, and not at the boundaries, due to the fact that the α-phase during phase recrystallization is formed at lead inclusions as embryos. In some two-phase brasses, lead is introduced specifically to improve the antifriction and cutting properties (ЛС74-3, ЛС63-3, ЛС60-1, ЛС59-1). But on other hand the strength of such alloys are reduces due to addition of lead. Doping brasses by aluminum, tin, nickel, manganese effectively increases the hardness, strength, corrosion resistance, technological properties of brasses (ЛО 62-1, ЛН 65-5, ЛМЦ 58-2). Doping brasses by iron and silicon improves the formation of fine structure. Siliceous brasses have high mechanical and antifriction properties, are easily processed by pressure and characterized by high fluidity (ЛК 80-3).

Brasses are widely used for the manufacture of shaped castings, corrosion resistant parts in general and marine engineering: bushings, gears, bearings, nuts, screws, fittings, etc.

Bronzes are marked with the letters «Бр», followed by letters and numbers that indicate the name and content as a percentage of alloying elements: «С» – lead, «О» – tin, «Ж» – iron, «А» – aluminum, «К» – silicon, «Мц» – manganese, «Н» – nickel, «Ф» – phosphorus, «Ц» – zinc, «Б» – beryllium, etc. For example, bronze brand БрАЖН 11-6-6 contains 11 % A1, 6 % Fe, 6 % Ni.

Alloying elements and their concentration determine the mechanical and technological properties of bronze. Bronzes are named corresponding to the main alloying element. For example, tin bronze, lead bronze, beryllium bronze etc.

Tin bronzes are widely used in industry. There are two groups of tin bronzes: double alloys of copper with tin and multicomponent (which contains, one main element and some alloying tin, impurities of lead, phosphorus, nickel and other elements). Significant intra dendritic liquation formation in the alloys of the Cu-Sn system (figure 6.4). As a result of which, under production conditions, the nonequilibrium δ-phase appears at concentrations higher than 6 – 8 %, instead of 13.5 % according to the state diagram. Depending on the Sn content, tin bronzes are divided into two groups by microstructure: single- and two-phases bronzes. Among the single-phase alloys are bronzes with a content of up to 6 – 7 % Sn. Their structure is determined by the α-solid solution of tin in copper. Copper mainly concentrated in the central dark regions of the dendritic branches. At the same time tin concentrated in the light regions near the dendrites surface. Such chemical inhomogeneity can be eliminated by homogenization annealing, after which the structure is an equilibrium grain of α-solution.

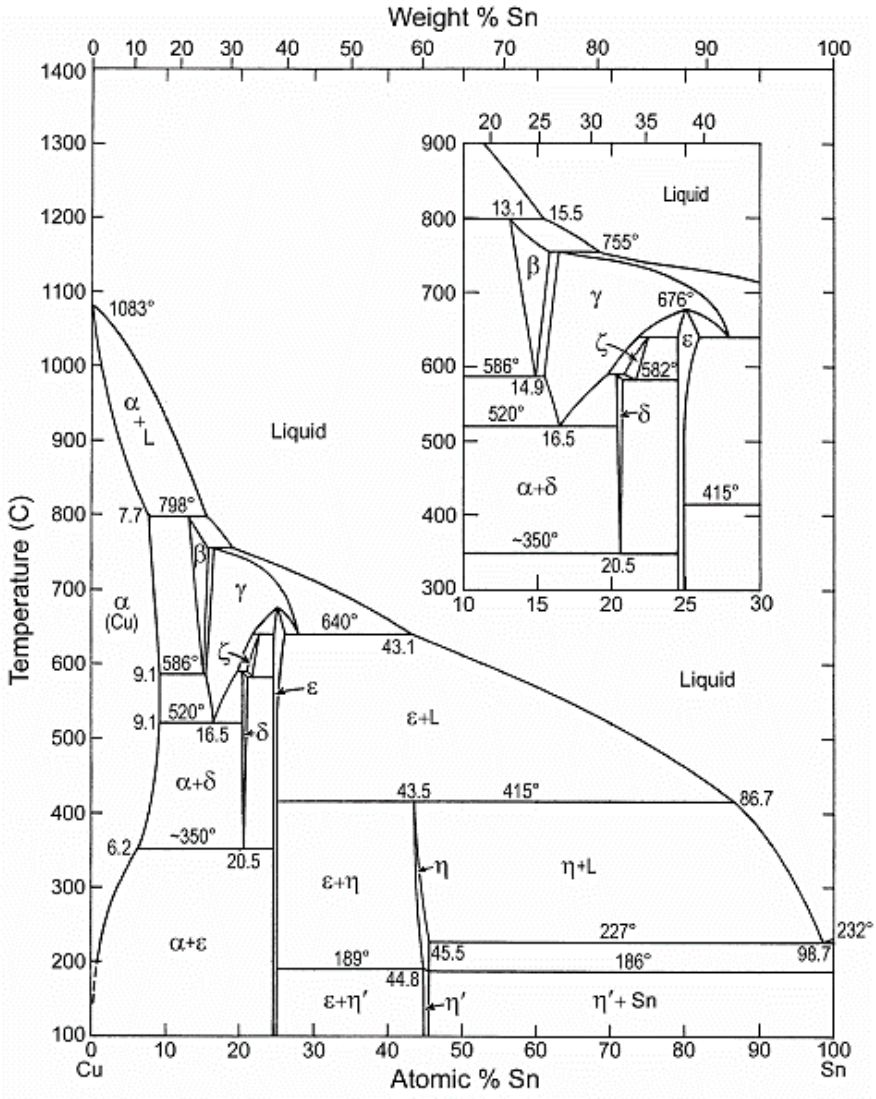


Figure 6.4 – Cu-Sn state diagram state [9]

The structure of cast biphasic alloys containing more than 7 % Sn consists of primary crystals of α-solution and eutectoid (α+ δ), where the δ-phase is an electronic compound $Cu_{31}Sn_8$. With the appearance of a brittle δ-phase in the structure of bronzes, the plasticity decreases and wear resistance increases. Therefore, tin bronzes with a sufficiently high eutectoid content are an excellent antifriction material and are used for the manufacture of bearing liners and worm wheels. To increase the antifriction properties, bronzes alloying by lead and phosphorus (БрОФ4-0.2, БрОФ6.5-0.15, БрОЦС6-6-3).

The wide range of crystallization of copper-tin alloys is the reason for their low fluidity and significant porosity of castings. When doped with zinc and phosphorus, double bronzes become quite fluid, well fill complex forms, have a very small volume shrinkage during solidification and therefore well transfer the shape of the product. This allows to use it to make artistic castings. Zinc doping also increases the strength of bronze (figure 6.5). Alloying bronzes by nickel increases the strength at room

temperature, improves bronze ductility, improve casting characteristics.

Recently, expensive tin bronzes have been replaced by aluminum ones, which not

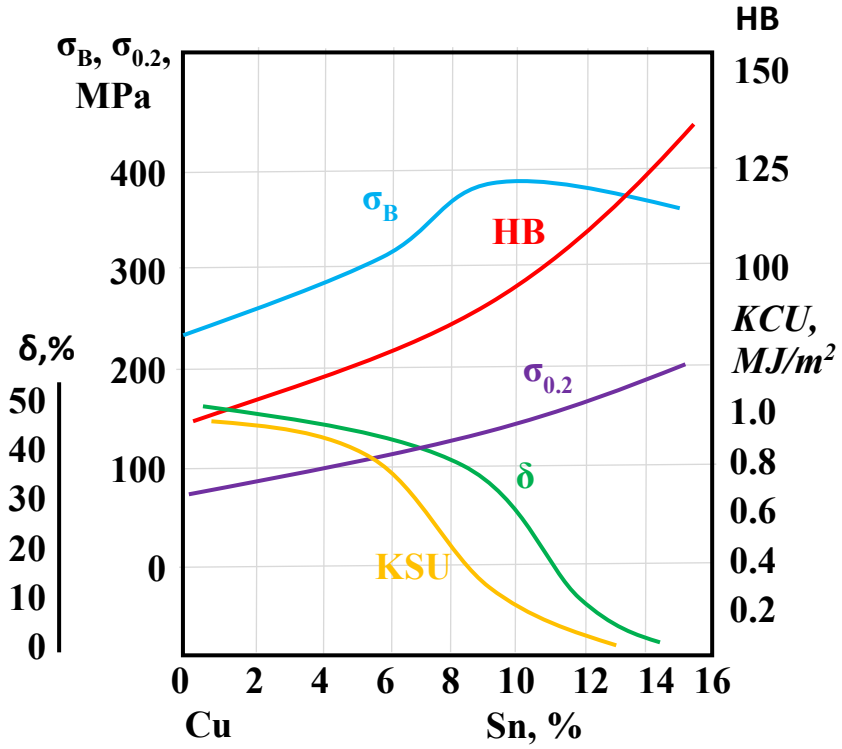


Figure 6.5 – Dependence of mechanical characteristics on concentration of Sn in Bronzes [9]

only do not yield to tin ones, but also exceed them in some properties. Double and alloy aluminum bronzes are used.

The microstructure of single-phase bronzes consists of a α-solid solution of aluminum in copper (figure 6.6). In the cast state, the crystals of the solution have a dendritic structure, and in the annealed state – polyhedral structure. When the aluminum content is more than 9.4 %, bronzes are two-phase. Its structure consists of α-phase crystals (light grains) and eutectoid $\alpha + \gamma_2$ (dark variegated field), where phase γ_2 is the chemical compound Cu_9Al_4. Eutectoid is formed by the decomposition of β-solid solution at 565 °C.

Alloys with α-structure (single-phase) are well processed by pressure at low and high temperatures. The γ_2 phase has a high hardness and insignificant ductility. So with the appearance of the eutectoid structure in the alloys, the strength of the alloys increases sharply with decreasing of ductility (figure 6.7). For this reason, two-phase bronzes are treated with hot pressure. Maximum strength is achieved in alloys with 10 – 11 % Al. Normalization with (600 – 700 °C) promotes increase of plasticity, after which the amount of eutectoid in the alloy decreases.

The strength of two-phase bronzes can be further increased by heat treatment (hardening and subsequent tempering). During accelerated cooling, the β-solid solution turns into martensitic γ'-phase. The mechanical properties of hardened bronzes change

with the subsequent tempering, as a result of which the γ'-phase decays with the formation of a dispersed eutectoid (α + γ_2). By changing the temperature and duration of the heat treatment, you can get the desired mechanical properties of the finished product.

The strengthening effect of aluminum bronzes is increased as a result of bronzes

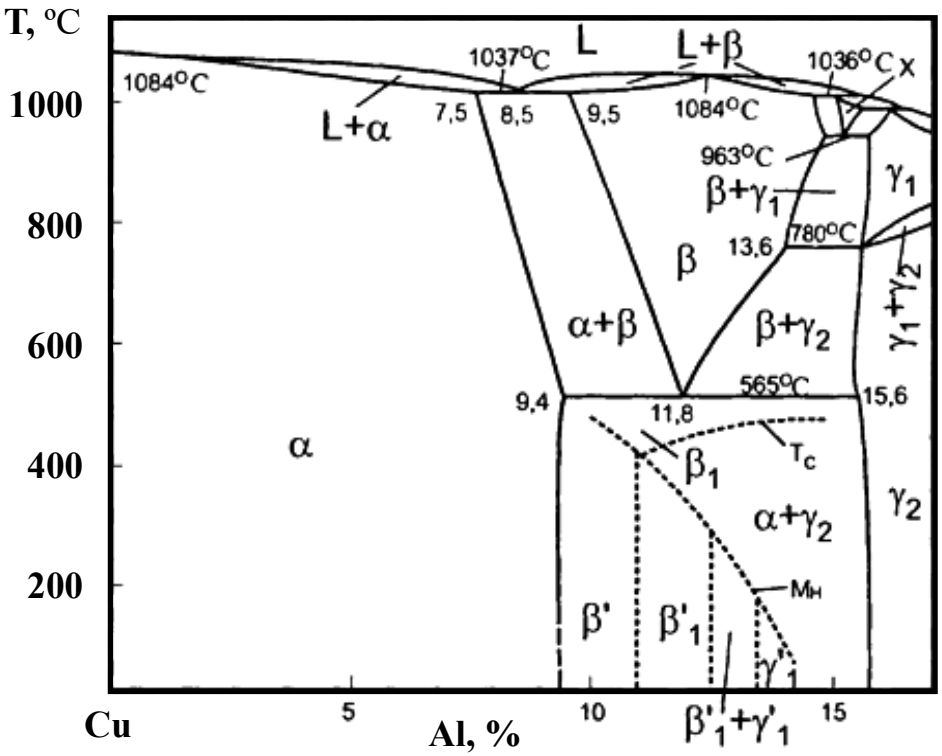


Figure 6.6 – Cu-Al state diagram [11]

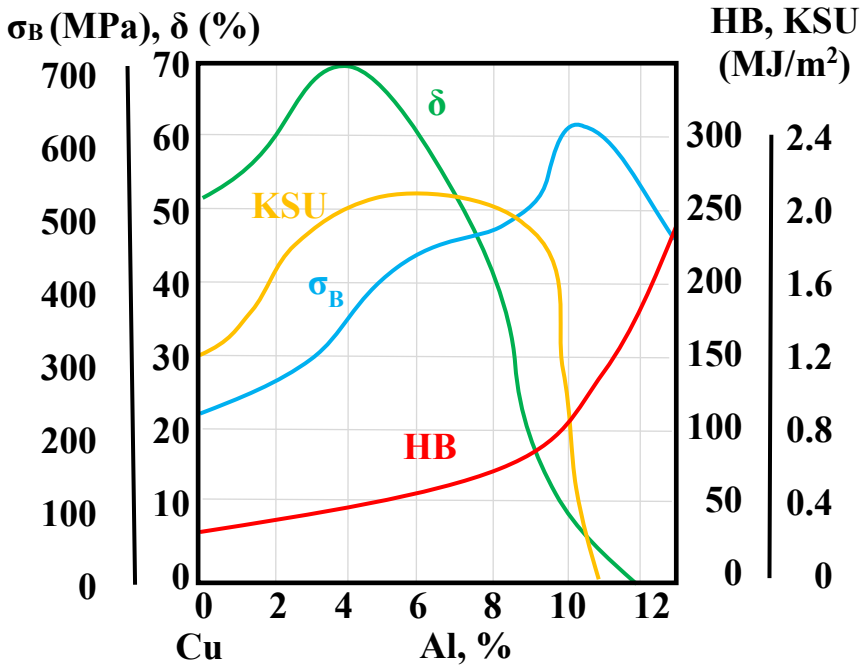


Figure 6.7 – Dependence of mechanical characteristics on concentration of Al in the aluminum bronzes [1, 8, 9, 11]

been doped with iron and nickel, which form highly dispersed intermetallic phases. Iron effectively grinds grain during recrystallization, slows down the process of eutectoid decomposition. As a result of which the two-phase crystals are crushed, so brittleness is reduced. Nickel significantly reduces the solubility of aluminum in copper with decreasing temperature of heat treatment. So, copper alloys doped with Al and Ni after heat treatment, which includes hardening and tempering, are strengthened by dispersed emissions of intermetallic Ni_3Al and NiAl. For example, the hardness of bronze БрАЖМ10-4-4 is 400 MPa, after hardening from 980 °C and tempering at 400 °C. Nickel also improves the corrosion resistance of bronzes, increases the recrystallization temperature and heat resistance. But most aluminum bronzes are alloys that are not hardened by heat treatment.

The increase in hardness, strength, corrosion resistance and antifriction properties occur when manganese is introduced into alloys (БрАМЦ10-2).

Depending on the structure and properties, aluminum bronzes are used as deformable (to obtain sheets, rods, etc.), and as cast (for the production of castings). Special aluminum bronzes are used for manufacturing of mechanical parts that work on friction (bushings, gears, worm gears, pump parts and turbines).

