doi.org/10.15407/tpwj2016.06.11

ELECTRON BEAM WELDING OF COMPLEX-ALLOYED HIGH-STRENGTH TITANIUM ALLOY

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The paper deals with features of joint formation in complex high-strength ($\alpha + \beta$)-titanium alloy in vacuum electron beam welding. Investigations were performed on samples of alloy of Ti–Al–Mo–V–Nb–Cr–Zr system produced by electron beam remelting. Influence of thermal cycle of welding and subsequent heat treatment on structural-phase transformations in the metal of weld and welded joint HAZ has been studied. A structure with prevalence of metastable β-phase forms in the metal of weld and HAZ, which promotes lowering of ductility and impact toughness values. Post-weld heat treatment is required to improve the structure and properties of EB-welded joints. The best combination of strength and ductility of studied welded joints was achieved after performance of furnace heat treatment (annealing at T = 900 °C for 1 h and cooling in the furnace), which promotes producing a practically uniform structure and metastable phase decomposition in the weld and HAZ. 8 Ref., 2 Tables, 8 Figures.

Keywords: *EBW, titanium alloys, heat treatment, welded joint, structure, mechanical properties*

Development of modern competitive equipment usually requires improvement of performance of metal structures and parts. These requirements also apply to high-strength Ti-based alloys, which have become widely accepted as structural material. Leading materials science centers of the USA, EU, Russia and China perform intensive work on upgrading the currently available titanium alloys. More over, possibility of creating new alloys with a large amount of alloying elements is studied [1].

Modern two-phase high-alloyed Ti-based alloys are characterized by high specific strength. At present ever more attention is paid to fabrication of welded structures and components from titanium alloys with ultimate tensile strength $\sigma_t \geq 1100$ MPa [2]. Alloys with ($\alpha + \beta$)-structure are widely applied as structural materials. They feature the best combination of technological and mechanical properties — they are stronger than single-phase alloys, can be easily forged, stamped, and heat-treated and have satisfactory weldability. Welded structures from these alloys are applied in aircraft engineering, rocket production, nuclear engineering, shipbuilding and chemical engineering [3, 4].

Weldability of two-phase high-alloyed titanium alloys, application of which can yield the greatest reduction of structure weight, is much worse than that of low alloys, and by this characteristic, they are inferior even to some high-strength steels. EBW is widely applied in fabrication of structures from high-alloyed titanium alloys, including also heat-hardenable two-phase alloys. High cooling rates at EBW and increased sensitivity of complex-alloyed titanium alloys to welding thermal cycle in a number of cases lead to lower ductility of the welded joint [5]. Therefore, two-phase titanium alloys require mandatory PWHT [6]. In development of new alloys, considerable attention is given to the possibility of producing welded joints with the strength of not less than 0.90–0.95 of base metal strength.

The objective of the work is studying the influence of thermal cycle of welding and PWHT on structural-phase transformations in the metal of weld and HAZ in EB-welded joints of complex-alloyed high-strength titanium alloy.

Table 1. Mechanical properties of complex-alloyed high-strength titanium alloy 8 mm thick

Metal condition	Tensile strength σ_t, MPa	Yield point σ_y, MPa	Relative elongation δ_5, %	Reduction in area ψ, %	Impact toughness KCV, J/cm^2
As-rolled	1259.9	1179.5	1.7	6.2	5.0
As-annealed at 850 °C for 1 h	1214.9	1089.2	10.0	18.5	9.0
As-annealed at 900 °C for 1 h	1186.0	1123.6	13.3	19.0	13.5

