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ARGON-ARC WELDING OF HIGH-TEMPERATURE TITANIUM ALLOY DOPED BY SILICON

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ABSTRACT

Welding of titanium alloys doped by silicon requires application of additional technological operations, such as local heat treatment and preheating. In view of the fact that tungsten electrode argon-arc welding became widely applied in industry, the possibility of application of preheating for argon-arc welding of high-temperature pseudo-α titanium alloy of Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si system was studied. In the work, preheating of the joints to the temperatures of 200 and 400 °C was used. The temperature of preheating before welding in the range of 200–400 °C does not influence the final microstructure of the produced welded joints. AAW-joints of high-temperature pseudo-α Ti–5.6Al–2.2Sn–3.5Zr–0.4Mo–l.0V–0.6Si alloy, produced with the preheating to 400 °C, have the highest ultimate tensile strength on the level of σ_t = 1160.1 MPa, impact toughness values of samples with a sharp notch are on the level of 8.3 J/cm^2.

KEYWORDS: titanium, titanium alloys, dispersion hardening, high-temperature pseudo-α titanium alloy, argon-arc welding, structure, properties, strength

INTRODUCTION

Alloys based on titanium have a high specific strength in the temperature range of up to 400 °C. Titanium alloys intended for use at elevated temperatures, such as VT3, VT9, VT8, belong to the group of pseudo-α alloys. In recent years, investigations are carried out in two directions — development of two-phase high-temperature (α+β)-titanium alloys, and a further improvement of the properties of existing pseudo-α alloys [1]. For example, the new high-temperature VT25U alloy [2] has the value of indices σ_t = 1080 MPa at 20 °C and σ_y = 784 MPa at 550 °C [3]. One of the ways of a further increase in the operating temperature of pseudo-α titanium alloys is additional doped by silicon [4, 5]. A significant disadvantage of titanium alloys doped by silicon is the difficulty of their welding, which is predetermined by the formation of cold cracks in welded joints. Therefore, welding of such alloys requires the use of additional technological operations, such as local heat treatment and preheating, and it is recommended to perform welding with an electron beam (EBW) [6].

Argon-arc welding with a tungsten electrode (AAW) or TIG-welding has become the most widely used in industry due to the fact that this method of welding is cheap and versatile [7]. The advantage of AAW over MIG welding is that the process can be performed without the use of filler metal [8], as well as by through penetration [9]. Since it was shown in [10] that in the case of EBW of alloys doped by silicon, the best set of properties is in the joints produced with the preheating and therefore, it is advisable to investigate the possibility of AAW with the use of preheating of high-temperature alloys doped by silicon, and compare the properties of joints produced by AAW and EBW.

The aim of the work is to determine the effect of preheating on the structure and properties of welded joints produced by argon-arc welding with a tungsten electrode (AAW) using preheating to 200 and 400 °C of an experimental high-temperature pseudo-α titanium alloy doped by silicon.

Table 1. Chemical composition of a high-temperature pseudo-α titanium alloy

Content of alloying elements, wt.%						Content of impurities, wt.%		K_β
Al	Sn	Zr	Mo	V	Si	[O]	[N]	
5.64	2.20	3.53	0.43	0.95	0.56	0.09	0.02	0.6

MATERIAL AND PROCEDURE OF INVESTIGATIONS

The structure and properties of welded joints produced by AAW of pseudo-α titanium alloy of Ti–5.6A1–2.2 Sn–3.5Zr–0.4Mo–1.0V–0.6Si system were studied. In this work, preheating of joints to the temperatures of 200 and 400 °C was used. A temperature of 400 °C is the limit temperature at which oxidation of parts of high-temperature titanium alloys does not occur.