Lead-bearing bronzes, which have good antifriction properties, are widely used for the production of responsible plain bearings. In double lead bronzes (БрС30), soft lead crystallizes last in the eutectic at the copper grains boundaries. Such heterogeneous structure has extremely high effect for providing antifriction properties. To ensure

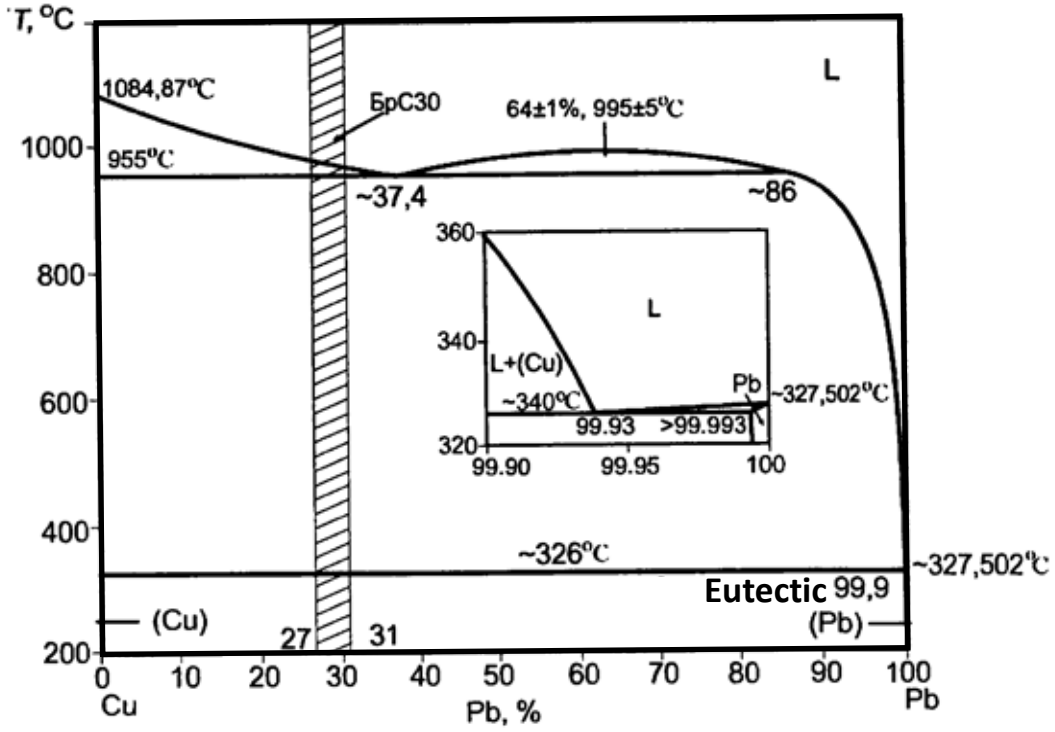


Figure 6.8 – Cu-Pb state diagram [11]

uniform distribution of lead in the structure during casting, special measures are used to

reduce liquation (in particular, rapid crystallization). For example, to increase the speed of crystallization, steel strips or blanks on which lead bronze is poured are cooled with water. Also, nickel (БрС60Н2.5) is added to the composition of lead bronzes to delay gravitational liquidation. The purpose of nickel is to promote the formation of a fine-branched network of primary copper-nickel crystals that delay liquation. The strength and hardness of БрС30 lead bronze is low, so it is used in the form of bimetal, which is obtained by casting a layer of bronze on the steel bearing housing. Thanks to the bimetallic design, the bearings can work at high sliding speeds and at higher specific cyclic shock loads. Such bimetallic bearings have a small weight, are easy to manufacture and can be easily replaced when worn.

Beryllium bronzes are characterized by exceptionally valuable qualities (БрБ2; БрБНТ1.7). The solubility of beryllium in copper in the solid state decreases with decreasing temperature, which provides the possibility of their thermal hardening (figure 6.9). After hardening, from temperatures corresponding to the region of existence of the α-solid solution, the structure of beryllium bronzes are supersaturated solid solution. Such alloys have high ductility sufficient for cold pressure treatment. The decomposition of supersaturated solid solution in the aging process with the formation of dispersed precipitates of the metastable γ′-phase, and then the stable γ-phase, based on the intermetallic leads to a strengthening of the alloy, but decreasing ductility. After heat treatment, these bronzes have strength limits at the level of 1150 – 1250 MPa, high elasticity, satisfactory creep resistance, as well as good corrosion resistance and high

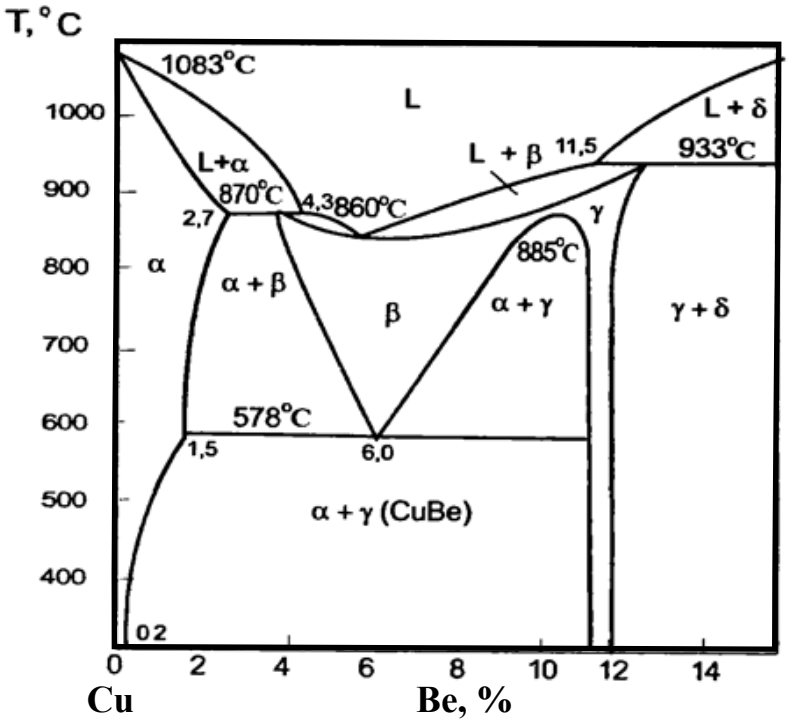


Figure 6.9 – Cu-Pb state diagram [10]

hardness. In addition, beryllium bronzes have a low tendency to cold brittleness and can

operate in the temperature range from –200 to +250 °C. They are used for manufacturying of parts for critical purposes: springs and elastic elements of electronic devices, membranes, cables, tools that work in explosive conditions, because beryllium bronzes do not give sparks on impact. Disadvantages of beryllium bronzes are high price, scarcity and toxicity of beryllium.

The properties of typical binary copper alloys are shown in table 6.1.

Table 6.1. Properties of typical binary copper alloys [3]

Alloy	Mechanical properties			Conductivity	Treatment
	$\sigma_в$, MPa	δ, %	HB		
Л70	680	3	180	0.065	cold-rolled
БрО10	275	3 – 10	70 – 80		cast
БрА7	860	3	250	0.087	cold-rolled
БрС30	80	6	25		cast
БрБ2	1250	3	370	0.07	after hardening and aging

The order of work execution

1. Using the state diagrams of Cu-Zn, Cu-Sn, Cu-Al, Cu-Be, Cu-Pb, consider the nature of phase transformations in alloys that have practical application.
2. Carry out microstructural analysis of single- and two-phases brasses (Appendix F).
3. Carry out microstructural analysis of single- and two-phases tin and aluminum bronzes in cast and annealed state, lead bronze in cast state, beryllium bronze after hardening and aging (Appendix G).
4. Draw schematically structures Cu-based alloys (Appendix F and G).

Check Questions

1. Describe the characteristic of copper?
2. Give the definition of brass.
3. Give the definition of bronze.
4. How many main groups are industrial copper-based alloys divided into?
5. What is the maximum solubility of zinc in copper in the solid state?
6. Specify the phase composition of brass Л59 at a temperature of 480 ºС.
7. How does alloying elements affect characteristics of bronzes?
8. What kind of bronzes are used in explosive conditions due to the absence of sparks on impact?

The result of the work

LAB NO. 7

ALUMINUM-BASED ALLOYS

Main goal: to study the structure and properties of aluminum-based alloys.

Equipment and materials:

1. Specimens of aluminum based alloys.
2. Optical microscopes MIM 7 or MIM 6.

Theoretical information

Aluminum

Pure aluminum – light metal with a density of 2.7 g/cm^3. Crystal lattice of aluminum is FCC with period 0.4041 nm. Aluminum conducts well heat and electric current (ρ = 2.6548 Ohm·mm^2/m). Mechanical properties of pure aluminum: $\sigma_в$ = 150 MPa, δ = 50 %.

High purity aluminum marked with different concentration of 99.85 to 99 % (A8, A7, A6, A5, A0), up to 99.99999 % (A99).

Technical aluminum is well-welded, has a high plasticity. Aluminum is used as an electrotechnical material.

Aluminum alloys

Aluminum with other elements forms alloys, the state diagrams of which are similar to the diagram Al-Cu (figure 7.1). Based on the state diagram, aluminum alloys are divided into three groups according to the technological properties:

1) deformable alloys which are not strengthening by heat treatment;

2) deformable alloys which are strengthening by heat treatment;

3) casting alloys.

For alloys of the Al-Cu system, the limits of concentration of these groups are:

1) to the limit of solubility at room temperature;

2) from the solubility limit at room temperature to the maximum solubility in the solid state;

3) from the limit of maximum solubility in solid state to the required concentration at the eutectic point.

Characteristics of typical aluminum alloys are presented in Table 7.1.

Heat treatment of aluminum alloys. Heat treatment is particularly important to formation final mechanical characteristics of aluminum alloys. On an example of alloys of the Al-Cu system, we will analyze the influence of heat treatment (hardening and aging) of aluminum alloys with 0.5 <Cu <5.6 % on structure and mechanical characteristics.

When the alloy is heated to a single-phase α-region, the phase dissolution δ-

($CuAl_2$) in the α-phase takes place.

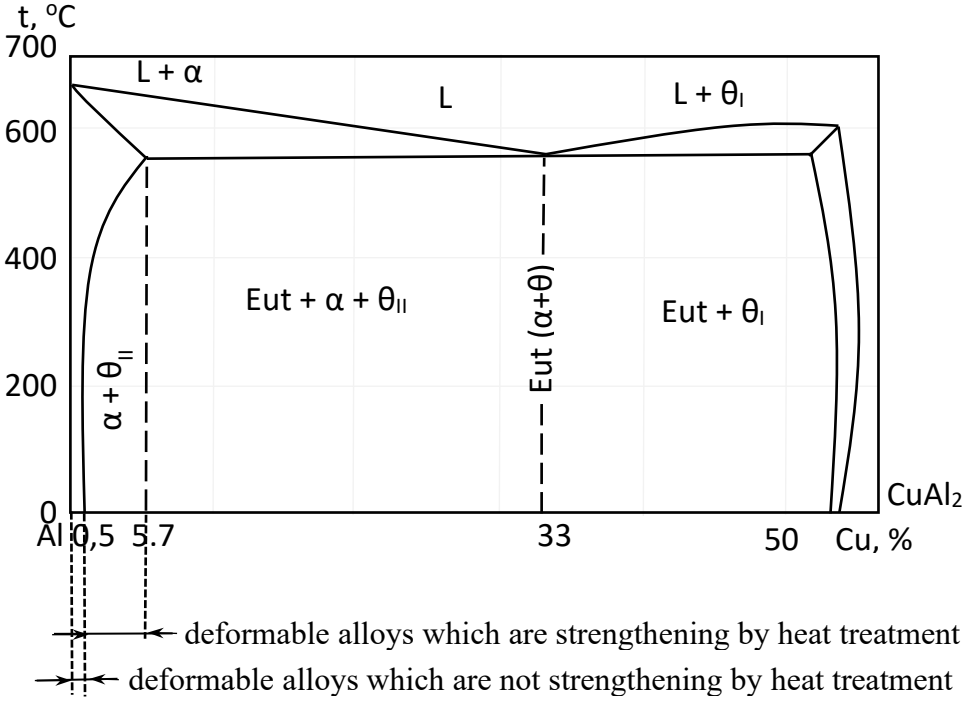


Figure 7.1 – Al-Cu state diagram [1]

Hardening of alloys of the Al-Cu system leads to the formation of unstable supersaturated α-solid solution. Such unstable structure returns to the more stable state over time. However, when the temperature rises, this process can accelerate. But as a result, the structure will be different. In general, 5 stages of change in the structure of hardened aluminum alloys are possible during tempering with different thermodynamic characteristics.

1. The essence of the tempering (aging processes) is that when at long temporal room temperatures (natural aging) or at low temperature heating below 150 ºC (artificial aging), copper atoms accumulate in disordered lamellar formations with diameter of 30 – 60 Å (3 – 6 nm) and thickness of 1 – 2 atomic layers or 5 – 10 Å (0.5 – 1 nm). Such zones are called the Guinier-Preston zones (GP1 zones).

2. In case of long aging or elevated temperature, the GP1 zones are increasing to a diameter of 200 – 300 Å (20 – 30 nm) and thickness of 10 – 40 Å (1 – 4 nm). These zones copper enrichment takes place to the chemical compound θ ($CuAl_2$) and the arrangement of the Cu and Al atoms in the lattice becomes orderly (θ′′-phase).

3. Further, the separation from the solid solution of the intermediate phase θ’ takes place. Such θ′ phase in composition corresponds to θ phase ($CuAl_2$), but has its own lattice coherently connected with the lattice of the α-phase. This stage is the beginning of the collapse of the solid solution.

4. Formation of the θ stable phase ($CuAl_2$) and the violation of the coherence of the lattices of α and θ phases.

5. Coagulation of θ phase particles.

Schematic representation of phase formations during aging of an aluminum-based α-solid solution saturated with copper is shown on figure 7.2.

Table 7.1 – Characteristics of typical aluminum alloys [3]

Alloy grade	Chemical composition, average content of components, %						Mechanical properties		Field of use
	Cu	Mg	Zn	Mn	Si	others	$\sigma_в$, MPa	δ, %	
Deformable aluminum alloys, which do not undergo heat treatment									
АМц	–	–	–	1.4		0.06 Ti	130	23	Tanks, boats shells, dishes.
АМг3	–	3.5	–	0.5	0.065		190	15	
АМг5	–	5	–	0.6			270	18	
Deformable aluminum alloys subjected to heat treatment									
Д1	4.3	0.6	–	0.6	0.8		410	15	Details of airplanes
Д16	4.3	1.6	–	0.6	0.5		520	11	
High strength deformed alloys									
В95	1.7	2.4	6.0	0.4	0.5	–	580	8	Details of planes, missiles
В96	2.5	2.8	8.0	0.4	–	0.22 Cr	670	7	
Forged aluminum alloys									
АК– 6	2.3	0.6	–	0.9			420	13	Pistons
Heat resistant alloys									
АК4–1	2.2	0.6		1.2	0.35	1 Fe, 1 Ni, 0.1 Ti	430	13	Details of planes, missiles
Cast aluminum alloys									
АК12					11		180	5	Cases of electric motors, pistons
АЛ 4		0.2		0.4	9.5		180	2	
АЛ8		10					350	10	
АЛ 9		0.3			7		180	2	
High strength casting alloys									
АМ4.5Кд	4.5	–	–	0.6	–	0.2 Ti, 0.1 Cd	490	6	Details of planes, missiles
ВАЛ12	1	3	6	0.5		0.15 Ti, 0.15 Zr	560	6	Details of planes, missiles
Heat resistant casting alloys									
АЛ1	4.2	1.5				2 Ni	260	0.6	Details of internal combustion engines
АЛ20	4	0.9		0.22	1.7	0.2 Cr, 1.4 Fe, 0.1 Ti	300	0.8	
САП						0.8 Al + 0.2 Al_2O_3	450	1.7	Turbine blades, compressors

Deformable aluminum alloys, which do not undergo heat treatment. These alloys include alloys of the system Al-Mn (group «АМц») and Al-Mg (group «АМг»). These alloys are well treated with pressure, well welded and has high corrosion resistant. The increase in strength is achieved by the hardening. Deformation strengthening of aluminum and its alloys is associated with an increase in the density of dislocations from 10^7 to 10^{11} cm^{-2}.

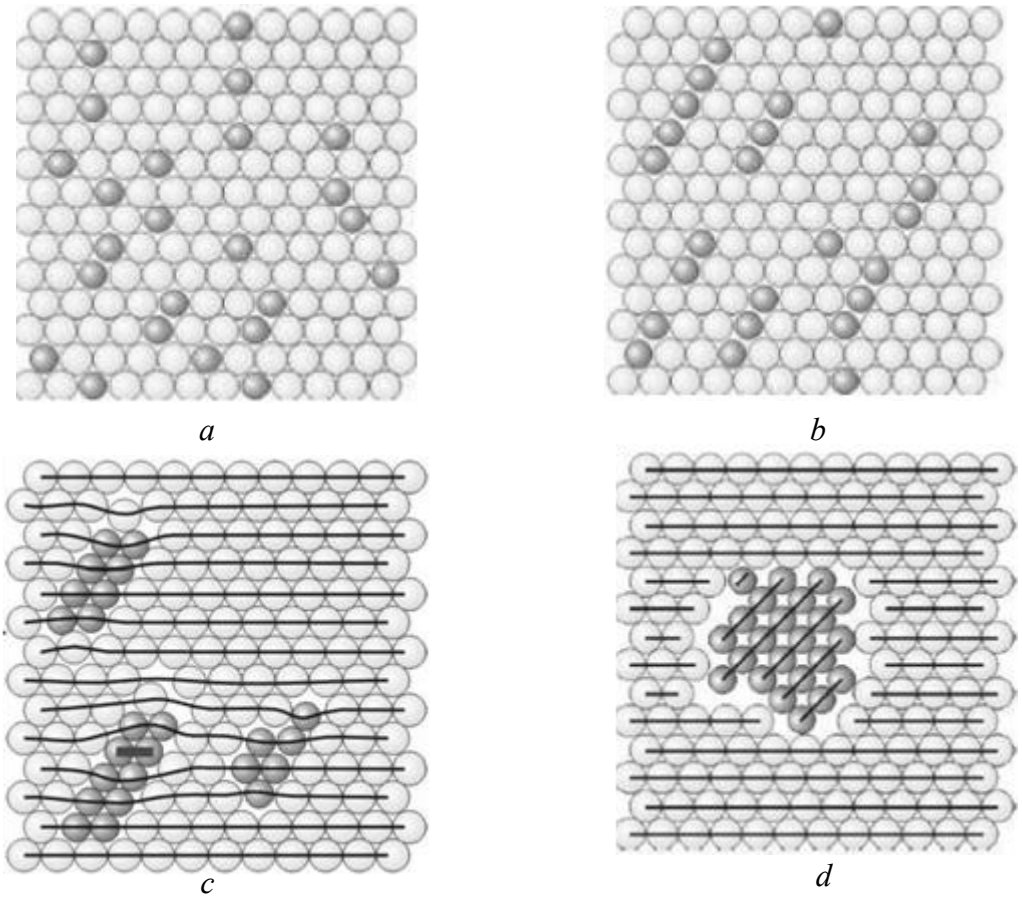
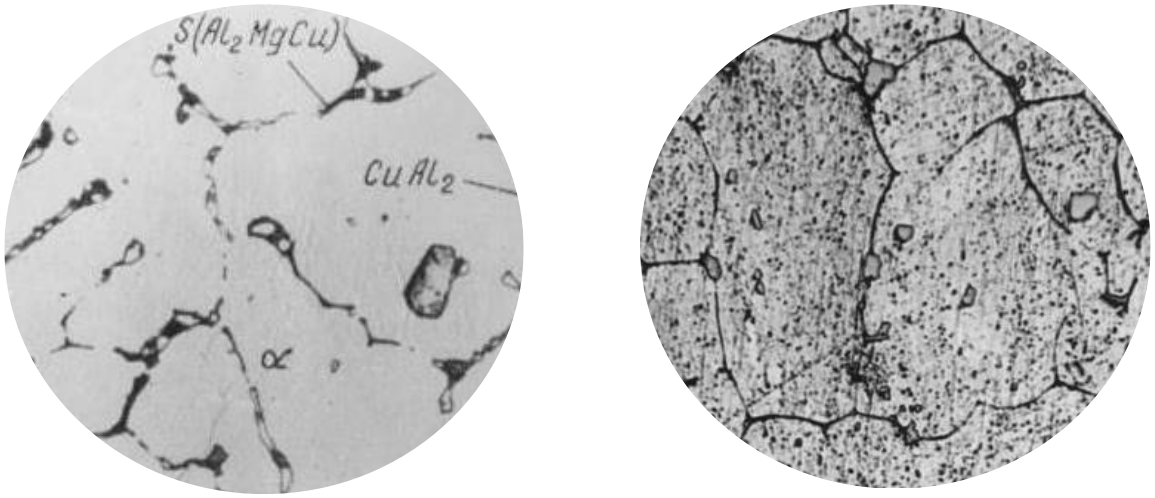


