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ELECTRON BEAM WELDING AND HEAT TREATMENT OF WELDED JOINTS OF HIGH-STRENGTH PSEUDO-β TITANIUM ALLOY VT19

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Titanium pseudo-β titanium alloys have high strength reaching 1200-1400 MPa in aged state, as well as high adaptability to manufacture in comparison with alloys of pseudo-α– or (α + β)-structure. Such advantages of pseudo-β titanium alloys, typical representative of which is high alloy VT19, make this class of titanium alloys promising for application in new technologies and equipment and during modernization of existing ones. The paper has studied the effect of mode of electron beam welding, modes of preheating and local heat treatment, as well as furnace annealing on properties of welded joints of pseudo-β titanium alloy VT19 produced by electron beam welding. Variation of speed of electron beam welding of alloy VT19 does not allow changing within the significant limits the relation between α- and β-phases in weld metal and heat-affected zone. Electron beam welding in combination with preheating allows regulating the relation between α- and β-phases in welded joint metal and reducing the content of β-phase in weld metal of alloy VT19 from 91 to 53 % , as well as increasing the strength of welded joints from 876 to 937 MPa. 11 Ref., 2 Tables, 6 Figures.

Keywords: *titanium, titanium alloys, pseudo-β titanium alloys, electron beam welding, structure, properties, local heat treatment, annealing, strength*

The main advantages of modern pseudo-β titanium alloys are their high adaptability to manufacture in comparison with alloys with pseudo-α- or (α + β)-structure, as well as their high strength properties. Such advantages of pseudo-β-titanium alloys, the characteristic representative of which is the high alloy VT19 make this class of titanium alloys challenging for using in new technologies and equipment, as well as in updating the existing ones [1]. The pseudo-β titanium alloy VST5553 (Ti–5Al–5Mo–5V–3Cr) is already applied in aircrafts of Boeing production [2]. An important task is the development of welding technology and heat treatment modes of produced joints, which should provide the optimum phase composition and strength level of at least 0.90–0.95 of the base material strength. This requires the use of additional technological operations such as preheating and postweld heat treatment [3]. The electron beam welding (EBW) allows combining such technological operations as welding and heat treatment, which will provide the high quality of the produced joints [4, 5].

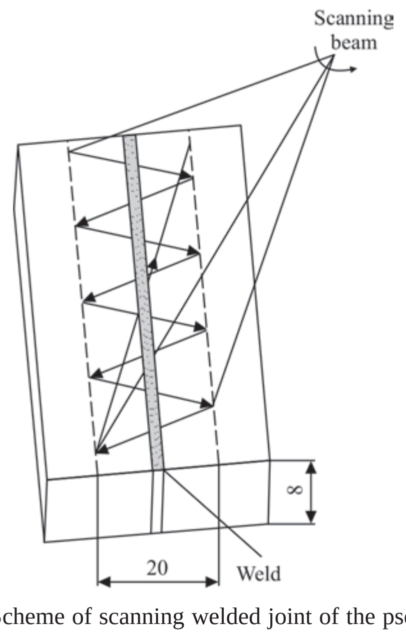

Figure 1. Scheme of scanning welded joint of the pseudo-β titanium alloy VT19 at a local electron beam heat treatment (750 °C, 10 min)

The aim of the work was to determine the influence of the EBW mode, the preheating and local heat treatment modes, as well as the modes of furnace annealing on the properties of pseudo-β titanium alloy VT19 joints, made by EBW.

The specimens with dimensions of 200×100×8 mm were welded. The EBW was carried out in the updated installation UL-144 equipped with the power unit ELA 60/60. The preheating was carried out to the temperature of 400 °C, the temperature control was performed using thermocouples attached from the root side of the weld. The detailed procedure of preheating is described in work [6]. The scheme of preheating and local heat treatment (LHT) is shown in Figure 1. The treatment zone width was 20 mm. The electron beam power during the process of LHT was about 3 kW, and was subjected to correction for maintaining the temperature in the treatment zone at the level of 750 °C.

The welding was carried out at the following conditions: U_{acc} = 60 kV, I_{beam} = 120 mA. The joints were produced at two welding speeds of 7 and 11 mm/s.

Some of welded joints were subjected to preheating to the temperature of 400 °C before welding. The welded joints, produced with preheating after welding, were subjected to LHT in a vacuum chamber by the mode providing heating to the temperature of 750 °C and 10 min holding. A part of the joints after welding was subjected to furnace annealing, providing heating to the temperature of 750 °C, and holding for 1 h and the subsequent furnace cooling. The appearance of specimens of welded joints is shown in Figure 2. According to data of X-ray inspection and analysis of structure, in all the specimens, welded by EBW, such defects as pores, lacks of penetration, cracks, nonmetallic inclusions are absent.