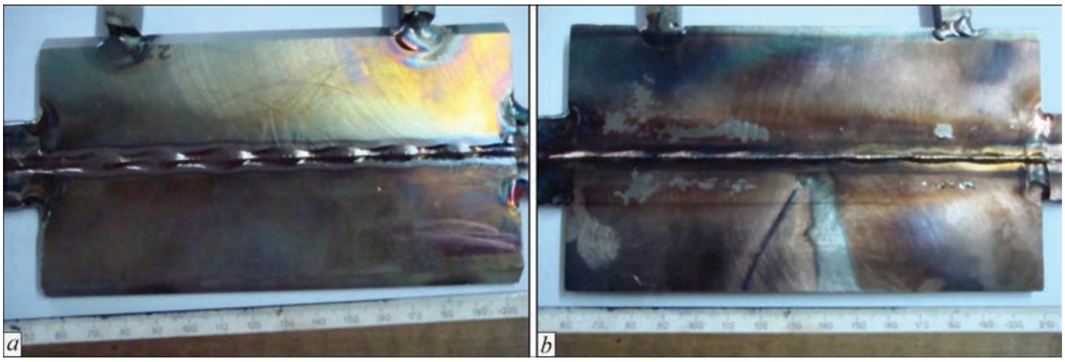

Figure 1. Appearance of EB-welded joint of complex-alloyed high-strength titanium alloy: *a* — face; *b* — root side

Materials and methods of investigations. We used 8 mm thick plates produced from ingots of test titanium alloy as research material [7]. After melting the ingots were subjected to thermodeformational treatment. Samples prepared for investigations had the following composition, wt.%: Ti–6.5Al–3Mo–2.5V–4Nb–1Cr–1Fe–2.5Zr. Mechanical properties of the studied alloy are given in Table 1.

EBW was performed in UL-144 unit, fitted with ELA 60/60 power source, in the following mode: accelerating voltage of 60 kV; beam current of 120 mA; circular scan diameter of 2 mm; welding speed of 25 m/h.

One of the advantages of EBW technology as regards titanium and alloys on its base, in addition to providing reliable protection of welded joints, is the possibility to perform local preheating and PWHT in the vacuum chamber [8]. Preheating of welded joints is a quite efficient technique, used in welding to prevent formation of cold cracks. However, as the studied alloy is not prone to cold cracking, preheating of surfaces being welded was not performed.

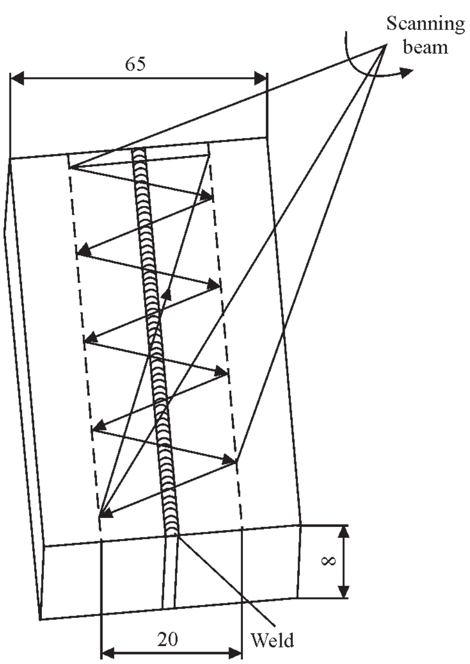

Figure 1. Schematic of EB-welded joint of complex-alloyed high-strength titanium alloy: *a* — face; *b* — root side

Figure 1 gives the general view of EB-welded joint.

To perform local PWHT the joint was heated by the electron beam developed into a rectangular scan. Heat treatment mode was selected, allowing for beam power and width of heated region (i.e. scan width). Electron beam power during local heat treatment was equal to about 3 kW and was corrected to maintain the required temperature in the treatment zone on the level of 850 °C. Treatment time was 5 min. Figure 2 gives the schematic of electron beam scanning at local PWHT of titanium alloy samples.

Postweld annealing of welded joints was performed in the furnace at 900 °C for 1 h.

