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INFLUENCE OF PREHEATING PARAMETERS AND LOCAL HEAT TREATMENT ON STRUCTURE AND PROPERTIES OF DISPERSION-STRENGTHENED JOINTS OF SILICON-CONTAINING TITANIUM ALLOYS MADE BY ELECTRON BEAM WELDING

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Titanium alloys have high strength and corrosion resistance in a broad temperature range. When developing promising alloys, it is necessary to increase both working temperatures of parts and components of future engines, and their specific strength. The work is a study of the influence of preheating and local heat treatment on the structure and properties of EB welded joints of experimental silicon-containing titanium alloys, namely pseudo α-alloy Ti–5.6Al–2.2Sn–3.5Zr–0.4Mo–1V–0.6Si and (α + β)-alloy Ti–4.3Al–4.4Sn–6Zr–1.6Mo–0.7V–4.3Nb–0.4Si. Welded joints of dispersion-strengthened titanium (α + β)-alloy Ti–4.3Al–4.4Sn–6Zr–1.6Mo–0.7V–4.3Nb–0.4Si have higher ultimate strength, reaching 1277 MPa that corresponds to 90 % of that of the alloy proper. Long-term strength σ_{100} at 600 °C temperature of welded joint of Ti–4.3Al–4.4Sn–6Zr–1.6Mo–0.7V–4.3Nb–0.4Si titanium alloy is equal to about 260 MPa that is on the level of 93 % of long-term strength of base metal. 12 Ref., 4 Figures, 3 Tables.

Keywords: *titanium, titanium alloy, dispersion strengthening, electron beam welding, structure, properties, strength, long-term strength*

Titanium alloys have high strength and corrosion resistance in a broad temperature range. In development of competitive engines, it is necessary to increase both working temperatures of parts and components of future engines and their specific strength [1]. This can be achieved, first of all, through improvement of alloying of titanium alloy. High-temperature titanium alloys, such as VT3, VT9, VT8 are traditionally included into the group of pseudo α-alloys. Over the last years, however, investigations are performed also in the direction of development of two-phase high-temperature (α + β)-titanium alloys, for instance, high-temperature alloy VT25U [2], which has σ_t = 1080 MPa, at 20 °C, and σ_t = 784 MPa at 550 °C, that exceeds the respective values of many high-temperature single-phase α-alloys or pseudo α-alloys [3]. In the case of dispersion-strengthened (α + β)-titanium alloys, their strength is also higher, making them potentially more promising for application in engine construction [4, 5]. Silicon as an alloying element improves high-temperature strength of titanium alloys due to blocking the movement of dislocations. However, silicon solubility in α-titanium is very low — on the level of tenth fractions of a percent (less than 0.2 % at 600 °C). Even small changes of silicon concentration can lead to a change of the properties of both base metal (BM), and their welded joints. An essential disadvantage of dispersion-strengthened titanium alloys is complexity of welding titanium, associated with initiation of cold cracks in welded joints. Therefore, electron beam welding (EBW) of such alloys requires application of additional technological operations, such as preheating and post weld heat treatment. Complication of the process of manufacturing parts from high-temperature titanium alloys requires improvement of the technology of their welding, particularly, of titanium alloys, additionally doped by silicon.

The objective of the work is determination of the influence of preheating and local heat treatment in EBW chamber on the properties of welded joints of experimental titanium alloys, doped with silicon.

Studied were the properties of EB welded joints of two types of titanium alloys, which belong to pseudo α-alloys and (α + β)-alloys: alloy 1 (Ti–5.6Al–2.2Sn–3.5Zr–0.4Mo–1V–0.6Si — pseudo α-alloy with coefficient of β-phase stabilization K_β = 0.1); alloy 2 (Ti–4.3Al–4.4Sn–6Zr–1.6Mo–0.7V–4.3Nb–0.4Si — two-phase (α + β)-alloy of martensitic type with K_β = = 0.33).

Ingots were produced in skull electron beam installation ISV-004 [6]. Table 1 gives the composition of both the alloys. Produced ingots were rolled to 13 mm thickness. After rolling the plates were annealed at the temperature of 800 °C for 1 h to stabilize the structure and relieve stresses.

