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INFLUENCE OF HEAT TREATMENT ON THE STRUCTURE AND MECHANICAL PROPERTIES OF PSEUDO α-TITANIUM ALLOY IN A WELDED JOINT

Valerii Bilous
Doctor of Technical Science, Senior Researcher*
Eduard Vrzhyzhevskyi
Leading Engineer*
Valery Kostin
Doctor of Technical Sciences, Senior Researcher*
Tatjana Taranova
PhD, Senior Researcher*
Volodymyr Zvorykin
PhD
TECHNOL LLC
Chervonopilska str., 2-G, Kyiv, Ukraine, 04123
Constantine Zvorykin
Corresponding author
PhD, Associate Professor
Department of Welding
National Technical University of Ukraine
“Igor Sikorsky Kyiv Polytechnic Institute”
Beresteiskyi ave., 37, Kyiv, Ukraine, 03056
E-mail: constantine.oleg@gmail.com
*E. O. Paton Electric Welding Institute
of the National Academy of Sciences of Ukraine
Kazymyr Malevych str., 11, Kyiv, Ukraine, 03150

The object of this study was the weld material of a new Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy, which was obtained by electron beam welding.

Electron beam welding (EBW) provides rapid melting and cooling with crystallization under significant temperature gradients. For the pseudo α-titanium alloy, this leads to the appearance of significant residual stresses in the joint and determines the specificity of the dispersion decay of the β-phase. Residual stresses are reduced by preliminary heating, removed by heat treatment. Such processing exerts a critical influence on the formation of the structure and phase composition of the weld and the zone of thermal influence of the electron beam; it can form macro defects, undesirable phases, and structural states.

The conditions of heat treatment have been determined to bring the welded joint from complex alloyed pseudo α-titanium alloy to the required level of mechanical characteristics. The structure, phase morphology, elemental composition, and mechanical characteristics of welded joints without additional heat treatment have been compared, with preliminary local heating of 400 °C, with additional post-weld local annealing at T_T=750 °C, t_T=4 minutes and sequential annealing in the furnace at T_T=850 °C, t_T=60 minutes. It has been established that a full cycle of heat treatment of a welded joint provides the highest characteristics of strength and plasticity, but local heat treatment also makes it possible to obtain a defect-free joint with satisfactory characteristics for less responsible products. It is shown how heat treatment of pseudo α-titanium alloy makes it possible to get rid of unwanted phase formations $(Zr,Ti)_5Si_3Al$ and transform them into $(Zr,Ti,Nb,Mo)_3SiAl$.

The results are promising for use in the production of aircraft engine parts

Keywords: electron beam welding, titanium alloys, heat treatment, mechanical properties, dispersion strengthening

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1. Introduction

Pseudo α-alloys of titanium, which are successfully deformed and have increased heat resistance, are used in the elements of the power structures of aircraft (aircraft, rockets, etc.), which enables a reduction in the weight of articles and improves their operational characteristics. For the use of such materials in complex structural elements, it is advisable to be able to weld metal elements both from the same materials and from dissimilar materials. In general, pseudo -alloys of titanium are welded quite successfully, but require vacuum conditions or a protective atmosphere.

Most alloys of this type have a multiphase composition and reach their optimal state by performing multistage processing. Melting of the alloy during welding changes its properties, which in most cases predetermines the need for further processing of the welded joint to optimize the structure and phase composition of the weld material and the heat-affected zone. At the same time, such treatment should not impair the properties of the main material. The study of such processes is necessary for each material or pairs of materials.

Two basic conditions must be met for welding identical alloys. It is required to obtain a weld without defects and achieve such a state of the material in the joint, which is close to the base material in terms of structure and properties. It is usually considered that the mechanical properties of the welded joint in the relevant parts should not decrease by more than 10 % from the mechanical properties of the base material.

Fulfillment of the first condition in most cases is associated with the correct selection of welding mode parameters. The second condition imposes requirements on the composition and structure of the welded material, which determine the level of its operational characteristics.

There are prospects of complex alloyed materials such as pseudo α-titanium alloy for industrial production, the need for their welding with each other and dissimilar materials. This predetermines the relevance of research on the effect of heat treatment on the structure and mechanical properties of the specified alloys in the welded joint.

2. Literature review and problem statement

The classification of titanium alloys and a description of their operational characteristics are given in [1]. It is shown that titanium alloys may contain the following alloying impurities: Al, C, N, O (α-stabilizers); Zr, Sn – neutral strengtheners; Mo, V, W, Nb, Ta are isomorphic β-stabilizers; Si, Cu, Pd, Fe, Cr, Mn, Ni, Co are eutectoid-forming β-stabilizers. It should be noted that such β-stabilizers as Si, Cu, and Pd ensure the eutectoid decay of the β-phase during cooling or during heat treatment. With impurities of Fe, Cr, Mn, Ni, Co, critically fast cooling is necessary for eutectoid decomposition of the β-phase. Work [1] describes the main types of titanium alloys observed under conditions close to stationary, but the issues related to their properties observed under conditions that differ significantly in terms of characteristics that such alloys have after fusion welding remained unresolved. That is, a new titanium alloy based on the composition of alloying elements can be classified by type, but for its successful fusion welding or in the solid state, research is needed on the defects of the weld, the structure, and mechanical properties of the welded joint.

For an integrative assessment of the influence of alloying elements on the phase composition of titanium alloys, the concept of Mo equivalent (Mo_{ekv}) was used in work [2], and the concept of Al equivalent (Al_{ekv}) was also used in [3]. In works [2, 3] it was shown that their authors used these concepts only to characterize the alloy as a whole. However, the same approach can be used to evaluate the weld material. The option of using such concepts for a limited volume of sections of the weld material is phenomenological in nature; this approach does not reflect the completeness of the structural and phase characteristics of titanium alloys. At the same time, it provides the possibility of using convenient technical parameters. As a result, it can be assumed that the molybdenum equivalent [2] in a complex titanium alloy corresponds to its concentration in the Ti-Mo system, at which the amount of the β-phase and its tendency to transform is similar to that of a complex titanium alloy. That is, as the molybdenum equivalent increases, the temperature at which the β-phase decay begins decreases, its stability increases, the share of the α′-phase increases, the duration of aging increases, and the critical intensity of cooling decreases. It can also be assumed that the equivalent Al_{ekv} [3] characterizes the elemental composition of the titanium alloy, at which the formation of the intermetallic Ti_3Al begins, which critically affects the mechanical properties of the alloy. For titanium alloys, the achievement of $Al_{ekv} \geq 9$ is critical, at which the high-temperature long-term strength of the alloy decreases.

Work [4] reports the results of research on improving the operational properties of welded pseudo α-alloys. The indicated results indicate the expediency of reducing solid-soluble strengthening with aluminum while maintaining the overall level of Al_{ekv}. This is achieved by increasing the amount of Sn, Zr, O, N and alloying with isomorphic and eutectoid β-stabilizers, limited use of eutectoid-forming β-stabilizers with variable solubility in the heat treatment temperature range. In [4], it was shown that such results relate to the properties of the studied structural titanium alloys, but the questions regarding the change in the local amounts of alloying elements remained unresolved. This is possible under the conditions of the formation of a weld in a new titanium alloy, which determines the relevance and necessity of separate control of the influence of the specified factor.

