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STRUCTURE OF HEAT-STRENGTH ALLOYS

Laboratory practical training on the discipline

"Materials of aviation equipment"

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The structures of heat-strong alloys based on nickel and titanium and the conditions of their formation are considered.

Designed for students studying in the field of training 22.03.01 – “Materials Science and Materials Technology”.

Content

Laboratory work No. 3. STRUCTURE OF HEAT-STRONG NICKEL ALLOYS

- Purpose of the work
- Theoretical part
- Influence of chemical composition on the properties of nickel alloys
- Phase composition and its influence on the properties of nickel heat-strong alloys
- Microstructure parameters and their influence on the properties of heat-strong nickel alloys
- Alloys under study
- Methodology of work
- Reporting requirements
- Control questions

Laboratory work No. 4. STRUCTURE OF HEAT-STRONG TITANIUM ALLOYS

- Purpose of the work
- Theoretical part
- Influence of chemical composition on the properties of titanium alloys
- Types of titanium alloy structures and conditions of their formation
- Alloys under study
- Methodology of work
- Reporting requirements
- Control questions
- Bibliography

Lab work №3

STRUCTURE OF HEAT-STRENGTH NICKEL ALLOYS

1. Purpose of the work

- determination of the influence of chemical composition on the formation of the microstructure of heat-strong nickel alloys;
- acquisition of the ability to analyze the microstructure and phase composition of heat-strong nickel alloys.

2. Theoretical part

Heat-strong materials are used to manufacture parts of installations that are subject to mechanical loads at elevated temperatures. For operating temperatures above 800 °C, nickel-based alloys are most widely used. Nickel oxidation occurs only at temperatures above 800 °C, which is significantly higher than the oxidation temperature of other metals.

Nickel alloys are used for the production of heavily loaded parts of gas turbine engines, such as turbine and nozzle blades, turbine disks.

High performance properties of nickel alloys can be ensured only with a certain ratio of phase composition, grain size and structural homogeneity.

Heat strength is the ability of a material to resist deformation and destruction at high temperatures. The main criteria for heat strength are *the creep limit and the tensile long-term strength limit*.

The creep limit is the stress that causes a given total deformation in a given time at a given temperature. The creep limit is designated:

$$\sigma_{\delta/\tau}^t,$$

where t — temperature, °C ;

δ is the total elongation, τ is the time, h .

For parts that operate for a long time at elevated temperatures, the creep rate is usually set at the steady state stage of the process, for example, 0.1 % per 10^4 or per 10^5 h.

The limit of long-term strength is the stress that leads to the destruction of a sample at a given temperature in a certain time corresponding to the operating conditions of the product. The limit of long-term strength is designated:

$$\sigma_{\tau}^t.$$

2.1. The influence of chemical composition on the properties of nickel alloys

The first domestic heat-strong alloy EI437B contained only three elements as alloying elements (AE), and one of the most heat-strong among deformable alloys EP741 contains 12 main AE, which are introduced into the alloy in carefully controlled quantities. Such a complex chemical composition of these alloys is

necessary for the formation of a certain structure and phase composition in them, ensuring high operational properties.

Let us consider the influence of AE on the structure and properties of nickel alloys.

Chromium (**Cr**) is the main element responsible for the heat strength of nickel alloys. To obtain high heat strength, up to 20 % *Cr* is added to nickel alloys. Chromium also contributes to strengthening the alloy by dissolving in the γ -matrix of the alloy and also forming the carbide Cr_{23}C_6 .

Aluminum (**Al**) and *titanium* (**Ti**) are among the main AEs that determine the heat strength of nickel alloys. They form a strengthening γ' - phase of the $\text{Ni}_3(\text{Al}, \text{Ti})$ type, the amount and dispersion of which have a significant effect on mechanical properties, primarily on heat strength and technological plasticity. The maximum total content of Al, Ti in modern nickel alloys reaches 8-10 %.

Niobium (**Nb**) behaves similarly to Ti. The concentration of Nb in the interaxial regions of nickel alloys is 2-3 times greater than in the axes of dendrites. Niobium is included in the composition of the γ' -solid solution, strengthening it, and in the composition of the γ' -phase, increasing its stability against coagulation.

Tungsten (**W**) and *molybdenum* (**Mo**) reduce the self-diffusion coefficient and shift the recrystallization temperature to higher temperatures, which also contributes to an increase in heat strength.

Their optimal total content for achieving high heat strength should be 6-10%. With a further increase in the content of W and Mo (up to 15%), there is a decrease in heat strength and technological plasticity.

Cobalt (**Co**) is introduced to increase the temperature of dissolution of the γ' -phase. Its content is from 5 to 30 %.

Additions of *magnesium* (**Mg**) in small quantities (0.01-0.05%), not exceeding the solubility limit in the nickel solid solution of the γ -matrix, contribute to a significant increase in the plastic characteristics and expansion of the hot working range of alloys. It is not contained in casting alloys.

The introduction of *boron* (**B**) into high-alloyed heat-strong alloys has the same effect as Mg. Boron, having an extremely low solubility in the matrix, segregates near the grain boundaries and promotes the spheroidization of carbide particles located predominantly along the grain boundaries.

The presence of Cr and Nb in high-alloyed heat-strong alloys plays a dual role. On the one hand, these elements contribute to the expansion of the regions of existence of alloys with a γ -structure. On the other hand, in alloys with a high Ti and Al content, these elements form refractory nitrides and carbonitride clusters, which significantly worsen the ductility of the alloy during hot working.

Rare earth elements *cerium* (**Ce**) and *lanthanum* (**La**) modify the cast structure. They, mainly dissolving in the boundary areas, have a refining effect on the boundaries. As for such elements as *yttrium* (**Y**), *rhenium* (**Re**), *hafnium* (**Hf**), *tantalum* (**Ta**), which also have a positive effect on heat-strong properties, they have not yet found wide application in the creation of domestic nickel alloys. A number of researchers have shown the positive effect of rare earth metals when introduced in quantities of up to 0.2%. Additions over 0.2 % reduce plastic characteristics due to

contamination of alloys with accumulations of oxides and nitrides of rare earth metals.