Figure 7.2 – Schematic representation of phase formations during aging of an aluminum-based α-solid solution saturated with copper: *a* – supersaturated α-solid solution; *b* – zone of GP1; *c* – zone of GP2; *d* – stable phase θ ($CuAl_2$)

Deformable aluminum alloys subjected to heat treatment. Such alloys include duralumins, which are complex alloys of the system Al-Cu-Mg or Al-Mg-Zn-Cu. Duralumins have low corrosion resistance, to increase which the manganese is added to the alloy. When aging of duralumins, phases of the type Al_2CuMg (S-phase) or Al_2Mg_3Zn (T-phase) and others are formed (figure 7.3).

Duralumins are subjected to hardening (heating temperature 500 ± 50 ºC) and natural aging, which is preceded by a 2 – 3 hour incubation period. During aging alloys retains high plasticity. Maximum strength is achieved after 4 – 5 days of exposure.

High-strength deformable alloys are alloys which, in addition to copper and magnesium, contain zinc (alloys B95, B96 have $\sigma_в$ = 650 MPa). These alloys are usually subjected to hardening and artificial aging.



a *b*

Figure 7.3 – The microstructure of duralumin Д16 in the cast state (*a*) and after quenching and aging (*b*), x200

Forged aluminum alloys. Forging and stamping from aluminum alloys corresponding to the DSTU and GOST standards marking «АК» or «АКУ». Forging and stamping from aluminum alloys АКУ-1, АК6, АК8 and others are produced at a temperature of 380 – 450 ºС. Forgings are hardened from 500 – 575 ºС and aging at 150 – 165 ºС for 6 – 15 hours.

Addition of Ni, Fe, Ti to alloys increases the temperature of recrystallization and heat resistance of alloys up to 300 ºС.

Cast aluminum alloys. Typical cast (foundry) aluminum alloys are alloys of the Al- Si system (10 – 13 % Si). Such alloys are called silumines. The state diagram will be Al-Si eutectic (figure 7.4). According to the state diagram, silumines can be pre-eutectic, eutectic, and post-eutectic (figure 7.5). The alloying silumines by: Cu, Mg, Zn contributes to increased strength, especially after hardening and aging; Ti, Zr, B, granulates the grains and increases the dispersion of eutectic components; Mn increases corrosion resistance; Ni, Fe increase the heat resistance of foundry aluminum alloys.

Significant increase in the strength of silumines is achieved by modifying the alloy in liquid state by a mixture of salts 2/3 NaF and 1/3 NaCl or 2/3 KF and 1/3 KCl or by 0.05 % Sr. The alloy structure without modification consists of primary silicon crystals and eutectic with a needle shaped form of eutectic silicon crystals. The addition of K, Na, Sr leads to an increase in supercooling, grinding and rounding of eutectic silicon, an increase in the mechanical properties of alloys in the Al-Si system. The nature of the structural changes of the Al-Si alloys in the interaction of the micro-admixtures K, Na, Sr is not finally cleared, but most researchers consider K, Na, Sr to be superficially active elements that can accumulate on the surface of the phases formed during the crystallization process and change them morphology shape the needle to the compact. Addition Na to the alloy leads to the displacement of the state diagram lines in the direction of increasing the concentration

of silicon in the eutectic (to a value of ~ 14 % Si). Therefore, the eutectic or pre-eutectic alloys before modification, (for example AK12, contents Si from 11 % up to 13 %), becomes post-eutectic after modification (figure 7.6).

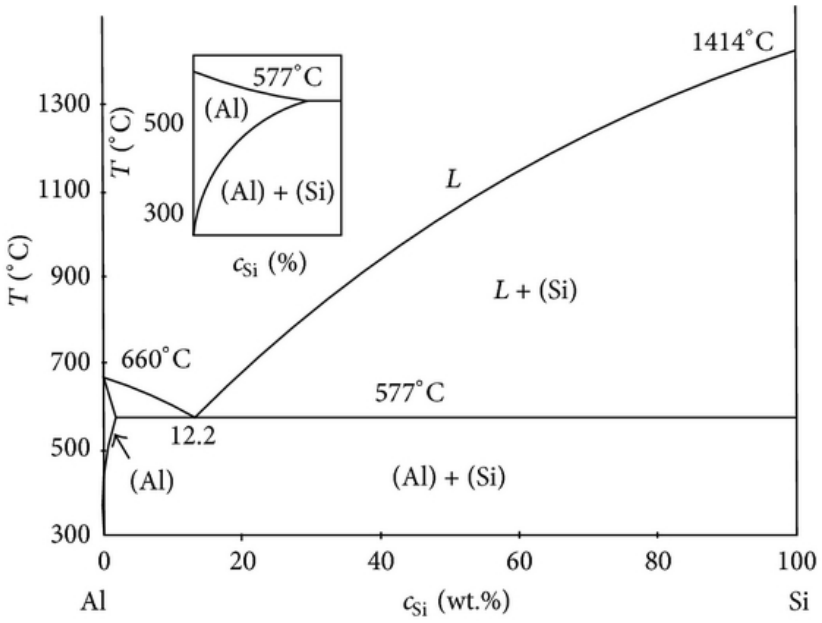


Figure 7.4 – Al-Si state diagram [12]

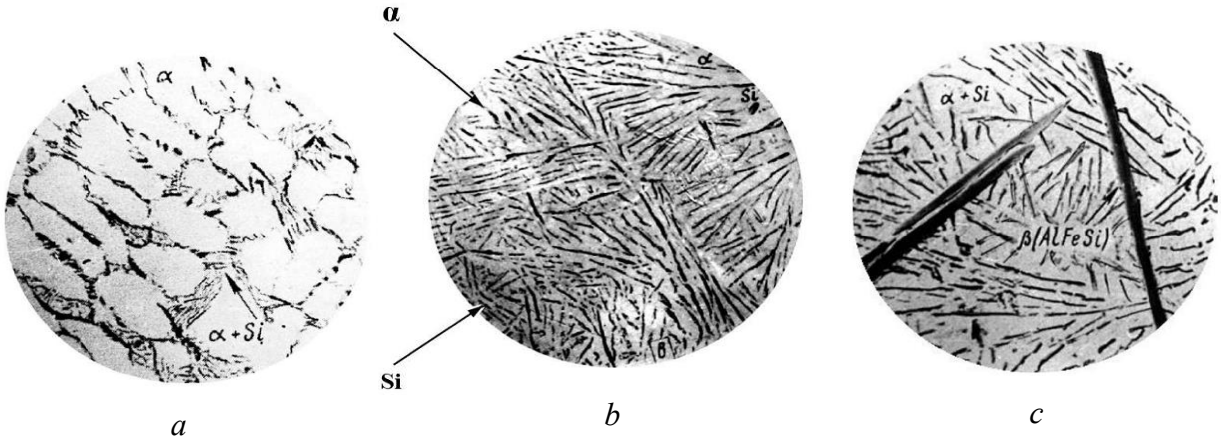
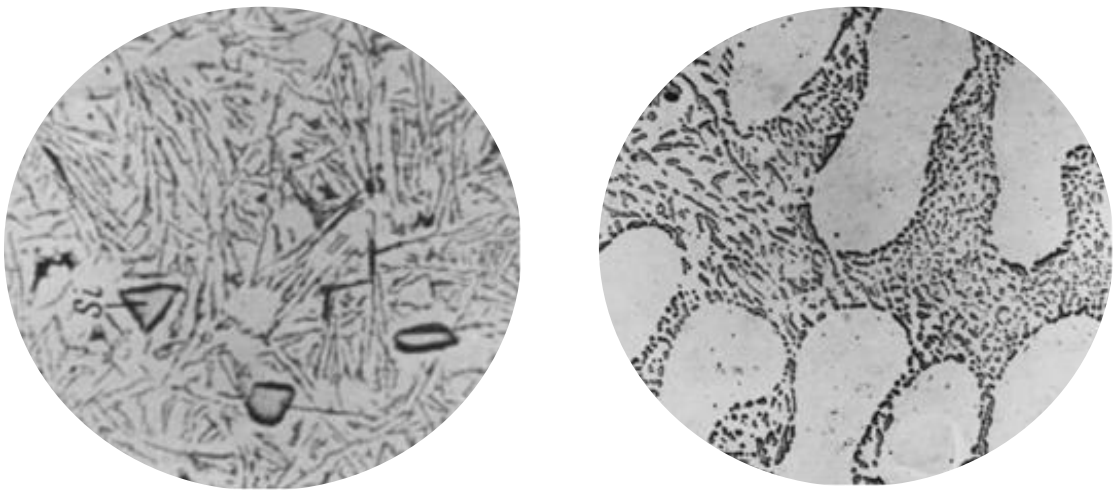


Figure 7.5 – The microstructure of unmodified silumines: *a* – pre-eutectic composition, *b* – eutectic composition, *c* – post-eutectic composition, x200

Marking of aluminum alloys according to world standards

According to European and American standards, aluminum alloys are divided into two large categories: forged and cast. Forged can be machined with different modes. In addition, many alloys undergo heat treatment: quenching and aging.

The Aluminum Association system is best known in the United States. Their alloy identification system uses different nomenclature for wrought and cast alloys but divides alloys into families for simplicity.



a *b*

Figure 7.6 – The microstructure of silumines AK12: *a* – unmodified (the structure of the pre-eutectic composition – needle eutectic and primary silicon crystals), *b* – modified with sodium (the structure of the pre-eutectic composition – light dendrites of α-solid solution and finely dispersed eutectic (α + Si)), x200

For deformable aluminum alloys, a four-digit system is used to create a list of families of deformable compositions as follows:

1xxx: controlled unalloyed composition, used mainly in the electrical and chemical industries;

2xxx: alloys in which copper is the main alloying element, although other elements, such as magnesium, may be specified. Alloys of the 2xxx series are widely used in aircraft, where their high strength is valued (yield strength up to 455 MPa);

3xxx: alloys in which manganese is the main alloying element used as general purpose alloys for architectural applications and various products;

4xxx: alloys in which silicon is the main alloying element used in welding rods and brazing sheets;

5xxx: alloys in which magnesium is the main alloying element used in boat hulls, ladders and other products exposed to the marine environment;

6xxx: alloys in which magnesium and silicon are the main alloying elements, commonly used for architectural extrusion and automotive components;

7xxx: alloys in which zinc is the primary alloying element (although other elements such as copper, magnesium, chromium, and zirconium may be specified) used in aircraft structural components and other high-strength applications. The 7xxx series are the strongest aluminum alloys with possible yield strengths higher than 500 MPa.

8xxx: alloys of different compositions. Alloys of the 8xxx series may contain significant amounts of tin, lithium and/or iron.

9xxx: reserved for future use.

Heat-treatable (precipitation-strengthened) aluminum alloys include 2xxx, 6xxx,

7xxx and some 8xxx alloys. Various combinations of alloying additives and mechanical properties of forged aluminum alloys are shown in table 7.2.

Table 7.2 – Composition and mechanical properties of some forged aluminum alloys according to the International Association of Aluminum Alloys [13]

Aluminum alloy grade	Chemical composition	Method of strengthening	Tensile strength range, MPa
1xxx	Al	Cold processing	70 – 175
2xxx	Al-Cu-Mg (1 – 2.5 % Cu)	Heat processing	170 – 310
2xxx	Al-Cu-Mg-Si (3 – 6 % Cu)	Heat processing	380 – 520
3xxx	Al-Mn-Mg	Cold processing	140 – 280
4xxx	Al-Si	Cold processing	105 – 350
5xxx	Al-Mg (1 – 2.5 % Mg)	Cold processing	140 – 280
5xxx	Al-Mg-Mn (3 – 6 % Mg)	Cold processing	280 – 380
6xxx	Al-Mg-Si	Heat processing	150 – 380
7xxx	Al-Zn-Mg	Heat processing	380 – 520
7xxx	Al-Zn-Mg-Cu	Heat processing	520 – 620
8xxx	Al-Li-Cu-Mg	Heat processing	280 – 560

Commonly used aluminum alloys in the aerospace industry

Aluminum and aluminum alloys are lightweight (about 70 % lighter than steel), strong and have high resistance to corrosion. That why aluminum alloys are particularly useful on aerospace industry. One of the most useful group of alloys on aircraft building that are 1st, 2nd and 3rd generation Al-Li alloys. Most of these alloys have been introduced since last 20 years and their development continues. However, some of the earlier ones have already been used in military aircrafts. These include AA2297 and AA2397, which have been used for Lockheed Martin F-16 bulkheads and other parts (Balmuth 2001; Acosta et al. 2002). Over the last decade several 3rd generation alloys have been qualified for applications in commercial transport aircraft, notably the Airbus A380, and there are ongoing developments (figure 7.7). Alloy producers develop basically similar alloys for different product forms and applications. Figure 7.7 shows that the potential exists for replacing virtually all the current conventional alloys by Al-Li alloys. The most important contribution to this potential is the development of a range of alloy empers that allow optimizations and trade-offs of properties, and hence considerable flexibility in matching the alloys to particular applications. The most common aluminum alloys used for the aerospace applications are: AA2024; AA5052; AA6061; AA7050; AA7068; AA7075; AA2219; AA6063; AA7475.

AA2024. Aluminum alloy 2024 is probably the most widely used alloy for aircraft. It was developed after experiments allowing small amounts of cold deformation and a period of natural ageing led to an increased yield strength.

AA2024 is a high-grade alloy with excellent fatigue resistance. It's used primarily in sheet forms such as for the fuselage and skins due to its high tensile strength of roughly 470 MPa.

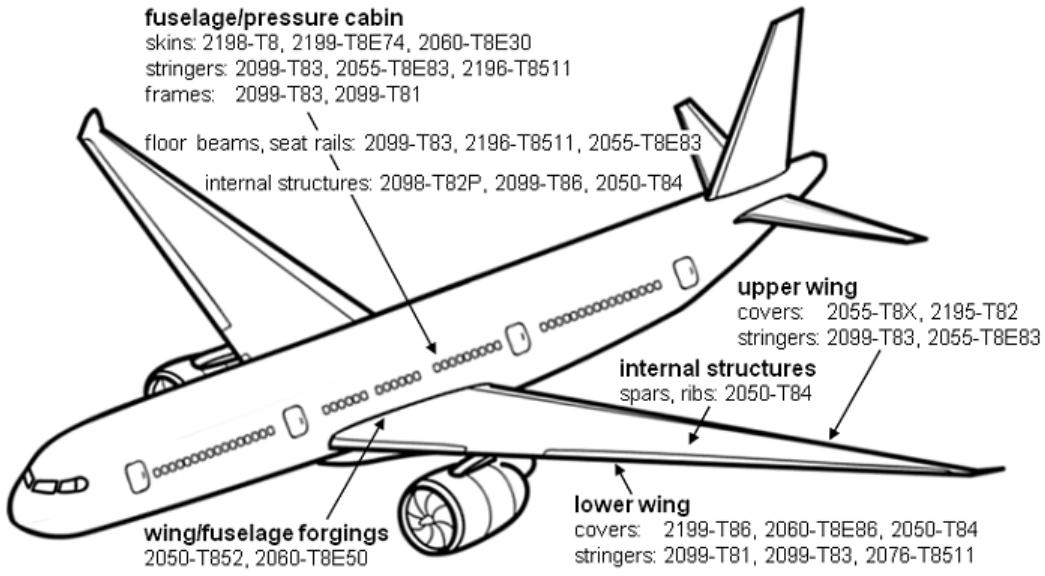


Figure 7.3 – Proposed use of third-generation Al–Li alloys for main structural areas in a transport aircraft [11].