Paper [5] reports the results of research that showed that aging processes are the predominant factor in the strengthening of pseudo α-titanium alloys. These processes determine the phase composition, number and distribution of finely dispersed phases formed during the phase decomposition of the β-phase. On the other hand, the aging regime for each new alloy is uncertain. Under the condition of forming a weld seam of pseudo α-titanium alloys, the need to establish not only the features of the structure of the formed material but also the determination of the necessary heat treatment becomes urgent.

In [6], it was established that for pseudo α-alloys of titanium containing silicon, silicide-based formations are typical fine-dispersed phases that provide strengthening. It is also shown that the formation of higher silicides leads to brittleness of the material. The research was carried out with the material obtained under stationary conditions, which does not fully correspond to the welding conditions. But the results reported in [6] are important and should be taken into account for each condition of formation of the similar material under study.

In [7], the results of studying the kinetics of hardening changes during aging of pseudo α-titanium alloy T1100 are given. It was shown that the hardness varied as follows: a decrease caused by dislocation recovery, an increase caused by silicide nucleation, a decrease caused by silicide coarsening, and an increase caused by $(Ti,Zr)_6Si_3/\alpha_2$ precipitation. The results of the work cannot be generalized to other pseudo α-titanium alloys, but the established trend provides an approach to choosing modes for their heat treatment.

According to the research results in [8], titanium alloys are classified as satisfactorily welded, but pseudo α-titanium alloys are classified as well welded. The same study determined that the most effective method for joining titanium alloys is electron beam welding (EBW). It is shown that the use of EBW for pseudo α-titanium alloys enabled the execution of welded joints with satisfactory structure and mechanical characteristics. These characteristics reach the level of 90 % of the strength limit of the main material. At the same time, the analysis from [8] gives reason to believe that there are currently no generalized recommendations for welding the entire spectrum of pseudo α-titanium alloys. That is, the research results reported in [8] provide basic recommendations for welding modes. This allows us to consider it appropriate to analyze the suitability of the specified recommendations for each new pseudo α-titanium alloy.

Work [9] shows the effectiveness of local heat treatment with an electron beam of welded joints from pseudo α-alloys of titanium Ti-6.08Al-2.18Sn-3.88Zr-0.39Mo-1.14V-0.65Si and Ti-5.5Al-3.02Sn-4.58Zr-0.1Mo-0.8Nb-0.59V-0.6Si, to improve mechanical characteristics. At the same time, the required level of operational characteristics was not achieved by local heat treatment in [9]. This treatment is recommended to ensure preserved welded articles before furnace heat treatment. However, the results do not close the way to the use of local heat treatment as a final treatment for other titanium alloys or temperature regimes.

Our review of the above literature revealed the following. For successful welding of a new pseudo α-Ti alloy, it is advisable to analyze the phase composition on the basis of the elemental composition, using at the same time an integrative assessment of the influence of alloying elements on the phase composition of titanium alloys. It is also necessary to take into account the fact that dispersion aging processes, which depend on the heat treatment of the alloy, have a decisive influence on the strength and plasticity of such alloys. According to the results of previous studies, it was found that the most influential on the mechanical properties of pseudo α-Ti alloys with a significant concentration of Si are phases based on titanium and silicon. In the process of dispersion aging, the level of strengthening changes at different stages due to changes in the dislocation structure and phase neoplasms. All this gives reason to assert that the analysis of the features of the phases formed by EBW in the joint material and which change under additional thermal influence provides the prospect for optimizing the technological cycle of welding a new pseudo α-Ti alloy.

3. The aim and objectives of the study

The purpose of our study is to substantiate the optimal process of obtaining a high-quality welded joint from the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy, which is a promising pseudo α-alloy. This will make it possible to recommend processing regimes based on the analysis of microstructure, phase composition, and mechanical tests.

To achieve the goal of the work, the following tasks were set:

– to determine the strength and plasticity characteristics of the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy made by electron beam welding according to the modes recommended for pseudo α-titanium alloys;

– to establish the influence of out-of-fire and furnace heat treatment on the structure and mechanical properties of the pseudo α-titanium alloy Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si in a joint made by electron beam welding;

– to analyze the structural and phase changes after heat treatment and their possible influence on the mechanical properties of the pseudo α-titanium alloy Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si in the welded joint.

4. The study materials and methods

The object of our study was the weld material of a new Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy, which was obtained by EBW.

The main hypothesis of the research assumed the possibility of bringing the weld material of Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy, obtained by EBW, to a state close in mechanical characteristics to the base material by means of heat treatment.

The main assumption in the work was the possibility of establishing the reasons for the change in the mechanical characteristics of the weld material based on the analysis of its structure and elemental composition.

The simplification adopted in the work was to establish the mechanical characteristics of the weld material based on the results of the study of 6 samples (in a series) cut from local areas of the welded joint.

The basic researched material in the experiments performed in this work was complex alloyed pseudo α-titanium alloy Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si.

Samples of heat-resistant complex-alloyed pseudo α-titanium alloy with the above composition Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si were produced by the electron beam melting method with an intermediate capacity and subsequent cutting of parallelepipeds 10×200×40 in size mm. According to the results of X-ray structural analysis, the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy is a two-phase alloy. It consists of the beta phase of titanium (β-Ti) – 2.4 % (lattice parameters a=2.9400, c=4.670) and the alpha phase of titanium (α-Ti) – 97.6 % (lattice parameter a=3.2225).

Electron beam welding (EBW) was carried out in the welding chamber of the UEL-144 installation (UEL-144, Pilot Paton Plant, Ukraine).

For welding, the procedure of forming a weld seam was used during butt welding in the free position of the samples without the use of forming devices and substrates [10]. Under such conditions, better results are achieved due to the provision of two-way exit of gases and metal vapors from the remelting channel.

Welded plates with a size of 200×40 mm and a thickness of 10 mm made of the alloy Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si were polished on all sides to a roughness of R_z=10 μm before welding and were assembled butt without a gap. In order to avoid the deplaning of these plates before the welding process, input and output strips were installed and welded across the sample from two sides. The length of the output strips, which were fixed in a special device, was 160 mm. The welded seam began and ended at the input and output strips.

Electron-beam welding was carried out with through penetration under the following mode: U_{acc}=60 kV, I_{eb}=90 mA, v_{eb}=7 mm·s^{-1}, P=5·10^{-3} Pa. At the same time, the sweep (cross section) of the beam during welding was elliptical, the movement of the beam was along the joint of the welded samples, the number of passes was one. After welding, the welded samples were cooled to room temperature in a vacuum in the welding chamber.

Preheating of the welded samples was carried out by electron beam scanning of the welded joint zone according to the parameters of electron beam welding. The final heat treatment was performed in a vacuum furnace SShV-1.25/25I1 at a pressure of P=5·10^{-3} Pa.

Chemical etching of the studied samples to reveal the microstructure was carried out according to the procedure from [11] in two stages: first in a 4 % solution of nitric acid (HNO_3) and then by electrolytic etching in a chromic anhydride reagent.

