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THE EFFECT OF ANNEALING ON THE STRUCTURE AND PROPERTIES OF WELDED JOINTS OF HEAT-RESISTANT PSEUDO- α -TITANIUM ALLOY Ti–Al–Zr–Sn–Mo–Nb–Si ALLOYING SYSTEM

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ABSTRACT

The effect of furnace annealing after electron beam welding (EBW) and gas tungsten arc welding (GTAW) on the properties of welded joints of a pseudo- α -titanium alloy of the Ti–Al–Zr–Sn–Mo–Nb–Si system was investigated. To compare the properties of welded joints in the as-welded state and after additional heat treatment, a quality criterion was introduced. It was established that annealing promotes the formation of a finer microstructure in the welded joints of the heat-resistant pseudo- α -titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system produced by EBW, resulting in a tensile strength of 980 MPa, which is 95 % of the base metal strength; the impact toughness of the annealed welded joints remained high at 17.9 J/cm². Annealing after GTAW also leads to microstructural refinement of the welded joints. A comparative analysis of the quality coefficients of EB and GTA welded joints demonstrated the superior combination of mechanical properties in EB joints, both in the as-welded state and after annealing. Annealing application enabled an improvement in the mechanical properties of EB joints to levels comparable to those achieved with additional local heat treatment (LHT).

KEYWORDS: heat-resistant titanium alloy, microstructure, mechanical properties, electron beam welding, gas tungsten arc welding

INTRODUCTION

In the last decades a significant increase in the scope of research is observed, the objective of which is producing titanium alloys with a new set of properties [1–3]. Heat-resistant titanium alloys with intermetallic strengthening are considered promising materials for aviation, space and automotive technology. The highest heat resistance is demonstrated by doped alloys of Ti–Si–X system, owing to formation of a framework of strengthening phases in the cast state, arising at eutectic crystallization in Ti–Al–Si system, α -Ti, Ti₃Al and TiAl acting as the matrix, and Ti₅Si₃ silicide being the strengthening phase [4–7]. One of such promising alloys is the experimental multicomponent pseudo- α -alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system, the average chemical composition of which is given in Table 1 [8, 9]. Investigations of the properties of welded joints of alloys containing a large number of alloying elements, revealed their significant disadvantages: high proneness to alloying element liquation, strong dependence of aging duration on the content of alloying elements and impurities, as

well as low thermal stability, which are due to precipitation of intermetallics in the structure of these alloys, for instance Ti₅Si₃ [10].

The most wide-spread method of fabrication of structures from titanium alloys is gas tungsten arc welding (GTAW). For heat-resistant titanium alloys, however, it is the most rational to apply electron beam welding (EBW). Possibility of performing local preheating and further local heat treatment (LHT) in the vacuum chamber is an essential advantage of EBW technology, used to prevent cold cracking in the welded joints [11, 12]. In case of making welded joints of promising heat-resistant titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system, EBW is complicated, in connection with a high content of silicon in the weld metal and the HAZ metal. As a result of the influence of the welding thermal cycle, structural changes take place in the weld metal and the HAZ of this alloy, resulting in formation of a stressed state and cold cracking at low ductility of silicon-alloyed metal.

In work [13], EBW influence on the structure of weld metal and the HAZ and the mechanical prop-

Table 1. Average chemical composition of the experimental heat-resistant alloy, wt.%

Al	Zr	Si	Mo	Nb	Sn	Ti
6.2–6.9	5.0–5.5	0.50–0.85	0.5–0.8	0.5–0.8	1.5–2.5	Base

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Table 2. Mechanical properties of wrought alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system at temperatures of 20 and 600 °C

Sample	20 °C			600 °C		
	σ_t	$\sigma_{0.2}$	$\delta_s, \%$	σ_t	$\sigma_{0.2}$	$\delta_s, \%$
	MPa			MPa		
Base metal	1101–1169	1052–1107	7.7–10.4	744–765	552–575	11.5–14.6

erties of welded joints on the heat-resistant titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system was studied, and it was shown that EBW application in combination with LHT to make welded joints of heat-resistant pseudo- α -titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system allows producing welded joints of equal strength to the base metal, but application of additional furnace annealing is required to ensure a homogeneous structure in all the zones of the welded joint, including the HAZ.

Titanium alloy welded joints can be produced by different methods, with different values of energy input and cooling rates of the metal of the weld and HAZ. On the whole, for titanium alloys increasing some mechanical properties, for instance, strength causes the respective lowering of the ductility and impact toughness values, but this occurs disproportionately. Therefore, it is rational to determine the influence of furnace heat treatment on the properties of EB welded joints of heat-resistant pseudo- α -titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system and to compare the properties of welded joints, produced by the most common method, namely GTAW.

Thus, it is necessary to study the influence of postweld heat treatment, namely annealing, on the structure and properties of welded joints of heat-resistant titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system to achieve a homogeneous structure and a complex of high mechanical properties of the welded joints, as well as to compare the mechanical properties of welded joints of the heat-resistant alloy, produced by two kinds of welding: EBW and GTAW.

The objective of the work is to determine the influence of heat treatment-annealing on the structure and properties of the base metal and welded joints of the heat-resistant titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system, produced by two kinds of welding: EBW and GTAW.

The heat-resistant titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system differs by a high sensitivity to the thermal welding cycle. GTAW and EBW are characterized by different values of welding energy input and cooling rates of the metal of the weld and HAZ. Therefore, at the first stage of the research we will assess the annealing influence on the structure of GTA and EB welded joints. At the second stage we will compare the mechanical property values of EB and GTA welded joints and their change after annealing.

