S.G. Hryhorenko, S.W. Achonin, W.Ju. Belous, R.W. Selin

Heat Treatment Effect on the Structure and Properties of Electron Beam Welded Joints Made of High-Alloy Titanium

Abstract: The article presents the specific formation of a joint made of high-strength high-alloy titanium alloy (α + β) subjected to electron beam welding in vacuum. Tests involved the use of Ti-Al-Mo-V-Nb-Cr-Fe-Zr specimens obtained through electron melting. The research involved tests focused on the effect of a welding thermal cycle and post-weld heat treatment on structural-phase transformations in the weld metal and HAZ of welded joints. It was revealed that the weld metal and HAZ were composed of a structure dominated by the metastable phase β, which led to the reduction of plasticity and toughness indexes. The improvement of the structure and mechanical properties of electron beam welded joints required the performance of post-weld heat treatment. The best mechanical characteristics of welded joints were obtained after a heat treatment performed in a furnace (annealing at T=900˚C for 1 hour and cooling along with the furnace) favouring the obtainment of an almost homogenous structure and the decomposition of metastable phases in the weld and HAZ.

Keywords: electron beam welding, titanium alloys, heat treatment, welded joint, structure, mechanical properties.

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The development of presently competitive devices usually requires increasing the operational characteristics of steel structures and their elements. Such requirements also refer to high-strength titanium alloys widely used as a structural material. The leading materials science centres in the USA, UE, Russia and China perform intense research on the modernisation of existing titanium alloys. The research is also focused on the possibility of developing new alloys containing significant amounts of alloying elements [1]. The commonly used structural titanium alloys are two-phase (α + β) alloys. Their principal advantage is the fact that a high level of technical and functional characteristics is obtained through the interaction of alloying agents and heat treatment. The two-phase structural alloys (α + β) are characterised by satisfactory weldability and higher strength than monophasic alloys; they are also relatively easy to forge, press and subject to heat treatment. Structures made of these alloys find applications in the aviation and aerospace industries, nuclear engineering, ship-building and chemical industry [2, 3]. Presently used two-phase titanium alloys are characterised by high unitary

Switlana G. Hryhorenko, PhD (DSc); Siergiej W. Achonin, PhD (DSc) hab. Professor; Walierij Ju. Belous, PhD (DSc) hab., Roman W. Selin – E. O. Paton Electric Welding Institute, the National Academy of Sciences of Ukraine

Table 1. Mechanical properties of 8 mm thick multi-component high-strength titanium alloy

Condition	Tensile strength R_m, MPa	Yield point R_e, MPa	Unit elongation a_5, %	Area reduction Ψ, %	Toughness KCV J/cm²
After rolling	1259.9	1179.5	1.7	6.2	5.0
After annealing at 850°C for 1 h	1214.9	1089.2	10.0	18.5	9.0
After annealing at 900°C for 1 h	1186.0	1123.6	13.3	19.0	13.5

strength. Nowadays, increasingly more attention is paid to issues concerning the making of welded structures and structural nodes using titanium alloys having ultimate strength $R_m \geq$ 1100 MPa [4].

The making of structures of high-alloy titanium alloys, including two-phase toughened alloys is performed using the electron beam welding technique (EBW). The local effect and intensity of the EBW process ensures the obtainment of deep and narrow welds as well as small heat affected zones (HAZ). However, the above-presented method is troubled by numerous disadvantages. In particular, high cooling rates during the welding process resulting in the formation of metastable phases leading to a considerable decrease in the plastic properties of the weld metal and of the zone close to the weld. An increase in plasticity is obtained through post-weld heat treatment. The primary objective of such a treatment is to modify the structure of the weld metal and that of the HAZ (by heating to specific temperature followed by cooling) thus obtaining the mechanical properties of welded joins as close to those of the base material as possible [5, 6, 7].

The purpose of the research work discussed in this article was to test the heat treatment effect on the structure and mechanical properties of electron beam welded joints made of high-alloy and high-strength two-phase titanium alloy.

Test Materials and Methods

The tests involved the use of 8 mm thick plates made of experimental titanium alloy (in the form of ingots) subjected to electron beam melting [8]. After melting, the ingots were subjected to thermal-strain treatment. The chemical composition of the test specimens (% by weight) was the following: Ti – 6.5, Al – 3.0, Mo – 2.5, V – 4, Nb – 1, Cr – 1, Fe – 2.5 and Zr. The mechanical properties of the test alloy are presented in Table 1.