The microstructure was studied using a NEOPHOT 32 optical microscope (Carl Zeiss Jena, Germany) and a JSM-840 scanning electron microscope (JEOL, Japan), which was equipped with an INCA PentaFET-X3 X-ray micro spectral analysis system (Oxford Instruments, Great Britain). The fracture surface was examined using the above-mentioned raster microscope. Microhardness was measured on a M-400 hardness tester (LESO, USA) under a load of 10 g.

For mechanical tests, samples were made from the base material and welded joints, the view of which is shown in Fig. 1.

Tensile tests were performed on a ZD-4 tensile machine (Germany). Impact viscosity measurements were performed on a Mohr & Federhaff Losenhausen (LOS) (Germany) installation.

The temperature was measured using a thermocouple (Fig. 2).

To record the thermal processing cycle of the welded joint, a tungsten-molybdenum thermocouple was placed in the area of contact of the welded samples (Fig. 2).

The Mo equivalent for local areas of elemental analysis was calculated according to the following formula [2]:

$$\begin{aligned}\mathrm{Mo}_{ekv}=&\%\mathrm{Mo}+\%0.22\mathrm{Ta}+\%0.28\mathrm{Nb}+\\&+\%0.44\mathrm{W}+\%0.67\mathrm{V}+\%1.6\mathrm{Cr}+\%1.7\mathrm{Mn}+\\&+\%2.9\mathrm{Fe}+\%1.25\mathrm{Ni}+\%1.7\mathrm{Co}-1.0\mathrm{Al}.\end{aligned} \tag{1}$$

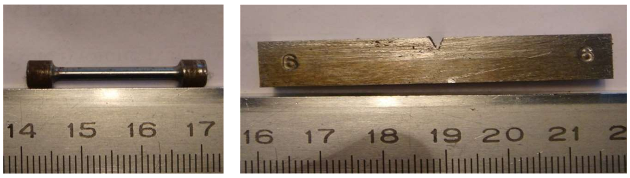
The equivalent Al_{ekv} was calculated according to the following formula [3]:

$$\mathrm{Al}_{ekv}=\%\mathrm{Al}+\%\mathrm{Sn}/3+\%\mathrm{Zr}/6+10[\%\mathrm{O}+\%\mathrm{C}+2\ \%\mathrm{N}]. \tag{2}$$

To characterize the properties of the weld material of the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy, the ratio of the fractions of aluminum and molybdenum equivalents $\pounds_{\mathrm{Al/Mo}}$ was calculated:

$$\pounds_{\mathrm{Al/Mo}}=\mathrm{Al}_{ekv}/\mathrm{Mo}_{ekv}. \tag{3}$$

The ratio of aluminum and molybdenum equivalents $\pounds_{\mathrm{Al/Mo}}$ was calculated for the local zones of the conducted micro-X-ray spectral analysis.



a *b*

Fig. 1. Test samples for carrying out mechanical studies: *a* – for tension; *b* – for impact viscosity

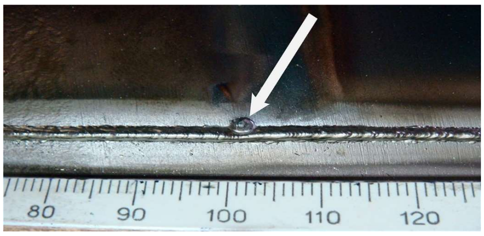


Fig. 2. Placement of the tungsten-molybdenum thermocouple in the area of the welded joint (indicated by the arrow)

5. Results of investigating the influence of heat treatment cycles

5. 1. Results of determining the critical characteristics for operation of a joint made of Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy

Welding of Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy elements was carried out taking into account the experience and results of electron beam welding modes reported in [8, 9]. Electron beam welding of Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy samples with the thermal cycle shown in Fig. 3 provided a visually defect-free welded joint (Fig. 4, *a*, *c*). At the same time, after storing the resulting welded joint for 240 hours, transverse cold cracks appeared on the surface of the weld (Fig. 4, *b*, *d*), which passed through the peri-seam zone and ended on both sides of the joint on the base material.

The occurrence of such defects leads to the impossibility of using the resulting Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy welds. The way to solve the problem of cold cracks in welded joints of the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy is to perform heat treatment, which usually makes it possible to reduce stress in the weld seam and the zone of thermal influence.

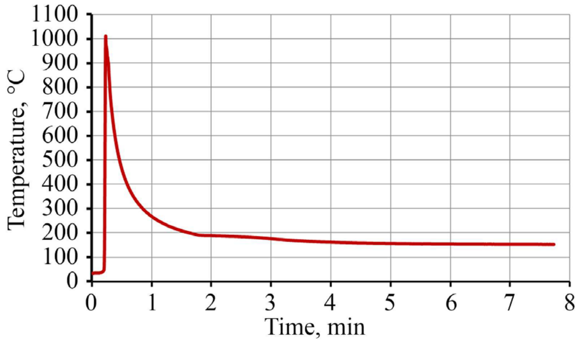


Fig. 3. The thermal cycle of a sample with a thickness of s=10 mm, obtained by through-flow melting under the mode I_{eb}=90 mA, v_{eb}=7 mm·s^{-1}

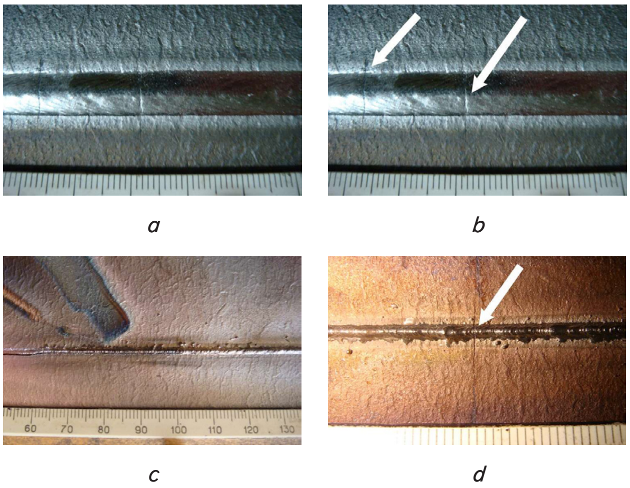


Fig. 4. Type of a welded sample from an alloy with a composition of Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si with a thickness of s=10 mm, obtained by through-flow melting under the mode I_{eb}=90 mA, v_{eb}=mm·s^{-1}: *a* – front side of the sample after welding (without cracks); *b* – the front side of the sample on which cold cracks appeared after exposure for 240 hours (indicated by an arrow); *c* – the root side of the sample after welding (without cracks); *d* – the root side of the sample on which cold cracks appeared after exposure for 240 hours (indicated by an arrow)

5. 2. Effect of heat treatment on the structure and properties of the welded joint of pseudo α-titanium alloy

In the process of choosing the type of heat treatment, those that do not require additional equipment and can be performed in the welding chamber of the UEL-144 installation are preferred. Furnace heat treatment complicates the technological process, and its use requires additional justification. Options for thermal effects on test samples are given in Table 1.

When making the welded joint according to the thermal cycle with index 3, the temperature change in the process of obtaining the sample is shown in Fig. 5.

On the surfaces of the welded joint made according to the specified thermal cycle, no cracks were found either on the face or on the root sides (Fig. 6, *a*, *b*), neither after the completion of the technological cycle, nor after storage for 720 hours.