Samples were cut up in «Isomet» unit of BUEHLER, using diamond disks. Chemical composition of test alloys was determined by spectral and chemical analyses. Metallographic examination and filming were performed in light microscope «Neophot-32» fitted with PC, digital camera OLYMPUS and archiving system. Sample hardness was determined in M-400 hardness meter (LECO) at 100 g and 1 kg load. Investigation of fracture surfaces of base metal and welded joints was conducted in high-performance multifunctional modern instrument — field emission Auger microprobe JAMP 9500F (JEOL). Testing for static tension and impact bending was performed to determine welded joint mechanical properties (according to GOST 1497–84).

Investigations were performed on the following samples of complex-alloyed high-strength titanium alloy:

- sample 1 — EB-welded joint;
- sample 2 — EB-welded joint with local PWHT (850 °C, 5 min);
- sample 3 — EB-welded joint with PWHT (furnace annealing at 900 °C, 1 h).

Investigation results. Local nature and intensity of EBW process provide a deep and narrow weld and small HAZ.

Metallographic investigations of sample 1 (Figure 3) revealed in welded joint metal cast crystallites

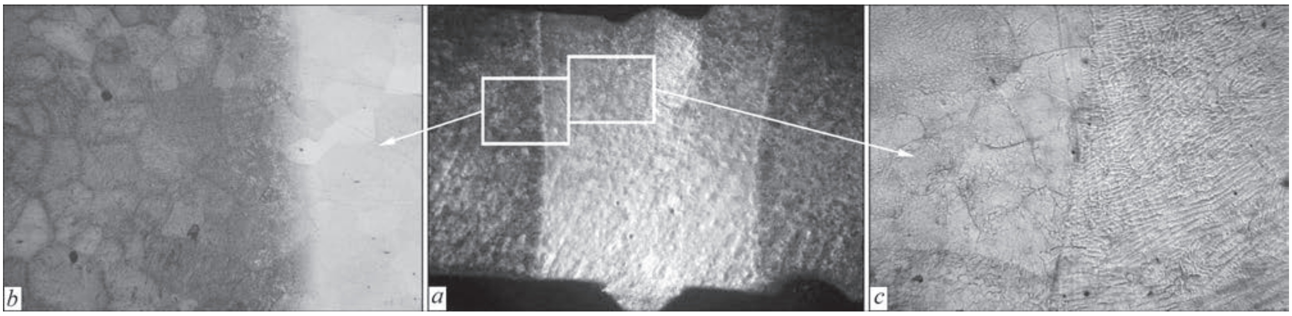

Figure 3. Structure of EB-welded joint of sample 1: *a* — general view (×10); *b* — BM microstructure (×50); *c* — microstructure of weld and HAZ (×100)

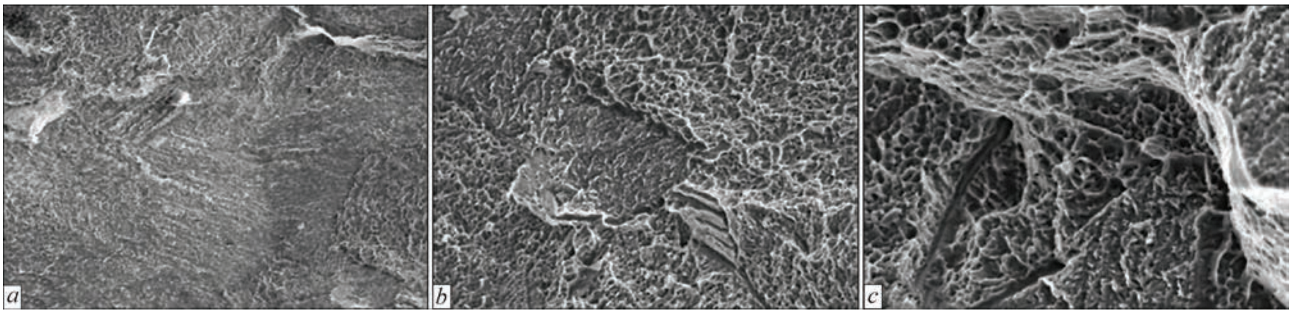

Figure 4. Fragments of fracture surface of sample 1: *a* — intergranular (×300); *b* — intragranular with separation (×500); *c* — pit type with separation and secondary cracks (×1000)