Research was performed using plates made from an ingot of heat-resistant titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system produced by the method of electron beam melting [12]. Hot-rolled plates 10 mm thick from the mentioned alloy were made in a reversible double-roll rolling mill 500/350 of Skoda Company [13]. Rolling began at the temperature of 1050 °C, the rolling end temperature was not lower than 800 °C. After rolling, the metal was annealed at 900 °C for 1 h. After deformation treatment the alloy had high strength values ($\sigma_t = 1135$ MPa) at room temperature (Table 2); at working temperature of 600 °C — $\sigma_t = 755$ MPa, the values of material room temperature ductility being equal to 9.0 % [9].

Electron beam welding was performed in UL-144 machine, fitted with ELA 60/60 power unit [11]. Argon-arc welding was carried out by the method, most widely used for titanium alloys — gas tungsten argon-arc welding (GTAW). GTAW was conducted at straight polarity direct current, using VDU 511 power source. Properties of EB welded joints 10 mm thick and GTA joints 6 mm thick were studied.

In order to assess the effectiveness of the selected mode of welding and postweld heat treatment of the welded joints on high-strength titanium alloys, a criterion of welding mode quality in conditional units was proposed [14], which consists of the contribution of the modes of welding and heat treatment into a comprehensive increase of the total indices of strength, ductility and impact toughness of titanium alloy welded joints relative to the base metal of the respective alloy. On the whole, for titanium alloys, increase in some mechanical properties, for instance, strength causes the respective lowering of the ductility and impact toughness values. In some cases, however, this occurs disproportionately. Analysis of the obtained results of testing the mechanical characteristics of the welded joints allowed us to conclude that titanium alloy welded joints have high ductility

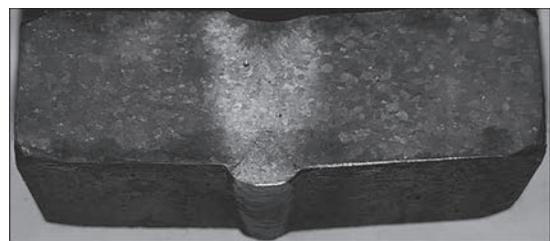


Figure 1. Macrosection of EB welded joint of the heat-resistant titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system in the state after annealing at 850 °C

values, and the impact toughness values are also at a high level. In case we consider only the strength and impact toughness values and accept their significance as equal, the following coefficient of welding mode quality was proposed:

$$K_{wm} = 0.5(\sigma_w/\sigma_{BM}) + 0,5 (KCV_w/KCV_{BM}),$$

where K_{wm} is the quality coefficient.

The strength coefficient was also calculated [14]:

$$K_s = \sigma_w/\sigma_{BM}.$$

INFLUENCE OF ANNEALING ON THE MICROSTRUCTURE OF EB WELDED JOINTS OF HEAT-RESISTANT TITANIUM ALLOY OF Ti–Al–Zr–Sn–Mo–Nb–Si ALLOYING SYSTEM

Welded joints of the heat-resistant titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system made by EBW even with application of local heat treatment have a heterogeneous nonuniform structure. To ensure formation of a homogeneous uniform structure in all the welded joint zones, including the HAZ, which eliminates the presence of metastable phases, as well as to relieve the welding stresses, welded joints of the heat-resistant titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system made by EBW and GTAW were subjected to furnace treatment — furnace annealing.

Annealing temperature was selected proceeding from the temperature of polymorphous transformation of the heat-resistant titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system. The temperature of polymorphous transformation of the heat-resistant titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system was established by the methods of mathematical modeling and was confirmed experimentally [15]. During cooling the temperature range of $\beta \rightarrow (\alpha+\beta)$ transformation is in the range of 995–1025 °C, and the $(\alpha+\beta) \rightarrow \alpha$ — transformation range is within 800–825 °C. Proceeding from that, the annealing temperature of 850 °C was selected.

Annealing of the heat-resistant titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system envisages heating up to the temperature of 850 °C, holding for 1 h, and further cooling in the furnace. Figure 1 gives an example of the transverse macrosection of the welded joint after annealing.

Figure 2 shows the structure of base metal in the central zone of a sheet after annealing at 850 °C. After the performed annealing, a clearer delineation of α -phase plates (Figure 2, *a*) and formation of intermetallic particles (Figure 2, *b*) are observed in the structure. In the base metal, not only clusters of dispersed particles in the form of chains are recorded after annealing, but also possibly monolithic silicide interlayers between plates of up to 7 μm length (Figure 2, *c*, *d*). In order to check this assumption, however, it is necessary to study the changes in the alloy phase