Table 1

Types of samples used in EBW with different types of heat treatment of welded joints of Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy

Heat treatment type index	Type of heat treatment
1	Initial state (without heat treatment)
2	Welded joint (EBW without heat treatment)
3	Pre-local heating to temperature T_T=400 °C+EBW
4	Preheating to temperature T_T=400 °C+EBW+ +local annealing at T_T=750 °C, t_T=4 minutes
5	Preheating to temperature T_T=400 °C+EBW+ +local annealing at T_T=750 °C, t_T=4 minutes, furnace annealing T_T=850 °C, t_T=60 minutes

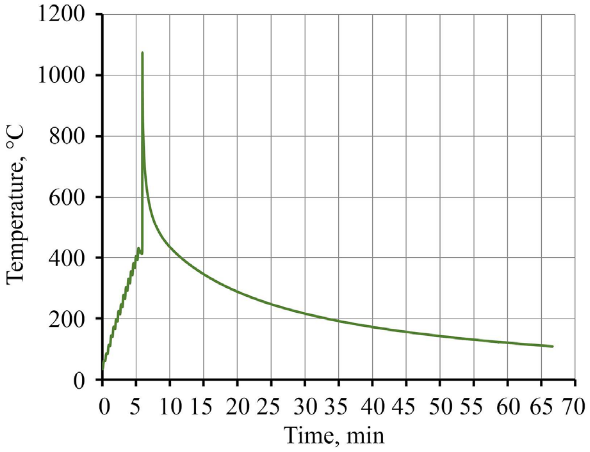
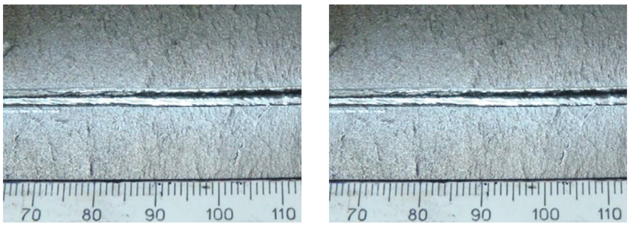


Fig. 5. Thermal cycle of a sample with a thickness of s=10 mm with preliminary local heating to T_T=400 °C and through melting under the mode I_{eb}=90 mA, v_{eb}=7 mm·s^{-1}



a *a*

Fig. 6. General view of the welded sample from an alloy with the composition of Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si with a thickness of s=10 mm, with preliminary local heating to T_T=400 °C and through penetration under the mode I_{eb}=90 mA, v_{eb}=7 mm·s^{-1}: *a* — front side of the sample after welding (without cracks); *b* — the root side of the sample after welding (without cracks)

A similar situation is observed when performing a welded joint, provided that local annealing is introduced into the technological cycle at a temperature of T_T=750 °C, t_T=4 minutes (the thermal cycle is shown in Fig. 7). No macro defects were found on the outer surfaces of such a welded joint (Fig. 8, *a*, *b*).

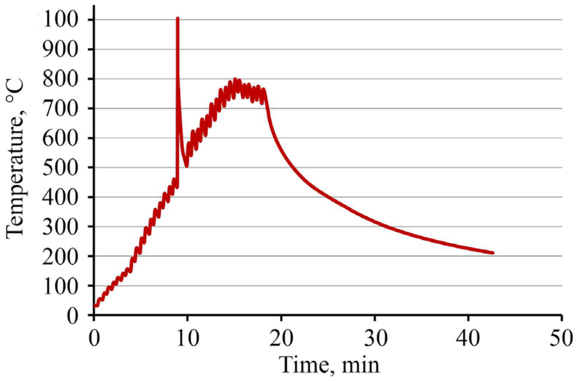
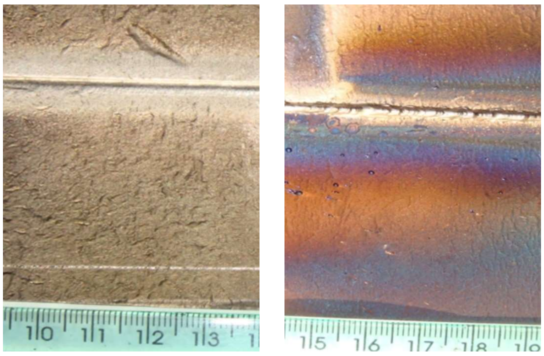


Fig. 7. Thermal cycle of a sample with a thickness of s=10 mm with preliminary heating to T_T=400 °C, through penetration under the mode I_{eb}=90 mA, v_{eb}=7 mm·s^{-1} and with local annealing at T_T=750 °C, t_T=4 minutes



a *a*

Fig. 8. General view of the welded sample from an alloy with the composition of Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si with a thickness of s=10 mm, preheated to T_T=400 °C, through penetration under the mode I_{eb}=90 mA, v_{eb}=7 mm·s^{-1} and with local annealing at T_T=750 °C, t_T=4 minutes:
a — front side of the sample after welding (without cracks);
b — the root side of the sample after welding (without cracks)

Furnace annealing at T_T=850 °C, t_T=60 minutes after the completion of welding processes with out-of-furnace heat treatment does not change the appearance of the external surfaces of the welded joint, on which no traces of macro defects are observed.

Thus, all three types of thermal cycles of heat treatment (with indices 3, 4, 5) make it possible to get rid of cold cracks that appeared during the storage of welded joints. In order to choose the most effective technological cycle for the execution of welded joints, studies of the mechanical characteristics of the welded samples were carried out, which were performed under different modes of heat treatment. The results of the study of mechanical characteristics are given in Table 2.

Our results (Table 2) showed that all options for heat treatment (indexes 3, 4, 5) lead to an increase in the strength and plasticity characteristics of the welded joint. The highest level of mechanical characteristics is observed during preheating to a temperature of T_T=400 °C+EBW+local annealing at T_T=750 °C, t_T=4 minutes and furnace annealing T_T=850 °C,

t_T=60 minutes (type of heat treatment with index 5). The smallest thermal impact (mode 3) makes it possible to reduce the residual thermal stresses and prevent the formation of cold cracks.

Table 2

Mechanical properties of the base metal and welded joints of heat-resistant titanium alloy obtained by EBW