The examinations of structure were carried out with the help of the optical microscope «Neophot-30», equipped with attachment for digital photography. The determination of the amount of β-phase in the weld metal, HAZ and base metal was performed experimentally on microsections. For this purpose, on scanned microsections the ratio of light regions of the structure, corresponding to β-phase, and dark regions of the structure, corresponding to α-phase was evaluated.

The mechanical properties of base metal and produced welded joints are shown in Table 1.

The base metal of VT19 alloy contains equiaxial polyhedral grains with dispersed precipitations of α-phase, uniformly distributed along the grain body (Figure 3, *a*). The size of α-particles is 1–2 μm and smaller. The amount of β-phase in the base metal in the as-rolled state is 44 % (Table 2).

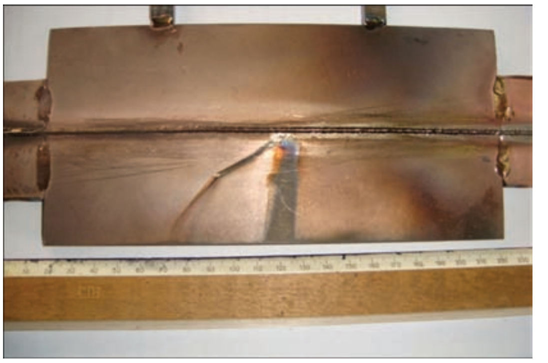

Figure 2. Welded joint of the pseudo-β titanium alloy VT19, made by EBW on the side of weld root

The carried out examinations of the joints structure allowed concluding that in the weld metal produced at the welding speed of 7 mm/s the large, equiaxial polyhedral β-grains predominate. The weld metal consists almost of a pure β-phase (Figure 2, *b*) with hair-like boundaries, the amount of β-phase is 99 %.

The HAZ region, adjacent to the weld, which subjected to a complete polymorphic transformation, is not wide, its width is 2–3 grains. The region of a complete polymorphic transformation consists of an almost pure β-phase (Figure 3, *c*).

The strength of welded joints is at the level of 91 %, their structure is non-equilibrium and requires the use of heat treatment to produce a homogeneous uniform structure.

The weld metal of VT19 alloy, produced at the welding speed of 11 mm/s, also consists of equiaxial β-phase grains elongated in the direction of heat removal, whose boundaries are revealed on the background of the dendritic structure (Figure 3, *d*), in some of the weld metal grains, there are few disperse phase precipitations. The amount of β-phase decreased slightly and amounts to 92 %. The strength of the weld joint is at the level of 94 % of the base metal in the as-rolled state.

It should be noted that the microstructure of welded joint of VT19 alloy, produced at the speed v_w = = 11 mm/s, is similar to the microstructure of welded

Table 1. Properties of welded joints of titanium alloy VT19, produced by EBW

Number of specimen	Type of specimen; welding speed; heat treatment	σ_t, MPa	σ_y, MPa	δ, %	ψ, %	*KCV*, J/cm^2
1	Base metal; after rolling	958	887	12	47	27
2	Welded joint; 7 mm/s	876	842	11.3	36.8	29
3	Welded joint; 11 mm/s	890.7	847.0	10.0	45.9	28
4	Welded joint; 7 mm/s; preheating to 400 °C	893	879	12	47	21
5	Welded joint; 7 mm/s; preheating to 400 °C, LHT at 750 °C, 10 min	937	868	5.3	19	20
6	Welded joint; 7 mm/s; annealing at 750 °C, 1 h	1026.7	985.7	12.0	31.5	26
7	Welded joint; 11 mm/s; annealing at 750 °C, 1 h	1023.7	984.9	8.7	30.6	27
8	Welded joint; 7 mm/s; preheating to 400 ° C, quenching in water and ageing at 450 °C	1285	1234	4.7	20.6	23