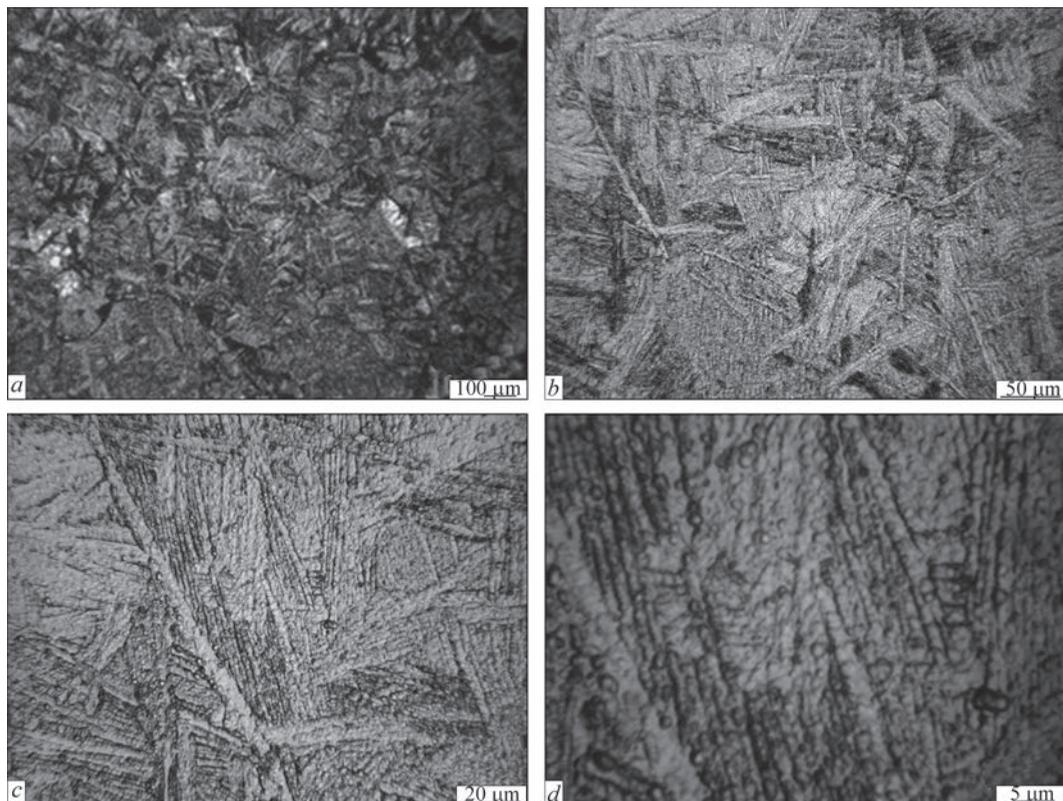


Figure 2. Microstructure of base metal of EB welded joint of the heat-resistant alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system in the state after annealing at 850 °C

composition by the methods of X-ray diffraction analysis and scanning electron microscopy. In work [8] it was shown that fine silicides within α -plates form during the eutectoid transformation and further lowering of silicon solubility in the titanium α -matrix. Work [8] presents the distribution of the main alloying elements in the cast metal of the alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system, from which we can see that alongside titanium, zirconium is also present in the silicides and their interlayers on the grain boundaries, i.e. complex silicides of $(\text{Zr}, \text{Ti})_5\text{Si}_3$ and $(\text{Zr}, \text{Ti})_3\text{Si}$ type form in the alloy. Zirconium and silicon are present both in the solid solution, and in the strengthening silicide phase, which is distributed along the boundaries of former β -grains. In work [9] a conclusion was made that the silicides form not only within the α -plates, but dispersed silicides are also distributed between the α -plates in the form of individual precipitates along the boundaries and inside the α -phase grains. There are quite a lot of silicides in the structure, but they are dispersed, and are distributed between the α -plates and in the form of individual precipitates along the boundaries and inside the α -phase grains [8].

The structure of the metal of the weld middle zone in welded joints of the heat-resistant alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system, produced by electron beam welding, after additional vacuum annealing at 850 °C, is shown in Figure 3.

A typical dendritic structure of the cast metal is formed in the weld zone (Figure 3, *a*). It is dense, and no defects of the type of porosity, cracks or nonmetallic inclusions were found in it. The size of dendrite branches in the cross-sectional section can be tentatively assessed by the difference in etchability of individual regions. It is equal to 100–500 μm . The boundaries of the dendritic regions have no excess phase precipitates and are not the weak points of the material. It is important that rapid cooling of the molten weld metal results in formation of quite dispersed packs of Widmanstätten morphology in the dendritic regions with the pack size (by the size of the largest plates) in the range of 20–50 μm (Figure 3, *b*), that is close to the characteristics of dispersity of the base metal structure. At the same time, comparing the structures of the upper and middle zone of the weld, we can conclude that a more dispersed structure forms in the weld middle, compared to its upper part. The difference, however, is not great, and it can be associated with different temperature-time conditions of weld metal crystallization.

Vacuum annealing at the temperature of 850 °C for 1 h intensified the diffusion processes, which resulted in a certain redistribution of alloying elements in the welded joint structure. Compared to the structure of the welded joint in the state after LHT [13], after vacuum annealing clusters of dispersed particles in the form of chains, as well as monolithic silicide interlay-