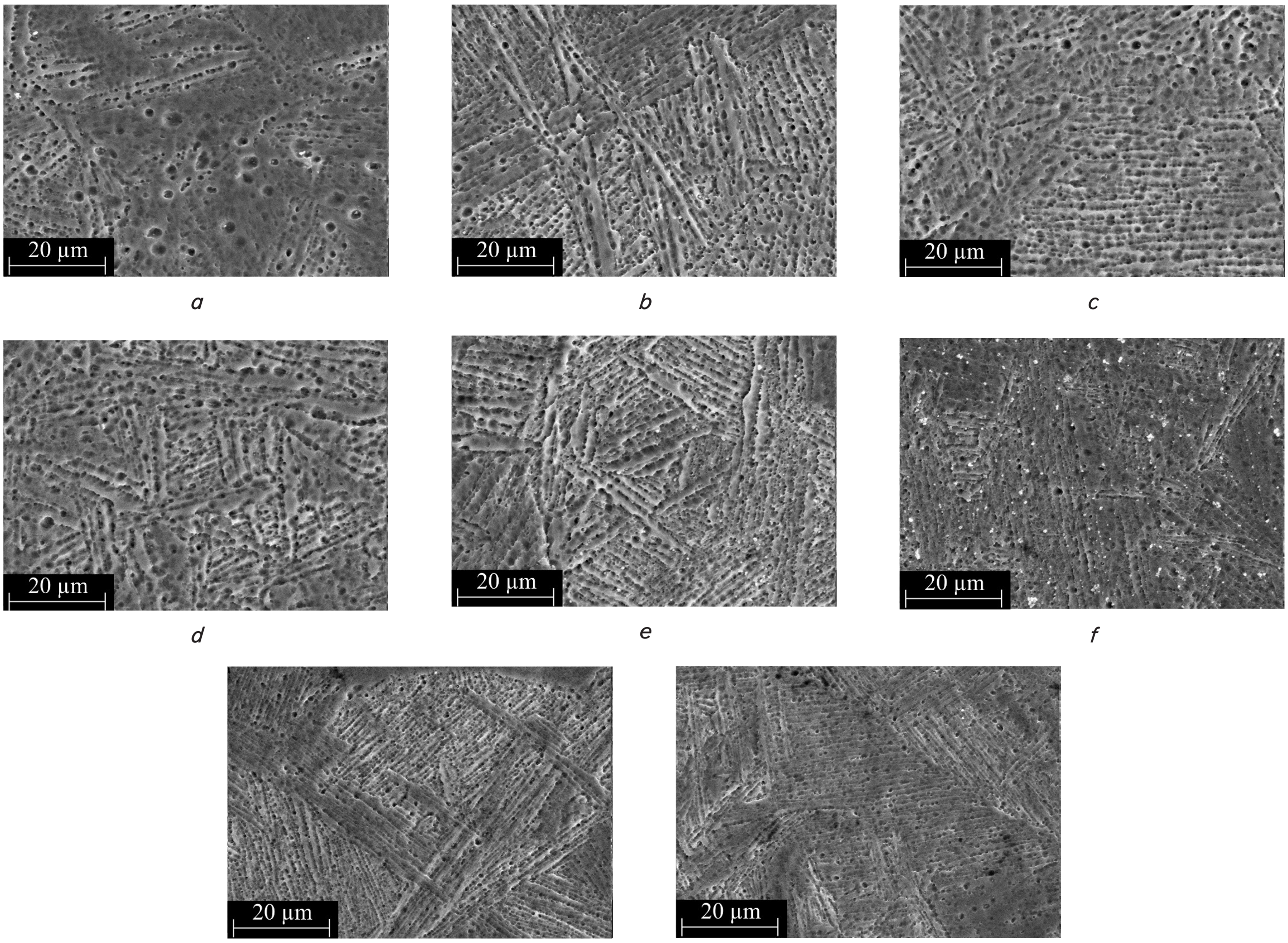
Types of samples by heat treatment modes	Place of rupture	Tensile strength σ_t, MPa	Yield strength $\sigma_{0.2}$, MPa	Relative elongation δ, %	Impact strength, KCV, J/cm^2 Weld/HAZ
1	Base metal	1,027.9	996.4	2.7	13.92
2	Welded connection	996.2	901.8	1.0	5.4
3	Welded connection	910.7	831.1	1.8	11.93
4	Welded connection	1,010.3	847.5	2.3	12.3
5	Welded connection	1,015.2	939.1	3.8	17.4

It should be noted that the strength characteristics σ_t, $\sigma_{0.2}$ of the welded joint after post-furnace heat treatment (Table 2) are 1.7...15 % lower than the same characteristics of the welded alloy, which is usually acceptable for less responsible joints of this type. After furnace heat treatment, the strength level is at least 94 % of the base metal, and the plasticity level of the material (δ, KCV) in the fracture zone exceeds the characteristics of the base material by up to 40 %.

5. 3. Structural and phase changes after heat treatment, their influence on the properties of the welded joint

The alloy with the composition Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si is a pseudo α-alloy and its mechanical properties are largely determined by dispersion hardening. Its metallographic structure is characterized by a basket-type structure with a predominant amount of α-phase. It should be noted that the lamellar α-phase in the structure is a defining structural component in the weld zone and in the material area of the thermally affected zone, as well as the α′-phase. The remnants of the β-phase are observed between the plates of the α-phase and needle-like grains of the α′-phase (Fig. 9).

Changes in the distribution of dispersed particles formed in the weld area and in the thermally affected zone under different thermal cycles are shown in Fig. 9. It was determined that without additional heat treatment in the grains of the α-phase in the weld, dispersed phase formations of 3–5 μm (Fig. 9, *a*) are observed, which in size significantly exceed other dispersed separations on the boundaries of the α′-phase. A smaller amount of a phase of this type is observed in the heat-affected zone without additional heat treatment (Fig. 9, *b*) and after welding with preliminary heating (Fig. 9, *c*, *d*).



a *b* *c*

d *e* *f*

g *h*

Fig. 9. The microstructure of an alloy with the composition Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si in the weld (*a, c, e, g*) and the thermally affected zone (*b, d, f, h*) after electronic-beam welding (EBW) under different modes of heat treatment of welded joints (Table 1): *a, b* – mode 2; *c, d* – mode 3; *e, f* – mode 4; *g, h* – mode 5

The introduction of additional local annealing (mode 4) leads to a decrease in the size of both α-phase plates and dispersed phase formations on its borders (Fig. 9, *e*, *f*). Furnace annealing (mode 5) leads to further grinding of both α-phase plates and α′-phase needle grains and dispersed phase formations (Fig. 9, *g*, *h*). The reduction of grain sizes of the main phase of the pseudo α-Ti alloy and silicide phase formations is a factor affecting the mechanical properties of the welded joint.

Analysis of the composition of dispersed phase formations in the material of the welded joint without additional heat treatment in the grains of the α-phase by the method of Auger spectroscopy revealed the presence of phases of two types: $(Zr,Ti)_5Si_3Al$ and $(Zr,Ti)_3SiAl$ (Fig. 10, *a*, *b*).

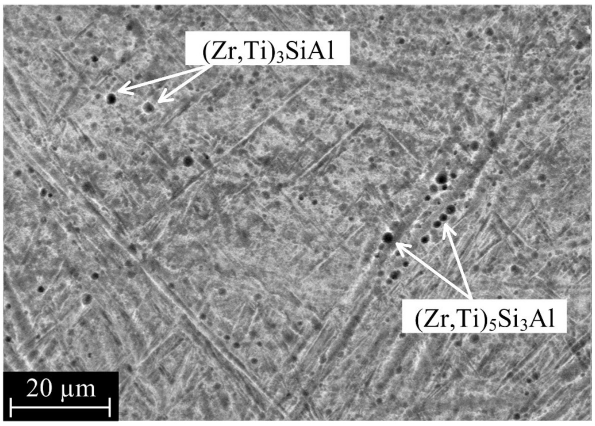
Dispersed allocations in the weld material after furnace heat treatment receive the refractory alloying elements Mo and Nb (Fig. 11, *a*, *b*). At the same time, a phase with a lower Si content was mainly detected – $(Zr,Ti,Nb,Mo)_3SiAl$.