Welding of samples of 150×70×13 mm size was performed in one pass in ELA60/60 unit. Three different preheating operations up to 200, 300 and 400 °C were performed for each of the studied alloys, and

Table 1. Chemical composition of silicon-containing dispersion-strengthened titanium alloys

Alloy	Alloying element content, %							K_β
	Al	Sn	Zr	Mo	V	Nb	Si	
1	5.6	2.2	3.5	0.4	1.0	–	0.6	0.1
2	4.3	4.4	6.0	1.6	0.7	4.3	0.4	0.33

temperature was monitored with thermocouples, attached from the weld root side. Detailed procedure is published in work [7]. Welding was performed in the following mode: U_{acc} = 60 kW, I_{beam} = 80 mA, V = = 7 mm/s. Appearance of welded joint of experimental ($\alpha + \beta$)-titanium alloy with dispersion strengthening, made by EBW with preheating and subsequent local electron beam heat treatment, is given in Figure 1.

Defects, most often observed in welded joints of both the alloys, included cold cracks, these cracks forming both in weld upper part, and in the heat-affected zone (HAZ). Local heat treatment directly after welding is an effective technological measure to prevent cold cracking in EBW [8]. Therefore, to produce crack-free sound joints local heat treatment (LHT) of the made joints was performed directly after welding in EB chamber. LHT included heating up to 900 °C and soaking for 5 min. After LHT the joint has no cold cracks.

Experimental alloy 1 in the condition after rolling and subsequent annealing has platelike structure with silicide concentration on plate boundaries (Figure 2, *a*) that is associated with the fact that silicon content in this alloy is above the limit of its solubility in α-phase. As is known, maximum solubility of silicon in α-phase is equal to 0.45 % at the temperature of 860 °C, and minimum temperature is less than 0.2 % at 600 °C [9]. In addition, silicon solubility in titanium can decrease in the presence of other alloying elements, such, as for instance, aluminium [10, 11]. Investigations of the structure of the welded joints showed that weld metal of experimental alloy 1 in as-welded and LHT condition consists of primary β-grains elongated in the direction of heat removal with platelike α-phase in the grain volume. After welding silicide particles are localized both along the boundaries of β-grains, and in the grain volume (Figure 2, *c*). Size of platelike α'-phase is equal to 0.3–1.5 μm, and that of silicide precipitates is 0.1–0.2 μm. After heat treatment silicide particles are located predominantly along the boundaries of α-plates (Figure 2, *d*), and in BM. Large equiaxed grains of β-phase form in the HAZ near-weld zone after heating up to temperatures exceeding polyamorphous transformation temperatures (PTT). At cooling to temperatures below PTT $\beta \rightarrow \alpha'$-transformation with formation of platelike α'-phase takes place in the volume of primary α-grains, as well as in the weld (Figure 3, *a*). After heat treatment silicides also predominantly fringe the boundaries of α-plates (Figure 3, *b*).

Work [12] shows that structural-phase state of metal of fusion zone of welded joint on titanium alloy 1 is characterized by formation of platelike α- and β-structures of an elongated shape. Here, phase precipitates of intermetallics of diverse stoichiometric composition are formed, such as Ti_3Si; Ti_5Si_3; $(Ti, Zr)_5(Si, Al)_3$; $(Ti,Zr)_2(Si,Al)$ and TiSi. These intermetallic phases differ essentially both by dimensions and by their distribution. Mean diameter of intermetallic precipitates is equal to 0.1–0.2 μm. Phase precipitation sites also feature formation of dense dislocation clusters in these zones. Presence of strongly elongated structural-phase formations promotes lowering of ductility of welded joint metal and increase of cracking susceptibility, respectively [12].

Experimental alloy 2 belongs to ($\alpha + \beta$)-alloys of martensitic type. Silicon content in this alloy is somewhat higher than the limit of its solubility in α-phase. BM of alloy 2 has thin plate structure (Figure 4, *a*). Weld of this alloy consists of primary β-grains of different shape (Figure 4, *b*). Metastable martensite α'-phase is detected in primary grain volume (Figure 4, *c*). Very fine particles of titanium silicides are observed against the background of acicular structure, which are located both on the boundaries and in the grain volume (Figure 4, *d*).

