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# STRUCTURE AND PROPERTIES OF ELECTROSLAG WELDED JOINTS OF VT6 TITANIUM ALLOY

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**ABSTRACT**

The paper presents the results of investigations of the quality of electroslag welded joints of 100 mm plates from VT6 titanium alloy. Investigations included X-ray inspection, chemical and gas analysis, optical metallography, mechanical tensile and impact toughness tests, as well as fractographic analysis. X-ray inspection and optical metallography of the welded joint showed absence of surface and inner defects in the weld metal and HAZ. Gas analysis of the weld metal demonstrated its correspondence to standard requirements to VT6 alloy. Ultimate strength of weld metal was equal on average to 90 % of base metal strength, and impact toughness (KCU) was 1.6 times higher than in the base metal. Fractures of metal of the weld and HAZ were of transcrystalline mode of a mixed type, with areas of both ductile and brittle fracture. It is shown that the welded joint mechanical properties are determined, primarily, by the size of grains and microstructure of the weld metal and HAZ, forming under the conditions of a low cooling rate and a high heat input, characteristic for electroslag welding process.

**KEYWORDS:** VT6 titanium alloy; electroslag welding; welded joint; structure; mechanical properties; fracture mode

## INTRODUCTION

Electroslag welding (ESW) is an effective method of joining thick-walled products from different metals and alloys [1–5]. One of the main advantages of ESW is high efficiency and the ability to join products of super-large thicknesses (up to 500 mm or more) in a one pass without edge preparation.

ESW is most widely used during joining of ferrous metallurgy products. However, ESW can also be effective in joining thick-walled components of titanium alloys, including high-strength ($\alpha+\beta$)-alloys [6–9]. In this case, an important task is to provide the necessary properties of welded joint.

Among the basic requirements for the quality of ESW of titanium alloys are the absence of critical surface and inner defects, the required gas composition of the weld metal and mechanical properties of the joint, which are determined by both the conditions of structure formation of weld metal as well as conditions of structure transformations in the heat-affected zone (HAZ) under the action of thermal cycle of welding.

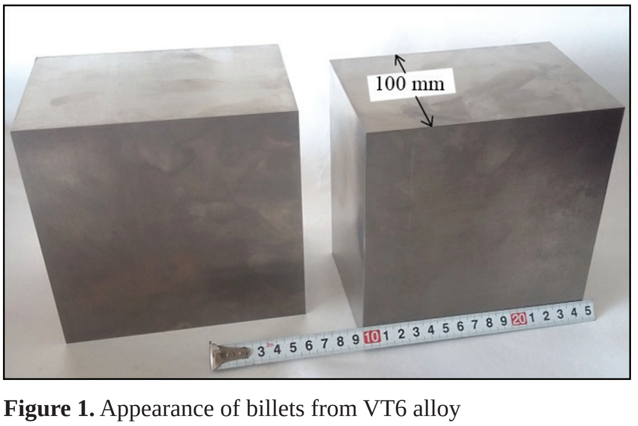


**Figure 1.** Appearance of billets from VT6 alloy



The aim of the work was to investigate the properties of the welded joint of plates of VT6 titanium alloy with a thickness of 100 mm, made by the ESW method.

## EXPERIMENTAL PART

The primary billets for welding were plates of VT6 alloy of 100×150×150 mm in the annealed state (Figure 1). ESW was carried out by a fusible nozzle of VT6 alloy with the use of welding wire of SPT2 alloy. The chemical composition of the used materials is given in Table 1.

The welded joints were subjected to X-ray inspection in the RAP 150/300 device. The transmission parameters were the following: anode voltage is 250 kV, anode current is 10 mA, exposure time is 8.5 min, distance is 500 mm and sensitivity of X-ray inspection is 1 mm.

The chemical composition of the metal was determined by the ICP-spectrometry method. The studies of mechanical properties included tensile and impact toughness (*KCU*) tests at room temperature. After the test on impact toughness, the specimens were subjected to fractographic analysis. The Brinell hardness was determined using a ball with a diameter of 10 mm at a load of 3 t. The Vickers microhardness tests were performed at a load of 100 g. Metallographic examinations were performed using the Neophot 32 microscope. To detect the structure, the specimens were etched in a solution containing $HF + HNO_3 + H_2O$ in