Melting of the ingot was carried out in the ISV-004 electron-beam equipment [11]. The chemical composition of the alloy is given in Table 1. The alloy has a β-phase stabilization coefficient K_β = 0.1. The produced ingot was rolled to a thickness of 13 mm. After rolling, to stabilize the structure and relieve stresses,

Table 2. Modes of one-sided AAW with through penetration of a high-temperature pseudo-α titanium Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy

Mode number	Welding current, I_w, A	Arc voltage, U_a, V	Welding speed, v_w, m/g	Length of the arc is preset, L_a, mm	Preheating temperature T_{pr}, °C
1	330	12	8	2	200
2	320	12	8	2	400
3 (over the flux)	400	12	16	2	200

Table 3. Parameters of welds of 8 mm thick samples of a high-temperature pseudo-α titanium Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0 V–0.6Si alloy, produced by AAW

Mode number	Width of the weld at the top, mm	Width of the weld at the bottom, mm	Weld area, mm^2	HAZ width, mm	Weld + HAZ area, mm^2
1	15.8	4.6	80.4	21.4	176.5
2	20.9	1.6	81.1	26.1	227.4
3 (over the flux)	8.8	3.5	55.6	14.7	113.2

the plates were subjected to annealing at a temperature of 800 °C for 1 h.

The annealed plates were treated in order to remove the oxidized layer to a thickness of 8 mm. AAW of samples with a total size of 150×80×8 mm was performed. Welding was carried out on one side in a one pass by through penetration without filler wire. Preheating during welding was performed by tungsten spirals fixed on a protective backup plate on the reverse side of the samples. A protective backup plate also performs the function of protecting the reverse side of the joint during welding and cooling of the weld metal. With this purpose, a heated shielding gas — argon is supplied to a backup plate during welding. The control of preheating temperature was carried out with the use of thermocouples attached to the facial side of the joint. The modes of one-sided argon-arc welding with a tungsten electrode by through penetration of a high-temperature titanium pseudo-α Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0 V–0.6Si alloy are given in Table 2.

EXPERIMENTAL STUDIES

The complete welding of 8 mm thick samples occurs during AAW without the flux by through penetration at a welding current of 320–330 A and a welding speed of 8 m/h (see Table 2). Welding with the preheating provides a slight reduction in welding current to 320A. AAW over the flux (mode No. 3) by means of constriction of the argon arc provides a significant reduction in heat input of welding and increases the welding speed while providing a full penetration of 8 mm thick metal.

Transverse macrosections of welded joints of a high-temperature pseudo-α titanium alloy with dispersion hardening, performed by AAW with the preheating to 200 and 400 °C, are shown in Figure 1.

The parameters of the produced welds are given in Table 3. The weld area in AAW over the flux is by 30 % lower than in AAW by through penetration. Thus, AAW over the flux allows performing welding of the titanium pseudo-α Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy on the modes with a minimum heat input and transverse area of the weld and HAZ metal.

RESULTS OF INVESTIGATIONS

The study of the microstructure of the produced welded joints produced made it possible to establish that in the state after rolling, the base metal of the alloy has a lamellar structure (Figure 2, *a*, *b*), consists of coarse primary grains (Figure 2, *a*) with a fringe fragmented during rolling, in which, after cooling of a rolled metal to the temperatures below T_{pr}, the β-phase de-

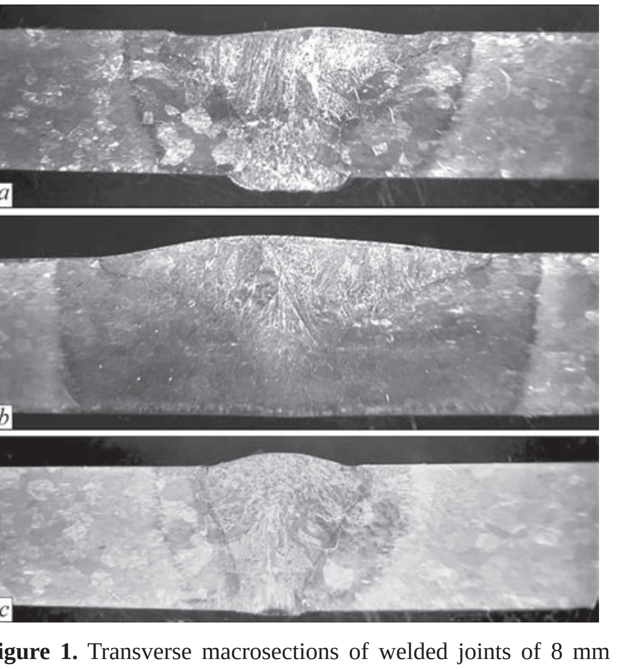

Figure 1. Transverse macrosections of welded joints of 8 mm thickness of a high-temperature pseudo-α titanium Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy: *a* — AAW with the preheating to 200 °C (mode No. 1); *b* — AAW with the preheating to 400 °C (mode No. 2); *c* — AAW over the flux with the preheating to 200 °C (mode No. 3)