AA5052. Of the non-heat treatable grades of alloy, 5052 provides the highest strength and is highly ductile, so it can be formed into a variety of shapes including engine components and fittings. It is also highly corrosion-resistant.

AA6061. This alloy is quite common in light aircrafts, especially homemade ones. It's easily welded and manipulated, is very light and fairly strong, making it ideal for fuselage and wings.

AA7050. This alloy has high corrosion resistance and maintains strength in wide parts. This makes it more resistant to fractures than other alloys. It's commonly used in wing skins and fuselage, especially in military aircrafts.

AA7068 is the strongest alloy available today. Combined with its low mass, it is perfect for military aircrafts that need to stand up to tough conditions and attacks.

AA7075. With similar strength properties to steel due to high concentration of Zn, 7075 has excellent fatigue resistance. It can be machined easily which meant it was a popular choice for fighter planes in World War II, including the Mitsubishi A6M Zero fighter used by the Japanese Imperial Navy on their aircraft carriers between 1940 and 1945. It is still used frequently in military aircrafts to this day.

Table 7.3 shows mechanical characteristics of useful aluminum alloys on aerospace industry.

Table 7.3 – Mechanical characteristics of useful aluminum alloys on aerospace industry [11]

Aluminum alloy grade	Temper	Density (g/cm^3)	Elastic Modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Fracture toughness (MPa√m)
2014	T6	2.80	72.4	415	485	26.4
2219	T62	2.84	73.8	290	415	36.3
2024	T4	2.77	72.4	325	470	22.0
7050	T74	2.83	70.3	450	510	38.5
7075	T6	2.80	71.0	505	570	28.6

The order of work execution

1. Using the state diagrams of Al-Cu and Al-Si, consider the nature of the phase transformations in useful alloys.
2. Perform the microstructural analysis (magnification x100 – x400 times) of duralumin Д16 in the following states: annealed, after hardening and artificial aging. Draw these structures.
3. To study and draw microstructure (magnification x100 – x400 times) of pre-eutectic silumines before and after modification by Na. Draw the structures of AK12 before and after modification.

Check Questions

1. Give determination of pure aluminum?
2. Which type of heat treatment is useful for aluminum alloys?
3. What is the essence of the aging process?
4. Which alloys are belonged to deformable aluminum alloys, which do not undergo heat treatment?
5. Which alloys are belonged to deformable aluminum alloys subjected to heat treatment?
6. Which alloys are belonged to forged aluminum alloys?
7. Which alloys are belonged to cast aluminum alloys?

The result of the work

LAB NO. 8

TITANIUM BASED ALLOYS

Main goal: to study the structure and properties of technically pure titanium and its industrial alloys. Get acquainted with the classification of titanium alloys and the corresponding modes of heat treatment.

Equipment and materials:

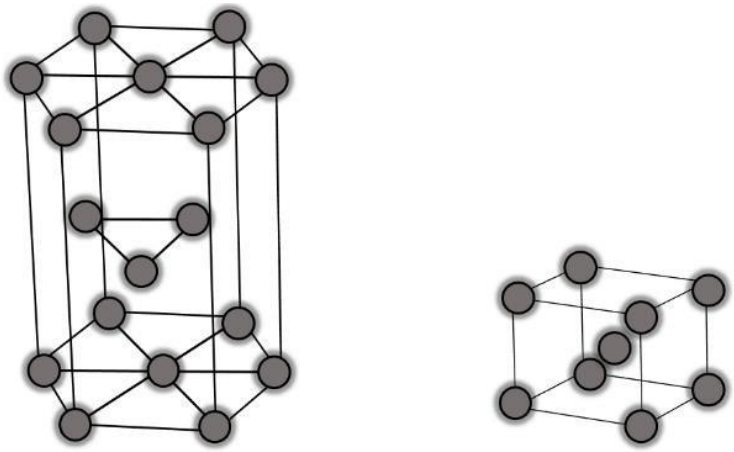
1. Specimens of titanium based alloys.
2. Optical MIM 7 or MIM 6 microscopes.

Theoretical information

Titanium

Titanium refers to relatively light metals (density 4.5 g/cm^3), tensile strength up to 270 MPa, elongation up to 25 %, hardness 100 – 140 HB, melting point 1672 °C and has high corrosion resistance. At heating temperatures above 250 °C, titanium is intensively oxidized.

Titanium has two allotropic modifications: up to 882 °C there are α-Ti with a HCP lattice, and above this temperature – β phase with the BCC lattice (figure 8.1). Polymorphic transformation of β-Ti → α-Ti during slow cooling occurs with the formation of polyhedral grains α-Ti. During rapid cooling in accordance with the martensitic mechanism, a needle structure is formed. To investigation the structure of titanium alloys, to do etching it in 3 % solution of HF and 3 % of HNO_3 in water.



HCP α phase BCC β phase

Figure 8.1 – Image of crystal lattices of α and β polymorphic modifications of titanium

Titanium, unlike other metals with HCP lattice, is characterized by high ductility, which is explained by the presence of a large number of sliding and twinning systems.

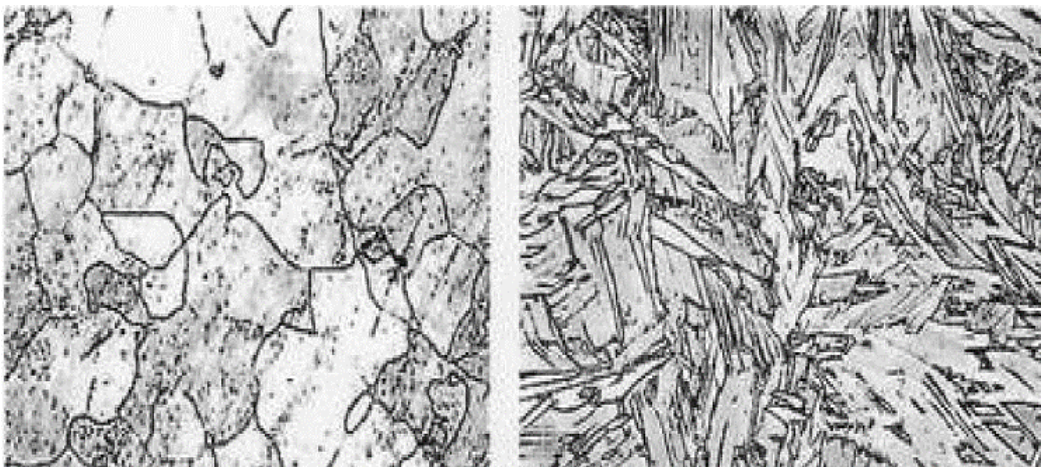
In general, the properties of titanium are affected by the degree of its purity, in particular the presence of hydrogen, oxygen, nitrogen and carbon (affects the embrittlement of Ti and its alloys and reduces ductility). For example, vacuum annealing is used to remove hydrogen from titanium alloys.

Titanium alloys

Titanium alloys corresponding to the DSTU and GOST standards marking «BT». Due to describing the microstructures of the obtained specimens, it should be remembered that titanium alloys according to the structure are divided into:

- α-alloys;
- pseudo α-alloys;
- α+β-alloys;
- pseudo β-alloys;
- β-alloys.

α-alloys (figures 8.2, 8.3 *a*), which have the structure of a solid solution of alloying elements in α-titanium. Technical titanium also belongs to this group. These are alloys of normal strength, with high resistance to destruction at elevated (350 – 500 °C) and cryogenic temperatures. These alloys have great thermal stability, strength and excellent weldability. α-alloys are not strengthened by the heat treatment and are used in an annealed state. The most technological and the most expensive α-alloys are alloys with zirconium. In the hot state, the alloys could be produces by rolling and stamping. α-alloys are supplied in the form of bars, forgings, pipes and wire (BT1-0, BT5, ПТ7М);



a *b*

Figure 8.2 – Microstructure of BT1-0 alloy (technically pure titanium: *a* – after annealing at 680 ºC; *b* – after quenching with 920 ºC in water, x300

Pseudo α alloys (figure 8.3 *b*) have mainly an α-structure, however, due to additional doping with β-stabilizers (Mn, V, Nb, Mo), they contain up to 5 % β-phase. They retain the advantages of α-alloys, and due to the presence of the β-phase, they are

characterized by good technological plasticity. Alloys with a low aluminum content (2 – 3 %) are well processed by pressure in the cold state and only require heating to 500 – 700 °C (OT4, OT4-1) when manufacturing parts of a complex shape.

Alloys with a high aluminum content during pressure treatment require heating to 600 – 800 °C. In addition to aluminum, the heat resistance of pseudo α alloys is favorably affected by zirconium and silicon. In particular, zirconium increases the solubility of β-stabilizers in the α-phase and increases the recrystallization temperature. Silicon forms dispersed silicides that are difficulty to dissolve in the α-phase, and thereby improves heat resistance. Therefore, pseudo α-alloys, with an increased aluminum content (7 – 8 %), alloyed with Zr, V, Mo, Nb and Si, are used to manufacture parts that work at high temperatures.

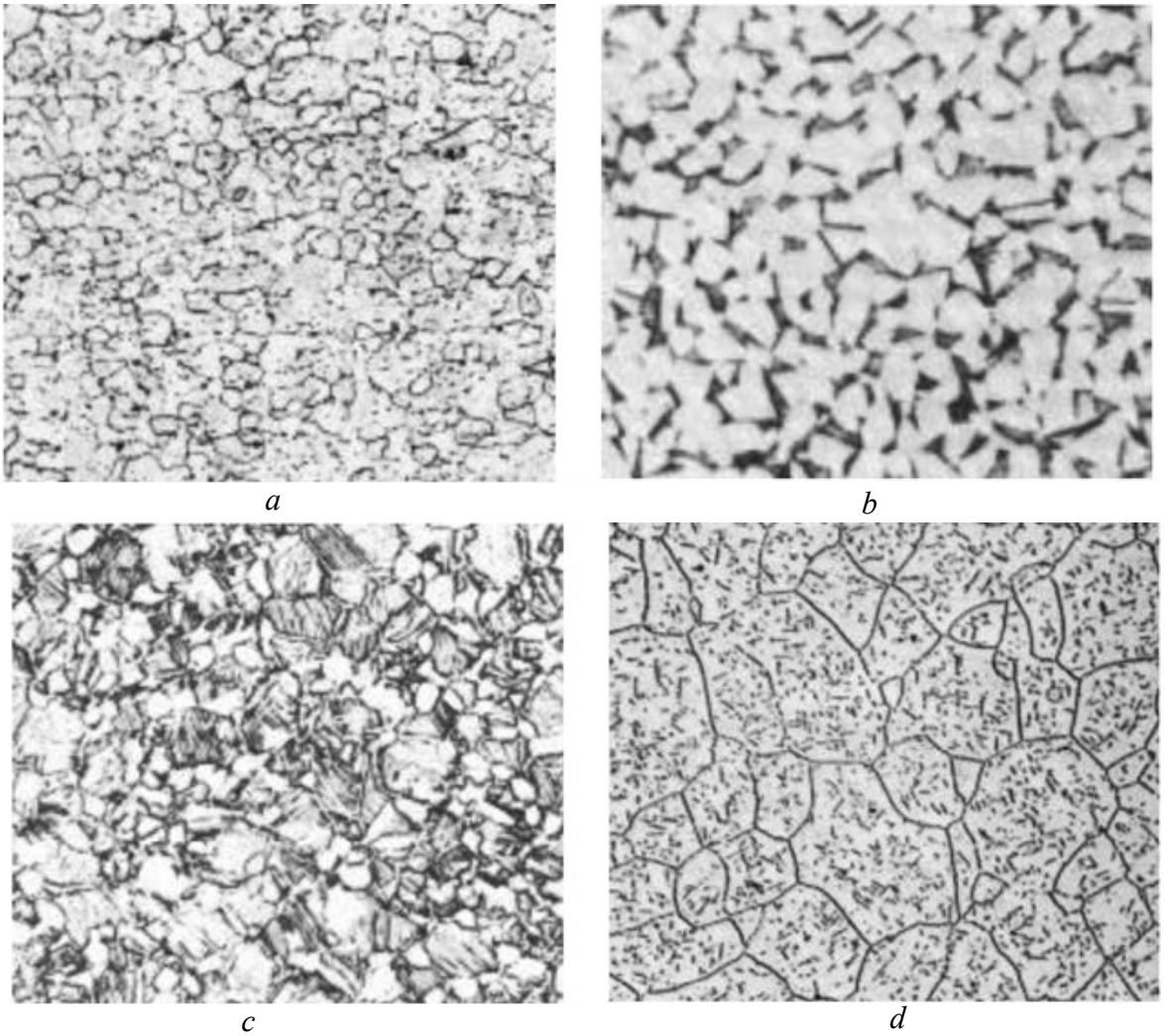


Figure 8.3 – Microstructures of the most common titanium alloys in the annealed state: *a* – α alloys; *b* – pseudo α alloys; *c* – two-phase (α+β) alloys; *d* – pseudo β alloys, x300

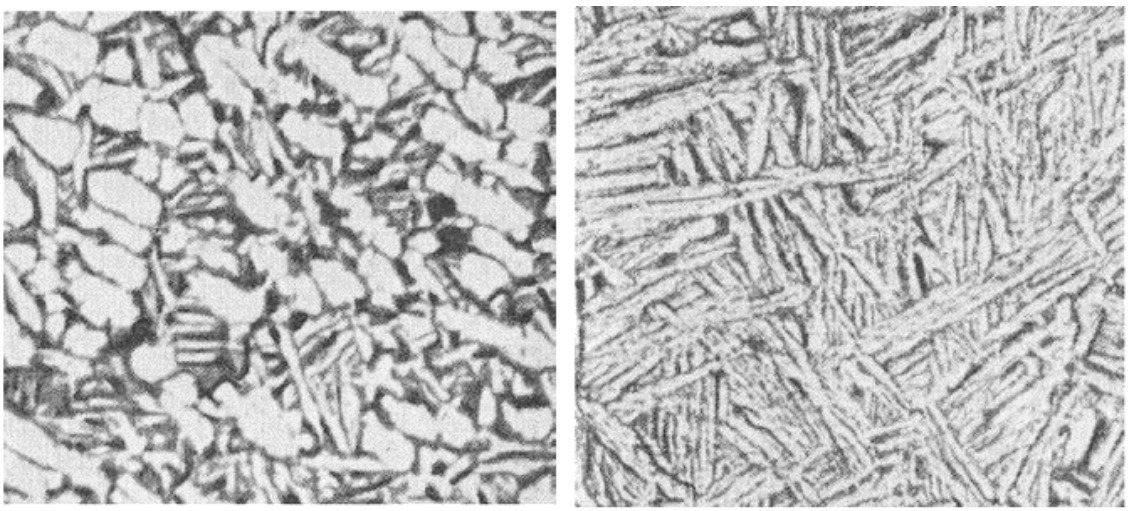
The disadvantage of these alloys is their susceptibility to hydrogen embrittlement. Hydrogen dissolves poorly in the α-phase and is in the form of a hydride phase in the

structure. Hydrides significantly impair plasticity (especially under slow loading) and ductility of alloys. Therefore, the permissible hydrogen content is in the range from 0.005 to 0.01 % (OT4-1B, VT20).

The structure of **two-phase (α+β)-alloys** (figure 8.3 *c*) consists of α and β-solid solutions. Such alloys are mostly alloyed with aluminum and β-stabilizers. Aluminum significantly strengthens the α-phase at room and elevated temperatures, increases the thermal stability of the β-phase, and reduces the density of (α+β)-alloys. This makes it possible to maintain the density at the level of titanium, despite the presence of elements of high density (V, Mo, Cg, Fe, Nb). The greatest strengthening of titanium is achieved by doping with β-stabilizers (Fe, Cg, Mn) and isomorphic stabilizers (Mo, V, Nb). Vanadium and niobium strengthen alloys less than other elements, but they deteriorate plasticity indicators to a lesser extent. Two-phase alloys are strengthened by heat treatment - hardening followed by aging. In the annealed and hardened states, they are characterized by plasticity, and after aging – high strength and heat resistance. In general, the greater the amount of β-phase in the structure of the alloy, the stronger it is in the annealed state and the more it is strengthened by heat treatment.

According to the structure after quenching, two-phase alloys are divided into two classes: martensitic and transition.