**Table 1.** Chemical composition of the used materials, wt.%

| Material | Ti | Al | V | Zr | Fe | Si | O | N | H |
|---|---|---|---|---|---|---|---|---|---|
| Base metal | 89.68 | 6.11 | 3.65 | 0.010 | 0.15 | 0.042 | 0.18 | 0.008 | 0.0022 |
| Consumable nozzle | 89.59 | 5.49 | 4.17 | 0.003 | 0.06 | 0.115 | 0.09 | 0.005 | 0.0029 |
| Welding wire | 90.93 | 3.99 | 3.02 | 1.550 | 0.07 | 0.083 | 0.05 | 0.018 | 0.0022 |

**Table 2.** Chemical composition of weld metal of VT6 alloy. wt.%

| Material | Ti | Al | V | Zr | Fe | Si | O | N | H |
|---|---|---|---|---|---|---|---|---|---|
| Weld metal | 90.07 | 5.32 | 3.55 | 0.54 | 0.11 | 0.022 | 0.14 | 0.009 | 0.0024 |
| Technical requirements | – | – | – | – | – | – | ≤0.2 | ≤0.05 | ≤0.015 |

equal proportions. In all cases, the studies were performed on the metal of three main zones of the welded joint: base metal (BM), HAZ and weld metal (WM).

## RESULTS OF EXPERIMENTS AND THEIR DISCUSSION

The appearance of the welded joints is shown in Figure 2. The surface of the weld is formed well, it has a silver colour without oxidized areas. Defects on the weld surface in the form of pores, lacks of fusion, undercuts and cracks were not detected. The absence of angular deformation in the welded plates should also be emphasized.

X-ray analysis showed absence of inner defects in the weld metal and HAZ.

The results of chemical analysis of the weld metal are given in Table 2. The obtained data show that the content of Al and V in the weld metal corresponds to the values of Table for VT6 alloy (5.3–6.8 % Al and 3.5–5.3 % V). In addition, the weld metal contains 0.54 % of Zr, which is associated with the presence of this element in the welding wire (Table 1).

It should be noted that the gas composition of the weld metal fully meets the requirements of the standard for the VT6 alloy (Table 2). This indicates that the developed method of ESW and the taken technological measures provide a reliable protection of the weld metal from interaction with atmospheric gases.

The macrostructure of the cross-section of the welded joint is shown in Figure 3. On the macrosection, structural zones of the welded joint are clearly visible: base metal; HAZ, where structural transformations under the effect of the welding thermal cycle occurred (areas of coarse and small grains, as well as the area of partial recrystallization); fusion line; weld metal.

The weld metal is characterized by a columnar structure with rather large crystallites, which diverge from the weld axis to the fusion line in the direction of heat removal. Such structure is typical for cast metal and is formed in the conditions of a high heat input and a relatively low cooling rate that are characteristic to ESW process.

The fusion line is blurred with a smooth transition from polyhedral equilibrium grains of HAZ metal to columnar crystallites of a weld metal (Figure 4).

In general, the macrostructure of the metal is dense, without pores, slag inclusions and other defects.

The study of the distribution of Brinell hardness showed that the highest hardness (*HB*) is in HAZ (285–295), the medium is in the base metal (277–282) and the lowest is in the weld metal (272–280) (Figure 5). Obviously, this is predetermined by a structur-

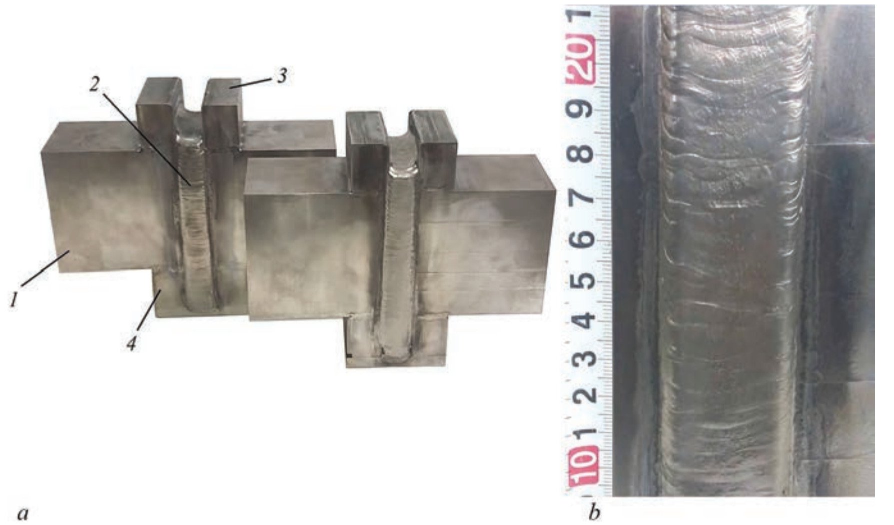


**Figure 2.** Appearance of welded joints (*a*) and weld surface (*b*): *1* — base metal; *2* — weld; *3*, *4* — technological straps


**Figure 3.** Macrostructure of welded joint (cross-section): *1* — BM; *2* — weld; 3 — HAZ

al factor and to a lesser extent by the chemical composition of the mentioned zones.