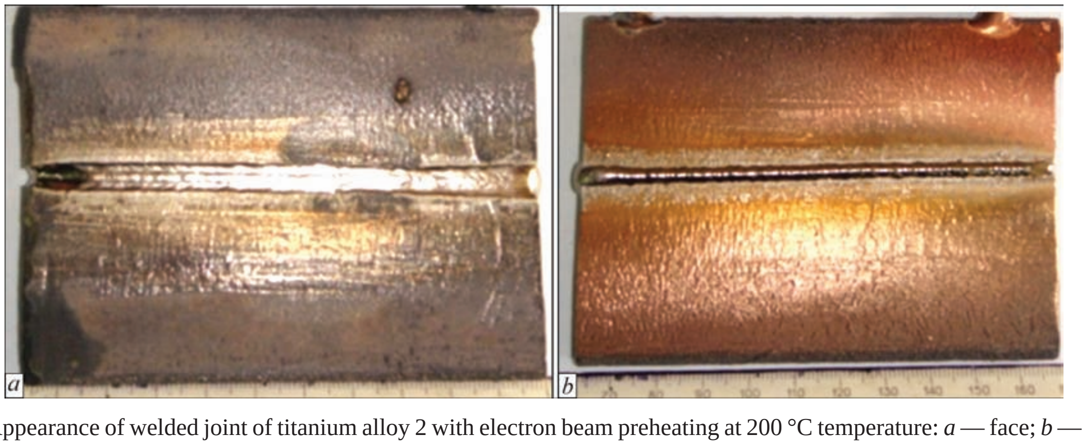

Figure 1. Appearance of welded joint of titanium alloy 2 with electron beam preheating at 200 °C temperature: *a* — face; *b* — weld root

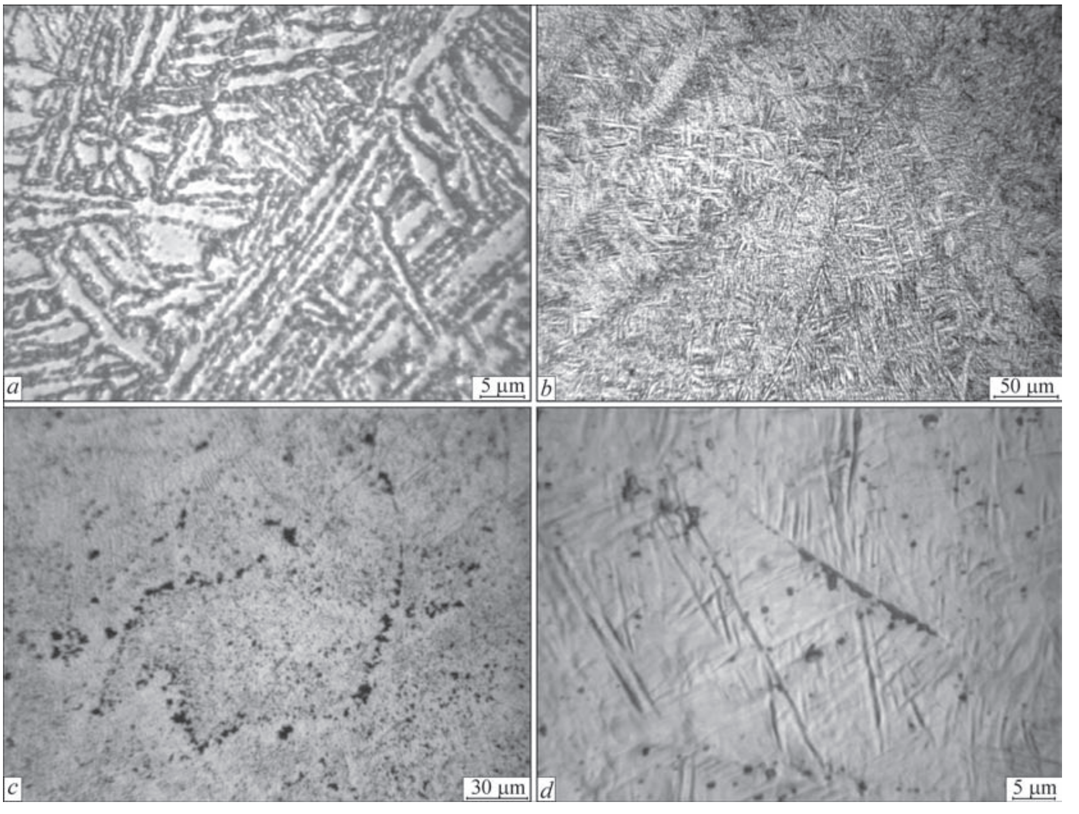

Figure 2. Microstucture of BM (*a*) and metal of EB weld of dispersion-strengthened titanium alloy 1 (*b*–*d*)