Alloys of the martensitic class have a low content of alloying elements (high-strength alloys BT6 (figure 8.4), BT14, BT16 and heat resistant alloys BT8, BT9, BT3-1). In the equilibrium state, their structure includes a relatively small amount of β-phase (5 – 25 %). After quenching, the structure of Martensite α (or α" – in alloys with a greater number of alloying elements) is formed. Figure 8.5 shows the structure of hot-rolled alloy BT3-1 (5.5 – 7.0 % Al; 2.0 – 3.0 % Mo; 0.8 – 2.3 % Cr; Ti), consisting of light α-phase grains and dark β-phase grains of complex composition.



a *b*

Figure 8.4 – Microstructure of BT6 alloy: *a* - after annealing at 730 ºC, *b* - after quenching from 920 ºC in water and aging at 500 ºC during 4h, x300

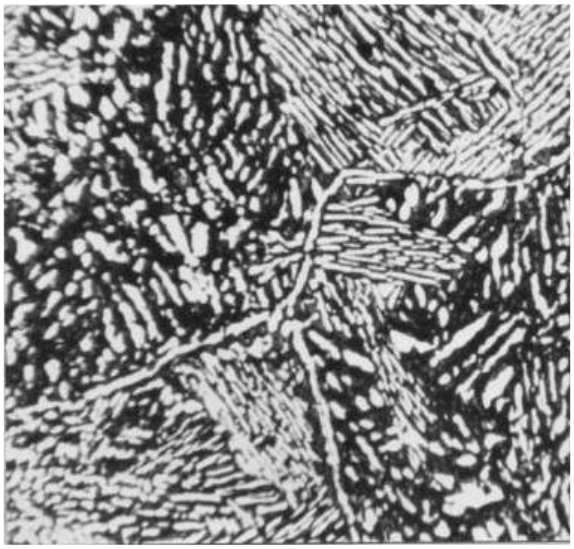


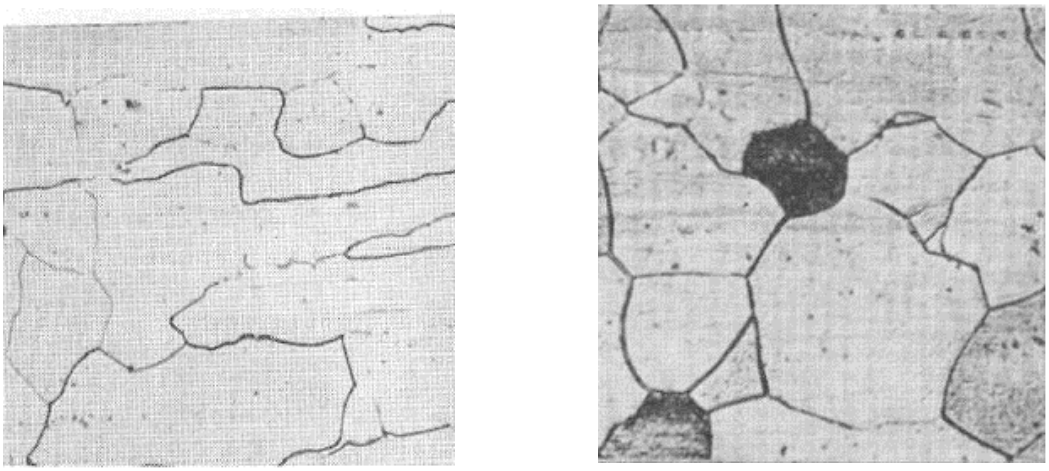
Figure 8.5 – Microstructure of hot-rolled BT3-1 alloy, x300

Alloys of the transition class (BT22, BT30) contain larger amounts of alloying elements. The equilibrium structure of such alloys contains a larger amount of β-phase (25 – 50 %). The structure of these alloys is sensitive to fluctuations in chemical composition and heat treatment modes. In particular, after quenching, in these alloys it is possible to obtain a single-phase undercooled structure or a structure consisting of β-phase and α"-Martensite. The presence of a large amount of β-phase provides the transition class alloys with the highest strength among two-phase (α+β)-alloys. For example, the BT22 alloy (50 % β-phase) after annealing is characterized by the same temporary rupture resistance as the BT6 alloy after strengthening heat treatment (quenching followed by aging).

Pseudo-β alloys (Figure 8.3 *d*) (BT35, BT19, BT15). These are highly alloyed alloys, mainly with β-stabilizers. The total content of alloying elements in them, as a rule, exceeds 20 %. Pseudo-β alloys are most often alloyed with Mo, V and Cr, less often with Fe, Zr and Sn. Aluminum in a small amount (about 3 %) present in almost all alloys. These alloys in the equilibrium state have a predominantly β structure with a small amount of α-phase. After quenching, a supercooled metastable β-phase structure is formed (figure 8.6). This provides great plasticity and good processing under pressure. After aging, the temporary fracture resistance of alloys increases approximately 1.5 times and reaches 1300 – 1800 MPa. The density of the alloys is in the range of 4900 – 5100 kg/m^3, and the specific strength is the highest among all titanium alloys. These alloys are characterized by low susceptibility to hydrogen embrittlement, but are sensitive to impurities: the presence of oxygen and carbon leads to deterioration of plasticity and ductility; welds have reduced plasticity.

Single-phase β-alloys are not of industrial importance, because in order to obtain a stable β-structure, the alloys have to be alloyed with a large number of expensive and

scarce isomorphic β-stabilizers (V, Mo, Nb, Ta). In addition, such doping leads to an increase in density.



a *b*

Figure 8.6 – Microstructure of BT15 alloy (pseudo β-alloy): *a* - after quenching from 920 ºC in water, *b* - quenching from 750 ºC in water and aging at 450 ºC during 2h, x300

Titanium and α-titanium alloys are subjected only to recrystallization annealing, and α+β-alloys can be strengthened by hardening with subsequent aging.

The presence of high temperature modification of β-solid solution in titanium alloys, capable of significant supercooling, causes the production of various structures depending on the modes of heat treatment. The polymorphic β → α transformation can have two different mechanisms. At high temperatures, i.e., with the small supercooling of the equilibrium β → α transition temperature, transformations occur by the usual diffusion mechanism. And at significant supercooling, therefore, when the mobility of atoms is small, according to the non-diffusion martensitic mechanism.

In the first case, a polyhedral structure of α-solid solution is formed, in the second – needle (plate) Martensite structure, denoted as α'. Alloying elements that reduce the conversion temperature contribute to the formation of Martensite. At low alloying, this requires intensive detail cooling. At the very high β-stabilizers concentration, the conversion temperature is reduced to zero and the β-solid solution is cooled to room temperature without transformation. The formation of Martensite in titanium alloys, in comparison with the hardening of carbon steel, is accompanied by a relatively low increase in strength.

Additional alloying can increase the strength of titanium alloys up to three times and, in some cases, corrosion resistance. In industrial titanium alloys, the main alloying element is aluminum. A whole group of welded alloys has been developed on the basis of the Ti-Al system. Other important elements are vanadium and molybdenum. High-strength titanium alloys are based on the triple Ti-Al-V system.

According to the influence on the temperature of polymorphic transformation of titanium alloying elements are divided into four groups:

• neutral hardeners (Sn, Zr, Ge, Hf, Th) practically do not affect the temperature of polymorphic transformation of alloys;

• α-stabilizers (A1, O, N, C) which increase the conversion temperature of alloys;

• β-isomorphic stabilizers (Mo, V, Nb, Ta), reduce the conversion temperature of alloys to room temperature;

• β-eutectoid stabilizers (Cr, Mn, Fe, Co, Ni, Cu, Si, H).

The basis of titanium alloys are solid solutions based on two polymorphic modifications of titanium. In addition, the structure of the alloys may contain carbides, hydrides, silicides etc.

According to the structure in the normalized state, industrial titanium alloys are divided into three main groups: α-, α+β- and β-alloys. In industry, alloys with the α and α+β structure are most useful. All industrial titanium based alloys contain aluminum. Ti-Al binary system is shown on figure 8.7. Aluminum increases the tensile strength but reduces the ductility of alloys.

Industrial titanium alloys are divided into deformable and foundry in terms of technological properties (the use of the foundry is limited, as titanium actively interacts with gases and molding materials). Technical titanium grades BT1 and BT2 are made in the form of semi-finished products (sheets, rods, tapes and forgings).

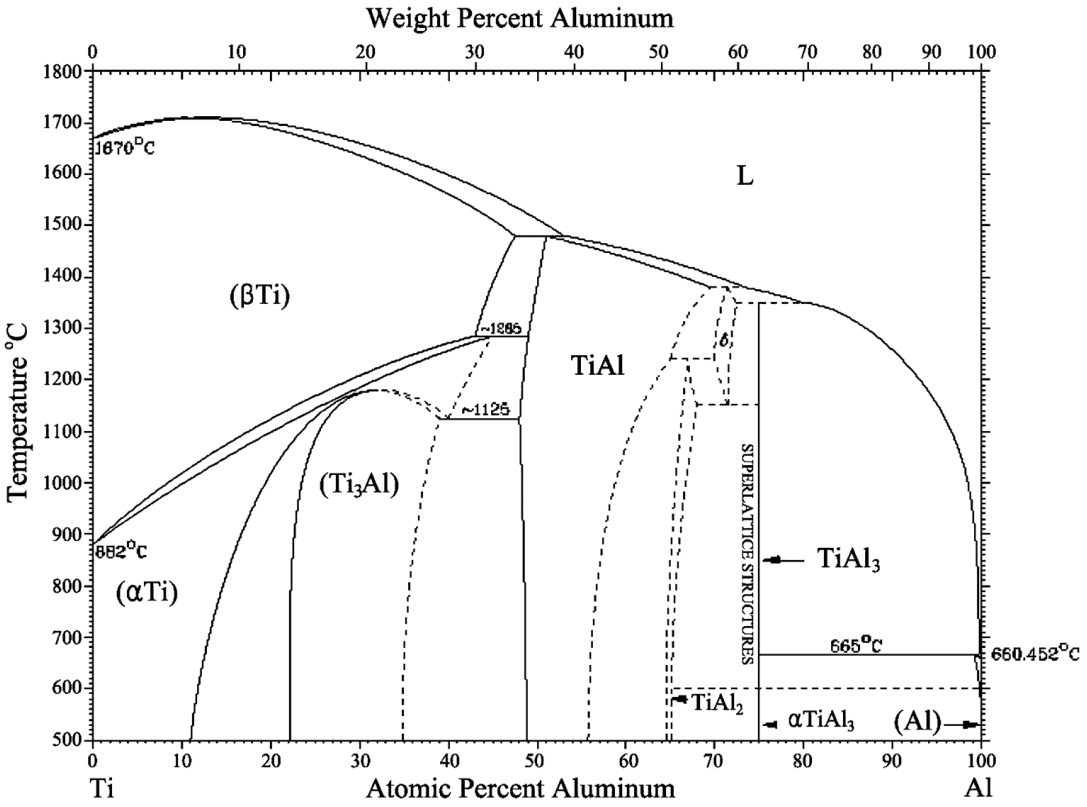


Figure 8.7 – Diagram state of Ti-Al [14]

Deformable titanium alloys include alloys BT6, BT8, BT5-1, BT15 and others. BT5-1 alloy is a deformable single-phase alloy with α-structure. It contains 5 % Al and

2.5 % Sn. The alloy is made in the form of sheets, rods, forgings and extruded products with the wide temperature range of application (from cryogenic to 450 °C). The structure of the alloy after deformation and annealing in the α-region consists of equilibrium polyhedral grains. The structure with irregularly shaped toothed grains is characteristic of the alloy after hot pressure treatment in the β-region and subsequent annealing in the α-region. The coarse-grained structure of the plate type with clear β-grain boundaries is formed after deformation of the alloy in the β-region, followed by the heat treatment in the same region.

Deformable alloy BT3-1 in composition coincides with the composition of the casting alloy BT3-1JI and is designed for long-term operation at 400 – 450 °C. Letter «Л» at the end means that the alloy is foundry. It is used to make rods, profiles and forgings. BT3-1 alloy is subjected to annealing, after which it acquires a (α+β)-structure with a content of 15 % β-phase. After annealing, aimed at stabilizing the structure and properties, the alloy consists of a light α-phase and a dark-colored β-phase with the release of its dispersed α-phase, which can only be seen at high magnifications in an electron microscope. If the alloy was overheated, then there is a structure of course "basket weave". In this structure, the boundaries of large grains of the transformed β-phase are clearly visible, inside of which light areas of the α-phase are visible along the perimeter.

High-alloyed and thermally strengthened alloy BT15 contains 3 % A1, 8 % Mo and 11 % Cr. In the annealed state, the structure is two-phase. After hardening from the β-region, its structure consists of light grains of the metastable β-phase. After aging, dispersed particles of the α-phase are formed inside the β-grains, which are visible only at high magnifications. This two-phase mixture is intensively etched and therefore looks dark under the microscope.

Two-phase α+β-alloy brand BT14 is subjected to hardening from 860 – 880 °C in water and subsequent aging at 480 – 500 °C for 12 – 16 hours.

The peculiarities of the structure of titanium alloys in the cast state are due to two reasons: significant overheating of the melt and low cooling rate. For this reason, cast titanium alloys have the coarse-grained structure. An increase in the concentration of alloying elements in alloys and a decrease in overheating during casting is accompanied by the formation of finer structures.

More technical titanium grade BT1Л (α-alloy) is used to obtain precise shaped castings of corrosion resistant fittings for chemical production. In the polymorphic transformation β→α and in the case of slow cooling, α-titanium is formed in the form of plates.

Binary casting alloy BT5Л (α-alloy) as an alloying element contains 5 % A1. The alloy has a narrow crystallization interval and rarely increased fluidity and is used for

injection molding. The structure of the alloy consists of α-phase plates.

ВТ3-1Л alloy is a two-phase hard-alloyed metal with the significant content of β-phase. It contains 6 % A1, 2.5 % Mo, up to 2 % Cr, 0.3 % Si, 0.2 % W, 0.5 % Fe, 0.5 % Zr and up to 0.15 % C. The alloy is characterized by high heat resistance and is used for manufacturing cast parts of aircraft engines operating at elevated temperatures. The structure of the alloy is characterized by the presence of relatively large initial α-grains, which have a thin layer of β-phase around the perimeter.

The most useful Ti-based alloy used in aircraft manufacturing is Ti-6Al-4V alloy (UNS R56400 or ASTM Grade 5), there are 50 % of whole titanium and titanium alloys production. Typical impurities content: O (0.2 %); N (0.04 %); H (0.015 %); Cu (0.35 – 1 %); Fe (0.35 – 1 %). Density: 4.54 g/cm^3. Mechanical characteristics of Ti-6Al-4V: yield strength (830 – 1100 MPa); ultimate tensile strength (895 – 1250 MPa) (higher content of O, N and C increases strength but decreases formability); high cycle fatigue (550 – 700 MPa); elastic modulus (120 GPa); creep resistance (up to 400 °C). Ti-6Al-4V alloy is used in for production of structural and engine parts of airplanes. That is because Ti-based alloys have higher specific strength and fatigue performance than Al and Fe alloys, moreover titanium alloys have higher corrosion resistance. 20 – 30 tons of total Boeing 747 (Jumbo Jet) mass, out of 180 tones, consist of titanium based alloys, and the vast majority of it is an alloy Ti-6Al-4V.

High-temperature Ti-alloys. The aim is to suppress creep is decrease diffusivity of part. Such alloys have smaller ratio of β-phase (5 – 10 % vs. 15 % in the Ti-6Al-4V). Increasing temperature led to dissolution of Ti_3Al particles (decreased strength). Maximum working temperature of such alloys is up to 550 °C (titanium IMI 834 alloy). Chemical composition of IMI 834 alloy: 5.8 % Al, 4 % Sn, 3.5 % Zr, 0.7 % Nb, 0.5 % Mo, 0.35 % Si, other is Ti. Such types of alloys mainly are used in production parts of airplanes engines and APU (auxiliary power unit).

The order of work execution

1. To study the classification of titanium alloys: by manufacturing technology, by mechanical properties, by the ability to be reinforced by heat treatment, by structure. The principle of marking of titanium alloys is considered.
2. To study the structure of titanium and titanium alloys in the cast state, after annealing and plastic deformation.
3. Draw structures and label structural components:
   – Microstructure of titanium alloy BT1-0 (after annealing at 680 °C; after hardening from 920 °C in water);
   – Microstructure of titanium alloy BT6 (after annealing at 730 °C; after hardening from 920 °C in water and aging at 500 °C, 4 hours);

– Microstructure of titanium alloy BT15 (after hardening from 920 ºC in water; hardening from 750 ºC in water and aging at 450 ºC during 2h).

Check Questions

1. Determine the characteristics of titanium.
2. Describe the structure of β-titanium.
3. Which types of titanium-based alloys do you know?
4. At what temperature is the polymorphic transformation of α-Ti → β-Ti occurs?
5. What is the main alloying element in industrial titanium alloys?
6. List the alloying elements that reduce the temperature of β-Ti → α-Ti transformation.
7. What should be done to obtain the finer grain structure titanium alloys in the cast state?
8. What is the chemical composition of the alloy BT15?

The result of the work

LAB NO. 9

AEROSPACE COMPOSITE MATERIALS

Main goal: to study the main types of structure of composite materials, in particular for aerospace purposes. To learn the typical structures and main properties of composite materials.

Equipment and materials:

1. Specimens of composite materials.
2. Optical MIM 7 or MIM 6 microscopes.

Theoretical information

Composite materials (CM) are such complex materials that consist of two or more components (matrix and reinforcing fillers), which differ significantly in their properties and do not dissolve when they are combined, and therefore have clear boundaries. The forces of interatomic interaction act between the structural components of such materials, which does not lead to the formation of extraneous substances during operation. CM in terms of specific strength, stiffness, strength (including for certain types also at high temperatures), resistance to fatigue loads and high manufacturability significantly prevail over many metal alloys. The appropriate level of properties for products made of composites can be formed at the stage of their design and implemented during their manufacture in the form of a part or product ready for further use.

The properties of CM are determined by the characteristics of the elements from which it is composed. The matrix provides stability of the shape and dimensions of the product. It takes on the external load and distributes it to all elements of the filler, protects them from external mechanical and chemical influence. The matrix will also determine the corrosion resistance of the composite and the temperature range of its usage.

According to their properties, all CM's are divided into two main groups – reinforced and those that have a special set of properties that are absent in natural materials. Composite materials are divided by the type of base into CM with a non-metallic matrix and CM with the metallic matrix. According to the type of reinforcing filler, CM's are divided into powder (of organic or mineral origin), fibrous and layered (figure 9.1).