Microstructure of the welded joint zones is shown in Figure 6.

Microstructure of the base metal (Figure 6, a) was characterized by the equiaxial (α+β)-structure with the Vickers hardness of the α-phase being 3360–3540 and of the β-phase being 3300–3540 MPa. The grain size was 10–15 μm.

The microstructure of the HAZ metal (Figure 6, *b–d*) consisted of polyhedral grains of (α+β)-structure, and in some areas it had an acicular structure. The plates of the α-phase were directed in parallel to each other, and also at the angles of 60 and 90° to each other. Their Vickers hardness was 3500–3800 MPa. The hardness of an acicular structure is 3850–3900 MPa. The average grains size of the HAZ metal was significantly larger than the size of the base metal grains and was 300–640 μm.

The weld metal had a two-phase (α+β)-structure with the α-phase in the form of plates and lamellas, separated by the β-phase interlayers (Figure 6, *e*, *f*). On the boundaries of cast crystallites, precipitations of the α-phase in the form of separate intermittent areas, as well as thin solid precipitations were observed.

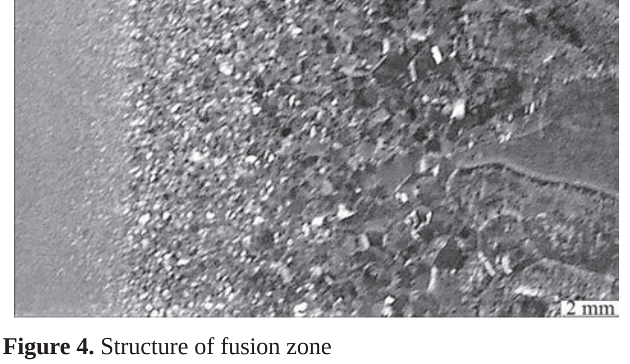


**Figure 4.** Structure of fusion zone

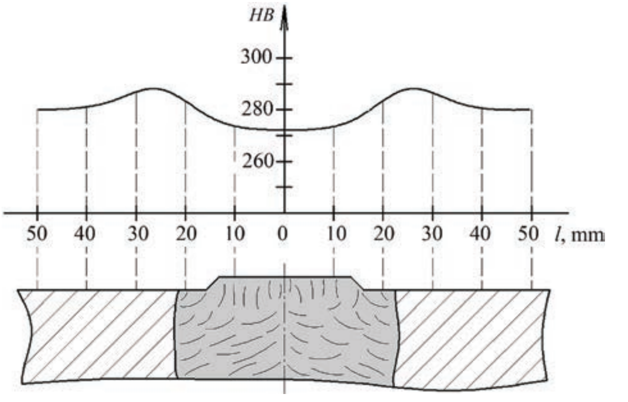


**Figure 5.** Distribution of hardness (*HB*) in the cross-section of welded joint

The width of grain boundaries ranged from 2.5 to 5.0 μm. The Vickers hardness of the α-phase was 3100–3700 MPa. It should be noted that near the fusion line, an acicular structure areas with a high hardness of up to 3900 MPa as compared to the hardness of adjacent plates at the level of 3300–3660 MPa occurred. In addition, the weld metal had areas of irregular shape that had a dispersed structure and an increased hardness of up to 4090 MPa. The size of the grains of the weld metal was the largest and amounted to 2–9 mm.

In general, except for the areas with acicular structure and clusters of the β-phase, Vickers hardness in the base metal, HAZ and weld metal was similar and ranged from 3200 to 3800 MPa.

The results of mechanical tests of the welded joint are given in Table 3 and in Figure 7.