Phase formations of this type have a critical effect on the plasticity of pseudo α-Ti alloys.

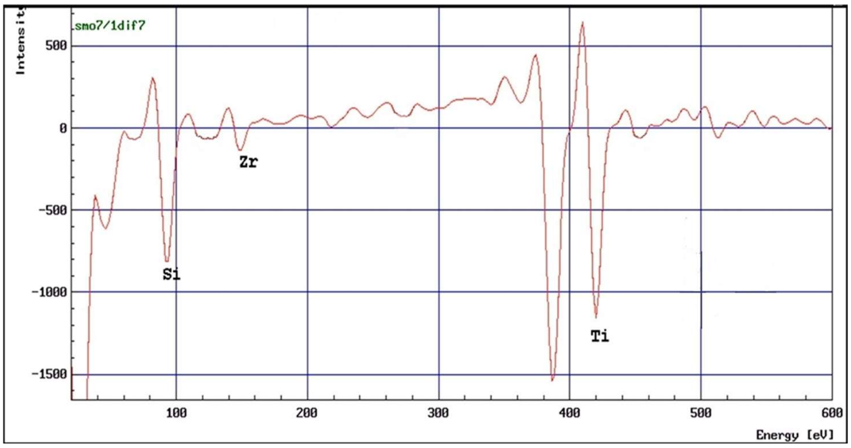
Our micro-X-ray spectral analysis revealed the existence of concentration inhomogeneity in the distribution of alloying elements across the cross-section of the weld. For an integrative assessment of the impact of the inhomogeneity of the distribution of alloying elements on the mechanical properties of the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy, equivalents for Mo (Mo_{ekv}) and Al were determined for the local zones of micro-X-ray spectral analysis.

Fig. 12–15, *a* show the results of metallography of materials in the area of welded joints, which were obtained under different regimes of thermal effects. The corresponding images indicate the points at which the X-ray micro spectral analysis was performed. Below, under the metallographic images (Fig. 12–15, *b*), are the results of calculating the ratios of aluminum and molybdenum equivalents, calculated from formula (3).

For α-alloys, the ratio of aluminum and molybdenum equivalents reaches 9, for pseudo α-alloys it does not exceed 3, for (α+β)-alloys it is about 1.5. For the investigated alloy with the composition Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si, the calculated Al_{ekv}/Mo_{ekv} indicator is 2.37, which corresponds to its classification as a pseudo α-alloy. In general, under all modes of heat treatment of the welded joint, the ratio of aluminum and molybdenum equivalents for the local zones of the micro-X-ray spectral analysis does not exceed the limits typical for pseudo α-alloys. Analysis of changes in $£_{Al/Mo}$, which characterizes the elemental composition of local zones, reveals the tendency of deviations of the elemental composition in the weld area from the average, which is decisive for the mechanical properties of titanium alloys.

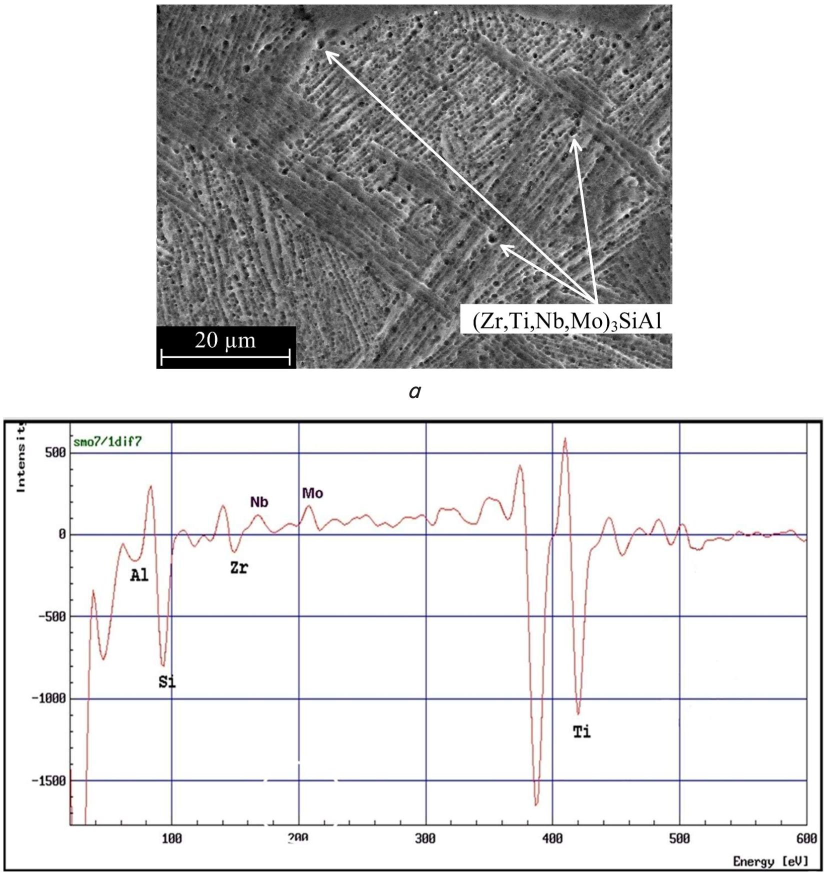


a



b

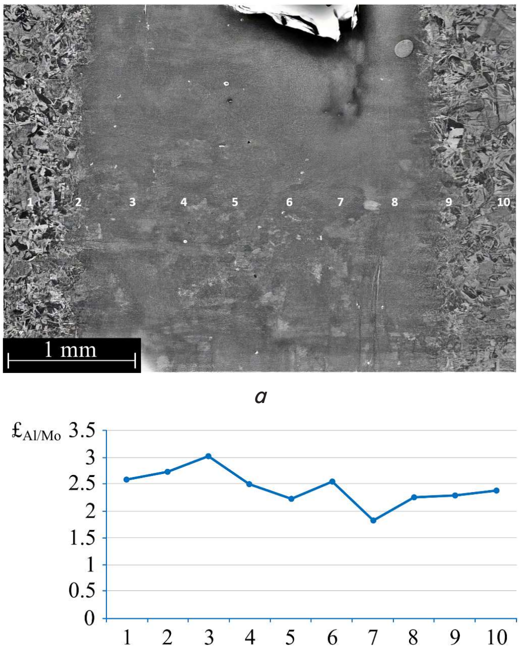
Fig. 10. Characteristics of a titanium alloy with the composition Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si and the composition of inclusions in the weld metal: *a* — microstructure after EBW (mode 2); *b* — characteristic Auger spectrum of dispersed inclusions, at. % in weld metal after EBW (mode 2)