CM with powdered fillers (figure 9.1 *a*) are characterized by isotropic characteristics, relatively low mechanical strength and relatively low impact toughness. CM with fibers fillers (figure 9.1 *b*) is characterized by the fact that the fibers will be strengthening components. So, strength, stiffness, heat resistance, vibration resistance

and other properties will depend on properties of fibers. Fiber orientation can be uniaxial, multidirectional biaxial, and multidirectional multi-axial volumetric.

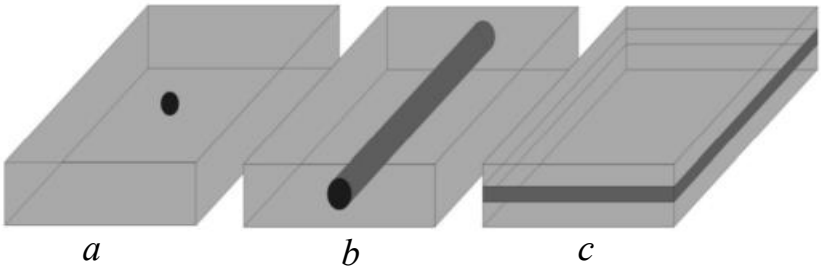


Figure 9.1 – Schematic distribution of CM by type of reinforcing filler:
a - powdery; *b* - fibrous; *c* – layered [15]

Layered CM (figure 9.1 *c*) are mainly related to strength structural materials. Sheet filler laid in layers will give them anisotropy or quasi-isotropy characteristics. In CM with a layered filler represented by sheets of matter, fibers, threads and tapes can be located either parallel to each other in the plane of laying or be located at each layer at some angles (figure 9.2). In the first case, the properties will be anisotropic, in the second - quasi-isotropic.

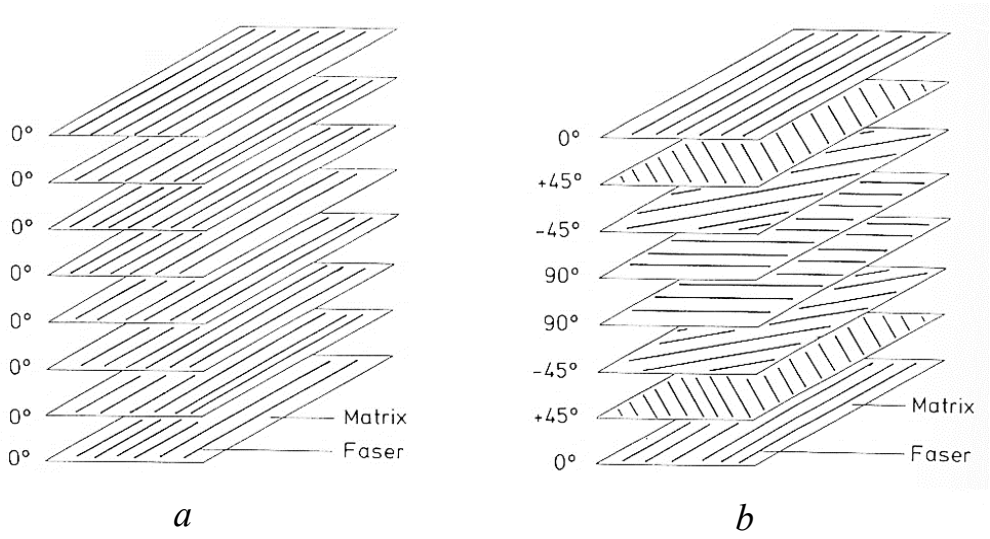
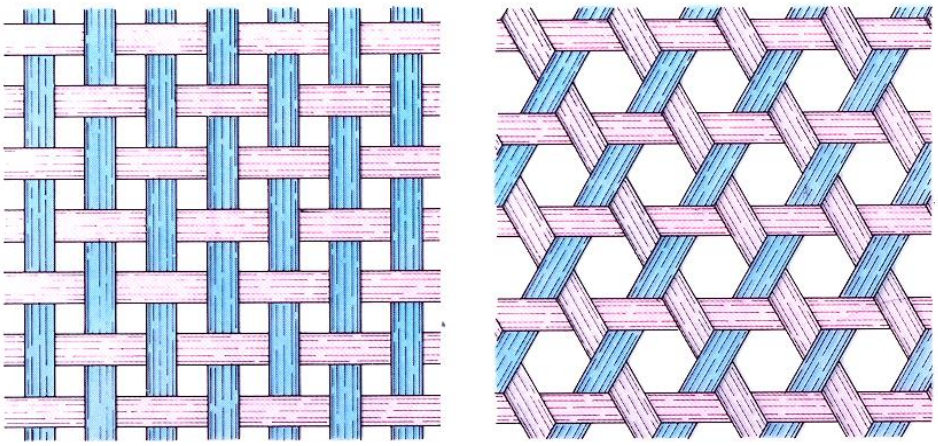


Figure 9.2 – Orientation of fibers in the layers of matter of the composite material
a – anisotropic properties; *b* – quasi-isotropic properties [16]

CM's with a non-metallic matrix can have a variety of polymeric, carbon, ceramic or even metallic materials as a base (matrix). From the group of polymer materials, epoxy, phenolformaldehyde and polyimide are most often used. Carbon matrices can be coked or pyrocarbon. Such carbon matrices are obtained by pyrolysis of carbon containing synthetic polymers. In this case, reinforcing fibers are used in the form of monofibers, tapes or meshes of various weaves (figure 9.3).



a *b*

Figure 9.3 – Schemes of reinforcement of layered composite materials
a-bidirectional; *b*-three-directional [15]

Among the most common non-metallic matrix composites in aircraft construction are fiberglass, carbon fiber, organoplastics and boroplastics.

Fiberglasses. Glass plastics are polymers filled with glass fibers (figure 9.4). Fiberglass can be thin (3 – 10 microns in diameter), medium (30 – 50 microns) and thick (150 – 200 microns). In the composite, it can be located in the form of individual fibers, bundles, threads, nets, fabrics, tapes, etc. By studying the macrostructure of a fiberglass product, you can determine the type of reinforcing filler. By studying the structure under a microscope, you can determine the shape and size of the elementary fibers. The shape can be solid or hollow, cylindrical, triangular, square, rectangular, hexagonal, ribbon, etc. It is quite difficult to visually determine the material of the matrix, and therefore chemical analysis and physical research methods are used. Most often, thermosetting binder materials (polyester, epoxy, phenolic, polyimide resins, etc.) are also used in the production of fiberglass, as well as thermoplastic polymers (polyethylene, polypropylene, polystyrene, polyamides, fluoroplastics, etc.). Fiberglasses are characterized by high anticorrosion and electrical insulating properties, high tensile and bending strength, medium hardness, radiolucency, resistance to variable loads, and sufficient thermal insulation properties.

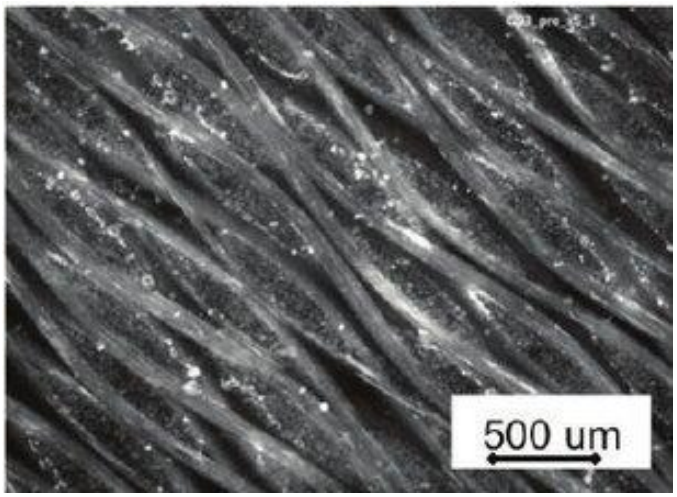


Figure 9.4 – Melamine matrix fiberglass [17]

Carbon plastics are polymers filled with carbon fibers (figure 9.5). On an industrial scale, carbon fibers are obtained by the method of pyrolysis in

an environment of inert gases of the original organic fibers. Carbon (graphite) fibers have a small diameter (6 – 12 μm) round or oval cross-section and can be found in the composite in the form of threads, bundles, ribbons, fabrics, etc. Carbon or graphite fibers, due to their low density (1900 kg/m^3), have very high specific characteristics of strength and stiffness. In terms of thermal and electrical conductivity, carbon plastics approach metals, have exceptionally high thermal resistance and chemical resistance to the most aggressive environments. Carbon fibers have a very low coefficient of thermal expansion, which makes it possible to make structures of high dimensional stability from carbon plastics. A significant disadvantage of carbon fibers is their low surface energy, due to which it is poorly wetted by polymeric binders. This result in the lower shear strength of the composite. Thermosetting and thermoplastic binders are used as matrices for carbon fibers.

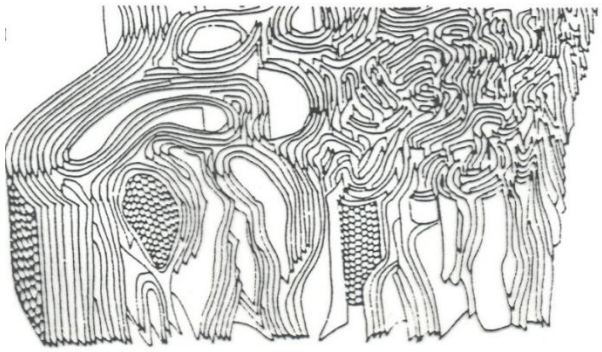


Figure 9.5 – Schematic representation of carbon fiber [18]

Organoplastics are composites consisting of polymer fibers and the polymer matrix (figure 9.6). Polymeric fibers can be natural (cotton, viscose) or synthetic (Capron, mylar, nylon, etc.). Matrices can be thermoset, capable of cold curing or at temperatures that do not lead to loosening of the fibers. Among this group of CM, organoplastics based on fibers from aromatic polyamides and an epoxy binder are of the greatest importance for aviation and space products. Reinforcing fibers have a diameter

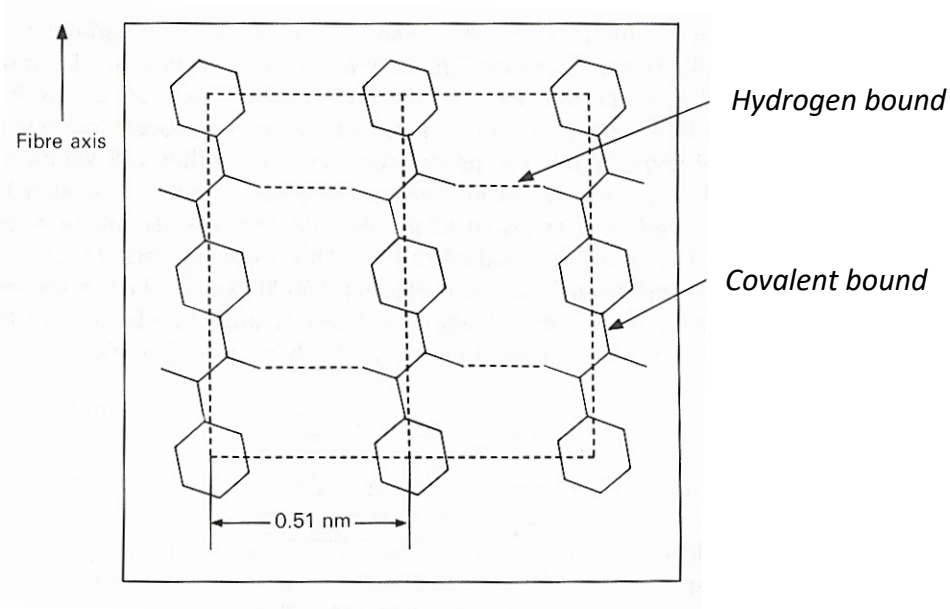


Figure 9.6 – Structure of aramid fibers typical Kevlar 49 [19]

from 10 to 12 μm and are characterized by the highest value of strength and modulus of elasticity among organic fibers at the density which does not exceed 1450 kg/m^3. In comparison to fiberglass or carbon fibers, they are less brittle, have higher chemically resistant to organic solvents and petroleum products, have high electrical resistance and heat-insulating properties. In the structure of organoplastics, aramid fibers can be contained in the form of threads, bundles, fabrics, knitwear, etc.

Boroplastics are polymers that are filled with boron fibers (figure 9.7). Boron fibers differ from those considered above by a relatively large diameter (100 – 200 μm), high stiffness and bending strength, uneven composition in the cross-section. The core of the fiber with the diameter of 12 to 14 μm consists of tungsten or carbon, behind which there is a transition layer of intermetallic, and then there is a fibrous body consisting of boron. Boron fibers have increased thermal and electrical conductivity. Thermosetting resins are mainly used as binders in the production of boroplastics: epoxy, polyester, phenol formaldehyde, etc. Boroplastics are used in structures with high compressive or bending stresses at normal or elevated temperatures. Boroplastics are very expensive, so it is more rational to use boron fibers as part of polyreinforced (hybrid) composite materials. Such composites can contain fibers of various combinations and quantitative ratios, combining all the best qualities of each of them. In addition to those considered above, polymer composites are used, which are additionally reinforced with metal wire or ceramic fibers.

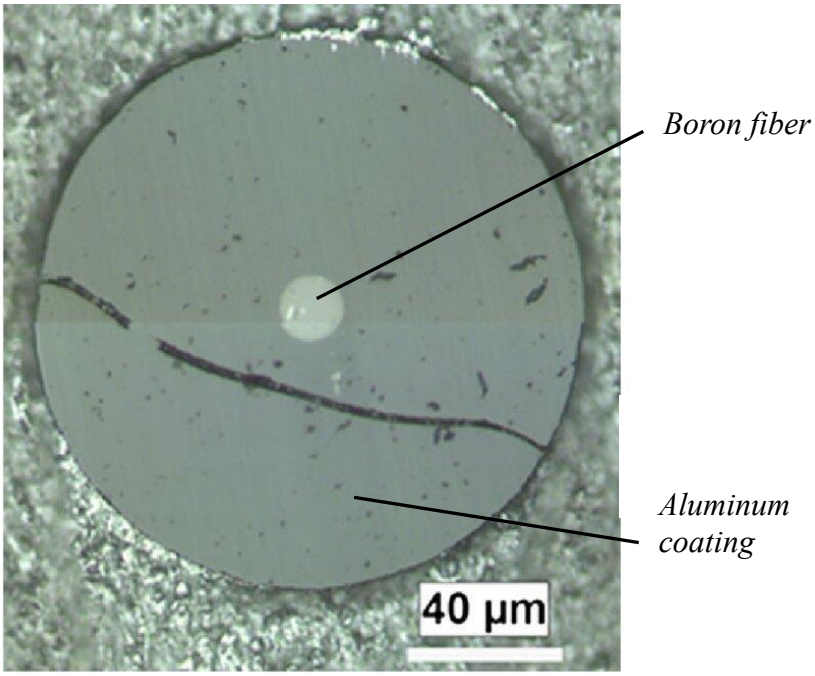


Figure 9.7 – Cross-section of a boron fiber after 10 min of immersion in molten aluminum containing 500 ppm Ti at 740 °C [20].

Technical ceramics. The ceramic matrix, depending on the composition, allows

to obtain ordinary or technical ceramics. Ordinary ceramics include silicates (SiO_2), and technical ceramics include various oxides, carbides, nitrides, borides, silicates, and sulfides. Technical ceramics are used for the manufacture of gas turbine blades, cylinder blocks of internal combustion engines, liners and nozzles of powder and some liquid jet engines, heat resistant wing edges, etc. (figure 9.8).

Figure 9.8 – Products from ceramic [21]

Metal composites with the metal matrix consist of technically pure metals or alloys, which are reinforced with heat resistant, high strength and high modulus fibers of two types: continuous or discrete. An important requirement when creating such composites is the absence of diffusion processes between the matrix and the filler, as their presence can lead to a decrease in the strength of the material. Discrete fibers are randomly arranged in the matrix, their diameter ranges from a few tenths to hundreds of micrometers. As the ratio of fiber length to its diameter increases, the degree of strengthening of the composite increases. Such fibers primarily include carbon, boron, ceramic fibers, as well as wire made of high strength alloyed steels and refractory metals (Ti, W, Mo, Nb, Be, etc.).

For example, molybdenum wire, sapphire fibers, silicon carbides and titanium boride are used to reinforce titanium based alloys. Boron and carbon fibers protected from oxidation, high strength fibers based on carbides, nitrides, borides and oxides, and wire made of high strength steels are used to strengthen alloys based on aluminum or magnesium. This aluminum based metal composites are the most widely used in aerospace engineering. They are significantly superior to non-reinforced aluminum alloys in terms of specific strength, stiffness and heat resistance and have a maximum operating temperature of up to +500 ºC. The scheme of manufacturing an air-cooled turbine blade from reinforced super alloy you can see on figure 9.9.