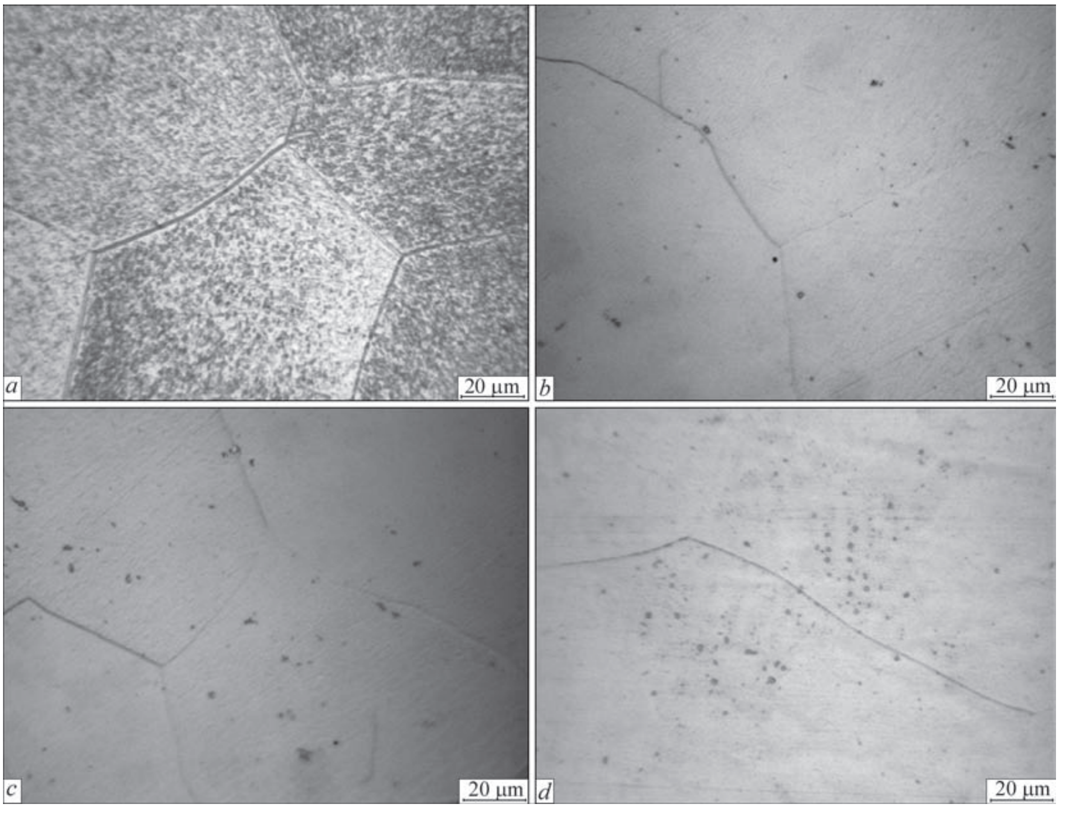

Figure 3. Microstructure of titanium alloy VT19 welded joint, produced by EBW, in the as-welded state: *a* — base metal; *b* — weld metal, v_w = 7 mm/s; *c* — HAZ metal, v_w = 7 mm/s; *d* — weld metal, v_w = 11 mm/s

joint produced at the speed v_w = 17 mm/s, despite the different speed of welding. Thus, after welding in the weld metal of welded joints, the β-phase is contained at the level of 92–99 %; the change in the welding speed does not allow changing the ratio between α- and β-phases within the essential limits.

The weld metal of VT19 alloy, produced at the welding speed of 11 mm/s using a preheating of 400 °C, consists of equiaxial grains of β-phase elongated in the direction of heat removal and on the background of the dendritic structure. During application of preheating and as the result of decrease in the cooling rate of a welded joint in many grains of weld metal the irregularly distributed fine-dispersed precipitations of other phase are fixed in a considerable amount (Figure 4, *a*), whose dimensions are less than 1 μm (Figure 4, *b*). The amount of β-phase, as a result of applying preheating, decreased significantly and equals 60 %. This allows confirming the efficiency of a local preheating.

In the weld metal, produced by EBW using LHT (750 °C, 10 min), the amount of fine-dispersed precipitations of another phase is increased (Figure 5, *a*). The amount of β-phase as a result of preheating is decreased significantly and amounts to 53 %. The strength of welded joints is at the level of 99 % of the alloy strength itself. This allows making the conclusion that after LHT the amount of metastable β-phase