a

b

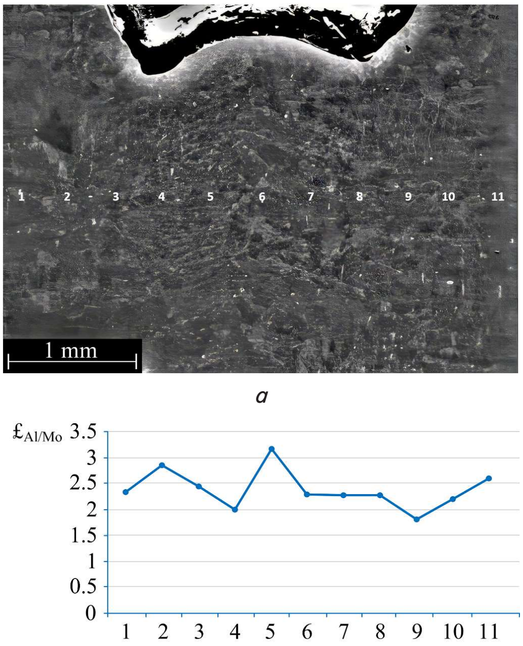
Fig. 11. Characteristics of a titanium alloy with the composition Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si and the composition of inclusions in the weld metal: *a* – microstructure after heat treatment (mode 5); *b* – characteristic Auger spectrum of dispersed inclusions, at. % in weld metal after heat treatment (mode 5)



a

b

Fig. 12. Research results after heat treatment of welded joints according to mode 2: *a* – metallographic structure of the weld material (with X-ray structural analysis points); *b* – ratio of aluminum and molybdenum equivalents $£_{Al/Mo}$ for local zones of micro-X-ray spectral analysis



a

b

Fig. 13. Research results after heat treatment of welded joints according to mode 3: *a* – metallographic structure of the weld material (with X-ray structural analysis points); *b* – ratio of aluminum and molybdenum equivalents $£_{Al/Mo}$ for local zones of micro-X-ray spectral analysis

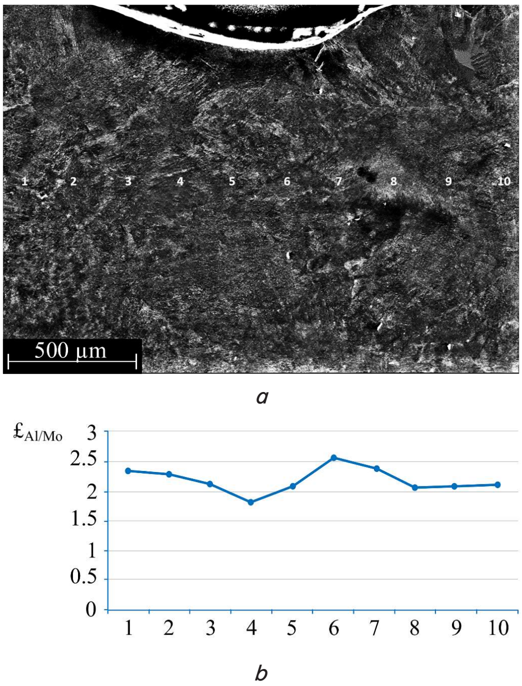


Fig. 14. Research results after heat treatment of welded joints according to mode 4: *a* – metallographic structure of the weld material (with X-ray structural analysis points); *b* – ratio of aluminum and molybdenum equivalents $£_{Al/Mo}$ for local zones of micro-X-ray spectral analysis

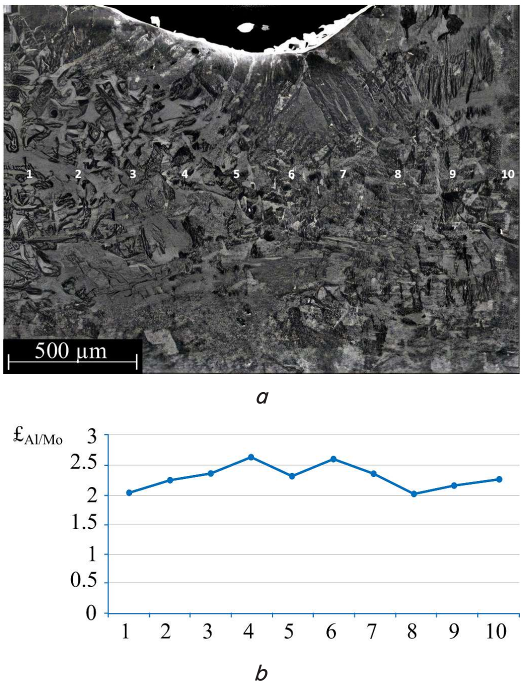


Fig. 15. Research results after heat treatment of welded joints according to mode 5: *a* – metallographic structure of the weld material (with X-ray structural analysis points); *b* – ratio of aluminum and molybdenum equivalents $£_{Al/Mo}$ for local zones of micro-X-ray spectral analysis

It should be noted that the influence of the through channel of the electron beam on the composition of the elements in the weld material was observed in particular in [12]. The loss of the components of the chemical composition from the joint zone largely depends on the vapor elasticity of the corresponding elements under welding conditions. The probability of loss of certain elements in the weld material is confirmed by the results of $£_{Al/Mo}$ changes in local areas of the weld without annealing after welding (Fig. 11, 12).

6. Discussion of results related to investigating the influence of heat treatment cycles on the mechanical properties of welded joints

The study of the effect of heat treatment cycles (Table 1) when making a joint made of Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy on its mechanical properties showed the possibility of obtaining a high-quality connection (Table 2).

While determining critical operational characteristics of the connection from the specified alloy, performed by EBW according to the regimes recommended for pseudo α-titanium alloys, the formation of cold cracks in the weld area after EBW was detected. This is associated with significant residual stresses that arise as a result of intense and rather short-term, less than 30 seconds (Fig. 3), exposure to the electron beam (mode 2). It was also found that a material is formed in the weld, which is in a thermodynamically unbalanced state. In such a titanium alloy, dispersion aging will continue even under the conditions of storage of welded joints. As was shown in [7], aging in a similar titanium alloy is accompanied by the movement of dislocations. Their interaction with large formations of $(Zr,Ti)_5Si_3Al$ (Fig. 9, *a*), which have a weak adhesive bond with the metal matrix, is explained by the fact that this can lead to the formation of crack nuclei and their opening under the influence of residual thermal stresses (Fig. 4).

When determining the effect of out-of-fire and furnace heat treatment on the structure and mechanical properties of the pseudo α-titanium alloy Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si in the connection made by EBW, it was found out that local heating of the weld joint zone (mode 3) ensures a longer time interval for relaxation processes to occur (Fig. 5). It also provides greater uniformity of distribution and smaller size of silicide formations $(Zr,Ti)_3SiAl$ and $(Zr,Ti)_5Si_3Al$. All this contributes to the reduction of residual thermal stresses and obtaining a weld with more complete dispersion aging. A larger number of formations is observed in the phase composition $(Zr,Ti)_3SiAl$, which contributes to the plasticity of the alloy (this is confirmed in [6]). As a result of research, it was found that local heating of the alloy Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si up to a temperature of T_T=400 °C prevents the formation of cold cracks in the weld after storing the welded joint for 240 hours (Fig. 6). It should be noted that in contrast to the results reported in [9], in which EBW with local heating was first proposed for Ti-6.08Al-2.18Sn-3.88Zr-0.39Mo-1.14V-0.65Si and Ti-5.5Al-3.02 alloys Sn-4.58Zr-0.1Mo-0.8Nb-0.59V-0.6Si, for Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy this approach provided a satisfactory level of mechanical characteristics of the connection.