Three structurally-different regions can be distinguished in the HAZ of alloy 2. Hear-weld zone consists of equiaxed polyhedral primary β-grains with acicular morphology of α′-phase (Figure 3, *c*). Located farther from the weld is HAZ region where partial recrystallization with formation of fine equiaxed grains proceeds. Located near BM is HAZ region which was heated to temperatures below PTT

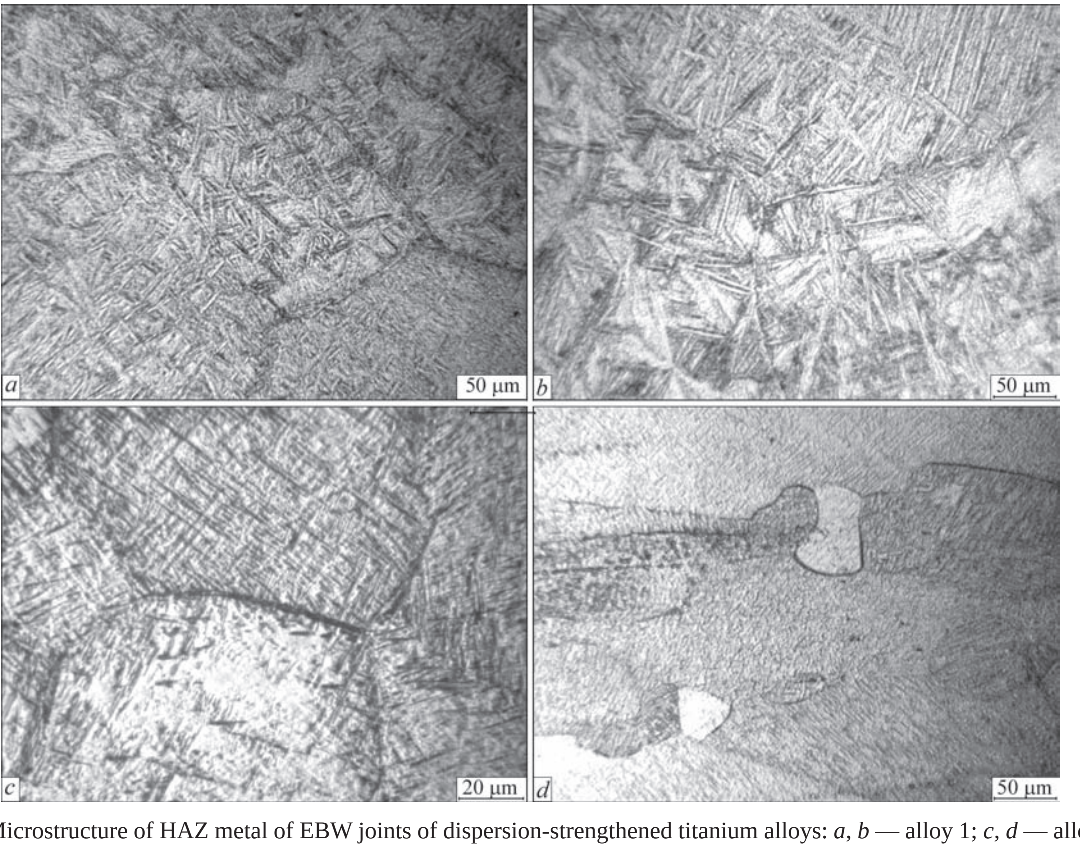

Figure 3. Microstructure of HAZ metal of EBW joints of dispersion-strengthened titanium alloys: *a*, *b* — alloy 1; *c*, *d* — alloy *2* (*a*, *c*, *d* — after welding; *b* — after LHT)