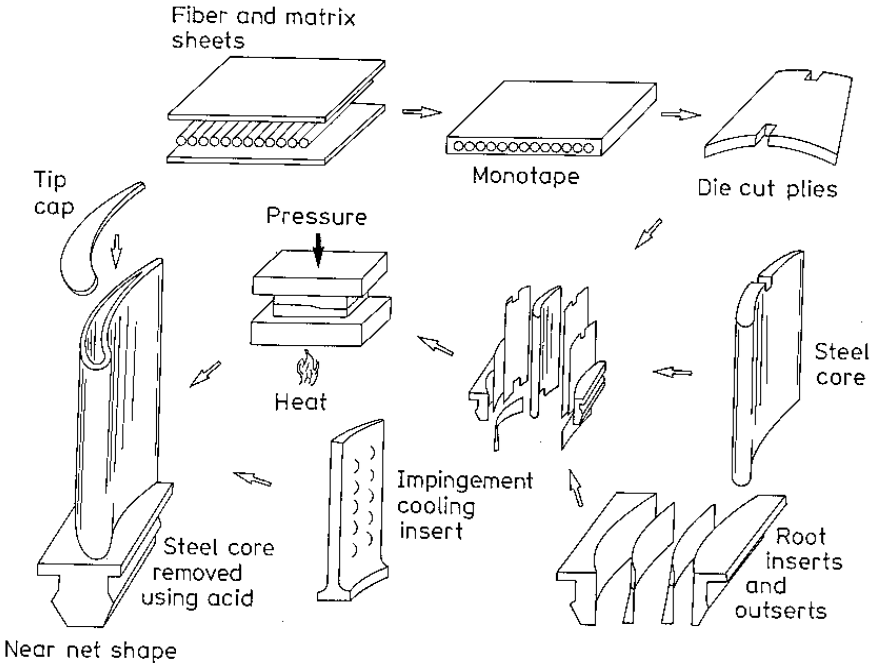


Figure 9.9 – Scheme of manufacturing an air-cooled turbine blade from reinforced super alloy [15]

In addition, it should be noted a group of metal composites, which consist of evenly distributed finely dispersed refractory particles in a metal matrix (dispersion-strengthened materials). The high strength of such composites is achieved when the size of the dispersed particles is from 10 to 500 nm and the average distance between them

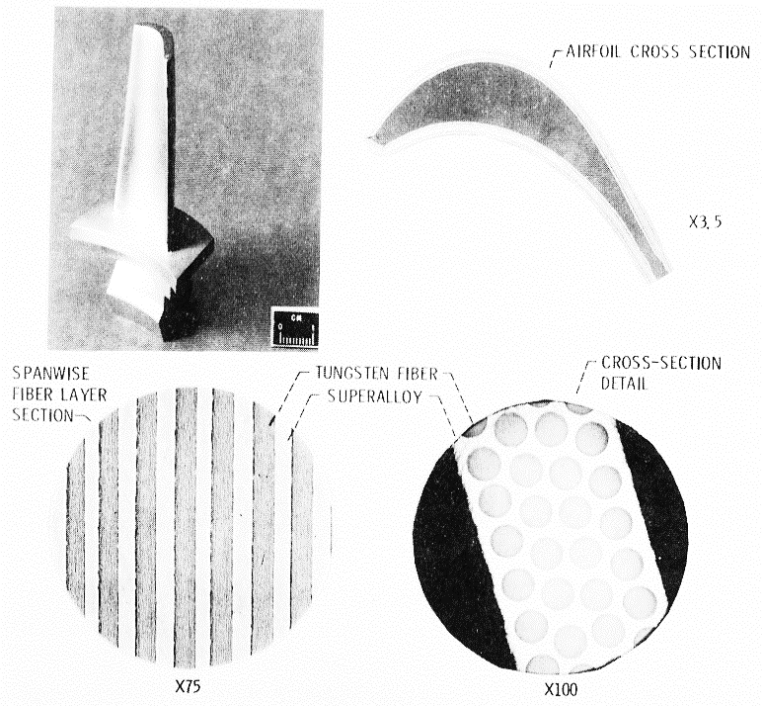


Figure 9.10 – Image and construction of an air-cooled turbine blade consisting of a matrix based on a superalloy and reinforcing inclusions based on tungsten fiber [15]

are 100 – 500 nm. The strength and heat resistance of such composites depends on the content of reinforcing dispersed particles. Examples of such CM's are sintered aluminum powders, nickel dispersion strengthened materials.

Metal composites are used quite widely in aircraft and rocket engineering for the manufacturing of highly loaded parts: skins, spars, ribs, panels, blades of compressors and turbines, various base units of structures, etc. (figures 9.9 and 9.10).

The order of work execution

1. To learn the theoretical information about composites.
2. Investigate the macro- and microstructures of composite materials and consider the structure of fibers. Draw these structures.
3. Determine the type of reinforcement in layered CM and estimate the volume fraction of fibers in the specimens.
4. Write the conclusions in which summarize all information from the lab on few sentences.

Check Questions

1. Give the definition of composite material (CM).
2. How are CM's classified?
3. How to determine what is the matrix and what is the filler?
4. What is the role of the matrix and the reinforcing components in the composite?
5. Give a brief description of composites with the non-metallic matrix.
6. Give a brief description of composites with the metal matrix.
7. Correspond the characteristics of CM based on ceramics with the CM based on metals.
8. How can we use composite materials on aircraft and spacecraft manufacturing?

The result of the work

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CONTENT

Appendix A

Assignment to the lab «Investigation of materials structure»

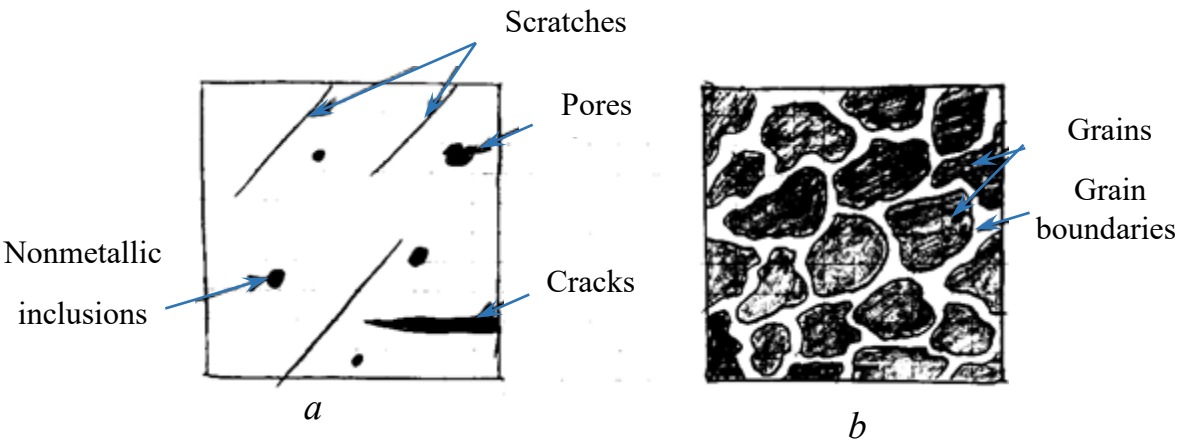


Figure A.1 – Schematic draw of microstructures of the cross section after polishing (*a*) and after etching (*b*)

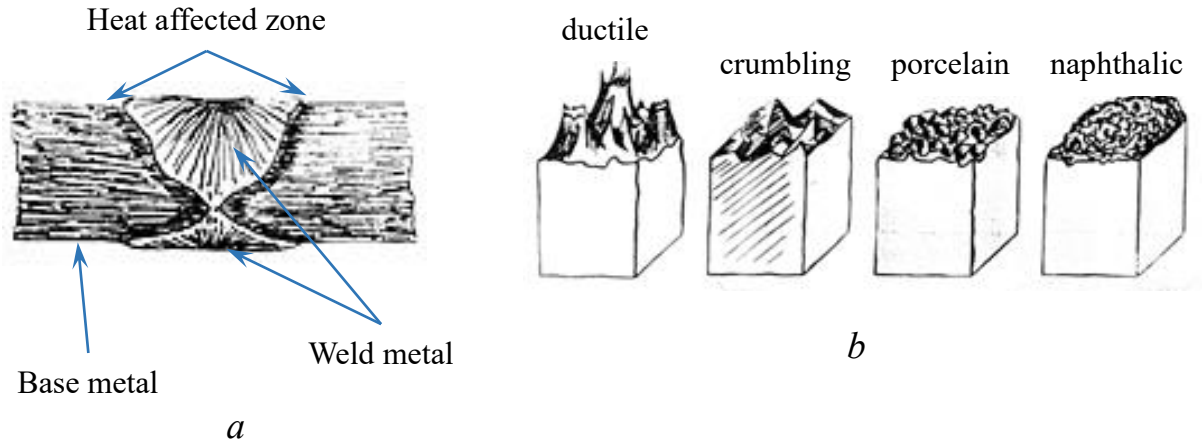


Figure A.2 – Schematic draw of macrostructures of weld joint (*a*) and typical fractures (*b*)

Appendix B

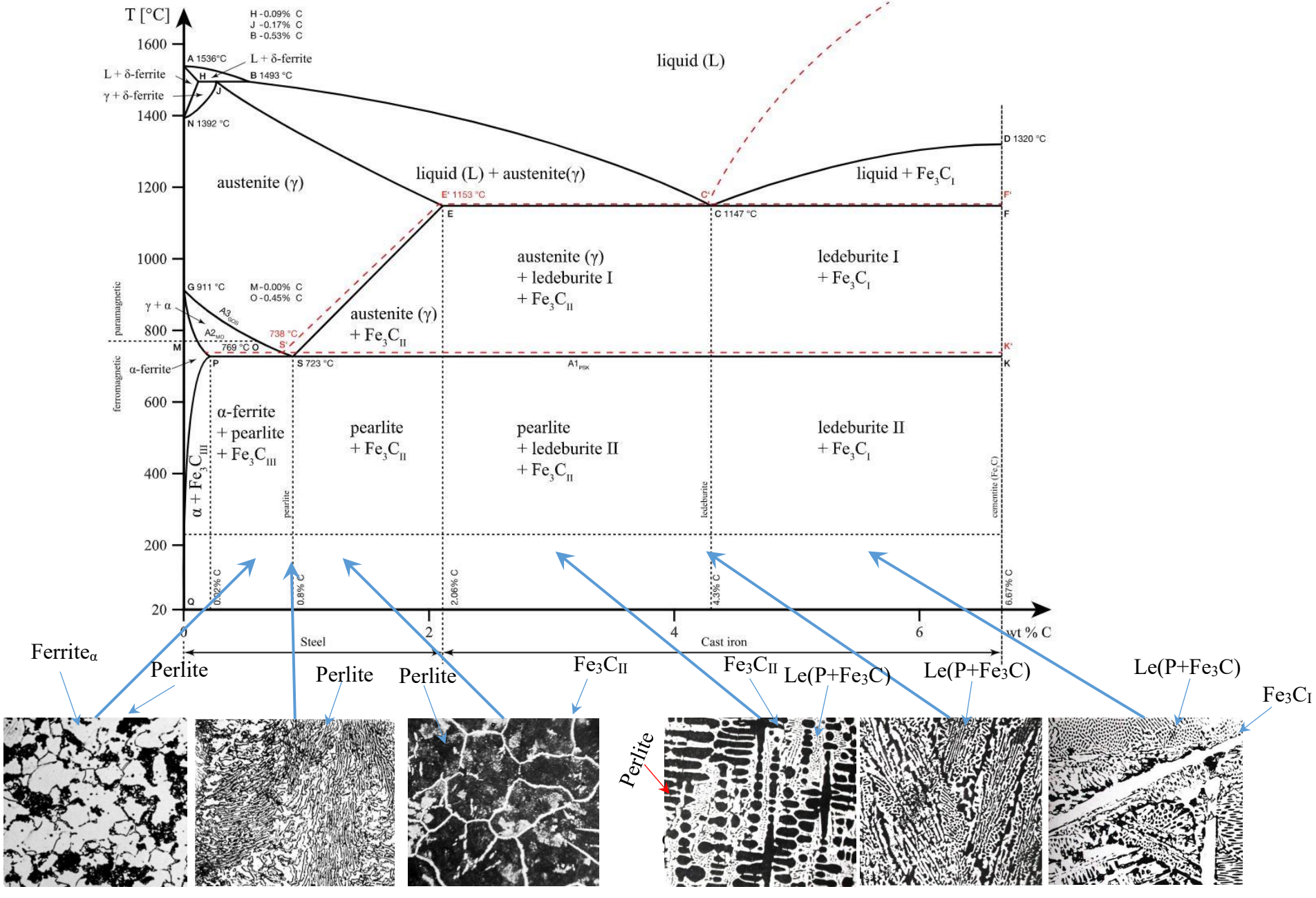
Data for completing the tasks of the lab «Plastic deformation and recrystallization of metals» in the distance form of education.

Table B.1. – Reference values of grain sizes during deformation and recrystallization.

% of deformation		**3 %**	**5 %**	**7 %**	**9 %**	**11 %**
Size of one grain, mm	**Grain 1**	11	6	5	3.5	1.4
	Grain 2	12	8	4	3.2	1.2
	Grain 3	7	11	3	3.0	0.5

Appendix C

Diagram state of Fe-Fe_3C and structures of steels and white cast irons.



Appendix D

Data for completing the tasks of the lab "Heat treatment of steel" in the distance form of education.

Table D.1. – Changes in the macrohardness of steels due to different temperatures and medium of hardening

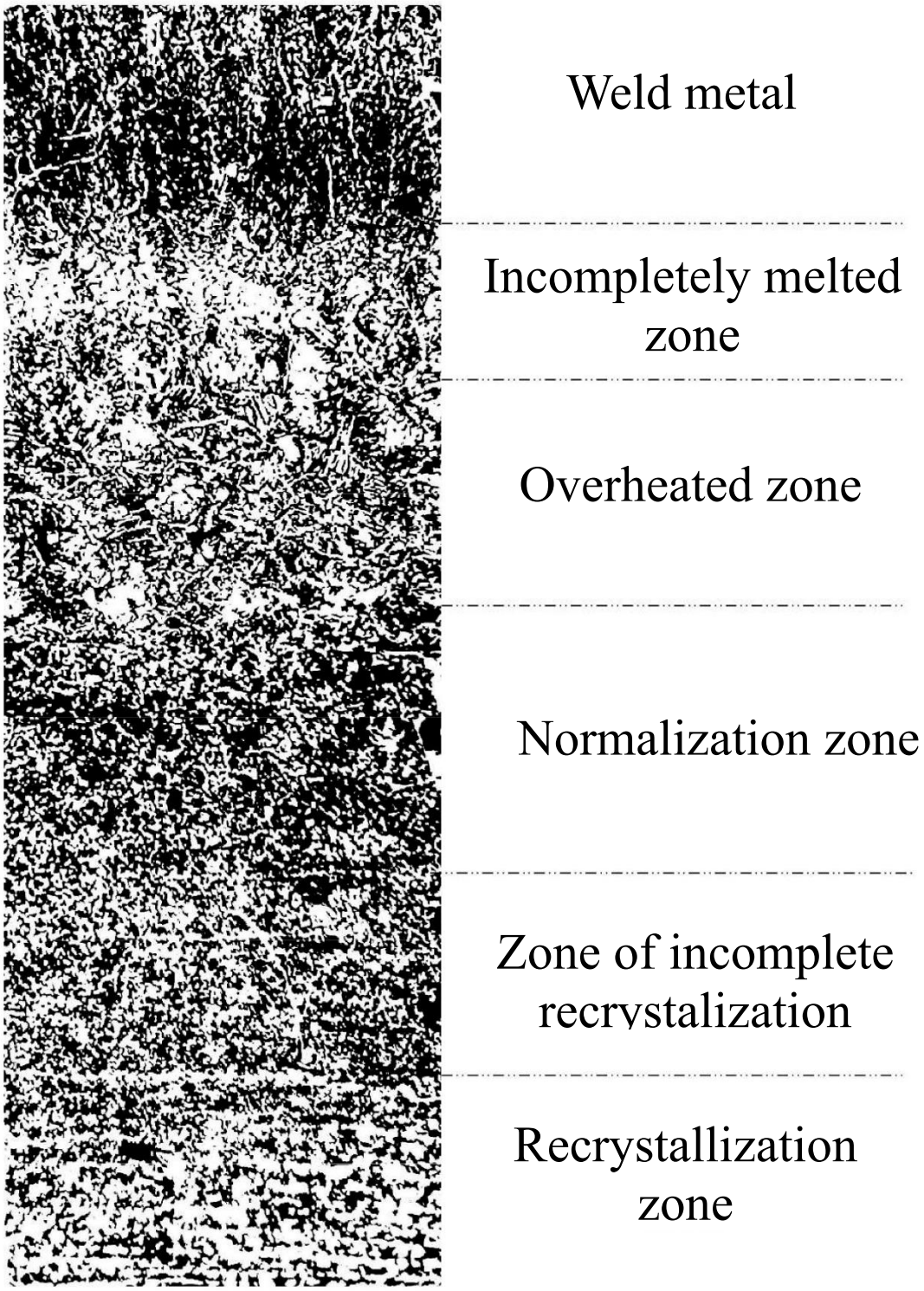
Steel grade	Heating temperature, °C	The cooling medium at (20 °C)	Macrohardness, HRC
Steel 20 (0.20 % C)	850	Water	20
Steel 45 (0.45 % C)	850	Water	54
	750	Water	41
	650	Water	21
Steel У8 (0.8 % C)	850	Water	63
		Oil	45
		Air	26

Table D.2. – Change in hardness of steel (0.8 % C) due to tempering at different temperatures

Tempering temperatures, °C	Hardness, HRC
20	63
100	62
200	59
300	45
400	40
500	25
600	18

Appendix E

The weld structure.