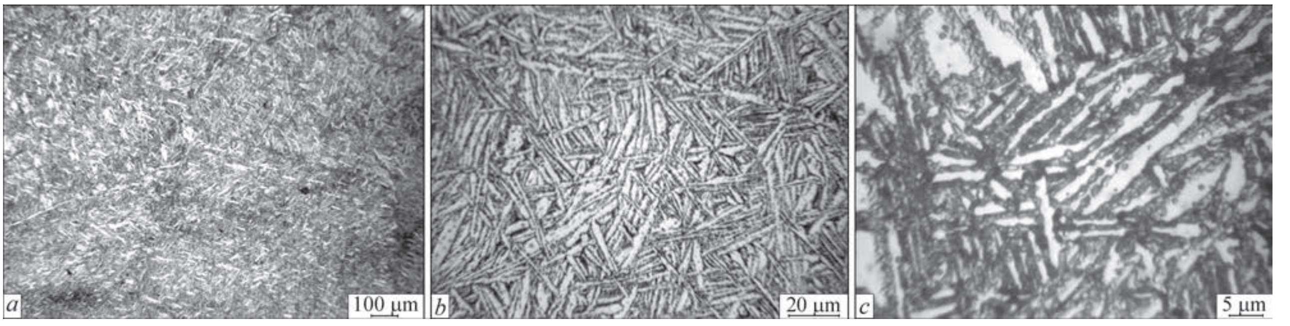

Figure 2. Microstructure of base metal of a high-temperature pseudo-α titanium Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy (description *a*–*c* see in the text)

cay occurred with the formation of α-phase plates, which form a basket-weave structure (Figure 2, *b*). The length of the plates is 5–30 μm, the thickness is 1–5 μm. At a higher magnification, it is seen that within the boundaries of α-plates (Figure 2, *c*) and within the boundaries of primary grains, a precipitation of a large amount of dispersed particles of up to 1 μm in size occurs. These dispersed particles are titanium silicide $(Ti, Zr)_5Si_3$, since the content of silicon in the alloy exceeds the limit of its solubility in α-titanium, which amounts to 0.12–0.45 % of silicon [12]. The particles of silicides are located relatively uniformly within the boundaries of primary β-grains (Figure 2, *c*).

Dispersed particles of silicides are located rather uniformly and do not form a visible pattern. On the distribution maps, the elements are also located rather uniformly without a visible pattern (Figure 3, *a*–*g*). However, on the spectra obtained when the microprobe is passing along the line through the particles, it is seen that at the places of the particle location, the concentration of silicon and zirconium grows (Figure 4, *a*–*c*) and the concentration of aluminium, tin, molybdenum and vanadium decreases (Figure 4, *d*–*f*). This again