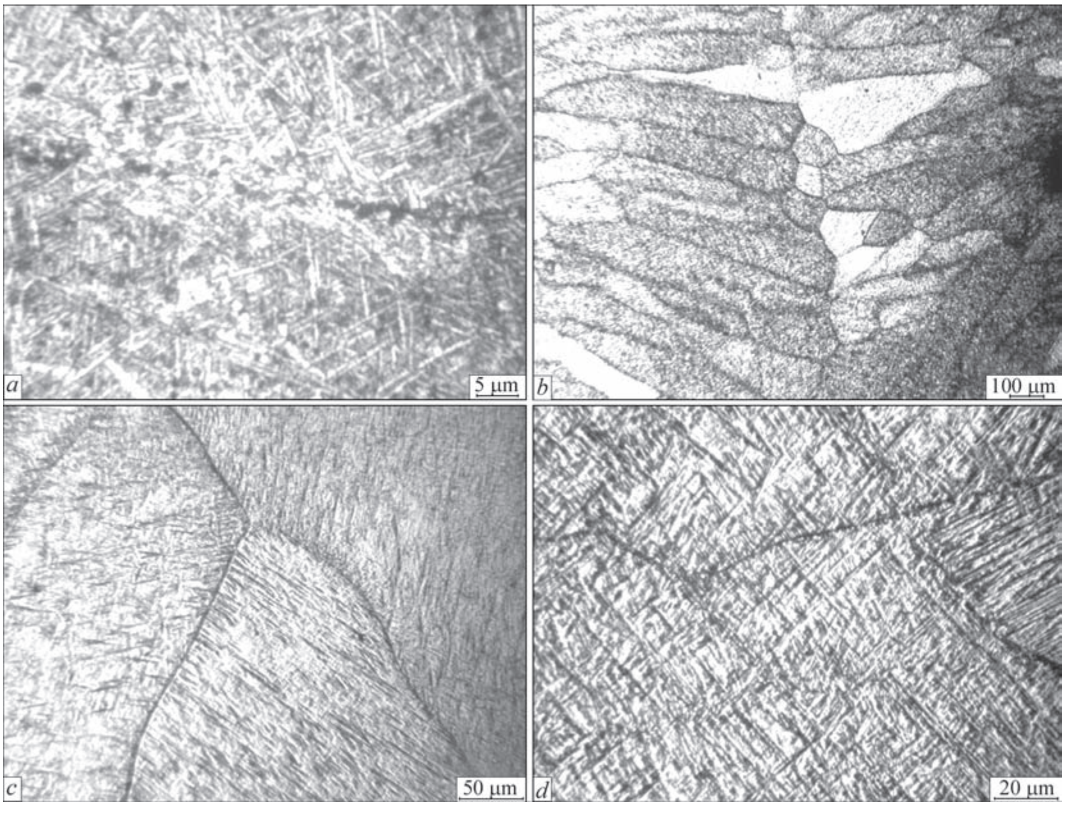

Figure 4. Microstructure of BM (*a*) and metal of EB weld of dispersion-strengthened titanium alloy 2 (*b–d*)

and recrystallization temperature, and which inherits BM structure, but has low etchability. In some local areas of the HAZ fine equiaxed grains are surrounded by eutectics (Figure 3, *d*) with high silicon content. Microstructure in the fusion zone is represented, similar to pseudo α-alloy, by platelike α- and β-phases of martensite type. On the whole, structure of weld and HAZ metal of alloy 2 is more uniform and finely-dispersed, compared to alloy 1. As shown in [12], the main difference in HAZ structure of these alloy joints consists in smaller dimensions of (α, β)-constituents and intermetallic phases. So, dimensions of platelike structures are equal to 0.2–0.5 μm, and mean diameter of intermetallic precipitates is equal to 0.01–0.06 μm, that is 2–3 times smaller in the cross-section, compared to the respective zone of pseudo α-alloy. Silicide and intermetallic phase distribution is more uniform through the entire metal volume.

Thus, dispersion-strengthened titanium alloy 2 has smaller dimensions of (α, β)-components, as well as silicide and intermetallic phases, compared to alloy 1, but presence of elongated platelike structures will

Table 2. Mechanical properties of base metal and EB welded joints of dispersion-strengthened titanium alloys

Material	Preheating temperature, °C	Temperature (°C); LHT duration (min)	σ_y, MPa	σ_t, MPa	Impact toughness *KCV*, J/cm^2	Remark
Alloy 1	–	–	1106.4	1208.2	9.05	Base metal
	–	–	–	1309.7	–	Brittle fracture
	200	–	–	1187.6	5.4	Same
	200	900; 10	810.5	1182.9	5.3	»
	300	–	–	1167.7	5.1	»
	300	900; 10	743.3	1089.0	4.9	»
	400	–	–	1192.0	4.4	»
	400	900; 10	789.8	1132.8	3.4	»
Alloy 2	–	–	1329.2	1422.2	4.2	Base metal
	–	–	–	1360.2	2.2	Brittle fracture
	200	–	–	1293.0	4.7	Same
	200	900; 10	–	1277.8	4.6	»
	300	–	–	1241.6	4.8	»
	300	900; 10	–	1219.8	4.5	»
	400	–	–	1329.7	4.5	»
	400	900; 10	–	1274.9	1.8	»

*Mean values from testing three samples are given.

promote, even though to a smaller degree, lowering of ductility and appearance of susceptibility to crack formation in the welded joint, that is indicative of the need for local postweld heat treatment.