Appendix F

The microstructure of brasses

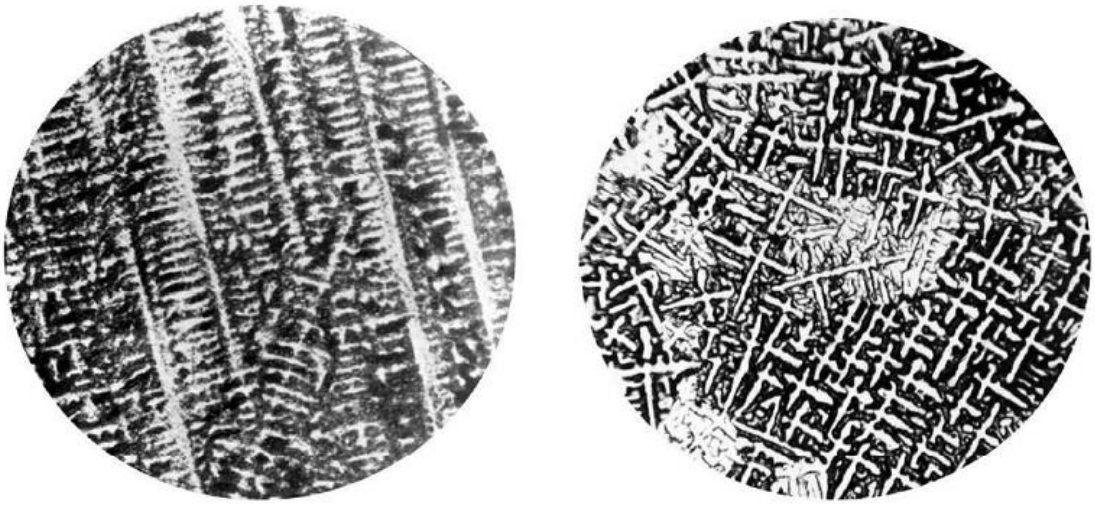


Figure F.1 - Microstructure of single-phase cast brasses

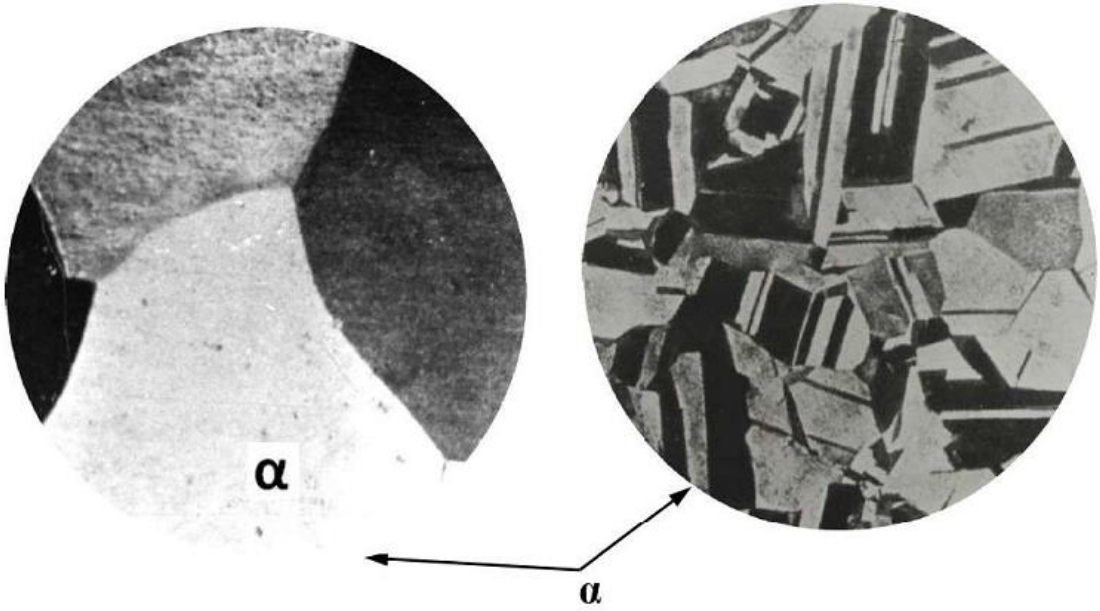


Figure F.2 - Microstructure of single-phase cast brasses after deformation and annealing

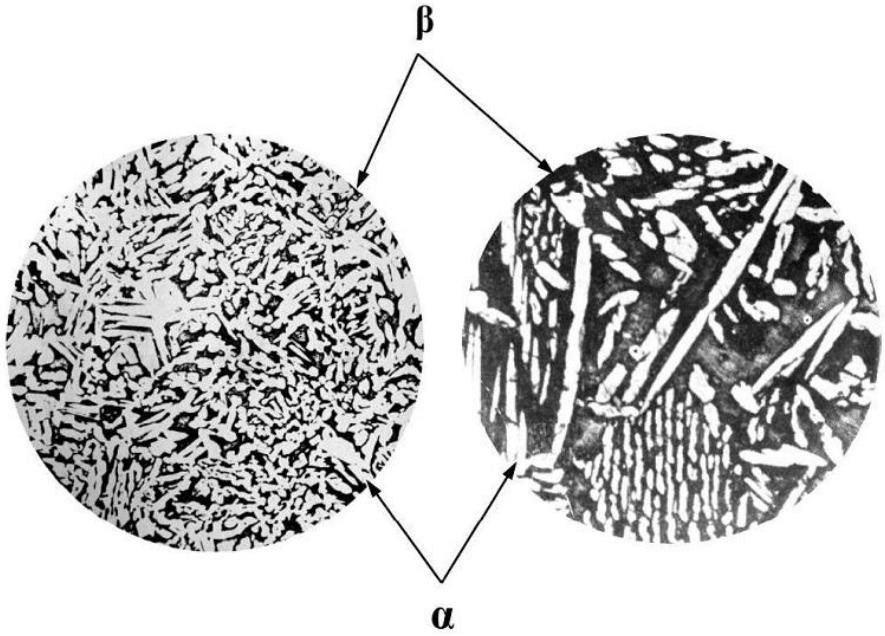
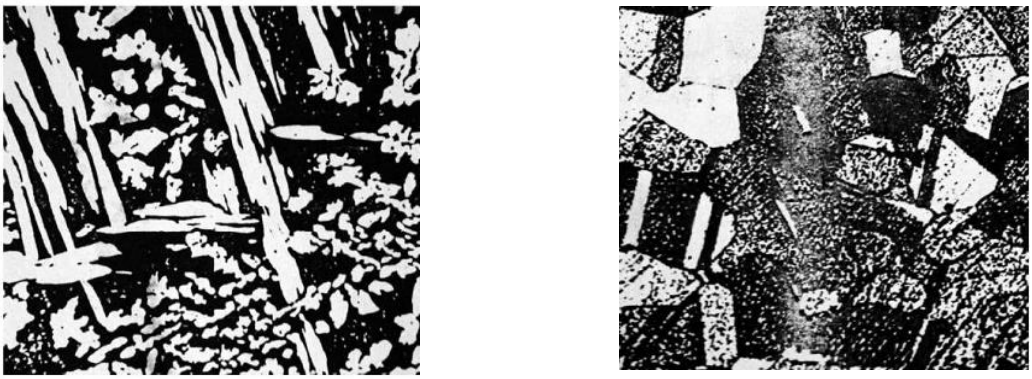


Figure F.3 - Microstructure of two-phase cast brasses



a *b*

Figure F.4 - Microstructure of two-phase cast brasses: cast Л59 (*a*), single-phase hot-rolled Л70 (*b*)

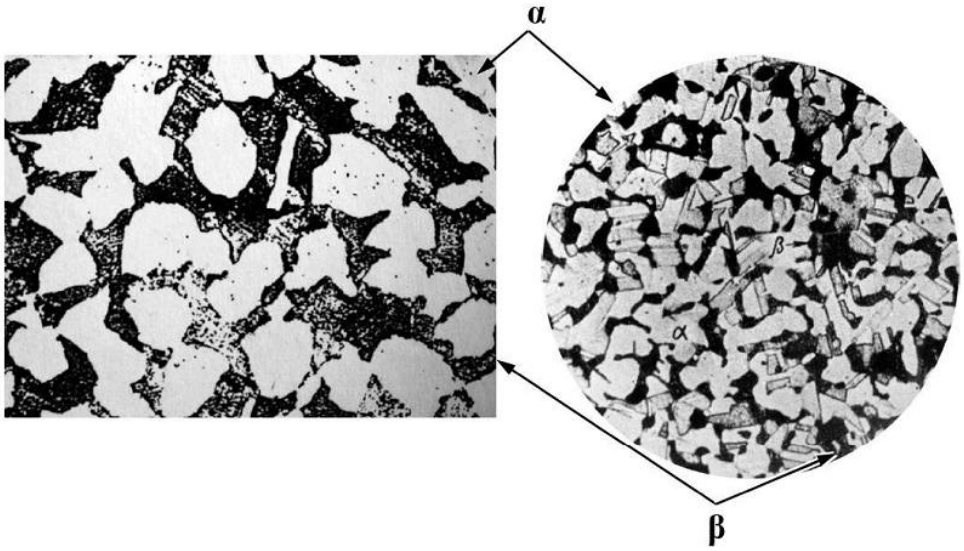
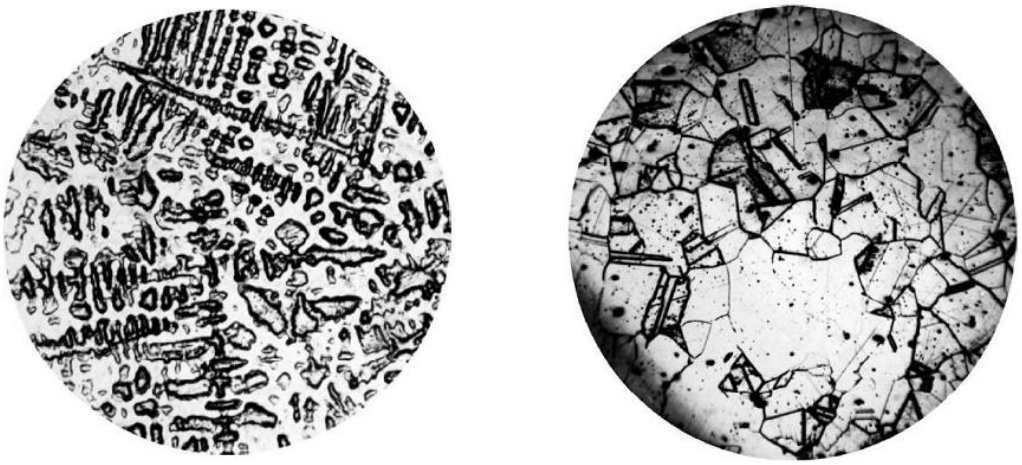


Figure F.5 – Microstructure of two-phase, hot-rolled brass Л82

Appendix G

The microstructure of bronzes



a *b*

Figure G.1 – Microstructure of single-phase tin cast bronze (6 % Sn) (*a*), after deformation and annealing (*b*), x200

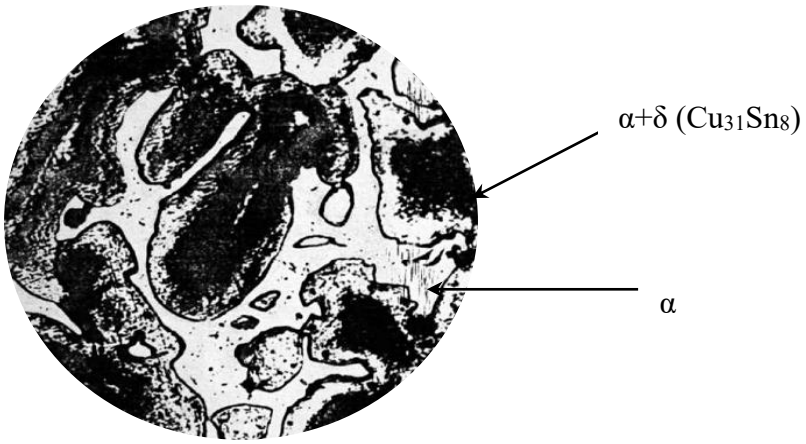


Figure G.2 – Microstructure of two-phase cast tin bronze БрО10, x100

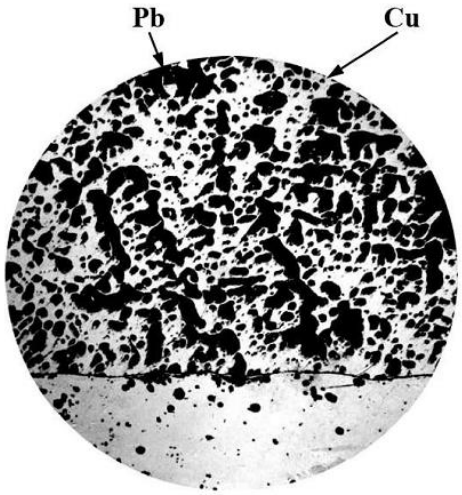


Figure G.3 – Microstructure of cast lead bronze, x100

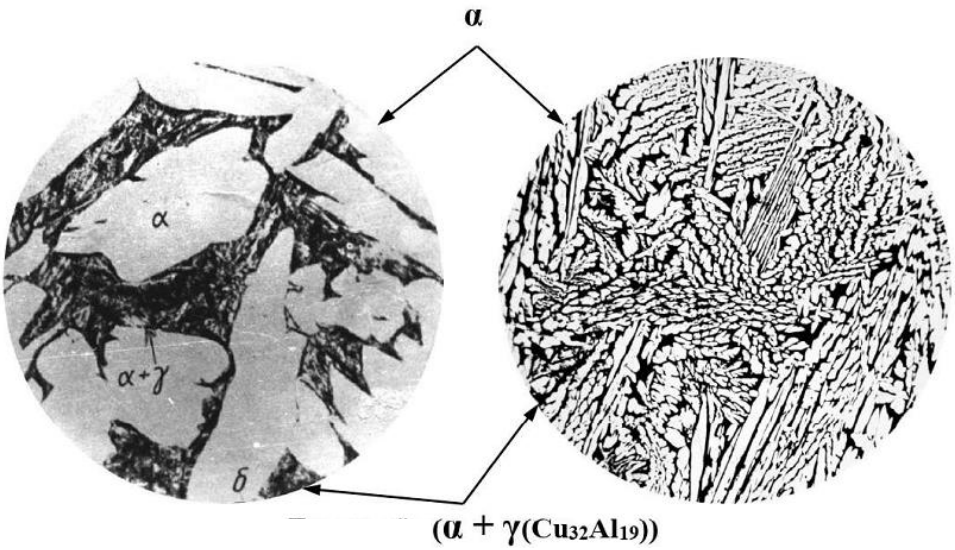


Figure G.4 – Microstructure of two-phase cast aluminum bronze, x200

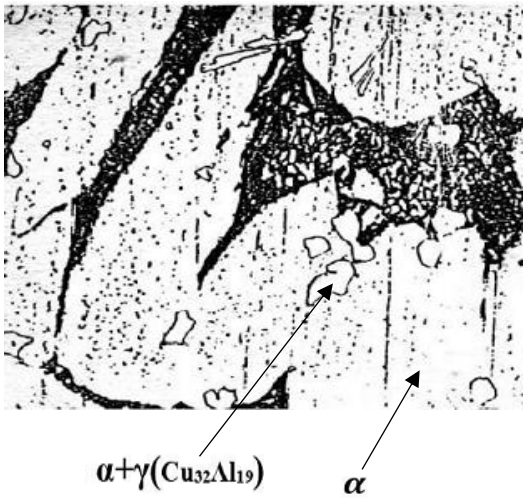


Figure G.5 – Microstructure of two-phase bronze БрАЖ9-4, x200

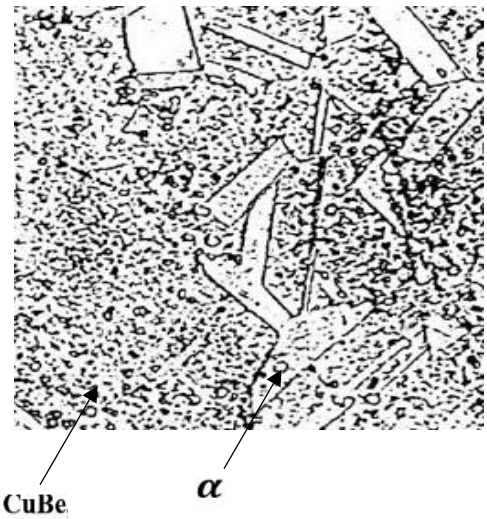


Figure G.6 – Microstructure of two-phase beryllium bronze БрБ2, x200

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АЕРОКОСМІЧНЕ МАТЕРІАЛОЗНАВСТВО

Лабораторний практикум

(Англійською мовою)

Матеріалознавство є дуже важливим у підготовці інженерів, які будуть конструкторами та технологами в аерокосмічній галузі. Розуміння процесів формування властивостей матеріалів залежно від їх будови, хімічного складу, способів обробки дасть можливість виконувати роботу на високому рівні. З іншого боку, застосування набутих знань у галузі авіаційного матеріалознавства дозволить покращити контроль якості продукції, що випускається, та можливість визначення відповідності технічним вимогам.

Лабораторний практикум складений за робочою програмою (силабусом) дисципліни «Аерокосмічне матеріалознавство» для студентів освітніх програм «Інженерія авіаційних та ракетно-космічних систем» та «Літаки та вертольоти» спеціальності 134 Авіаційна та ракетно-космічна техніка. Крім студентів інженерних спеціальностей у галузі авіації та ракетобудування, посібник буде корисним аспірантам, науковцям та спеціалістам інших технічних спеціальностей, діяльність яких пов’язана з підбором матеріалів тощо.

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