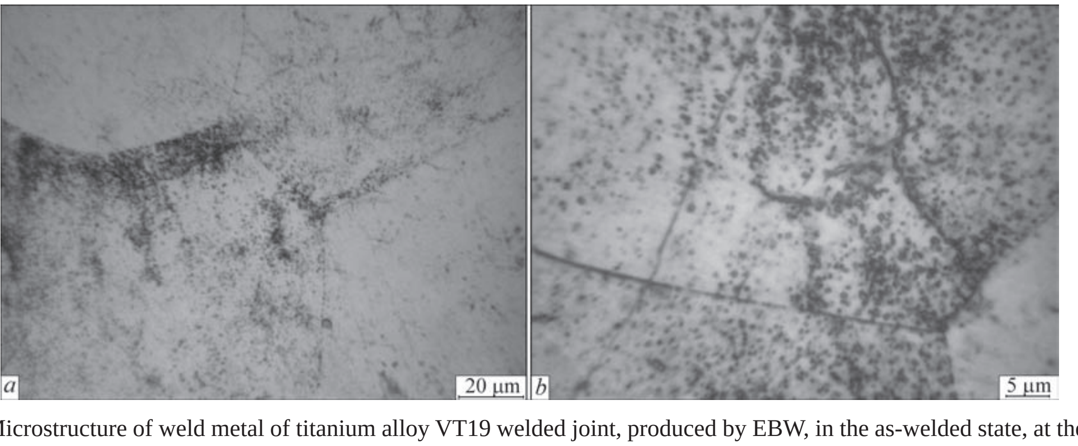

Figure 4. Microstructure of weld metal of titanium alloy VT19 welded joint, produced by EBW, in the as-welded state, at the speed of v_w = 7 mm/s using preheating to 400 °C

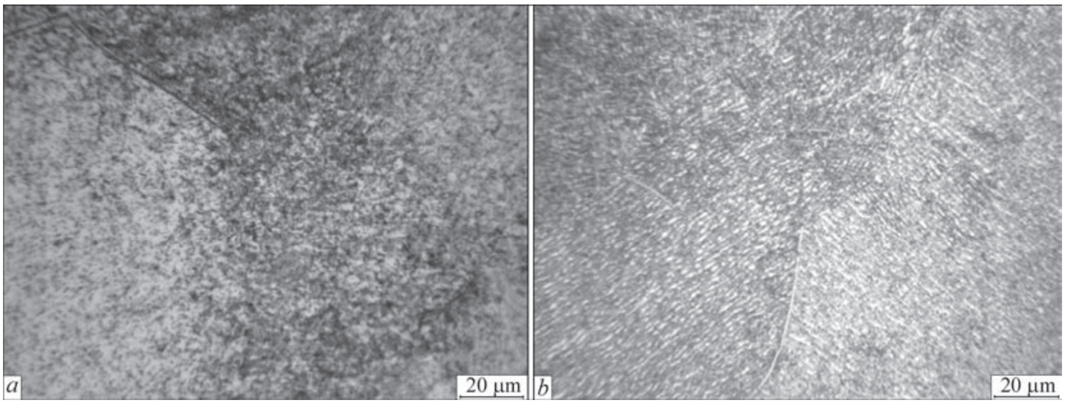

Figure 5. Microstructure of weld metal of titanium alloy VT19 welded joint, produced by EBW at the speed of v_w = 7 mm/s using preheating to 400 °C: *a* — in the state after LHT at 750 °C, 10 min; *b* — after furnace annealing at 750 °C, 1 h

in weld metal decreases to a greater extent as compared to EBW with preheating to 400 °C only. The further increase in the strength of welded joints is limited by the strength of the base metal. Thus, the application of EBW in combination with preheating and LHT makes it possible to obtain the equal-strength welded joints of the titanium alloy VT19.

For comparison, a part of welded joints, produced at the welding speed of 7 mm/s, was subjected to furnace annealing at a temperature of 750 °C for 1 hour with the subsequent furnace cooling. The investigations showed that in this case the weld metal consists of equiaxial β-grains elongated in the direction of heat removal, which, as a result of annealing were subjected to decomposition with the formation of a uniform homogeneous two-phase structure (Figure 5, *b*) consisting of the particles of α and β-phases. The particles of α-phase have lamellar morphology, the length of α-plates is 1–5 μm at a thickness of 0.5–0.8 μm. The amount of β-phase as a result of using furnace annealing is minimal for welded joints and is at the level of 35 %. The strength of welded joints in this case is maximal and amounts to 105–107 % of the strength of alloy in the as-rolled state. It should be noted, that the alloy VT19 allows using heat treatments at lower temperatures as compared with high-strength two-phase alloys, such as VT23, T110 or T120 [7]. Thus, the annealing temperature is 750 °C, which is lower than the temperature of LHT being 850 °C or the temperature of recommended vacuum annealing of 900 °C for T120 alloy.

Table 2. Volumetric content of β-phase in BM and weld metal of titanium alloy VT19 welded joints, produced by EBW

Number of specimen	Type of specimen; welding speed; heat treatment mode	β-phase, %
1	Base metal	44
2	Welded joint; 7 mm/s	99
3	Welded joint; 11 mm/s	92
4	Welded joint; 7 mm/s; preheating to 400 °C	60
5	Welded joint; 7 mm/s, preheating to 400 °C, LHT at 750 °C, 10 min	53
6	Welded joint; 7 mm/s; annealing at 750 °C, 1 h	34
7	Welded joint; 11 mm/s; annealing at 750 °C, 1 h	37

Thus, the application of EBW technology in combination with preheating and LHT allows producing the equal-strength welded joints of titanium alloy VT19, at the same time in order to produce a homogeneous uniform structure in all the zones of welded joint, it is necessary to apply a furnace annealing at the temperature of 750 °C for 1 h.