disoriented in the center, and oriented in the direction of heat removal along the edges, with clearcut dendritic structure. Weld metal microstructure is practically single-phase and consists of β-phase. Partial decomposition of β-phase with precipitation of fine particles of α-phase is observed in individual grains and along their boundaries. Hardness of weld metal is 2790–3210 MPa, weld width is 3–4 mm. In the HAZ, near the weld, the structure consists of large polyhedral grains of β-phase, with precipitates of fine-needled α-phase in the grain body. Individual grains with a substructure are also observed on weld–HAZ boundary. When getting closer to base metal, the size of β-phase grains becomes smaller. HAZ metal hardness is equal to 2690–3300 MPa, HAZ width being approximately 2–3 mm. Base metal structure consists of packs of parallel plates of (α + β)-phase. Grain size is 0.088–0.125 mm, base metal hardness being 3340–3430 MPa.

Fractographic studies of sample fracture surface after mechanical testing (Figure 4) showed that surface relief is weakly pronounced and fracture mode is of mixed type. Brittle fracture mode is 65 % quasi-cleavage, and that of ductile fracture is 35 % pit structure.

Metallographic investigation of sample 2 (Figure 5) showed that after local PWHT structural uniformity of welded joint becomes higher. Weld and fusion line are not as clearcut as after welding. The weld is a mixture of elongated and polyhedral β-grains with disoriented precipitates of α-phase plates. Weld metal hardness is equal to 3220–3450 MPa. HAZ consists of coarse polyhedral β-grains with precipitates of disperse α-phase. Hardness is equal to 3250–

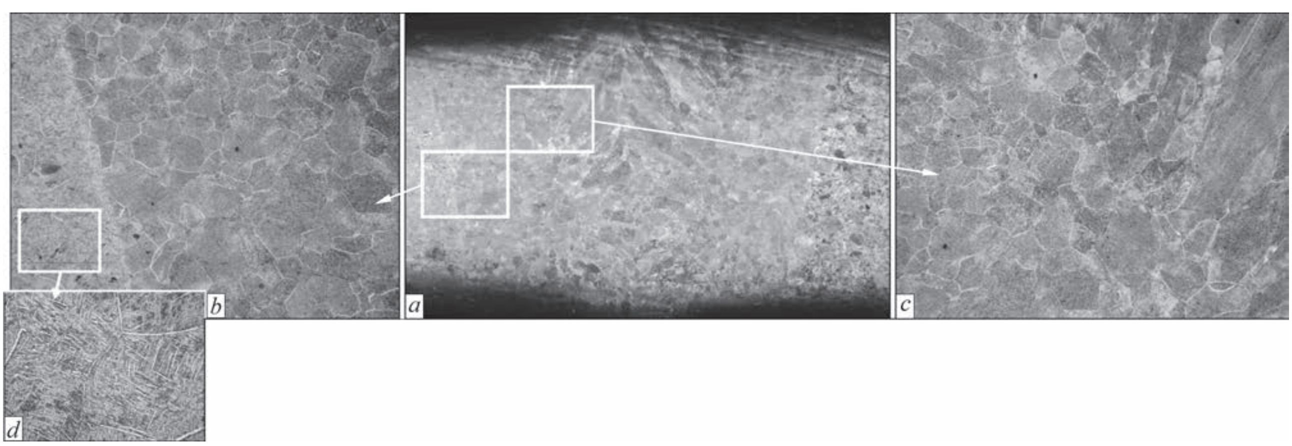

Figure 5. Structure of EB-welded joint of sample 2 after local PWHT (850 °C, 5 min): *a* — general view (×10); *b* — microstructure of HAZ–BM boundary (×50); *c* — microstructure of weld and HAZ (×50); *d* — microstructure of BM (×500)