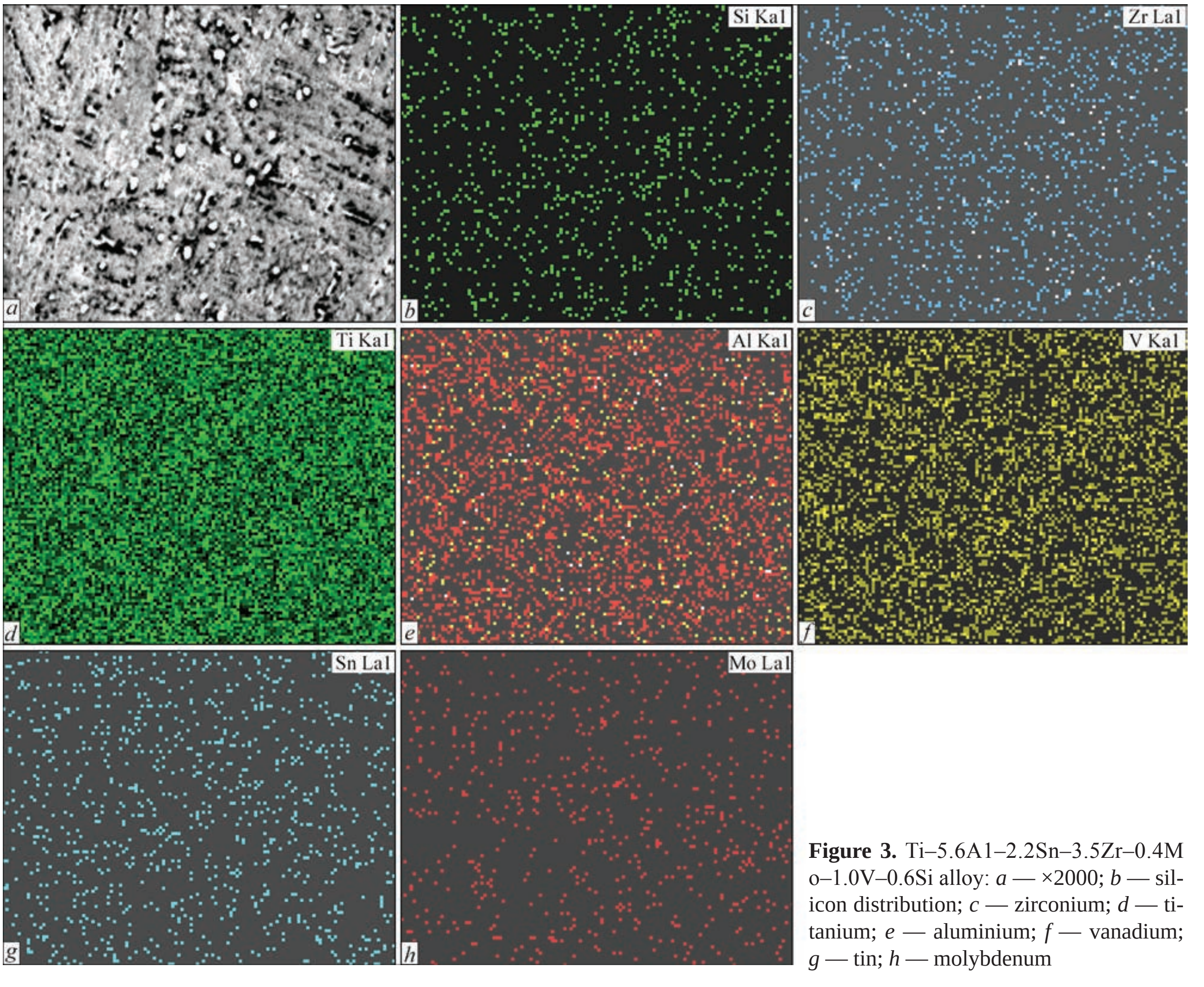

Figure 3. Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy: *a* — ×2000; *b* — silicon distribution; *c* — zirconium; *d* — titanium; *e* — aluminium; *f* — vanadium; *g* — tin; *h* — molybdenum