The process of electron beam welding was performed in a UL-144 machine provided with an ELA 60/60 power supply. Welding parameters are presented in Table 2.

Table 2. Electron beam welding parameters used when welding the high-strength titanium alloy

Parameter	**Value**
Accelerating voltage	60 kV
Current	120 mA
Diameter of circular oscillations	2 mm
Welding rate	25 m/h

In addition to providing the vacuum shield of the entire welding area, one of the advantages of electron beam welding in relation to titanium and its alloys is the possibility of local heating and post-weld heat treatment performed in a vacuum chamber [8]. The preheating of welded joints is a sufficiently effective method preventing cold crack formation during welding. As the alloy subjected to the tests was not susceptible to cold cracking, the preheating procedure was not applied.

In order to perform the local heat treatment, after welding the joint was subjected to electron beam heating using rectangular oscillations. The heat treatment conditions were adjusted taking into consideration the beam power and the width of the zone subjected to heating.

During the local heat treatment, the electron beam power amounted to 3 kW and was corrected in order to maintain a temperature of 850°C in the zone subjected to the treatment. The heat treatment lasted 5 minutes. Figure 1 presents a scheme of electron beam scanning used when performing the local heat treatment of the specimens made of titanium alloy.

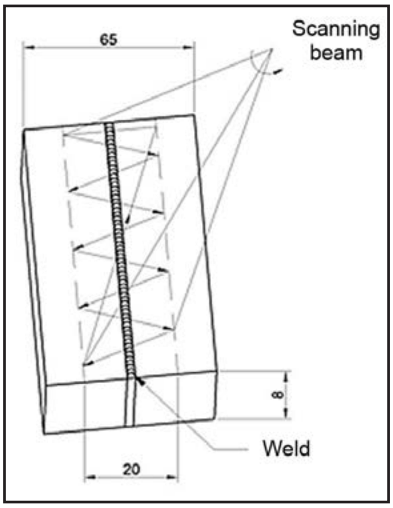

Fig. 1. Schematic scanning of the welded joint subjected to electron beam local heat treatment

The annealing of the welded joints was performed in a furnace at a temperature 900°C and lasted 1 hour.

The specimens were cut using an IsoMet machine provided with diamond discs and manufactured by the Buehler company. The chemical composition of the experimental alloys was determined using spectral and chemical methods. The metallographic tests and photographs were made using a Neophot-32 light microscope (Germany) provided with a computer, a digital camera manufactured by Olympus and an archiving system. Hardness was determined using an M-400 hardness tester manufactured by Leco (Usa) under a load of 100 g and of 1 kg. The surfaces of the fractures of the base material and welded joints were tested using a Jamp 9500F modern multifunction technically advanced microprobe with a high-emission field emission cathode (Jeol Ltd, Japan). The mechanical properties of the welded joints were determined using static tensile tests, performed in accordance with Gost 1497-84, and toughness tests.

The tests were performed using the following specimens:

– *specimen no. 1* – electron beam welded joint made of high-alloy and high-strength titanium alloy;
– *specimen no. 2* – electron beam welded joint made of high-alloy and high-strength titanium alloy subjected to post-weld local heat treatment (850°C, 5 minutes);
– *specimen no. 3* – electron beam welded joint made of high-alloy and high-strength titanium alloy subjected to post-weld local heat treatment (annealing in the furnace at T=900°C, 1 hour).

Test Results

The metallographic tests of ***specimen no. 1*** (Fig. 2) revealed that the weld metal contained solid crystallites misoriented in the centre and oriented in the heat discharge direction on the edges (with distinct dendritic structure). The microstructure of the weld metal was practically monophasic, composed primarily of phase β. Single grains and their boundaries revealed the partial decomposition of phase β with precipitates of fine particles of phase α. The hardness of the weld metal amounted to 2790÷3210 MPa; the width of the weld amounted to 3÷4 mm. In addition to the weld, the HAZ contained the structure composed of large polyhedral grains of phase β with the precipitates of fine-acicular phase α in the grain. The «weld–HAZ» boundary also contained single grains with substructure. The size of phase β grains decreased along with the decreasing distance to the base material. The hardness of the HAZ amounted to 2690-3300 MPa. The width of the HAZ amounted to approximately 2÷3 mm. The structure of the base material was composed of packets of parallel lamellas of phase ($\alpha + \beta$). The grain size amounted to 0.088÷0.125 mm. The hardness of the base material amounted to 3340÷3430 MPa.