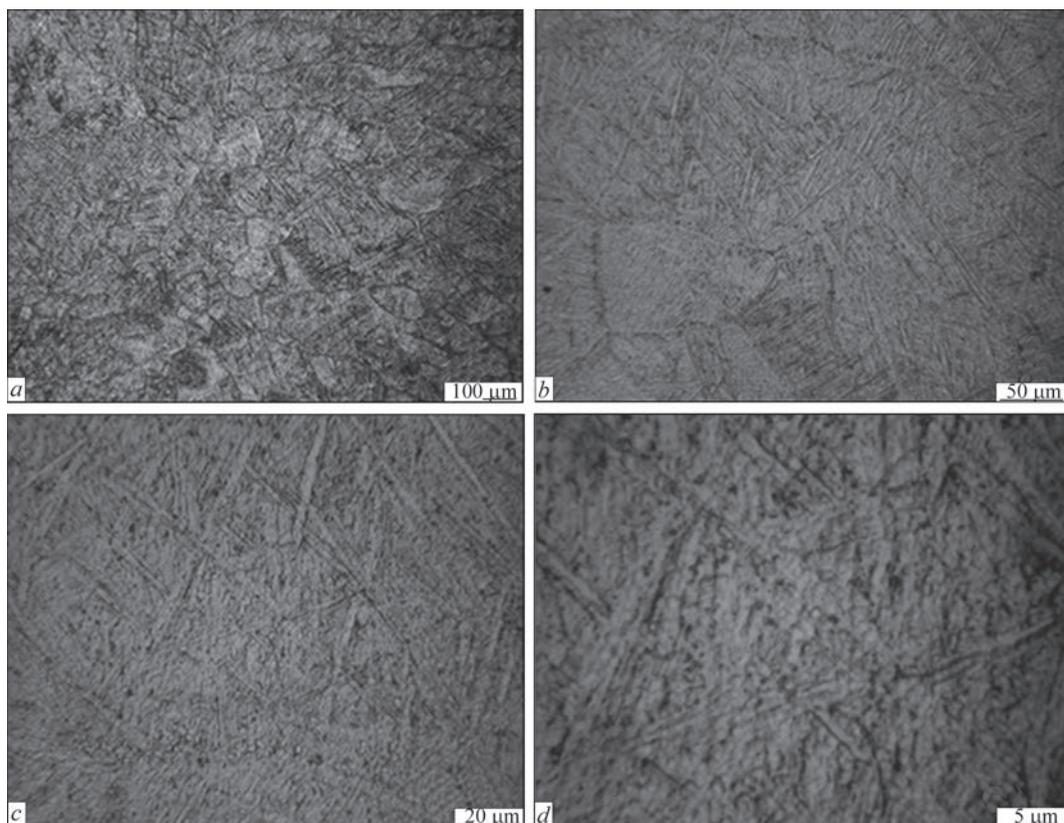


Figure 3. Microstructure of the weld metal of EB welded joint of the heat-resistant alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system after annealing at 850 °C

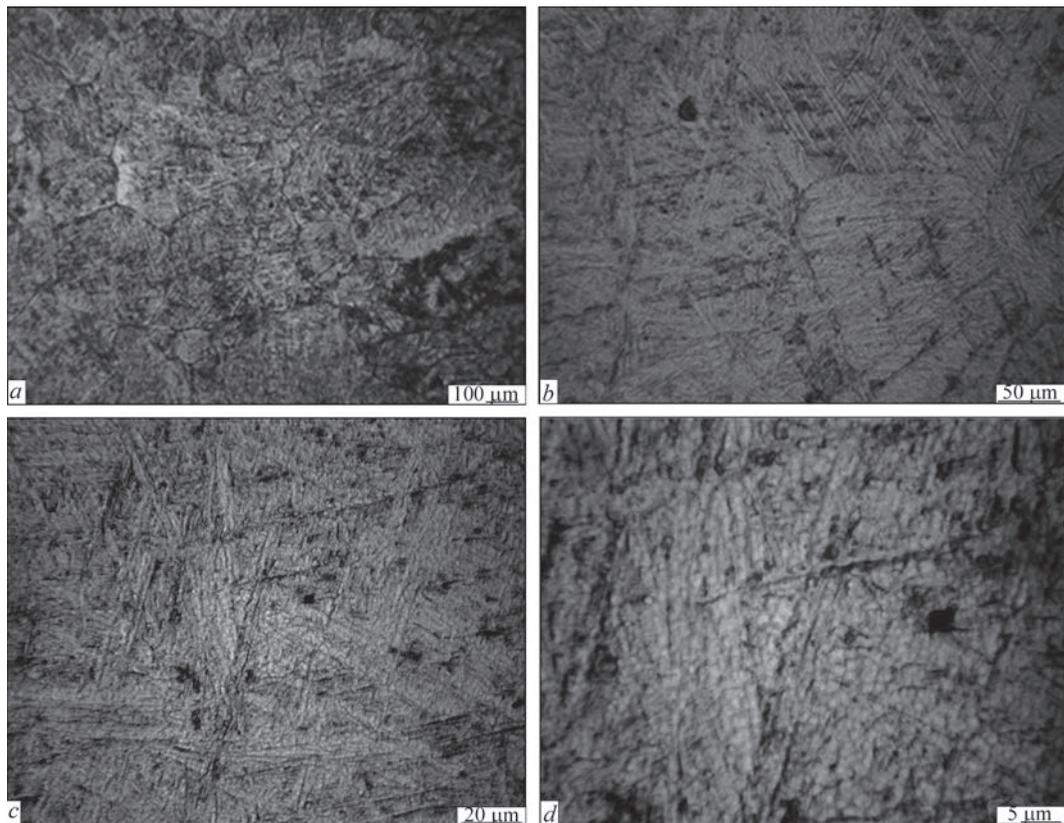


Figure 4. Microstructure of the metal in the fusion zone of EB welded joint of the heat-resistant alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system after annealing at 850 °C

ers up to 7 μm long are recorded on the boundaries of the platelike α -phase (Figure 3, *c, d*).

Microstructure of the fusion zone in the EB welded joint of the heat-resistant alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system, in the state after annealing at 850 °C, is shown in Figure 4.

No significant difference in the morphology or dimensional characteristics of the structural components was found between the samples after LHT [13], and samples annealed in the vacuum at 850 °C. This can be associated with the fact that the temperature of both the treatments did not exceed that of the phase transformation point for this alloy, so that the repeated crystallization processes did not develop, while the processes of recrystallization in the heat-resistant alloy proceed slowly at these temperatures.

The HAZ metal structure in samples of the EB welded joint of the heat-resistant alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system after annealing at 850 °C is shown in Figure 5. Analysis of the microstructure reveals that the HAZ preserves the main morphological and dimensional characteristics of the base metal. No difference in the structure was observed after different heat treatment modes, namely annealing and LHT [13]. During annealing at 850 °C a clearer delineation of the α -phase plates is observed in the structure, due to precipitation of the β -phase along the plate boundaries and there is a possibility of formation of intermetallic particles. In the fusion zone metal not only clusters of dis-

persed particles in the form of chains, but also monolithic silicide interlayers between the plates are recorded on the boundaries of the platelike α -phase as a result of the influence of annealing at 850 °C (Figure 5, *c, d*). Etching of the sections of the welded joint of the alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system was improved, compared to etching of the sections of the welded joint after LHT, as a result of decorating of the plate boundaries by the dispersed particles. The effectiveness of vacuum annealing can be fully evaluated when establishing the mechanical characteristics of the welded joints.