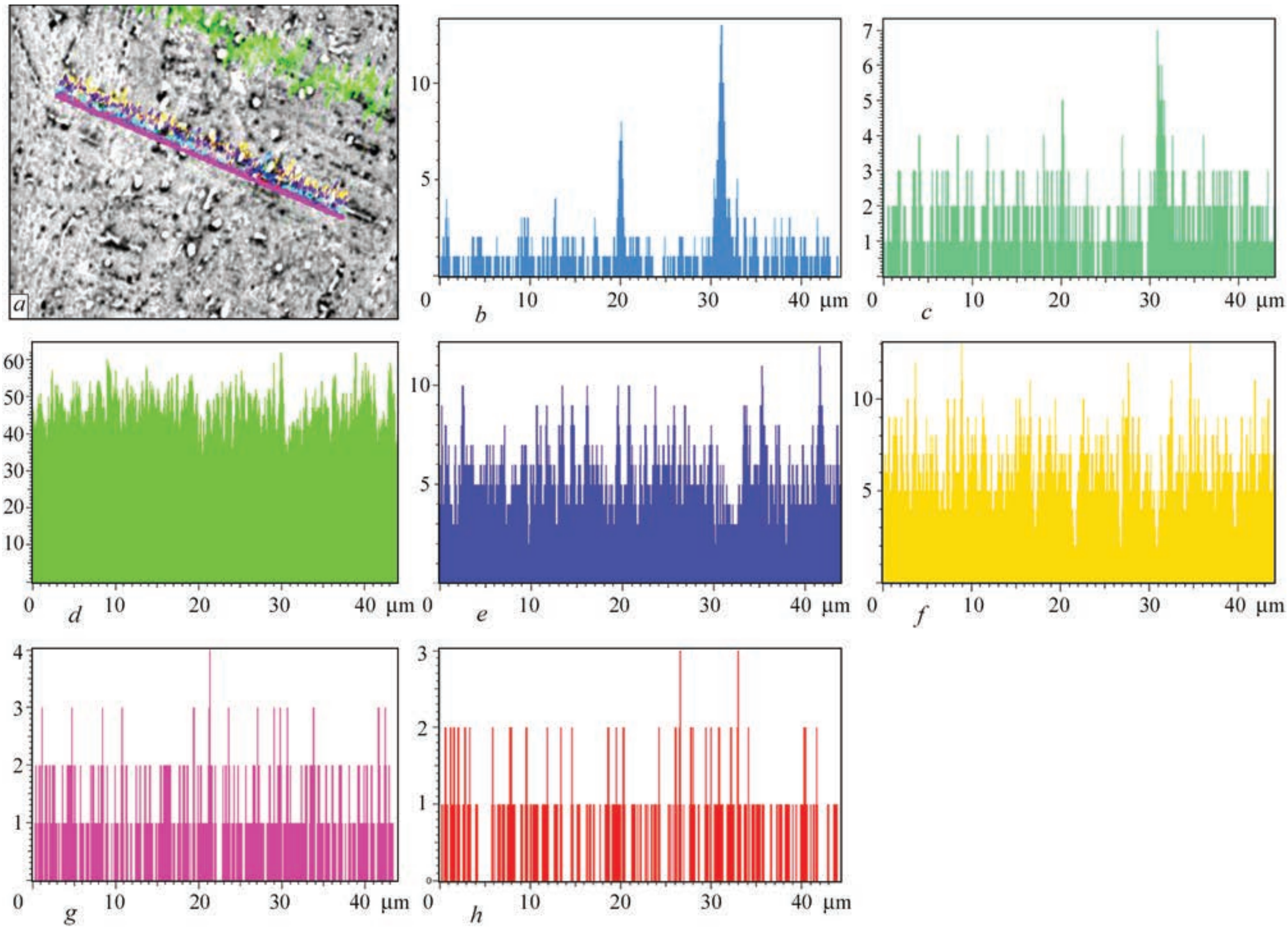

Figure 4. Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy: *a* — ×2000; *b* — spectrum of silicon; *c* — zirconium; *d* — titanium; *e* — aluminium; *f* — vanadium; *g* — tin; *h* — molybdenum

indicates that this alloy should contain complex compounds of the type $(TiZr)_5Si_3$ or $(TiZr)_6Si_3$.