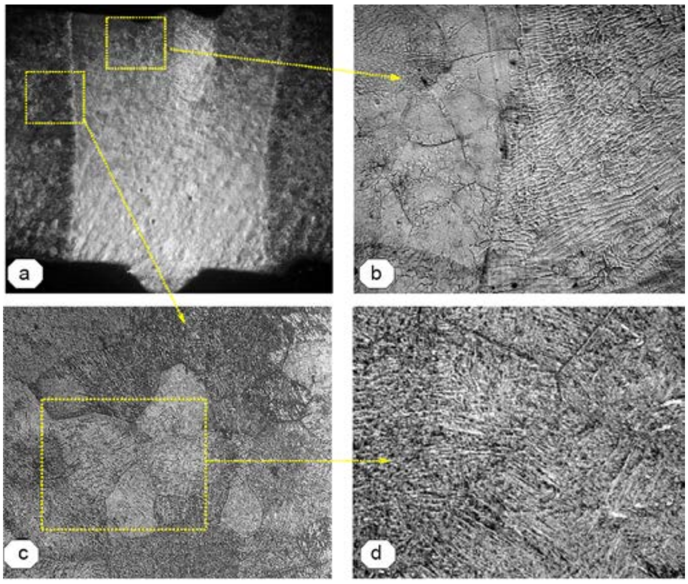

Fig. 2. Structure of the welded joint in specimen no. 1: a – main view (x10); b – microstructure of the weld and HAZ (x100); c, d – microstructure of the base material (x50 and x500 accordingly)

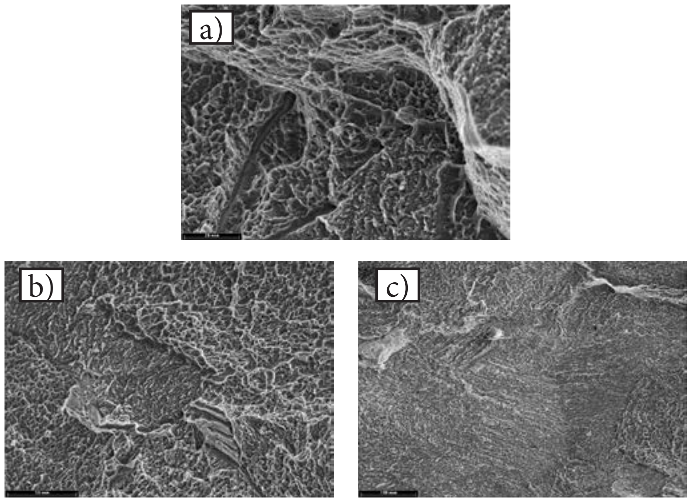

Fig. 3. Fragments of the crack surface of specimen no. 1: a – intercrystalline (x300); b – transcrystalline in combination with the dividing fracture and secondary cracks (x1000); c - pit-like dividing fracture with secondary cracks (x1000)

The fractographic tests concerning the crack surface after the mechanical tests (Fig. 3) revealed that the surface relief was poorly expressed and that the mechanism of decohesion was mixed in nature; the mechanism of brittle cracking was quasi-splitting 65% and that of ductile cracking – pit-like structure 35%.

The metallographic tests of ***specimen no. 2*** (Fig. 4) revealed that the local heat treatment increased the structural homogeneity of the welded joint. The weld and the fusion line were not revealed as distinctly as after welding. The weld was the mixture composed of elongated and nearly equiaxial grains β with misoriented precipitates of plastic phase α. The hardness of the weld metal amounted to 3220–3450 MPa. The HAZ was composed of two polyhedral grains of phase β with precipitates of dissipated phase α. The hardness of the weld metal amounted to 3220–3450 MPa.