2.2. Phase composition and its influence on the properties of nickel heat-strong alloys

The main phases in heat-strong nickel alloys:

1. *Matrix (base)* of the alloy. It is a γ - solid solution on a nickel base with an FCC lattice. The composition of this phase usually includes Co , Cr , Mo , W , V and Fe . Alloys whose matrix is a complex alloyed solid solution tend to be maximally strengthened.

2. *Intermetallic strengthening phase* $\text{Ni}_3(\text{Al}, \text{Ti})$, commonly referred to as the γ' -phase, has a FCC lattice stable at very high temperatures with a period only 0.1% greater than that of the γ -phase. The $\text{Ni}_3(\text{Al}, \text{Ti})$ compound has a high melting point (1350 °C), high ductility and oxidation resistance, satisfactory processability and low cost of the initial components. It can form during crystallization or precipitate in dispersed form from a supersaturated solid solution of the matrix. Depending on the discrepancy between the lattice parameters of the matrix and the precipitates of γ' -particles , the latter can have different shapes:

- *spherical* shape with a discrepancy between lattice parameters of up to 0.2 %;
- *cubic* - with a discrepancy of 0.5-1.1% and
- *lamellar* - if the discrepancy is more than 1.25 %.

Also, other forms of γ' - particle precipitates of different sizes can be encountered in nickel alloys. Figure 3.1 shows the most frequently encountered types of γ' - particle precipitates in domestic nickel-based alloys.

Cubic particles of the γ' -phase are precipitated *coherently in the matrix*. The coherent boundary of the γ' -particles results in low surface energy at the interphase boundaries and dimensional stability. *In nickel alloys, the γ' -phase is the main strengthening phase.*

Strengthening increases with increasing volume fraction of particles, with a certain dispersion of particles and distance between them. It has been experimentally established that the most effective strengthening is achieved with the precipitation of at least 30-40 % of the γ' -phase in alloys, and the average distance between particles should be ~ 50 nm .

Heat-strength properties also depend on the lattice mismatch between the strengthening coherent γ' - phase and the matrix. If the mismatch is large enough, the alloys rapidly become softer at high temperatures due to the intense coagulation of the strengthening phase particles. A large lattice mismatch between the coherent γ' - particle and the matrix causes significant interphase energy, which is the driving force in particle coarsening.

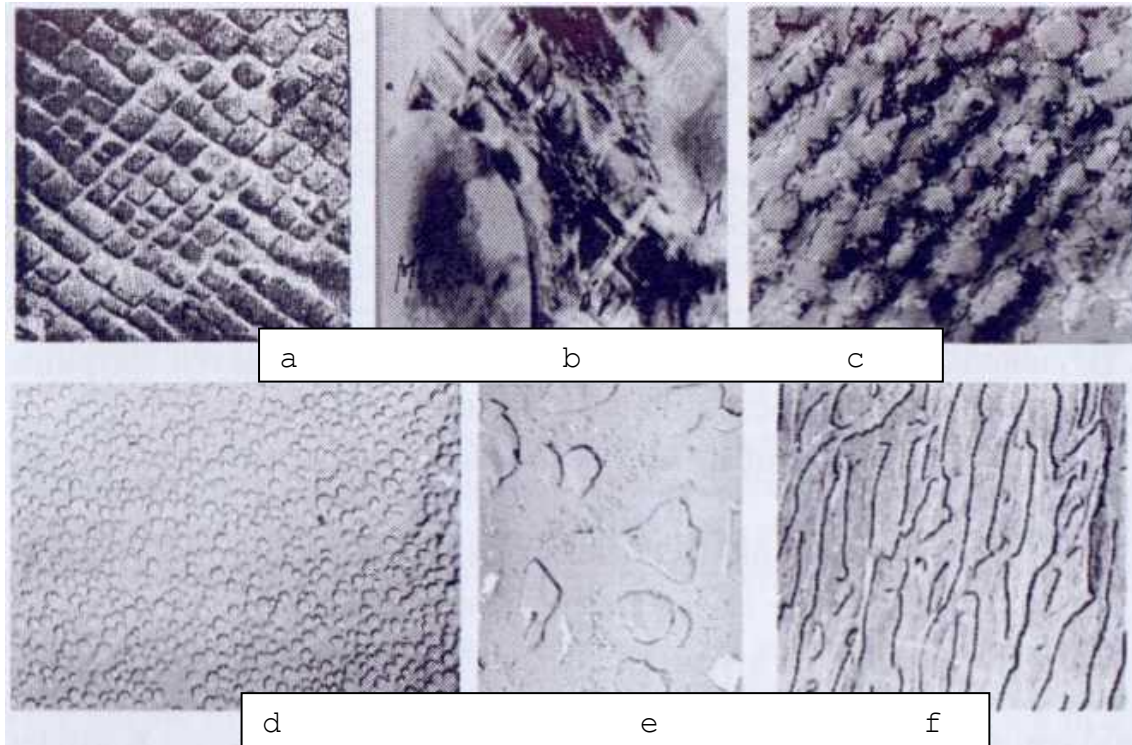


Fig. 3.1. Examples of different morphologies of γ' -particles in nickel-based alloys: *a* - cubic shape of γ' -particles of the casting alloy JS6U (TEM replicas, x 12000); *b* - the same, TEM of thin foils, x 16000; *c* - γ' -particles of granulated JS6U alloy decorated with dislocations after heating to 1100 °C and holding for 30 min; *d* - typical precipitation of the γ' -phase with a spherical particle shape after high- temperature heating and cooling (TEM replicas of the deformed EP741 alloy after heating to 1200 °C, 4 h, cooling in air, x8000); *e* - coagulated γ' -particle (TEM replicas of the deformed EP741 alloy after annealing at 1100 °C , 8 h, x8000); *f* - elongated particles of the γ' - phase in the JS6U alloy after long-term strength tests (TEM replicas, x12000)

7

In nickel alloys with a total content of Al and Ti of more than 7 % , eutectic precipitation is observed (γ - γ'). Such precipitates, observed, for example, in the microstructure of EP741 and JS6U alloys in the form of large white particles, are concentrated along the boundaries of crystallites or in interdendritic regions (Figs. 3.2 and 3.3, *a*, *b*). The eutectic (γ - γ'), which is often called the primary γ' -phase, reduces the plastic properties of the alloy, and often the destruction of the alloy begins along the boundaries of the eutectic (Fig. 3.2, *b*). This phase completely dissolves at a temperature of 1220 °C.