Analysis of mechanical characteristics of welded joints of both the alloys is given in Table 2. Strength of welded joints of alloy 2 is higher by 8 % than that of alloy 1 joints at practically equal impact toughness of samples with a sharp notch. Increase of preheating temperature up to 300 and 400 °C is not favourable for welded joint properties, but leads to lowering of impact toughness of joints of both the alloys.

Thus, performed studies led to the conclusion that 200 °C is the optimum preheating temperature for EBW of alloy 2. In this case, welded joint strength is on the level of 90 % of BM strength.

As welded joints of dispersion-strengthened titanium alloy 2 have a more uniform structure with 2–3 times smaller dimensions of (α, β)-components and silicide phases, as well as higher mechanical properties, long-term strength studies of both the alloy proper and its welded joints were performed for this alloy. Testing was conducted according to GOST 10145–81 «Metals. Method of testing for long-term strength». This required making standard samples of MI-83 type with a cylindrical part of 5.0 mm diameter, which were placed into the grips of tensile testing machine MP-3G (GOST 1533–81). Sample testing temperature was 600 °C and was maintained constant with the accuracy of ±2 °C. Table 3 shows the obtained results.

Analysis of the obtained results allowed plotting the following dependence: load (σ, MPa) — time to fracture (τ, h), and making the following conclusions: long-term strength σ_{100} BM of titanium alloy 2 with dispersion strengthening is equal to about 280 MPa, long-term strength σ_{100} of welded joint of titanium alloy 2 is equal to about 260 MPa.

Thus, conducted investigations led to the conclusion that long-term strength of welded joint of titanium alloy 2 with dispersion strengthening, produced by EBW with preheating at the temperature of 200 °C and LHT by the electron beam in the welding chamber at the temperature of 600 °C is on the level of 93 % of BM long-term strength.

Table 3. Long-term strength of titanium alloy 2 and its welded joints at 600 °C temperature

Sample type	Load σ, MPa	Time to fracture, τ, h	Relative elongation δ, %	Reduction in area ψ, %
Base metal	650	2.15	9.2	18.6
Same	600	3.10	14.6	39.2
»	450	19.00	26.9	50.6
»	400	19.30	22.0	61.6
»	350	26.30	26.4	54.9
»	300	58.00	21.3	69.7
Welded joint	260	87	11.9	18.3
Same	260	120	9.2	6.75
»	300	37	10.4	13.9

Conclusions

1. Welded joints made by EBW of dispersion-strengthened titanium pseudo α-alloy Ti–5.6Al–2.2Sn–3.5Zr–0.4Mo–1V–0.6Si have dimensions of α'-phase in the range of 0.3–1.5 μm, silicide inclusions — of 0.1–0.2 μm, ultimate strength of the joints reaching 1182 MPa that is equal to 97 % of that of the alloy proper.

2. Welded joints of dispersion-strengthened titanium ($\alpha + \beta$)-alloy Ti–4.3Al–4.4Sn–6Zr–1.6Mo–0.7V–4.3Nb–0.4Si have high ultimate strength reaching 1277 MPa, that corresponds to 90 % of that of the alloy proper, and 2–3 times smaller dimensions of ($\alpha + \beta$)-components and intermetallic phases. They, however, are prone to cracking and require performance of local postweld heat treatment.

3. Optimal preheating temperature in EBW of high-temperature titanium α-alloy Ti–5.6Al–2.2Sn–3.5Zr–0.4Mo–1V–0.6Si and ($\alpha + \beta$)-alloy Ti–4.3Al–4.4Sn–6Zr–1.6Mo–0.7V–4.3Nb–0.4Si is equal to 200 °C.

4. Long-term strength σ_{100} at 600 °C temperature of welded joint of titanium alloy Ti–4.3Al–4.4Sn–6Zr–1.6Mo–0.7V–4.3Nb–0.4Si is equal to about 260 MPa, that is on the level of 93 % of BM long-term strength.

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