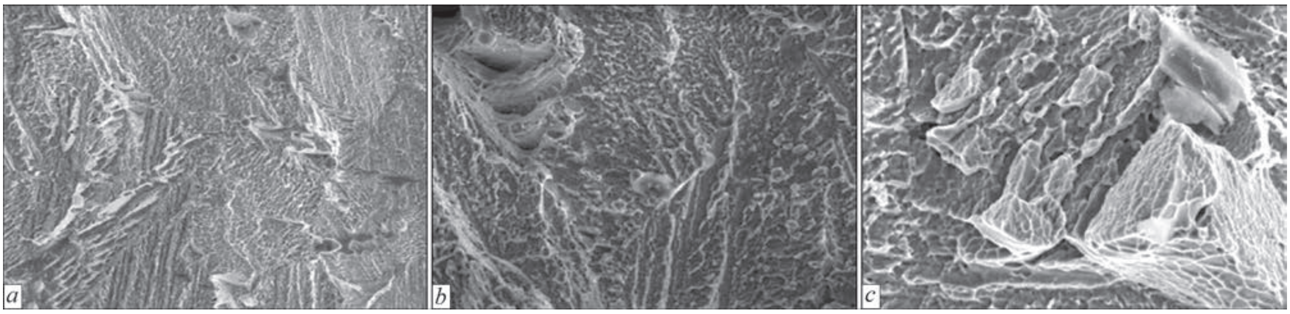

Figure 6. Fragments of fracture surface of sample 2: *a* — intergranular (×300); *b* — intragranular in combination with separation (×500); *c* — pit type with separation (×1000)

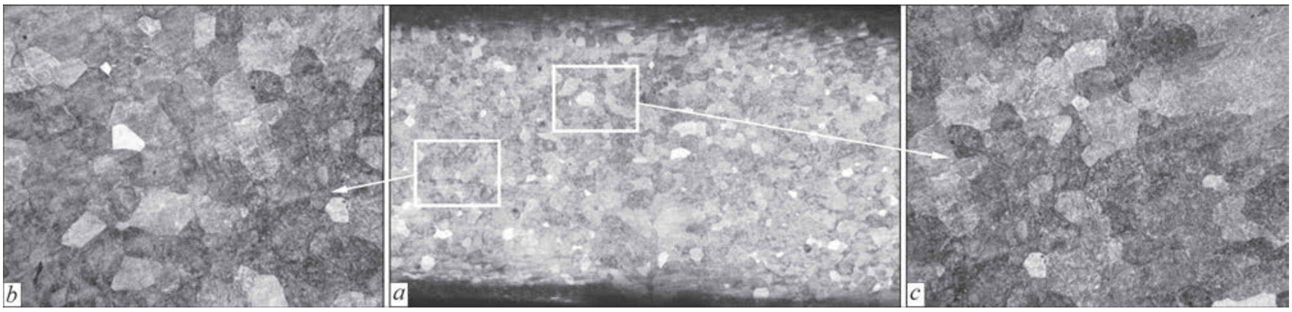

Figure 7. Structure of EB-welded joint of sample 3 after postweld furnace annealing (900 °C, 1 h): *a* — general view (×10); *b* — microstructure of HAZ–BM area (×50): *c* — weld and HAZ microstructure (×50)