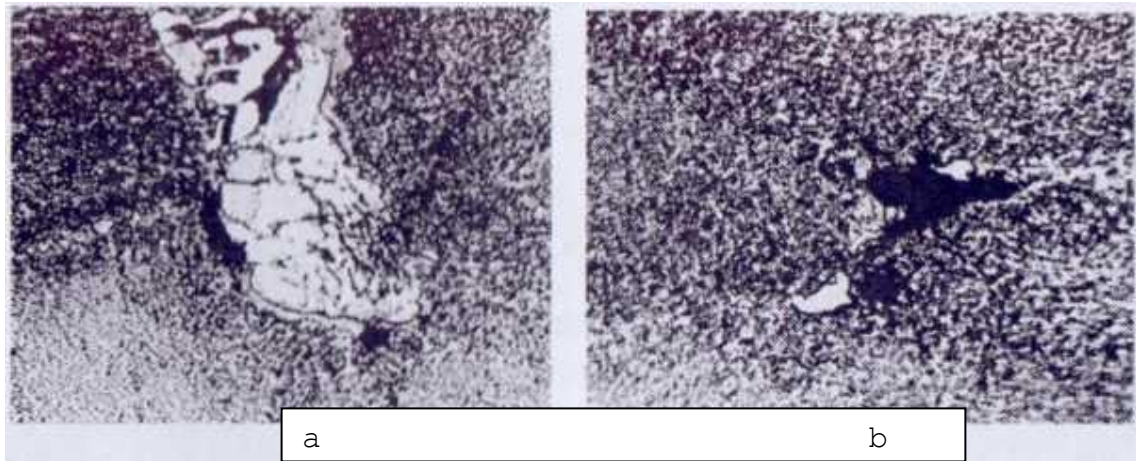


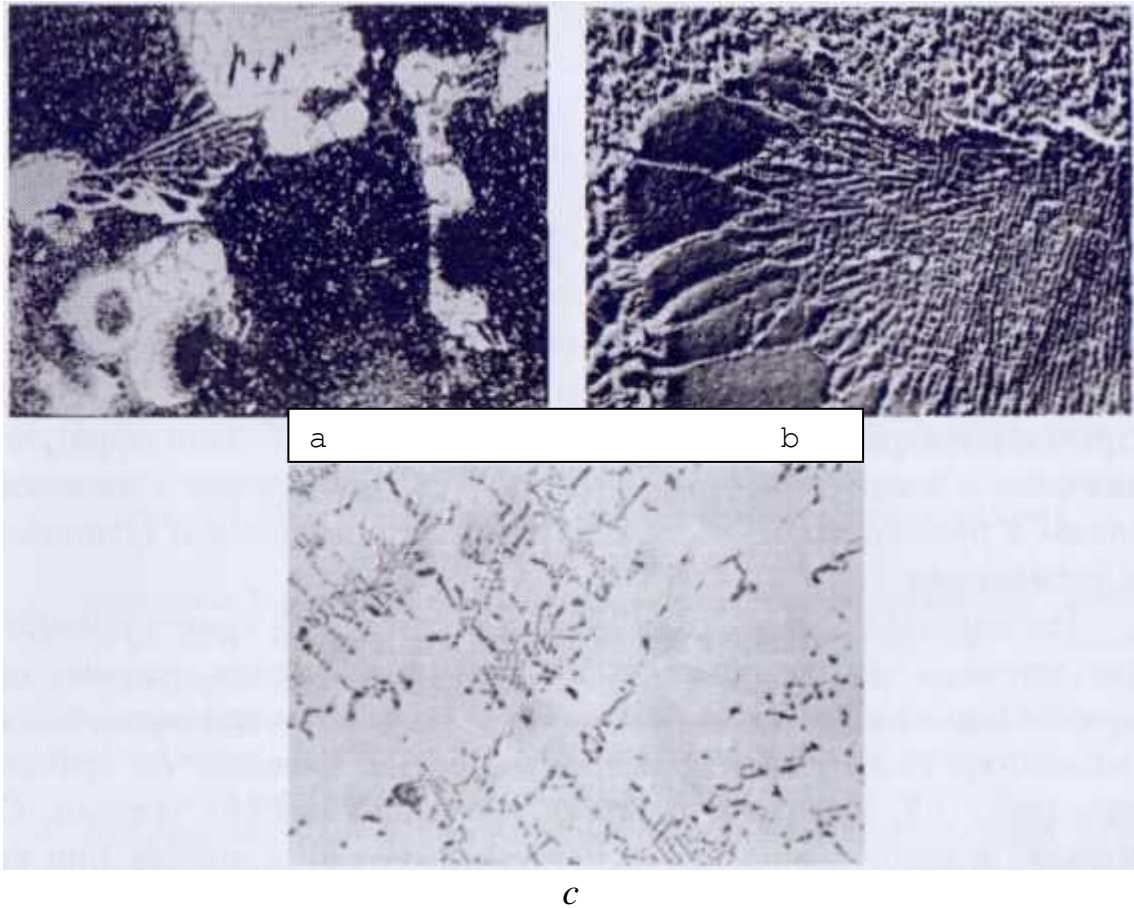
Fig. 3.2. Microstructure illustrating the initiation of a crack along the eutectic boundary ($\gamma - \gamma'$) during deformation of the EP741 alloy by $\varepsilon = 20\%$ at a temperature of $1100\text{ }^{\circ}\text{C}$, (x1000)

3. *Carbides* are among the most important structural components of nickel-based alloys, providing grain size regulation and contributing to strengthening. Nickel alloys contain carbide phases of the MC, $M_{23}C_6$, M_6C type. They are formed by the chemical interaction of carbon, contained in nickel alloys within 0.05-0.2%, with chemically active and refractory elements.

Primary carbides of the MC type are formed during crystallization in the form of large, randomly located particles of irregular shape. They can be located along the boundaries and inside the grains, as well as in the interdendritic areas. Carbides located along the grain boundaries (Fig. 3.3, *c*) are the cause of cracks. They lead to destruction during endurance tests at room and elevated temperatures, as well as to thermal fatigue. At the same time, small globular carbides of the MC type (Fig. 3.1, *b*) have a positive effect, preventing the propagation of fatigue cracks.