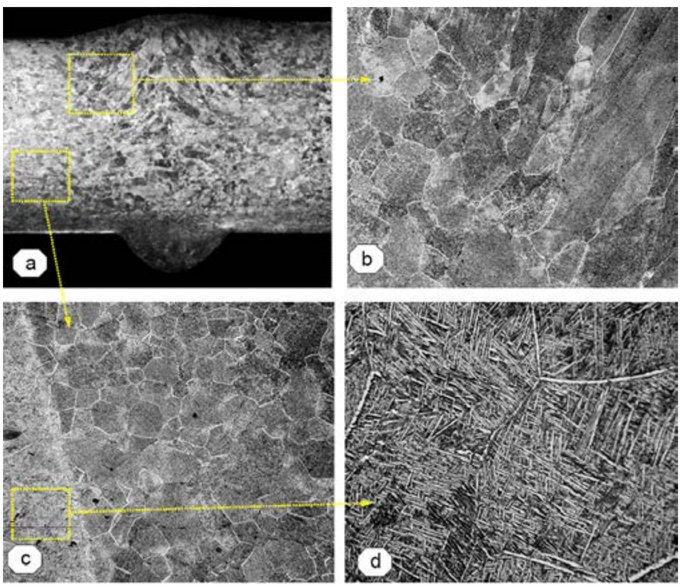

Fig. 4. Structure of the welded joint in specimen no. 2: a – main view (x10); b – microstructure of the weld and HAZ (x100); c – microstructure of the base material – HAZ (x50); d – microstructure of the base material (x500)

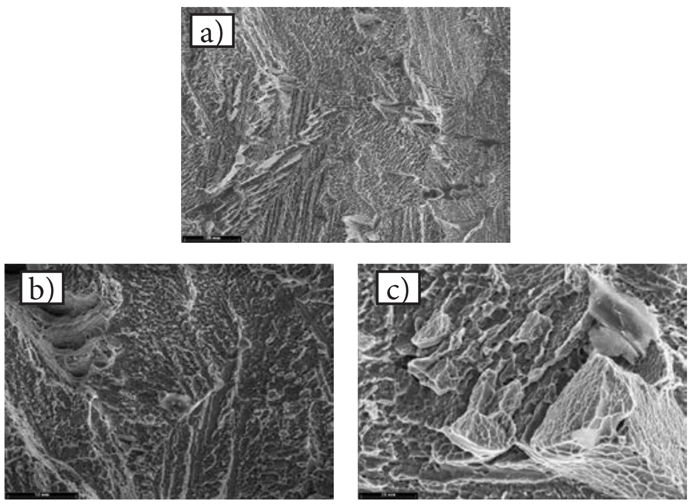

Fig. 5. Fragments of the crack surface of specimen no. 2: a – intercrystalline (x300); b – transcrystalline in combination with the dividing fracture (x500); c – pit-like dividing fracture (x1000)

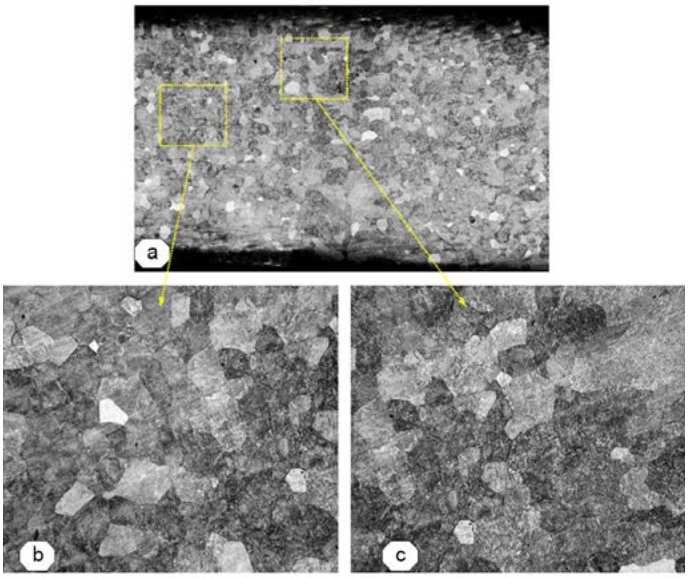

Fig. 6. Structure of the welded joint in specimen no. 3: a – main view (x10); b – microstructure of the base material – HAZ (x50); c – microstructure of the HAZ and of the weld (x50)