The weld metal of the welded joint produced by AAW with the preheating to 400 °C consists of primary grains elongated in the direction of heat removal (Figure 5, *a*). The intragranular microstructure of the weld metal belongs to the same type as the microstructure of BM. The difference is in the size of

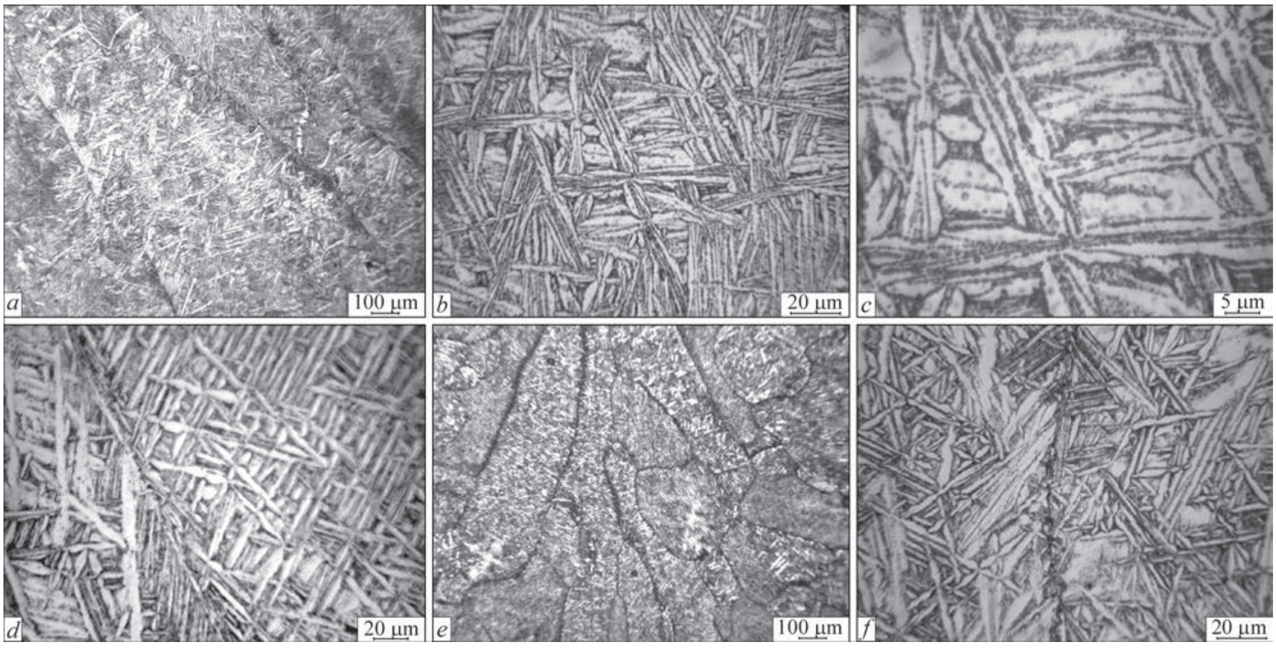

Figure 5. Microstructure of weld metal of joints of a high-temperature pseudo-α titanium Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy, produced by AAW in the state after welding: *a*–*c* — mode No. 2 (400 °C); *d* — No. 1 (200 °C); *e*, *f* — No. 3 over the flux (200 °C)