In modern nickel alloys, during low-temperature treatment or during operation at temperatures of $750\text{...}950\text{ }^{\circ}\text{C}$, partial dissolution of the MC carbides and formation of carbides of the $M_{23}C_6$ type occur, and carbides of the M_6C type are formed at temperatures above $1000\text{ }^{\circ}\text{C}$. These carbides can be located mainly along grain boundaries surrounded by a plastic γ' - phase, which prevents embrittlement of the alloys. Carbides of the $M_{23}C_6$ type have the formula $Cr_{21} (Mo, W)_2C_6$, and carbides of the M_6C type have the formula $(Ni, Co)_2W_4C$.

In the serial alloy EI437, the carbide phase is observed in the form of coarse precipitates along the grain boundaries. The alloy EI698, which differs from the alloy EI437 in its Nb content, has more dispersed carbide particles of irregular shape. On unetched sections, they are identified as light-gray particles and represent a carbide of the type $(Nb, Ti, Cr, Mo)C$.



Rice. 3.3. Eutectic γ and γ' and carbides in the JS6U alloy:

*a - metallography with etching, x400; b - TEM of two-stage replicas, x4000;
c - metallography, without etching, x 120*

Thus, the presence of Nb and Mo in this alloy leads to a change not only in the shape of the carbides, but also to the appearance of a more stable carbide of the MC type. Alloying with Nb also leads to a decrease in the grain size variation of the EI698 alloy. This alloy also contains orange particles, which are carbonitrides of the (Ti, Cr, Nb) CN type.

Primary carbides of the MC type in the casting alloy JS6U as a strengthening phase are not considered in the literature. In deformable nickel alloys, discrete precipitation of carbides along the boundaries is accompanied by the formation of boundary zones depleted in chromium and the γ' -phase. Such zones are less strong but more plastic compared to the rest of the grain volume. Due to this, stresses concentrated along the grain boundaries can be relieved by local plastic deformation, rather than by cracking, which leads to an improvement in long-term strength and ductility. Carbides have the most effective strengthening effect with their high dispersion, uniform distribution in the volume and at the boundaries, and a low tendency to coagulation and dissolution at high temperatures.

In addition to the phases listed, other stable phases may also be encountered in nickel alloys. Among them are *borides* of the M_3B_2 type. However, borides, as an independent phase, are formed in significant quantities only at boron (B) concentrations greater than 0.012%, which is possible only in special cases of boron alloying. Also, non-metallic inclusions in the form of oxides of the SiO_2 , TiO_2 , Al_2O_3

type , as well as *nitrides and carbonitrides* may be found in the structure of nickel alloys .

2.3. **Microstructure parameters and their influence on the properties of heat-strong nickel alloys**

Important characteristics of the microstructure are the grain size and the degree of its homogeneity, which largely determine the mechanical properties of deformable nickel alloys. This has caused the need to standardize the grain size in products. Enlargement of the grain has a positive effect on heat strength, but at the same time other properties are reduced: plasticity, short-term strength, etc. Therefore, to achieve high heat strength with satisfactory values of other characteristics, the grain size must correspond to 1-3 points on the GOST 5639-82 (Russian National standard) scale.

The grain size in alloys depends on the temperature, the degree of deformation preceding heat treatment, and the size of the original grain. The temperature range of primary recrystallization depends on the degree of deformation: the higher it is, the lower the temperature of primary recrystallization and the more completely it is completed.

The grain growth of heat-strong nickel alloys is also affected by the dispersion of carbides and the presence in the alloy of dispersed particles of various oxides and nitrides introduced during melting. These particles, insoluble at very high temperatures, are considered as "barriers" that inhibit grain growth.

3. **Studied alloys**

To study the structure and properties, the most widely used nickel alloys for the production of disks, blades and parts such as rings for aircraft engines are EI437, EI698, EP742, JS6U.

Alloy EI437 (CrNi77TiAlB) belongs to the alloys of the quaternary system Ni - Cr - Al - Ti . The main strengthening phase is $Ni_3(Ti, Al)$. The alloy structure also contains some amount of primary carbides, nitrides and carbonitrides of titanium.

The EI437 alloy is characterized by good technological plasticity . It is successfully deformed on hammers and presses in the temperature range of 1000-1150 °C. In this temperature range, the alloy can be subjected to plastic deformation without destruction by 50 % on a hammer and 70% on a press in one stroke of the working tool . The alloy is prone to strong strain strengthening, especially at temperatures below 1000 °C.

The alloy is widely used in aircraft engine building. It is used to manufacture turbine and compressor disks, compressor blades and supporting ring parts operating at temperatures of 550-750 °C.

Alloy EI698 (CrNi73MoNbTiAl) belongs to the Ni - Cr - Al - Ti - Mo - Nb system . It is a modification of alloy EI437 and is additionally alloyed with Nb and Mo. These AEs contribute to increasing the heat strength of the alloy.

The microstructure of the cast alloy EI698 at room temperature is non-uniform: it consists of dendrites of a solid solution of variable composition based on Ni , the main strengthening γ' - phase of the $Ni_3(Al, Ti, Nb)$ type , which is released during

cooling of the ingot. The microstructure of the alloy also contains carbides of the (Nb , Ti , Mo)C type , nitrides TiN , carbonitrides (Nb , Ti , Mo) CN .

The alloy has satisfactory technological plasticity . The temperature range of plastic deformation is 1000-1180 °C. The alloy can be subjected to plastic deformation by 40% on a hammer and by 50% on a press in one stroke of the working tool without destruction. The alloy is prone to strong strain strengthening, especially at temperatures below 1050 °C. Alloy EI698 is less prone to the formation of a coarse-grained and inequigranular structure after recrystallization than EI437.

Alloy EI698 is widely used in aircraft engine building for the production of compressor and turbine disks, blades and supporting ring parts operating at temperatures of 550-750 °C.

Heat-strong alloy EP742 is a modification of alloy EI698VD. The higher heat strength of this alloy compared to alloy EI698 is due to the increased content of Al , Ti , Mo, Nb , Ce, B, as well as the introduction of cobalt (Co) into the alloy .

The EP742 alloy in the deformed and heat-treated state has the following phase composition: γ -solid solution of variable composition, γ' -phase of the composition (Ni , Cr , Co)₃(Ti , Al , Nb), monocarbides of the composition (Ti , Nb)C, nitrides and carbonitrides of titanium, borides of M₃B₂ . After heat treatment , it contains up to 35-38% of the strengthening γ' - phase.