The highest values of the yield and tensile strength were observed in the base metal, and the lowest were in the weld metal. In average, the strength of the weld metal amounted to about 90 % of the strength of the base metal. The strength of HAZ was slightly higher than in the weld metal but lower than the strength of the base metal. It can be assumed that a decrease in the strength of the weld metal is associated with a lower content of gas impurities (O, N, H) and also alloying elements (Al, V) with respect to the base metal, which contribute to an increase in titanium strength (Tables 1, 2). However, relative elongation and reduction in area of the weld metal were also lower than those in the base metal. This indicates that reducing the mechanical characteristics of the welded joint during

**Table 3.** Mechanical properties of welded joint of VT6 alloy

| Material | $\sigma_y$, MPa | $\sigma_t$, MPa | δ, % | ψ, % | *KCU*, J/cm$^2$ |
|---|---|---|---|---|---|
| BM | 929.9 | 971.4 | 16.9 | 44.1 | 38.7 |
| WM | 806.4 | 874.7 | 10.6 | 34.2 | 61.9 |
| HAZ | 817.2 | 878.0 | 9.3 | 23.4 | 55.9 |

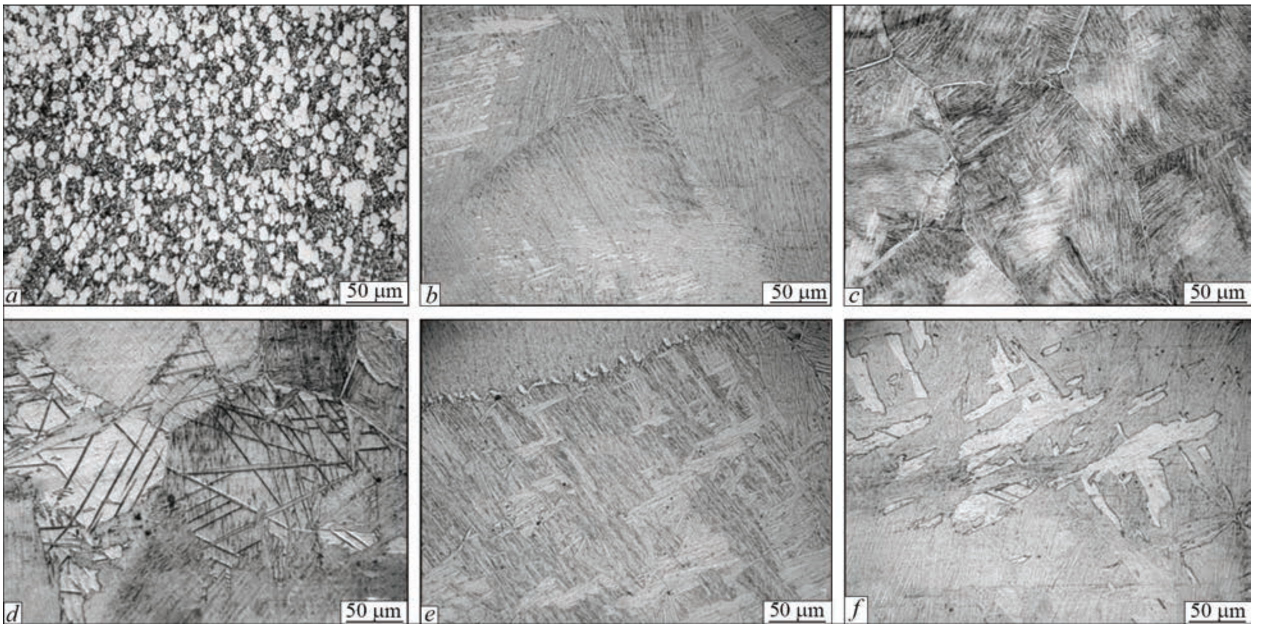


**Figure 6.** Microstructure of welded joints: *a* — base metal; *b–d* — HAZ; *e, f* — weld metal

tensile tests is mainly associated with the structural factors and the size of the weld metal grains.

Another picture was obtained during the tests on impact toughness. In this case, the weld metal had the values of impact toughness 1.6 times higher than those in the base metal. This is probably associated with the extremely large size of crystallites of the weld metal (up to 9 mm), which could cause the fact that only a few crystals crossed the plane of the notch of the specimens where the fracture occurred. In turn, this led to a transcrystalline mode of fracture and an increase in impact toughness of the weld metal. In addition, an increase in impact toughness may be associated with a low content of impurities on the boundaries of grains in the weld metal.

Thus, the mechanical properties of the welded joint, which are determined by the properties of the weld metal and HAZ, are associated primarily with the size of grains and microstructure, and secondly, with the chemical composition and content of harmful impurities. Large transverse size of grains and unfavourable acicular (α+β)-microstructure in the weld metal and HAZ most negatively affect the tensile strength and ductility (relative elongation and reduction in area) of electroslag welds.