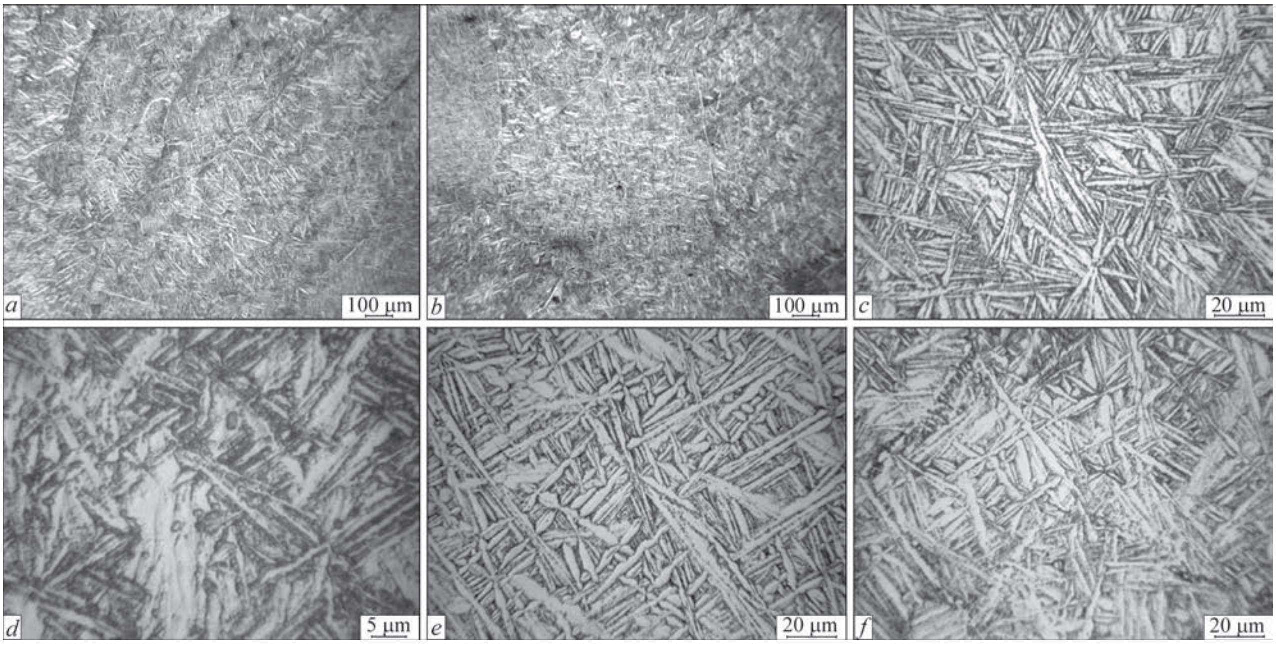

Figure 6. Microstructure of metal of HAZ joints of a high-temperature pseudo-α titanium Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy, produced by AAW in the state after welding: *a–c* — mode No. 3 (400 °C); *d*, *e* — No. 2 (200 °C); *f* — No. 4 over the flux (200 °C)

the formed α-plates, their length in the weld metal is somewhat larger, it is mainly 5–60 μm (Figure 5, *b*, *c*), although certain plates can be found, whose length exceeds 100 μm. Dispersed particles, which are titanium silicide, are also localized in the weld metal at the boundaries of grains and plates (Figure 5, *c*), β- or α-phase of other degree of alloying present in the pseudo-α alloys is also localized there.

The microstructure of the weld metal of the welded joint produced by AAW with the preheating to 200 °C is identical to the microstructure of the weld metal produced with the preheating to 400 °C. The basket-weave structure in the weld metal produced on the mode No. 1 is formed by α-plates, the length and thickness of which correspond to these parameters in the weld metal produced on the mode No. 2. The plates of a large length exceeding 100 μm are observed here (Figure 5, *d*). The distribution and sizes of dispersed particles of Ti_5Si_3 titanium silicide in the weld metal are similar to those in the weld of the joint considered above.

The microstructure of the weld metal of the joint produced by AAW over the flux with the preheating to 200 °C is shown in Figure 5, *e*, *f*. As is seen on the abovementioned images, the type of intragranular microstructure of the weld metal of this joint, parameters and nature of the distribution of structural components coincide with the corresponding structural elements of the weld metal produced by AAW without application of fluxes. Therefore, the use of a flux in the welding process did not affect the intragranular microstructure of the weld metal of a high-temperature pseudo-α titanium Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy. Obviously, the use of a flux only affected the size of the zones in the welded joint.

In the fusion zone of the joints produced by AAW with the preheating to 400 °C, it can be seen how the large equilibrium grains of the HAZ near-weld zone are replaced by the elongated grains of the weld metal (Figure 6 *a*, *b*); the intragranular structure of the near-weld zone, BM and weld metal are similar. The length of the plates is 5–30 μm, the thickness is 1–5 μm (Figure 6, *c*). The distribution of dispersed particles and

Table 4. Mechanical properties of joints of a high-temperature pseudo-α titanium Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy, produced by AAW and EBW with the preheating