Alloy EP742 is characterized by reduced technological plasticity. The temperature range of plastic deformation is 1120-1030 °C. It can be deformed on hammers and presses, and is prone to strong strain strengthening.

The alloy is used for aircraft engines of civil and military aircraft, and serial production of stamped disks has been established based on this alloy . The introduction of this alloy made it possible to create an aircraft turbine with qualitatively new parameters.

Heat-strong alloy JS6U is the most complex serial alloy on a nickel base. It consists of 13 alloying components. The alloy contains the maximum total content of Al and Ti (up to 9%), which, with strong alloying of the matrix, ensures the precipitation of 60 % of the strengthening γ' -phase. The temperature of complete dissolution of this phase is 1230 °C. The melting onset temperature (when heating an ingot with a diameter of 160 mm) of the alloy is 1240-1250 °C. The narrow temperature range of the single-phase region (10-20 °C) and high carbon content (0.13-0.20%) transferred the JS6U alloy to the category of casting alloys.

Turbine blades for aircraft engines operating at temperatures of 950-975°C are mass-produced from the JS6U alloy using the precision investment casting method .

4. Methodology of work

Students receive:

- an album with the microstructure of nickel alloys after various types of heat treatment, as well as individual photographs with the microstructure of the alloys;
- a pre-prepared collection of microsections of the cast structure of nickel alloys EI437, EI698, EP742, JS6U;
- microsections of EI698 alloy after standard heat treatment and hardening from temperatures of 1050 °C and 1200 °C.

When performing laboratory work it is necessary:

- to study and characterize the microstructure of alloys using an optical microscope at a magnification of x400;
- study the fine structure of heat-strong nickel alloys using the album, revealed using an electron microscope and thin foil and replica methods;
- to identify patterns in the change in the intensity of carbide phase precipitation using sections of EI698 alloy after various hardening modes .

5. **Reporting requirements**

The report must contain:

- topic and purpose of the work;
- a brief summary of the work with characteristics of the main heat-resistant nickel alloys;
- drawings of the microstructure of the alloys studied;
- histograms of the distribution of γ' - particles;
- conclusions on the work.

6. **Control questions**

1. What phases are found in nickel alloys?
2. What types of carbides are found in nickel alloys, what is their shape, and how are they arranged?
3. Explain the mechanism of strengthening action of γ' -phase in nickel alloys.
4. Explain the role of each AE in the formation of the microstructure of nickel alloys and their influence on properties.
5. Provide a description of the alloys being studied in terms of structure and properties.
6. What temperatures correspond to the beginning and end of the dissolution of the γ' -phase in the alloys studied?
7. Explain the type of distribution curves of γ' - phase particles by size depending on the heating temperature.

Lab work №4

STRUCTURE OF HEAT-STRONG TITANIUM ALLOYS

1. Purpose of the work

- to determine the influence of chemical composition on the formation of the microstructure of heat-strong titanium alloys;
- learn to analyze the microstructure and phase composition of heat-strong titanium alloys.

2. Theoretical part

For operating temperatures up to 650 °C, titanium-based alloys are most widely used.

Titanium alloys are used for the production of parts in the compressor of gas turbine engines, such as compressor blades, disks, and various shaped parts.

2.1. The influence of chemical composition on the properties of titanium alloys

Technical titanium, containing no more than 0.05-0.1% impurities, has high plasticity ($\delta = 50-60\%$, $\psi = 70-80\%$), but low strength ($\sigma_u = 200-250$ MPa). By rational alloying, the strength of titanium is increased to $\sigma_u = 1600$ MPa, which is maintained almost up to 350 °C.

To obtain alloys, titanium is alloyed with Al, Mo, V, Mn, Cr, Sn, Fe, Zr, Nb. These elements have different effects on titanium polymorphism:

1. *α -stabilizers* are elements that increase the temperature of polymorphic transformation (T_{pp}) of titanium. Among metals, α -stabilizers include Al, Ga, In, and among non-metals C, N, O. The listed non-metals are harmful impurities, so they are not used as alloying elements. The main α -stabilizer in almost all industrial titanium alloys is *aluminum*, which has a number of advantages: it reduces the specific gravity of alloys, increases corrosion resistance, and makes alloys cheaper.

2. *β -stabilizers* are elements that reduce the T_{pp} of titanium. They can be divided into three subgroups.

In titanium alloys with elements of the *1st subgroup*, at a sufficiently low temperature, a eutectoid decomposition of $P-ni + y$ occurs; these include Si, Cr, Mn, Fe, Co, Ni, Cu are called *eutectoid-forming β -stabilizers*.

In titanium alloys with elements of the *2nd subgroup* β -solution is preserved up to room temperature. These elements include V, Mo, Nb, Ta. Since they form continuous solid solutions with β -titanium, they are called *isomorphic β -stabilizers*.

In alloys of *subgroup 3*, the equilibrium β -phase is also stabilized at room temperature, but continuous solid β -solutions are not formed. The elements of this subgroup include Re, Ru, rhodium Rh, osmium, and iridium, which are called *quasi-isomorphic β -stabilizers*.

3. The third group is represented by alloying elements that have little effect on the T_{pp} of titanium. These are tin, zirconium, germanium, hafnium and thorium, which are called *neutral strengtheners*.

2.2. Types of titanium alloy structures and conditions of their formation

Depending on the shape of the structural components, all types of structures observed in titanium alloys belong to one of two types: a structure with a *globular* shape of α - phase particles and a structure with a *lamellar* α -phase. In practice, they are often called *equiaxed* and *needle* structures.

The most realistic way to obtain a structure with a globular α -phase is plastic deformation at temperatures below T_{pp} and with sufficiently large compressions (more than 60-70%). The actual shape of the α - phase crystals in such a structure can be close to spheroidal (equiaxed), disc-shaped , fibrous, worm-shaped , and their sizes can vary from several microns to tens of microns.

The lamellar structure in titanium alloys is formed during the polymorphic $\beta \rightarrow \alpha$ transformation. It has a polyhedral or ellipsoidal (after deformation) shape with an α -phase layer along the boundaries. The width of the α - layer increases with decreasing cooling rate. It is not observed during rapid cooling.