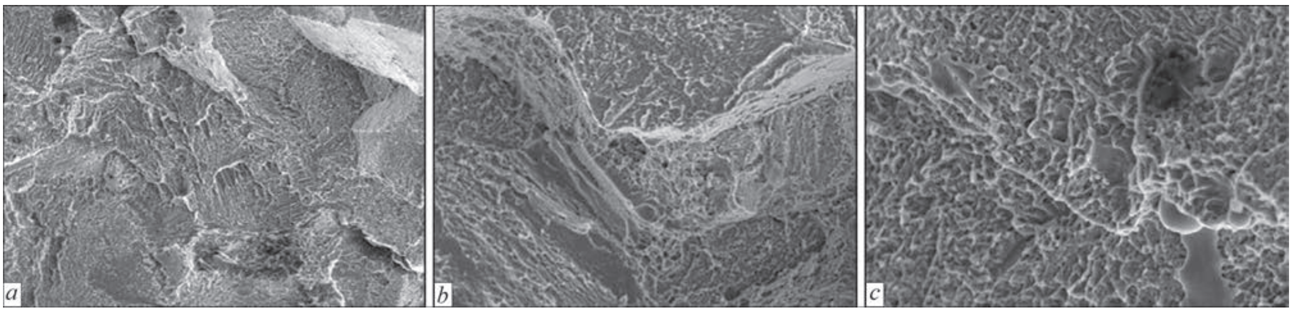

Figure 8. Fragments of fracture surface of sample 3: *a* — intergranular (×300); *b* — intragranular in combination with separation (×500); *c* — pit type (×1000)

3450 MPa. Base metal structure is presented by finer polyhedral grains with plate-like ($\alpha + \beta$)-phase and hardness from 3420 to 3600 MPa.

Fractographic studies of the sample showed that fracture surface has a complex microrelief (Figure 6). The crack runs along the interfaces of β-phase matrix and disperse needle-like α-phase. Fracture surface contains cleavage facets against the background of intergranular fracture (separation sections). Fracture surface has many elevations in the form of steps.

Metallographic investigations of sample 3 (Figure 7) showed that after furnace heat treatment the studied sample structure becomes practically uniform, and no boundaries between the weld, HAZ and base metal are detected. The structure over the entire studied surface has different grains with plates of ($\alpha + \beta$)-phase of different size. Hardness (from weld center into base metal) is equal to 3340–3440 MPa.

Fractographic studies showed that sample fracture is of a mixed nature (Figure 8). Fracture contains 30 % of brittle component and 70 % of ductile component. The crack propagated strictly perpendicular to the applied load. Brittle fracture proceeds in the mode of intragranular cleavage, and ductile fracture results from micropore coalescence. The observed cleavage facets are divided by separation sections. Separation

Table 2. Mechanical properties of EB-welded joints of complex-alloyed high-strength titanium alloy

Sample number	Sample condition	σ_t, MPa	σ_y, MPa	δ_5, %	ψ, %	*KCV*, J/cm^2	
						Weld	HAZ
1	As-welded	1415	1380	2.0	6.6	7.2	6.0
2	Local PWHT (850 °C for 5 min)	1258	1216	4.3	9.2	7.3	14.4
3	Furnace PWHT (900 °C for 1 h)	1131	1089	12.0	24.5	12.4	12.7

occurs in those cases, when material has sufficiently high ductility.

Table 2 gives the results of mechanical testing of the studied samples.

Analysis of the Table leads to the conclusion that PWHT increases the values of ductility and impact toughness of welded joint of complex-alloyed high-strength titanium alloy. Particularly effective is furnace treatment (annealing at 900 °C for 1 h), which leads to significant increase of ductility and impact toughness in combination with a slight lowering of strength characteristics.

Conclusions

1. Structure and properties of welded joints of complex-alloyed high-strength (α + β)-titanium alloy produced by EBW were studied. It is found that the alloy has satisfactory weldability, but the structure in the metal of the weld and HAZ is not uniform and metastable phases are observed that leads to lowering of strength and ductility values.

2. Heat treatment of EB-welded joints of complex-alloyed high-strength (α + β)-titanium alloy, improves structural uniformity, lowers the probability of cracking in them and promotes improvement of mechanical property values.

3. After local PWHT of welded joints, toughness values increase only slightly, that is attributable to incomplete decomposition of metastable structures, resulting from short-time thermal impact (heating at 850 °C for 5 min).

4. The best combination of strength and ductility of the studied welded joints was achieved after furnace PWHT (annealing at 900 °C for 1 h and cooling with the furnace). Such treatment promoted formation practically uniform structure, decomposition of metastable phases in the weld and HAZ, that lead to significant improvement of ductility and impact toughness values.

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Received 26.04.2016