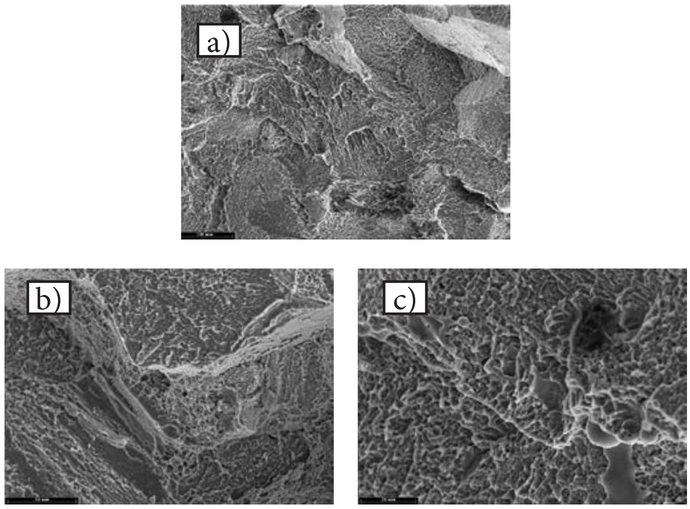

Fig. 7. Fragments of the crack surface of specimen no. 3: a – intercrystalline (x300); b – transcrystalline in combination with the dividing fracture (x500); c – pit-like dividing fracture (x1000)

The structure of the base material was composed of fine polyhedral grains with lamellar phase ($\alpha + \beta$); the hardness amounted to between 3420 and 3600 MPa.

The fractographic tests revealed that the crack surface micro-relief was complex (Fig. 5). The crack ran along boundaries dividing the matrix of phase β and dispersive acicular phase α. The crack surface contained splitting facets against the background of intercrystalline cracking segments (ruptured segments) as well as contained numerous step-like elevations.

The metallographic tests of ***specimen no. 3*** (Fig. 6) revealed that after the heat treatment performed in the furnace, the structure of the specimen became nearly homogenous, without visible boundaries between the weld, HAZ and the base material. Over the entire surface, the structure contained polyhedral variously-sized grains with variously-sized lamellas of phase α+β. Hardness (between the weld centre and the base material) amounted to 3340–3440 MPa.

The fractographic tests revealed that the cracking of the specimens was mixed in nature (Fig. 7). The fracture contained 30% of the brittle and 70% of the ductile constituent. The crack was perpendicular in relation to the applied load. Brittle cracking occurred in accordance with the transcrystalline splitting mechanism, whereas ductile cracking resulted from the joining of gas micro-cavities. The splitting facets were divided by ruptured segments. The rupture took place when the plasticity of the material was sufficiently high.

Table 3 presents the results concerning the mechanical tests of the electron beam welded joints made of high-strength titanium alloy containing several alloying components.

Table 3. Mechanical properties of the electron beam welded joints made of high-strength titanium alloy

Specimen no.	Specimen condition	Tensile strength, Rm, MPa	Yield point Re, MPa	Unit elongation, a5, %	Area reduction Ψ,%	Toughness KCV, J/cm²	
						weld	HAZ
1	EBW, after welding	1415	1380	2.0	6.6	7.2	6
2	EBW + LHT (850° - 5 min.)	1258	1216	4.3	9.2	7.3	14.4
3	EBW + HT (900° - 1 h)	1131	1089	12.0	24.5	12.4	12.7

The analysis of the results presented in Table 3 revealed that the post-weld heat treatment increased the plasticity and toughness of the welded joint made of high-alloy and high strength titanium alloy. The increase in these properties after the local heat treatment was ascribed to the initiation of the decomposition of metastable structural constituents in the weld metal and in the HAZ. However, such a short heat treatment proved insufficient for the entire decomposition of the metastable structure and the obtainment of necessary plasticity characteristics. The most effective was the heat treatment performed in the furnace (annealing at a temperature of 900°C for 1 hour) leading to the significant increase in plasticity and toughness accompanied by only a slight decrease in mechanical characteristics.

Conclusions

1. The tests involved the structure and properties of electron beam welded joints made of high-alloy high-strength titanium alloy ($\alpha + \beta$). The alloy was characterised by satisfactory weldability, yet the structure of the weld metal and that of the HAZ were heterogeneous and contained metastable phases decreasing plasticity and toughness.

2. The heat treatment of electron beam welded joints of the high-strength titanium alloy ($\alpha + \beta$) increased its structural homogeneity, decreased the likelihood of crack formation and improved mechanical characteristics.

3. The local heat treatment of the welded joints increased their toughness indicators only slightly, which could be ascribed to the incomplete decomposition of metastable structures due to the short thermal effect (heating at T=850°C for 5 minutes).

4. The most favourable combination of strength and plasticity was obtained after performing a heat treatment in the furnace (annealing at T=900°C for 1 hour and cooling along with the furnace). Such a heat treatment led to the formation of nearly homogenous structure, decomposition of metastable phases in the weld and HAZ, which, as a result, significantly increased toughness and plasticity.

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