A characteristic feature of the plate-type structure in titanium and its alloys is, in most cases, the significant size of the primary β - grains, which can reach several thousands micrometers. The intragranular structure of the plate-type structure is characterized by the presence of a complex of fragments or colonies consisting of alternating, parallel or misoriented plates of the α - phase and the second phase, resembling in its appearance the structure of plate pearlite in steels.

An analysis of a large number of microstructures of two-phase titanium alloys shows that after slow cooling, each β - grain can have a rather limited set of different orientations of the α -plates. When the α -colonies are large compared to the β - grain, colonies of the same orientation are rarely found in one grain, and when the colonies are small, their orientation is inevitably repeated within the β -grain, forming a unique pattern of α - colonies. Such a structure is called a *basket-weave structure*. The shape of the α - phase crystals in the lamellar structure and their ordered arrangement within the former β -grains are primarily due to the presence of size and orientation correspondences between the lattices of the original and resulting phases. In order to emphasize the hereditary crystallographic community of the low-temperature α - phase and the high-temperature β -phase in the lamellar structure, an additional term " β -transformed structure" is often used.

Another important condition for the formation of a lamellar structure is the emergence of a second phase during polymorphic transformation along the nucleation front of the α -phase, which is either an α -phase with a composition different from the matrix, or a β -phase. The lamellar character of the β - transformed structure is most clearly expressed in ($\alpha+\beta$)-titanium alloys, which have an increased amount of the second phase.

In alloys with a polyhedral structure, the second phase is located along the boundaries of α - grains. Its quantity is also greater, the higher the content of β - stabilizing elements. However, it is also present in small quantities in alloys that are considered as single-phase.

Thus, most α - titanium alloys are actually two-phase in the annealed condition.

The lamellar structure of titanium alloys is very stable. It is known that in steels, to refine such a structure and convert lamellar pearlite into globular, cyclic annealing

at temperatures close to A_{c1} , long-term annealing at temperatures slightly below A_{c1} , and quenching from temperatures in the γ -region with subsequent recrystallization annealing are used.

In titanium alloys, unlike steels, *it is not possible to achieve similar correction of the lamellar structure using heat treatment methods*. Cyclic annealing of the alloy at temperatures of 950-1030 °C ($T_{pp} = 990-1000$ °C) causes only slight coagulation - of the α - phase, without leading to its spheroidization .

For the convenience of assessing the structure of semi-finished products and monitoring their quality, various *scales of macro- and microstructures have been developed*, some of which are shown in Fig. 4.2 *a, b* .

The scales presented are a generalization of production experience in monitoring the structure of semi-finished products made of titanium alloys . The standard types of structures presented in them reflect many features of the structure of titanium semi-finished products, their dependence on the alloy composition and deformation conditions.

For example, the first two or three types of microstructures given in these scales characterize the microstructure obtained by deformation at temperatures in the $(\alpha+\beta)$ region. The structures of the next two or three types, which are often called the "basket-weave" structure, are formed by deformation near the temperature of the polymorphic transformation or in cases where deformation begins at temperatures in the β region and ends at temperatures in the $(\alpha+\beta)$ region. The remaining structures correspond to various conditions of deformation at temperatures in the β region.

Along with deformation at temperatures in the β -region, the deformation process of $(\alpha+\beta)$ -titanium alloys can be carried out in a two-phase region or begin in the first one and end in the second one.

Fig. 4.1 schematically shows the main types of structures formed from a lamellar structure during deformation in the $(\alpha+\beta)$ region.