Figure 8 shows the fractograms of the specimens after the tests on impact toughness. The inspection of the fracture surfaces at a small magnification (×100) showed the following: the fracture mode of the base metal is transcrystalline (Figure 8, *a*); the fracture surface is matt; the main crack propagates strictly perpendicularly to the applied load (mainly on the grain body); the fracture mode of the weld metal and HAZ is transcrystalline of a mixed type (Figure 8, *d*, *g*); the

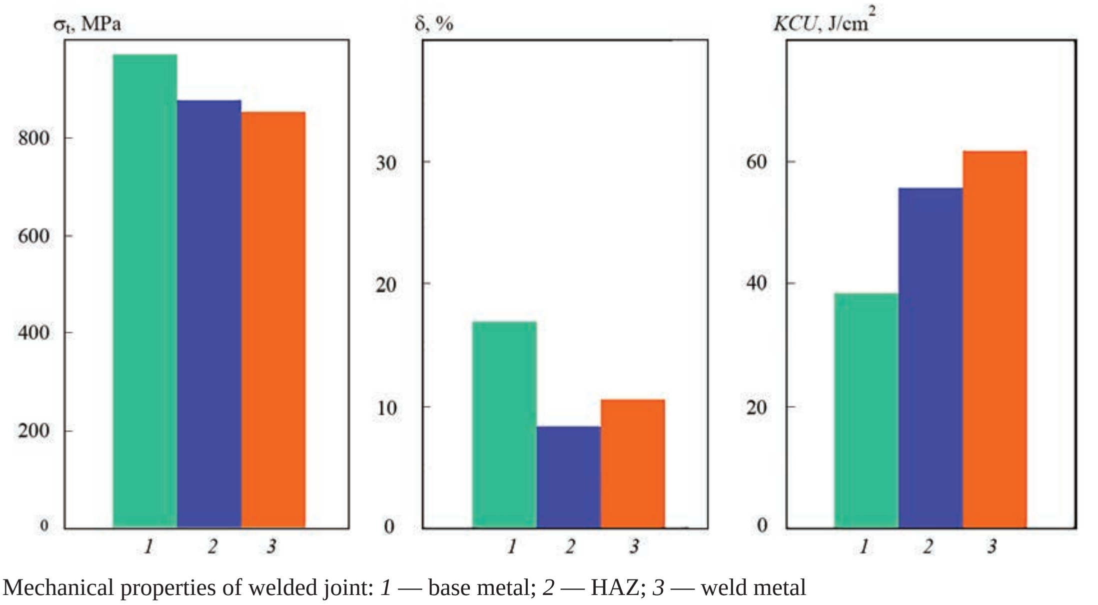


**Figure 7.** Mechanical properties of welded joint: *1* — base metal; *2* — HAZ; *3* — weld metal

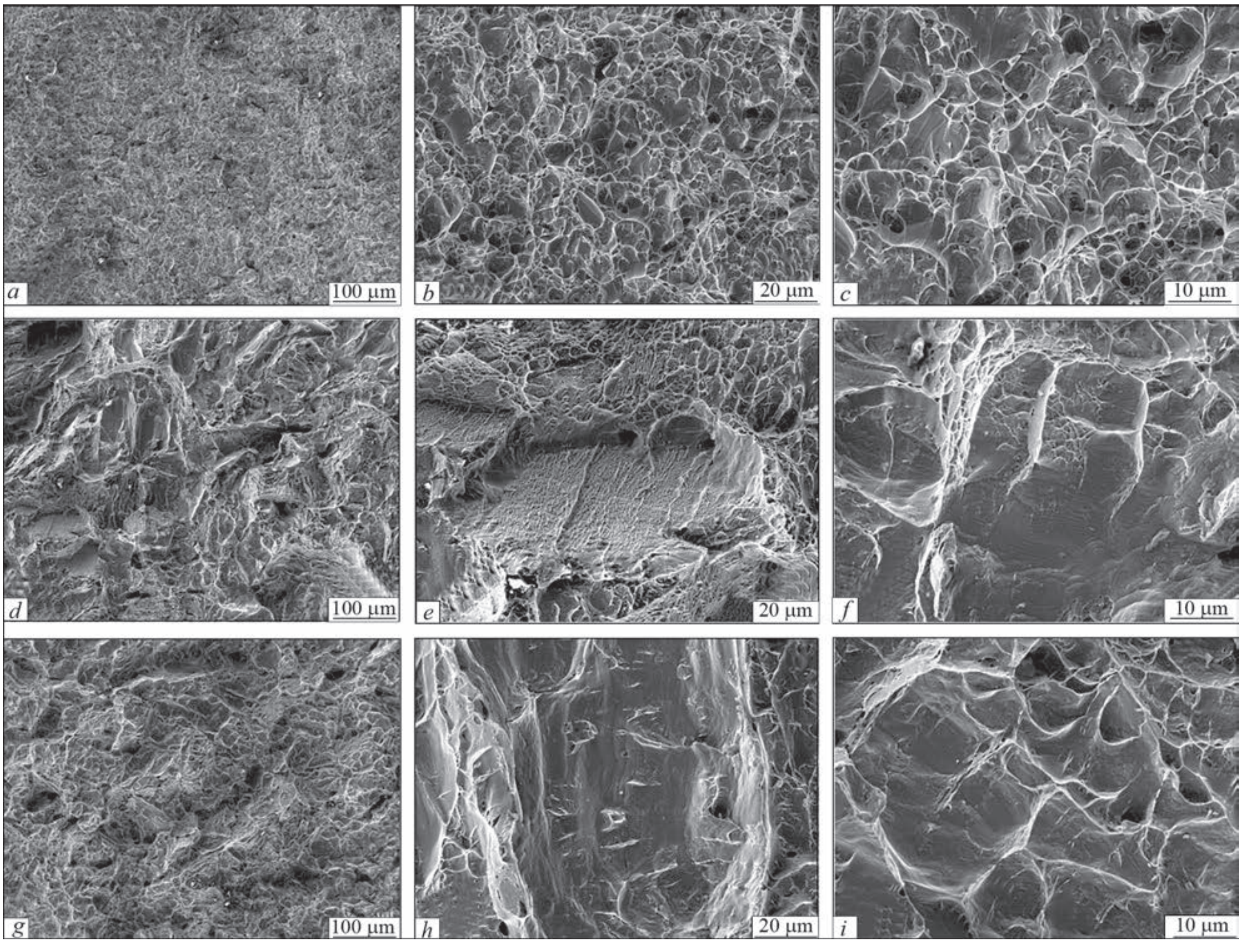


**Figure 8.** Fractograms of specimens after tests on impact toughness: *a–c* — base metal; *d–f* — HAZ; *g–h* — weld metal

surfaces of fractures are matt and shining, but more matt component is observed; the main crack changes its direction in the process of propagation.

The further studies were performed at increased magnifications. It was found that the fracture mode of the base metal is transcrystalline, ductile, with a pit surface (Figure 8, *b*, *c*). The weld metal and HAZ are characterized by transcrystalline fracture of a mixed type with the areas of both ductile (pit) as well as brittle (spalling facets, quasi-spalling) fractures (Figure 8, *e–h*). But it should be noted that as compared to HAZ, the surface of the fracture of the weld metal had pits and facets of a larger size, which indicates a significant growth of grains in this area.