Although application of different modes of heat treatment did not lead to any essential changes in the welded joint microstructure, the difference in the intensity of structure etching and in the quantity of the β -phase on the boundaries of α -phase plates allows us to assume that the mechanical properties of the joints could change under the annealing influence, as a result of relaxation of the mechanical stresses and due to excess phase formation. More over, vacuum annealing at the temperature of 850 °C intensified the running of the diffusion processes, which resulted in a certain redistribution of the alloying elements in the structure of the welded joints proper. Silicon has diffused to a large extent to the boundaries of the platelike α -phase, forming there not only clusters of dispersed particles in the form of chains, but also monolithic silicide interlayers between the plates.

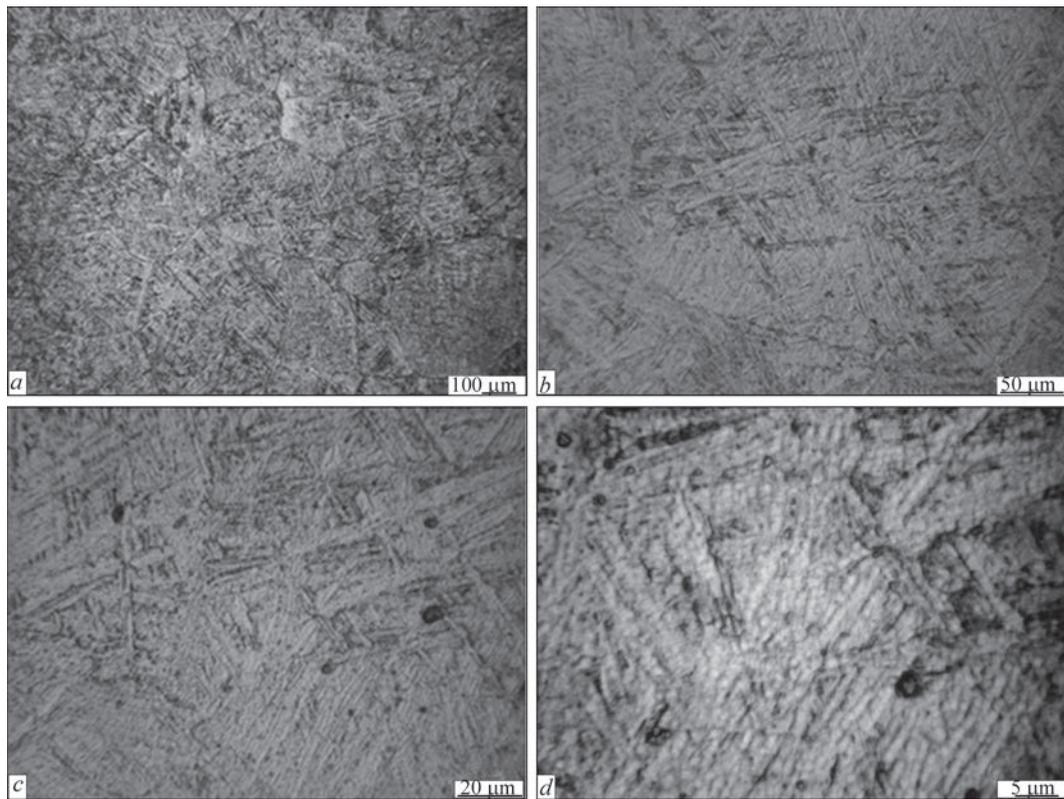


Figure 5. Microstructure of the HAZ metal of the weld in EB welded joint of the heat-resistant alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system after annealing at 850 °C

ANNEALING INFLUENCE ON THE MICROSTRUCTURE OF GTA WELDED JOINTS OF THE HEAT-RESISTANT TITANIUM ALLOY OF Ti–Al–Zr–Sn–Mo–Nb–Si ALLOYING SYSTEM

Weld metal microstructure in the GTA welded joint in the state after annealing at 850 °C for 1 h is shown in Figure 6. Microstructural analysis reveals that the typical dendritic structure of the cast metal formed during welding is preserved in the weld metal after annealing (Figure 6, *a, b*). It is dense and no defects of the type of porosity, cracks or nonmetallic inclusions were found in it. The size of the dendrite branches in the cross-section of the microsection, which can be tentatively assessed by precipitation of α -phase interlayers on the boundaries of the dendritic regions, is equal to 200–300 μm .

As a result of molten metal cooling during welding rather dispersed packs of Widmanstatten morphology are formed in the dendritic regions. In case of application of GTAW with through penetration coarsened packs of the dimensions in the range of 10–30 μm (by the size of the largest plates) form in the weld metal. With lowering of the specific power during welding in the case of GTAW over a layer of flux a reduction in the pack dimensions and increase in the microstructural homogeneity are observed, which should have a positive impact on the welded joint mechanical properties. Subsequent annealing at 850 °C (Figure 6, *c, d*) leads to an even greater refinement of the weld metal

structure due to formation of dispersed precipitates of the β -phase inside the primary packs of α -phase crystals. These precipitates, however, decorate the boundaries of the primary dendrite branches, leading to their more contrast delineation at small magnifications (Figure 6, *b*). The influence of additional precipitation of β -phase crystals on the mechanical properties requires further study. Precipitates of dispersed crystals should have a positive effect on the strength properties, but their precipitation exactly along the dendrite boundaries can facilitate crack propagation. It follows from the analysis that preheating to 400 °C has virtually no effect on the morphology and dimensional parameters of the microstructure (although there is a slight tendency to coarsening), but the structure of the samples, produced using GTAW with a lower specific power with preheating to 400 °C, is characterized by a more complete precipitation of the β -phase during weld metal crystallization.