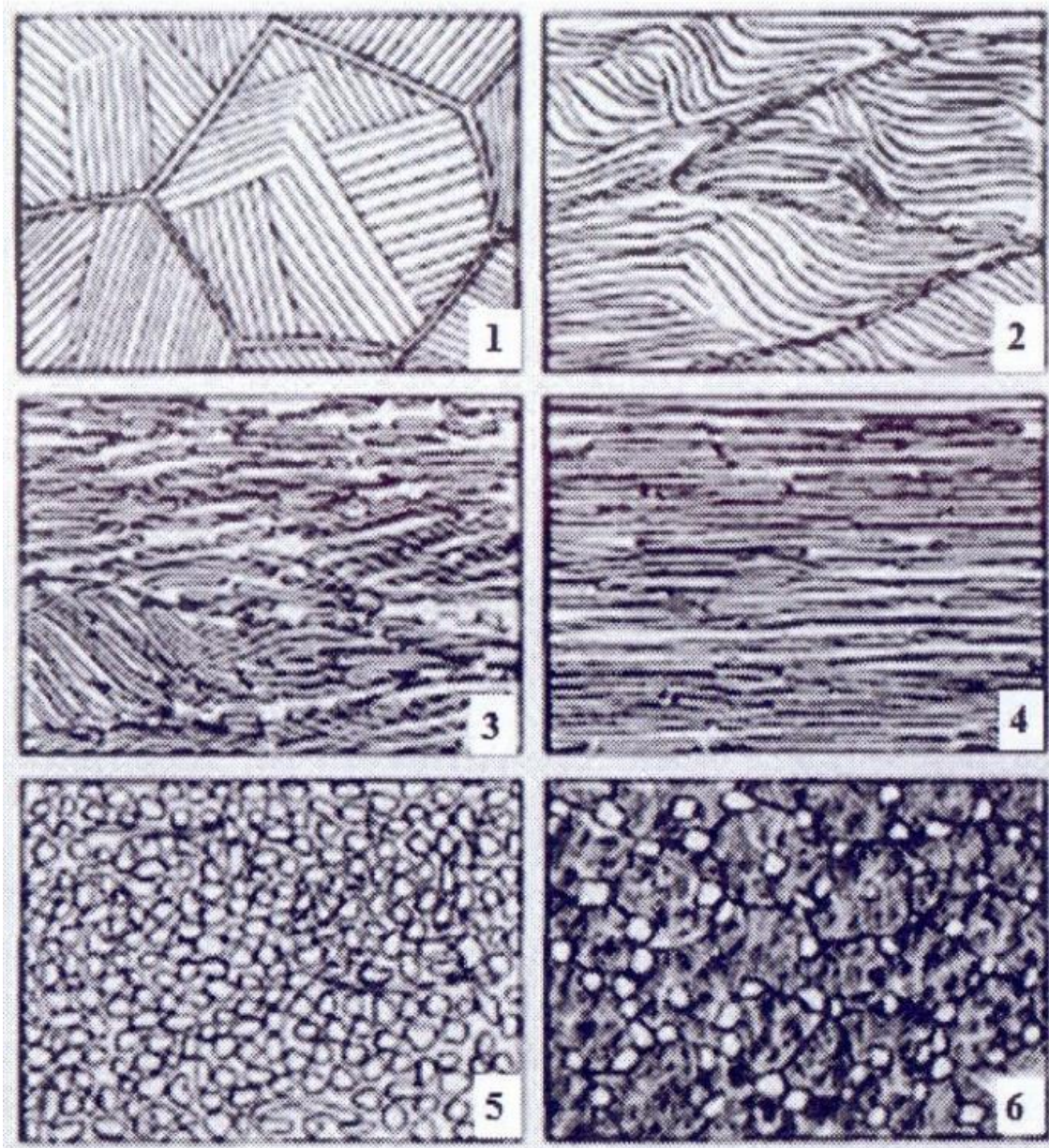


Fig. 4.1. Scheme of structure formation during deformation at temperatures correspond to $(\alpha+\beta)$ - regions: 1-4 – change in structure with increasing degree of deformation, 5,6 – with increasing deformation temperature

In contrast to deformation at temperatures of the β -region, during deformation at temperatures of the $(\alpha+\beta)$ -region, a change in β -grains and α -plates occurs - simultaneously . They are flattened, stretched along the direction of metal flow, and crushed. The difference between the boundary and intragranular α - phase disappears steady. After deformation to a degree exceeding 60-70 %, *no visible traces of the lamellar structure* remain . At certain temperatures and degrees of deformation, recrystallization occurs, and recrystallization in the α -phase outpaces recrystallization in the β -phase. Recrystallized α -grains have a spheroidal shape. In the non-recrystallized state, the shape of α -crystals can be disc-shaped (most often in forgings and stampings), fibrous (in rolled and forged rods), etc.

According to the structure during equilibrium cooling, titanium alloys are

divided into *five groups*:

1. α -*alloys*: the structure of these alloys is represented by a solid solution of alloying elements in hexagonal close packed (HCP) crystalline lattice of titanium with the addition of neutral strengtheners - Sn , Zr . These include alloys VT5, VT5-1.

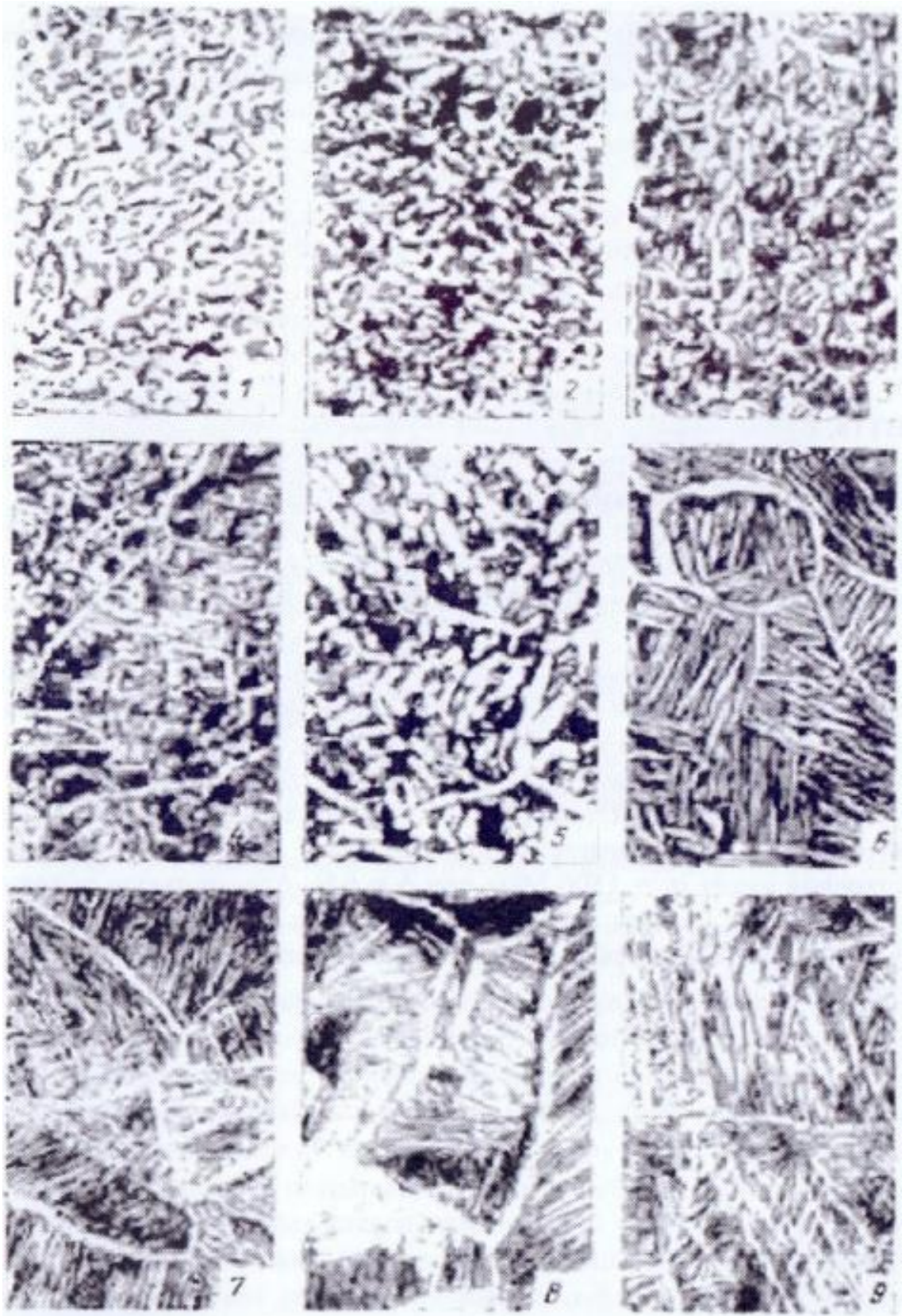
2. *Pseudo- α -alloys*: the structure of these alloys is represented by α -solid solution and up to 5% β -phase. In addition to Al , the alloys contain up to 1 % V, up to 0.3% Zr . These include alloys OT4-0, OT4-1, VT4 , OT4-2, VT18, VT20.