In general, it can be suggested that branching of cracks in the weld metal and in HAZ contributed to the fact that their propagation requires more energy, as a result of which the impact toughness increased as compared to the base metal, where the fracture occurred without branching.

## CONCLUSIONS

1. ESW of plates of titanium VT6 alloy of 100 mm thickness was performed.

2. X-ray analysis and optical metallography showed absence of pores, cracks, slag inclusions, lacks of fusion and other inner defects of the welded joint on macro- and microlevels.

3. The gas composition of the weld metal meets the technical requirements for VT6 alloy, which indicates a reliable protection of the welding pool metal from interaction with atmospheric gases.

4. The tensile strength of the weld metal is about 90 % of the strength of the base metal, but the impact toughness of the weld metal is 1.6 times higher than the impact toughness of the base metal.

5. The fracture mode of the weld metal and HAZ is transcristalline of a mixed type with the presence of both brittle as well as ductile areas on the fracture surface. The fracture surface of the weld metal is characterized by the most considerable relief that indicates a significant growth of grains in the area.

6. The mechanical properties of the welded joint, first of all, are associated with the size of the grains and microstructure of the weld metal and HAZ, which are formed in the conditions of low cooling rate and high heat input, which is characteristic of ESW.

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## CONFLICT OF INTEREST

The Authors declare no conflict of interest

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