Metal structure in the fusion zone of samples produced by GTAW over a layer of flux with lower energy input values in the state after annealing at 850 °C for 1 h, is shown in Figure 7. Dependence of the fusion zone microstructure on GTAW technological scheme is similar to the one observed during analysis of the weld structure. The fusion zone metal is dense and no defects of the type of porosity, cracks or nonmetallic inclusions were found in it. Quite dispersed packs of ($\alpha+\beta$)-Widmanstatten morphology are formed in the weld metal in the dendritic regions (Figure 7, *a*). The dimensions of

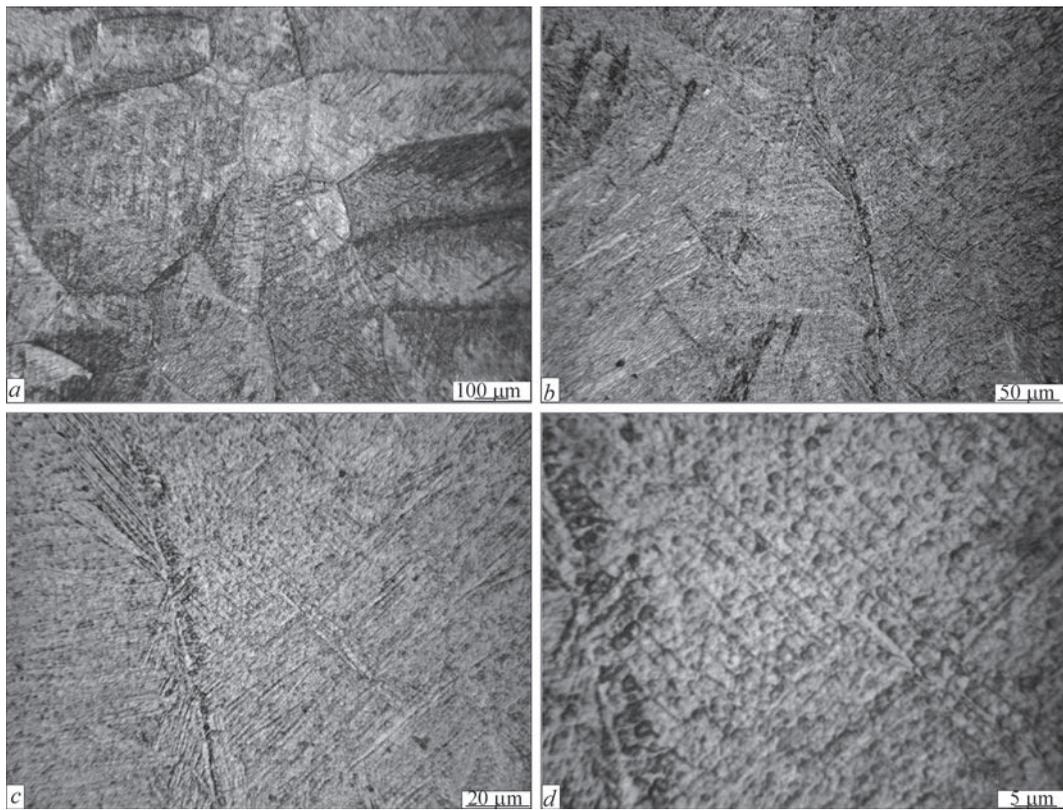


Figure 6. Microstructure of the weld metal of GTA welded joint of the heat-resistant titanium alloy of Ti-Al-Zr-Sn-Mo-Nb-Si alloying system after annealing at 850 °C

the dispersed ($\alpha+\beta$)-Widmanstätten packs by the largest plate size are equal to 10–30 μm . At lowering of the specific power in welding a reduction in the pack

dimensions and an increase in the homogeneity of the microstructure are observed, that should have a positive effect on the welded joint mechanical properties.