Since the strength of pseudo-β-alloy VT19 in the wrought and hardened state can exceed 1500 MPa [8], and for high-strength titanium alloys and for pseudo-β-alloy VT19 the quenching in water with the subsequent ageing is an effective hardening heat treatment [9–11], therefore, the feasibility of increasing the strength of joints, produced by EBW, was studied. For this purpose, a part of the specimens of number 2 (Table 1) was subjected to additional hardening heat treatment: quenching, which envisages heating to 800 °C, 1 h holding at 800 °C, quenching in water, ageing at 450 °C for 4 h.

The investigations of structure of the produced joints allowed making the conclusion that after hardening heat treatment consisting of quenching and subsequent ageing, the fine-dispersed decomposition

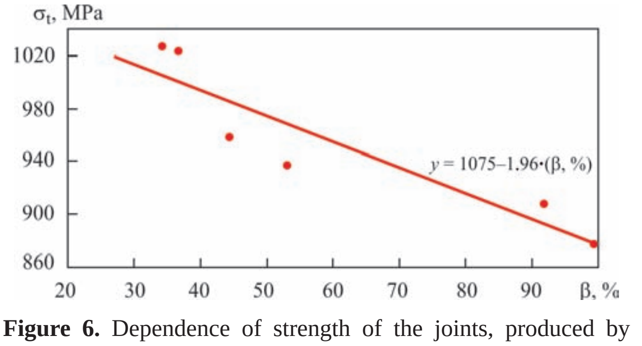

Figure 6. Dependence of strength of the joints, produced by EBW, on the amount of β-phase in the weld metal of titanium alloy VT19

products are formed in the weld metal and HAZ metal of this welded joint, the size of which is mainly amounts to 1.0–1.5 μm.

The carried out investigations allowed making a conclusion that as a result of quenching and subsequent ageing, in welded joints of VT19 alloy, produced by EBW, the most fine-dispersed intragranular structure of weld metal is formed, in which the size of decomposition products more often does not exceed 1 μm, in the HAZ the size amounts to 1–1.5 μm. The fine-dispersed structure in all the zones of welded joint of VT19 alloy provides it with high strength, reaching σ_t = 1285 MPa, at high impact strength *KCV* = 23 J/cm^2.

It should be noted that for welded joints of titanium pseudo-β VT19 alloy, the effective hardening heat treatment is quenching into water with subsequent ageing, which provides the strength of the joints at the level of 130 % of strength of the alloy in as-rolled state.

The investigations of microstructure of produced welded joints and their comparison with the results of evaluation of mechanical properties of joints allowed establishing the inverse dependence of strength of the titanium pseudo-β VT19 alloy joints, produced by EBW on the amount of β-phase in the weld metal (Figure 6). This dependence has the form σ_t = 1072–1.96 (β, %), according to which the minimum values of strength of welded joints (σ_t = 881 MPa) are obtained at the 99 % content of β-phase, and the maximum values (σ_t = 1054 MPa) are obtained at the 25 % content of β-phase.

Conclusions

1. The variation of speed of EBW of VT19 alloy does not allow changing significantly the ratio between α– and β-phases in the weld and HAZ metals, the structure of joint, made at speed of 11 mm/s is similar to the structure of joint, produced at speed of 7 mm/s.

2. EBW in combination with preheating allows regulating the ratio between α– and β-phases in the welded joint metal and reducing the content of β-phase in the weld metal of VT19 alloy from 91 to 53 %, increasing the strength of welded joints from 876 up to 937 MPa and, as a result, providing the strength of welded joints, equal to that of base metal.

3. To form the homogeneous structure, increase the strength of base and welded joint metals up to 1020 MPa level, provide complete decomposition of metastable phases, the joints of VT19 alloy should be subjected to furnace annealing at the temperature of 750 °C for 1 h, as a result of which the strength level of the joints is increased to 105–107 % of that of the alloy after rolling.

4. The quenching in water with next ageing provides high strength values of the joint of VT19 alloy at the level of 1285 MPa. In this case a fine-grained intragranular structure is formed in the weld and HAZ metal, in which the size of α-phase particles does not exceed 1.5 μm.

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