Mode number	Preheating temperature, °C	Ultimate tensile strength σ_t, MPa	Yield strength σ_y, MPa	Relative elongation δ_s, %	Impact toughness *KCV*, J/cm^2	Notes
Base metal	–	1208.2	1106.4	–	9.05	–
AAW mode No. 1	200	778.4	564.1	15.2	7.2	Fracture of MI12 samples over the weld
AAW mode No. 2	400	1160.1	–	–	8.3	Same
EBW	200	1187.6	–	–	5.4	–
EBW	400	1192.0	–	–	4.4	–

its sizes correspond to those in BM and the weld (Figure 6, *d*). In general, the microstructure of the metal of the near-weld zone of the welded joint, produced by AAW with the preheating to 200 °C (Figure 6, *e*), and welding over the flux (Figure 6, *f*), are completely identical to the microstructure of the near-weld zone of the welded joint, produced by AAW with the preheating to 400 °C.

The determination of mechanical properties of the produced welded joints allowed making a conclusion that the highest strength is in the joints produced with the preheating to 400 °C (Table 4) and is at the level of 96 % of the strength of the base metal.

The strength of the welded joints of Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy, produced by AAW with the preheating to 200 °C is lower than the strength of the joints made with the preheating to 400 °C and amounts to 64 % of the strength of the base metal with almost equal impact toughness of the samples with a sharp notch. An increase in the preheating temperature from 200 to 400 °C has a favourable effect on the properties of the welded joints and leads to a slight increase in the impact toughness of the joints. It should be noted that the fracture of the samples of the type MI-12 at static tension occurred over the weld metal.

DISCUSSION OF INVESTIGATION RESULTS

It is necessary to note the similarity of intragranular microstructures of different zones, such as base metal, weld metal and HAZ metal of each of the considered welded joints. A uniform homogeneous structure should guarantee close properties not only of different zones of one and the same area of a welded joint, but also of all the three considered welded joints. Thus, the analysis of the microstructure of all zones of welded joints allows making a conclusion that the preheating temperature before welding in the range of 200–400 °C does not affect the final microstructure of welded joints of a high-temperature pseudo-α Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy after welding.

If we compare the joints produced by AAW with the joints produced by EBW with the preheating [10], it can be concluded that the strength of the welded joints of Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy produced by AAW with the preheating to 400 °C, amounts to 97 % of the strength of the joints made by EBW with the preheating to 400 °C [10]. However, the impact toughness of the samples with a sharp notch of the joints produced by AAW is almost twice higher and amounts to 8.3 J/cm^2 (Table 4).

For the welded joints of Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy, produced by EBW, an increase in the preheating temperature from 200 to 400 °C has no favourable effect on the properties of welded joints and leads to a decrease in the impact toughness of the joints of both alloys. For the joints of this alloy produced by AAW, an increase in the preheating temperature from 200 to 400 °C leads to an increase in the strength and impact toughness.

The conducted investigations made it possible to conclude that for AAW of a high-temperature pseudo-α Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy, the optimum preheating temperature is 400 °C. In this case, the strength of welded joints is not less than 90 % of the strength of the base metal. The values of the impact toughness of the samples with a sharp notch (8.3 J/cm^2) are close to the indices for the base metal (9.0 J/cm^2).

CONCLUSIONS

1. The weld metal of a high-temperature pseudo-α Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy after welding has a basket-weave structure from the plates of α-phase, the length of plates is 5–30 μm, the thickness is 1–5 μm, and dispersed particles of titanium silicide and β-phase are localized on the boundaries of grains and plates.

2. The preheating temperature before welding in the range of 200–400 °C does not affect the final microstructure of welded joints of a high-temperature pseudo-α Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy produced by AAW in the state after welding.

3. The highest ultimate strength is in the AAW-joints of a high-temperature pseudo-α Ti–5.6A1–2.2Sn–3.5Zr–0.4Mo–1.0V–0.6Si alloy, produced with the preheating to 400 °C, which is on the level σ_t = 1160.1 MPa and corresponds to 96 % of the strength of the base metal and 97 % of the strength of the joints made by EBW with the preheating to 400 °C, the index of impact toughness of the samples with a sharp notch of the joints produced by AAW is twice higher and amounts to 8.3 J/cm^2.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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