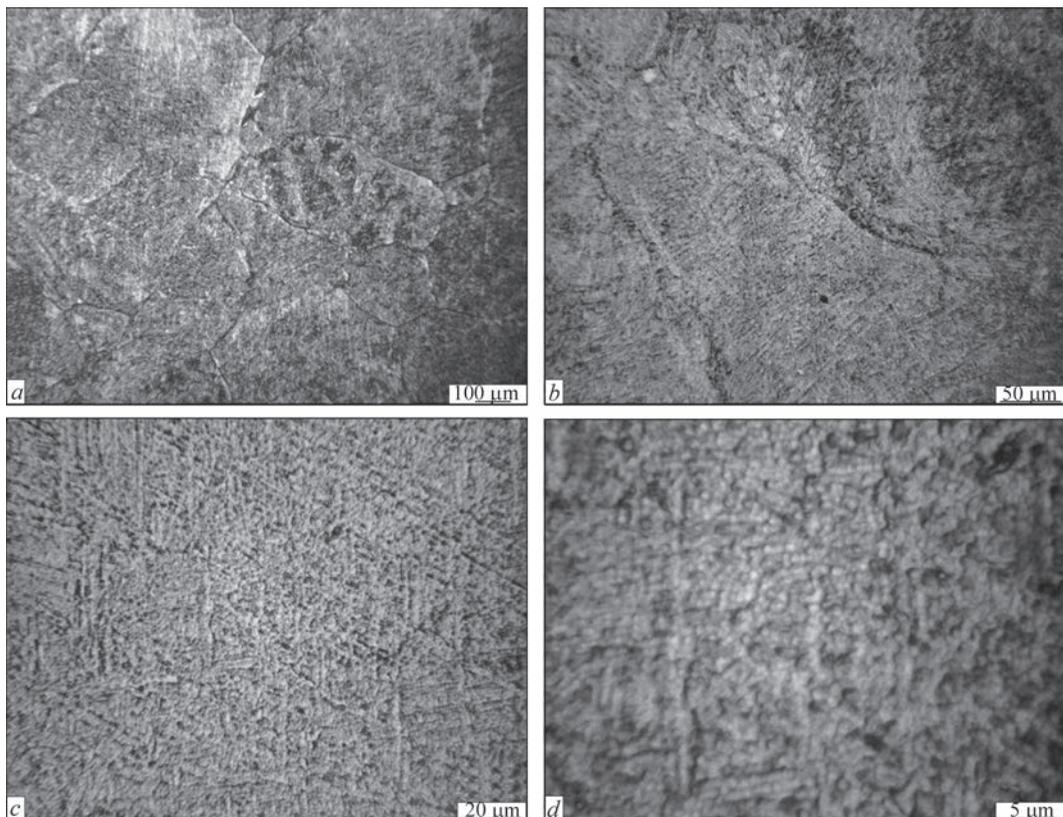


Figure 7. Microstructure of the fusion zone metal in GTA welded joint of the heat-resistant titanium alloy of Ti-Al-Zr-Sn-Mo-Nb-Si alloying system after annealing at 850 °C

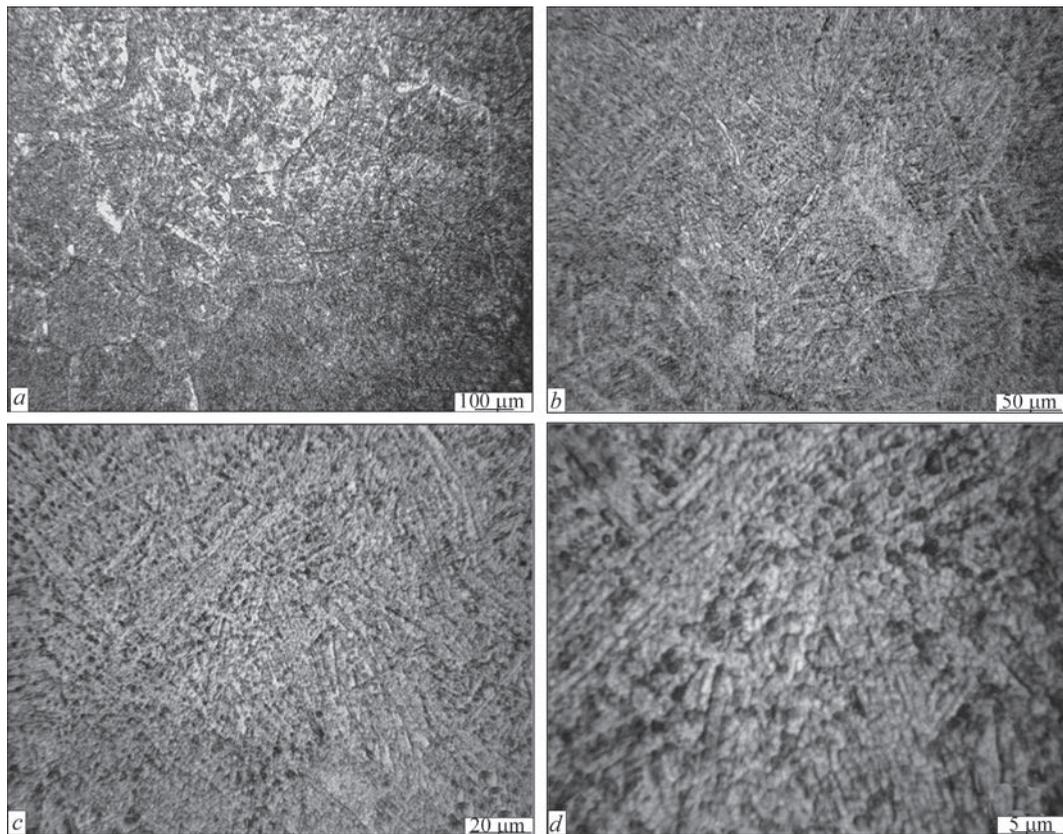


Figure 8. Microstructure of the HAZ metal in GTA welded joint of the heat-resistant titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system after annealing at 850 °C

Welding with a lower level of specific power and subsequent annealing at 850 °C (Figure 7, *a–c*) leads to an even greater refinement of the weld metal structure due to formation of dispersed β -phase precipitates inside the primary packs of α -phase crystals (Figure 7, *d*). These precipitates also decorate the boundaries of the primary dendrite branches, leading to their more contrast delineation at small magnifications (Figure 7, *c*). Additional precipitation of β -phase crystals can influence the mechanical properties.

Dependence of the HAZ microstructure on GTAW technological scheme practically coincides with the regularities revealed during analysis of the structure of the fusion zone metal. At lowering of the specific power in welding due to application of GTAW over a layer of flux (Figure 8, *a, b*) the HAZ metal preserves the finely dispersed structure of basket weave type, which should have a positive effect on the welded joint mechanical properties.

Welding with a lower level of specific power and subsequent annealing at 850 °C (Figure 8, *a, b, d*) leads to an even greater refinement of the weld metal structure, due to formation of dispersed precipitates of β -phase inside the primary packs of α -phase crystals. As no liquid phase formed in the HAZ, the effect of decorating the boundaries of primary dendrite branches is absent, so that the influence of additional precipitation of β -phase crystals on the mechanical

properties in this case, should be favourable for the alloy mechanical properties.

Comparing the welded joint regions, namely base metal, weld metal, fusion zone metal and HAZ metal, we should note the similarity of metal microstructure in different welded joint zones after the influence of furnace annealing.