Alloys of these two groups do not strengthen during heat treatment , so they are used in annealed condition.

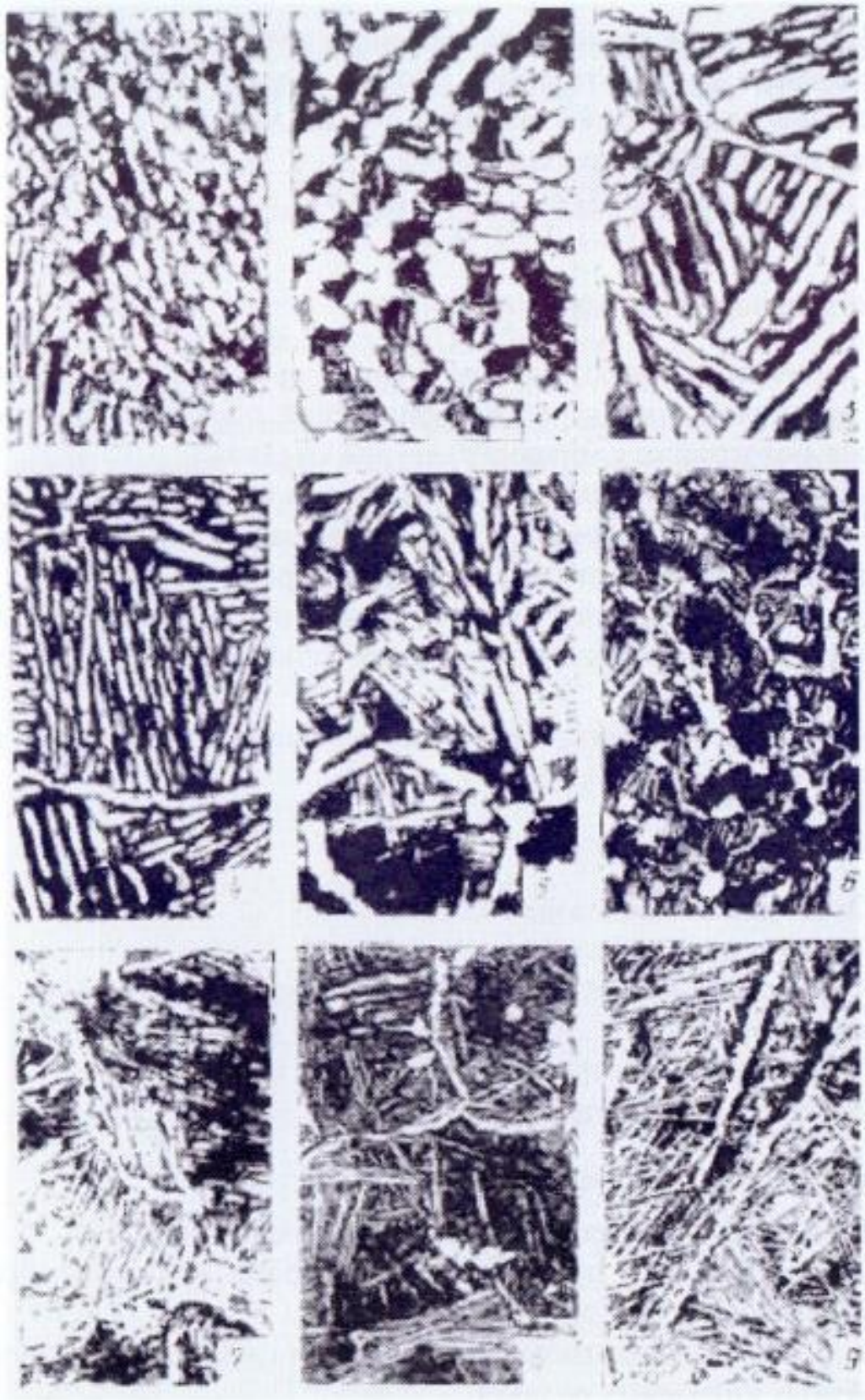
3. ($\alpha+\beta$) - *alloys* : VT 6 , VT3-1, VT 8 , VT9, VT14, VT16, VT23, VT25, VT33. These are martensitic alloys that are strengthened by heat treatment. Alloy VT25 is classified as an ($\alpha+\beta$)-alloy with a predominance of the α - phase.

4. ($\alpha+\beta$) - *transition class alloys*: VT22, VT30. In a stable state, these alloys contain from 25 to 50 % of the β -phase, have a high dispersion of the α - and β - phases, are distinguished by the maximum strengthening effect during processing and high strengthenability .

5. β - *alloys*: VT 15, VT32, 4201. Alloys with β - structure find limited application. For example, alloy VT15 after hardening and aging has $\sigma_B = 1500$ MPa at $\delta = 6$ % , however, such high strength cannot be realized in welded joints due to unsatisfactory weldability of this alloy.



a



b

Fig. 4.2. Microstructure scales of semi-finished products made of titanium alloys: a — rolled rods; b — stampings

3. Studied alloys

To study the structure and properties, the most widely used titanium alloys for the production of disks, blades and shaped parts of aircraft engines were selected:

- α -alloy VT5 in cast condition;
- pseudo α - alloys OT4-1, VT20, VT18U;
- ($\alpha+\beta$)-alloys VT3-1, VT9 , VT6.

4. Methodology of work

Students receive an album with the microstructure of titanium alloys with different structures and heat treatments, as well as individual photographs with the microstructure of the alloys.

When performing laboratory work it is necessary:

- study the album and characterize the microstructure of the alloys using the microstructure scale (Fig. 4.2);
- to study the fine structure of alloys, revealed using electron microscopy methods of thin foils, and to characterize;
- to identify patterns of formation of the structure of α - and β - phases during various treatments.

5. Reporting requirements

The report must contain:

- topic and purpose of the work;
- a brief summary of the work with characteristics of the main titanium alloys;
- drawings of the microstructure of the alloys studied;
- conclusions on the work.

Control questions

1. What phases are found in titanium alloys?
2. What forms do the α - and β - phases take during heat treatment, deformation, and how are they arranged?
3. Explain the mechanism of formation of globular structure in two-phase nickel alloys.
4. Provide a description of the alloys being studied in terms of structure and properties.

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