It was found that the additional thermal effect on the welded joint from the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy during local annealing at a temperature of T_T=750 °C, t_T=4 minutes (mode 4) provides the duration of thermal exposure up to 20 minutes (Fig. 7). In this way, the time of relaxation processes after welding increases.

In the course of the analysis of causes of the influence of out-of-furnace and furnace heat treatment on the mechanical properties of the studied pseudo α-titanium alloy in the welded joint, changes in the ratio of aluminum and molybdenum equivalents $£_{Al/Mo}$ for local zones of micro-X-ray spectral analysis in the weld area were considered. The analysis of these changes revealed a tendency to the appearance of concentration inhomogeneities in the weld after welding with a through electron beam (Fig. 12–15). It was determined that such inhomogeneities are significantly reduced (Fig. 14) using local electron beam annealing (mode 4) and practically disappear (Fig. 14) after furnace annealing (mode 5). This is probably due to the diffusion absorption of concentration inhomogeneities beyond the limits of dispersion decay products, which may arise as a result of exposure to an electron beam [12]. On the other hand, this can be explained by the occurrence of concentration inhomogeneities of alloying elements in the weld, which probably creates areas with lower strength. This is possible because the concentration of alloying elements, which determine the value of $£_{Al/Mo}$, affects the mechanical characteristics of the titanium alloy. It is precisely such areas that can lead to a decrease in the level of $\sigma_{0.2}$ for a short duration of thermal exposure. In general, this is confirmed by the results of other studies [4].

As a result of the research reported in this work, it was found that diffusion processes can affect the characteristics of dispersion aging in the weld material under mode 5 processing, which largely determine the mechanical properties of pseudo α-titanium alloys. As it was established by the results of the analysis of dispersed formations (Fig. 10), during the heat treatment of the welded joint, the vast majority of dispersed formations are saturated with alloying elements and change from $(Zr,Ti)_5Si_3Al$ and $(Zr,Ti)_3SiAl$ to $(Zr,Ti,Nb,Mo)_3SiAl$. Considering the significant increase in plasticity of the weld material after furnace heat treatment (Table 2), such changes in dispersion aging products can be considered positive. This is also consistent with the results reported in [6] regarding the negative impact of higher silicides (in this case, $(Zr,Ti)_5Si_3Al$) on the plasticity of pseudo α-alloys.

In addition, it was found that the $(Zr,Ti)_5Si_3Al$ phase is not observed after the heat treatment of the welded joint under mode 5. This confirms the assumption that it is owing to the phase optimization factor that the highest level of mechanical characteristics of the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy weld joint is achieved using furnace annealing T_T=850 °C, t_T=60 minutes.

The substantiation of the optimal process of obtaining a high-quality welded joint from the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy, which is a promising pseudo α-alloy, concerns the discovery in this work that the use of preheating (mode 3), the introduction of short-term annealing after welding (mode 4), and additional furnace annealing (mode 5) ensures a consistent increase in the mechanical characteristics of the welded joint. It was also found that preheating prevents the formation of cold cracks in the weld area. At the same time, modes 3 and 4 can be considered acceptable according to the level of the obtained characteristics, and mode 5 is recommended. When using mode 5, the strength characteristics of the welded joint compared to the base material decrease by less than 6 % while the plasticity characteristics increase (Table 2). The results and the reason for such changes can be explained by a number of factors indicated above.

Special features of this study regarding the process of obtaining a high-quality welded joint of pseudo α-titanium alloys include the consideration of doping of dispersion aging products with molybdenum and niobium, which was not paid attention to by the authors in other specialized works. The factor of occurrence and influence on the mechanical properties of concentration inhomogeneities in the distribution of alloying elements in the weld material of pseudo α-titanium alloys was also overlooked by researchers. But it was the consideration of these features that has made it possible to obtain high mechanical characteristics of the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy welded joint in our work.

On the other hand, it should be noted that the results of this study do not provide the possibility of their generalized use for welding other pseudo -alloys of titanium or under the conditions of application of other welding technologies. Of course, the results of this work could be used as a prototype when solving similar problems.

The main drawback of this work is the lack of a study on the mechanical characteristics of welded joints of Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy at high temperatures. This is what does not allow us to recommend the above modes of the process of obtaining a high-quality welded joint for structures operating at elevated temperatures. This investigation is planned by us in the next stage of research.

Another drawback worth considering is that the reasons for the decrease in the size of both α-phase plates and dispersed phase formations on its borders (Fig. 9, *d*, *e*) after local annealing (mode 4) remain undetermined. It is characteristic that the same trend developed during furnace annealing (mode 5). Furnace annealing leads to further grinding of both α-phase plates and needle-like grains of the α′-phase and dispersed phase formations (Fig. 9, *g*, *h*). As a version, it can be assumed that thermal annealing at temperatures of 750 °C and 850 °C leads to a partial reverse α→β transition and subsequent repeated dispersion aging during cooling. However, we plan to perform a detailed analysis of the specified uncertain reasons and trends regarding the processes of obtaining a high-quality welded joint from the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy in further research.

The results of the work could prove useful in the field of aircraft and rocket engineering, in particular when using the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy for the manufacture of tubular parts of gas turbine engines. At the same time, additional research is needed to apply the results of this work to welded elements operating under mechanical loads at high temperatures. Using the results of this work gives grounds for choosing the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy of Ukrainian production as a structural material of the welded part, but it requires additional analysis regarding its operating conditions.

7. Conclusions

1. At EBW of the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy with through penetration under the mode U_{acc}=60 kV, I_{eb}=90 mA, v_{eb}=7 mm·s^{-1}, a welded connection without macro defects is formed. As a result of storing the resulting joint for 240 hours, transverse cold cracks are observed on the surface of the weld.

2. Pre-heating of the welded Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy to a temperature of T_T=400 °C prevents the formation of cold cracks after storing the welded joint for 240 hours. But such heat treatment leads to a

decrease in both strength and plasticity of the material in the weld zone compared to the base material.

Preheating to a temperature of T_T=400 °C of the Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy and performing local annealing at a temperature of T_T=750 °C, t_T=4 minutes after welding ensures an increase in characteristics strength and plasticity of the material in the weld zone to a satisfactory level.

Furnace annealing at T_T=850 °C, t_T=60 minutes of the welded joint of Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy after welding with preheating to temperature T_T=400 °C and further local annealing at T_T=750 °C, t_T=4 minutes ensures the approximation of the strength characteristics of the connection to the indicators of the base material and exceeding such indicators in terms of plasticity.

3. The use of local annealing at a temperature of T_T=750 °C, t_T=4 minutes after welding leads to equalization of the concentration of elements that determine the molybdenum and aluminum potential of titanium alloys. This probably increases the mechanical characteristics of the welded joint of Ti-6.1Al-6.0Zr-6.3Sn-3.2Mo-1.1Nb-1.2Si alloy.

An increase in the temperature and annealing time of the welded joint to T_T=850 °C, t_T=60 minutes leads to changes in the dispersion of $(Zr,Ti)_5Si_2Al$ and $(Zr,Ti)_3SiAl$ in the weld material to $(Zr,Ti,Nb,Mo)_3SiAl$. Such changes in dispersion-strengthening phase separations can be the reason for increasing the plasticity of the weld material.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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