MECHANICAL PROPERTIES OF WELDED JOINTS OF HEAT-RESISTANT PSEUDO- α -TITANIUM ALLOY OF Ti–Al–Zr–Sn–Mo–Nb–Si ALLOYING SYSTEM AFTER ANNEALING

Determination of the mechanical properties of EB welded joints of heat-resistant pseudo- α -titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system in as-annealed state led to the conclusion that after the influence of annealing the strength values of the welded joints somewhat decreased and are at the level of 980 MPa (Table 3). It should be noted that the impact toughness values of the welded joints are also at a high level of 17.9 J/cm². The values of impact toughness (*KIC*) after annealing increased for all the welded joints.

Comparison of the quality coefficients for the EB welded joints lead to the conclusion that LHT application allows obtaining a higher set of mechanical characteristics ($K_{wm} = 1.126$), compared to EBW without the LHT, while annealing application allowed increasing the values of mechanical characteristics of

Table 3. Mechanical properties of EB and GTA welded joints of the heat-resistant titanium pseudo- α -alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system

Sample	σ_1	σ_{02}	$\delta_s, \%$	$KCV, J/cm^2$	K_{wm}	K_s
	MPa					
Base metal after annealing	1028	996	2.7	14	–	–
EB welded joint	996	901	–	12.3	0.919	0.96
EB welded joint with LHT at 750 °C	1041	1012	–	17.4	1.126	1.01
EB welded joint, mode 2 after annealing	980	899	–	17.9	1.1157	0.953
GTA welded joint	969	890	11.2	8.9	0.787	0.94
GTA welded joint after annealing	995	908	–	9.7	0.829	0.967

an EB joint without LHT application to the level of those of EB joints with LHT.

Comparison of the quality coefficients for GTA welded joints leads to the conclusion that annealing application allowed obtaining the strength values of GTA joints at the level of those of EB welded joints.

Comparison of the quality coefficients for the welded joints produced by EBW and GTAW leads to the conclusion about a higher complex of mechanical characteristics of EB joints, both after welding and after annealing.

DISCUSSION OF THE RESULTS

Pseudo- α -alloys, to which the experimental heat-resistant titanium alloy also belongs, have a number of important advantages compared to the heat-resistant titanium alloys of other classes, which are particularly important for the welded joints. The quantity of the β -phase in the experimental alloy is such ($K_\beta < 0.2$) that it should have all the main properties and advantages of single-phase α -alloys, and also have positive properties, which distinguish the alloys of this class from α -alloys. The martensite α' -phase, forming at cooling from the temperatures above the critical one, is close to the α -phase by its physical and mechanical properties. The quantity of the β -phase in the experimental alloy is so small that its eutectoid decomposition, even if it takes place, cannot lead to any noticeable deterioration of the physical-mechanical properties. Due to that the structural pseudo- α -alloys feature good weldability and high thermal stability, inherent to α -alloys. Addition of small amounts of β -stabilizing elements above their solubility in α -titanium, in connection with heteronization of the structure, results in a significant increase of the strength and heat-resistance at moderate temperatures, without any noticeable lowering of their ductility, or even in an increase in their technological ductility. Pseudo- α -alloys practically do not lend themselves to strengthening heat treatment which is highly important for the welded joints, as in the HAZ, which is adjacent to the weld, unfavourable combinations of temperatures and cooling rates almost always arise, which may lead to brittleness, for instance two-phase titanium. Studies of the heat-resistant pseudo- α -titanium alloy showed that the microstructure in different regions of the welded joints is identical, and it is similar for differ-

ent methods and modes of welding and heat treatment. It can be assumed that the metal phase composition in different regions of the welded joints will not have any marked differences. The change in the welding heat input makes a greater contribution to the joint structure. So, at application of GTAW with through penetration coarsened packs are formed with the dimensions (by the largest plate size) in the range of 10–30 μm . At lowering of the specific power a reduction in the pack dimensions and an increase in the microstructure homogeneity are observed, which should have a positive effect on the welded joint mechanical properties.

Thus, in GTAW with a lower linear power a fine highly homogeneous structure is formed, which potentially can have higher mechanical characteristics. Application of vacuum annealing to the welded joints of the heat-resistant pseudo- α -titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system, produced by the technology of GTAW with a lower linear power, allows additional refinement of the structure, having a positive effect on the mechanical characteristics. However, the tendency to β -phase precipitation on the dendrite boundaries in the weld metal zone can potentially facilitate crack propagation. At EBW annealing also leads to structure refinement and silicon redistribution with formation of monolithic silicide interlayers between the plates.

After the annealing influence, the strength values of EB welded joints somewhat decreased, and impact toughness (KCV) values increased after annealing for all the welded joints. Note that the strength values of all the welded joints are higher than 0.95 of base metal strength.

CONCLUSIONS

1. It is shown that annealing results in the formation of a finer structure in the metal of EB welded joints of the heat-resistant pseudo- α -titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system with precipitates of dispersed silicide particles in the form of chains and monolithic silicide interlayers up to 7 μm long between the plates. Such a structure ensures the strength values of the welded joints at the level of 980 MPa, which is equal to 95 % of base metal strength, and the impact toughness values of the welded joints in as-annealed state are at a high level of 17.9 J/cm².

2. It is established that application of annealing after GTA welding of the heat-resistant pseudo- α -titanium alloy of Ti–Al–Zr–Sn–Mo–Nb–Si alloying system leads to refinement of the welded joint microstructure, reduction of the dimensions of dispersed (α + β)-Widmanstätten packs to 10–30 μm , and to an increase in the impact toughness (KCV) values.

3. Comparison of the quality coefficients for EB and GTA welded joints leads to the conclusion about a higher complex of mechanical characteristics of the EB joints, both after welding and after annealing. Annealing application allowed raising the values of mechanical characteristics for EB joints without LHT application to the level of characteristics of EB joints with LHT.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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