Research of Ti-6Al-4V titanium alloy welded joints made by electron beam welding, designed for operation in cryogenic conditions

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Abstract. The article is based on realization of metallographic research in order to prove quality and following application of welded joint with the changed construction of coupling edges for details made of titanium alloy Ti-6Al-4V. The welded joint has been gained by electron beam welding. The expertise of macro- and microstructures has been realized, the hardness has been changed and testing of mechanical qualities under room and reduced temperature has been realized. The conclusion of possibility of application electron beam welding for welded joints of titanium spherical tanks is based on the research.

1. Introduction
Various titanium alloys are widely used in rocket and space and aviation equipment, working under elevated loads and cryogenic temperatures. This is due to their high specific strength, ability to withstand loads at low temperatures, corrosion resistance.

There is a list of restrictions that must be followed while using titanium alloys vessels, operating under pressure. This is the necessity of using only butt welded joints, to eliminate stress concentrators, the absence of a gas-saturated layer on the surface of parts, providing a "smooth" change in hardness from the base metal to the weld metal.

The aim of the work is to confirm the possibility of applying electron beam welding of titanium spherical balloons (figure 1) with the change of construction of welded edges, working at low temperatures.

Figure 1. Appearance of TSB, welded from hemispheres EBW, ~x0,2
In contrast to the traditional way of making a butt joint, there are two elements that are made while preparing butting edges for welding. First of all, outside the edge there is a landmark made in the form of a chamfer with a depth of 1.0 ÷ 1.5 mm with an angle of 10° to 12° for visual guidance of the electron beam into the welded joint. Secondly, inside of each detail there is a ledge with a height and width of 0.1–0.2 mm and 0.04–0.08 mm (respectively) from the joint thickness [1] (figure 2).

Welding is performed on the ELU-8 installation in the lower position with through penetration. No filler materials were used. After welding, heat treatment of joint was made in vacuum (annealing [2]).

For metallographic researches, two types of welded joints were made: a classic butt joint and a joint with a change in the geometry of the edges.

2. Research methodology
The research included: examination of macro- and microstructures. The microstructure included the research for the presence / absence of a gas-saturated (alpha) layer, measurement of the hardness of the main material and the material of the welded joint, identification of metallurgical defects in the welded joint.

2.1. Macrostructure Research Methodology
The macrostructure research in the cross section of the welded joint was carried out visually without using magnifying devices. Sections of the cross section were made for this process, they were brought to a surface cleanliness of $Ra_{0.8-0.4}$ on the “Neris”machine according to the requirements of GOST 2789-73. The macrosections were etched by immersion for 3-5 min in a reagent. After etching macrosections are washed with flowing warm water and dried with filter paper. The macrostructure allows detection of lack of penetration, the presence of slag inclusions, root defects, understatement of the weld, cracks, fusion, etc., evaluation of the size and shape of a macrograin, and also identification of the zone of thermal influence (by structural changes).

2.2. Microstructure Research Methodology
The microstructure was studied using an Altami MET 1C inverted microscope at magnifications of 50–1000x in reflected light. The microstructure was studied using an Altami MET 1C inverted microscope at magnifications of 50–1000x in reflected light. Pre-made microsections (up to $Ra_{0.025}$
surface cleanliness) are examined under a microscope to detect defects (lack of fusion or non-fusion, microcracks, the presence of microporosity and other defects), then, to reveal the microstructure, they are etched for 5-10 seconds with a reagent. Etching reveals the presence of an alpha layer from the surface, visible by structural changes (the presence of the α phase), the type of microstructure. The presence of a gas-saturated layer, if any, that does not differ in microstructure (but at the same time oxygen is already in the alloy solution), was determined by the values of hardness (microhardness, according to the Vickers method). The gas-saturated layer is determined by measuring the microhardness (according to Vickers) from the surface of the weld and the heat-affected zone (heat affected zone) and differing in its overestimated values in comparison with the core of the metal / metal of the weld.

2.3. Hardness measurement.
The hardness and the change in its values from the base material to the welded joint material was measured using a DuraScan 50 G5 hardness gage according to the Vickers method at a load of 50 g (HV_{0.05} – recommended load) on untrained microsections. The hardness was measured in the direction from the base material to the welded joint, including hardness in the weld, as well as along the cross section of the weld in the direction from the root of the weld to its reinforcement.

3. Results and discussion

3.1. Macrostructure
The macrostructure of the samples cut for the study showed that there are some defects such as lack of penetration, undercutting of the base material, and deep penetration (examples in figures 3, 4, 5). They appeared while testing the technology of the weld and using the classical method (edge seam, but using feeding collars). Figures 3 and 4 show that the feed collars, without being melted, do not provide the necessary reinforcement of the weld. In Figure 5, the presence of gas pores was detected in the weld reinforcement zone when studying the macrostructure.
It should be noted that the fusion zone, in general, is satisfactory, with a smooth transition of the structure from the weld to the base material (welded). The macrograin of welded joints is large, had a dendritic shape with a length of ~ 1-4 mm, in the fusion zone - a grain has polyhedral shape and becomes smaller in the heat-affected zone (near-weld zone) upon transition to the structure of the base material.

Applying the modified design for the welded joint, we obtained a satisfactory (by the type of macrostructure) welded joint without metallurgical defects (Figure 6).

The macrostructure of the welded joint with structural changes in the butt joint has a grain of both polyhedral and columnar shape with a size of ~ 2 mm and a length of 2-3 mm, the structure in the fusion zone has a smooth transition to the zone of thermal influence, then to the base metal of the part. At the root of the weld, the grain is finer than in its middle part and in the reinforcement zone.

The heat-affected zone after EBW in Ti-6Al-4V titanium alloy parts is ~ from 2mm to 4mm.

3.2 Microstructure, hardness, gas-saturated layer and mechanical properties

3.2.1. Microstructure type. The microstructure of the Ti-6Al-4V titanium alloy is considered to be an intermediate one between the structures of α- and β-alloys in composition and transformations, therefore it is considered to be two-phase (contains α + β-phases).

The microstructure of the main material of the part (in the procurement stage) which has previously undergone the “stamping” operation, is controlled for the type of microstructure and the presence of a gas-saturated layer according to the requirements of OST before welding. The microstructure of the base material corresponds to type 2–3 according to the scale of microstructures of IS alloys (Figure 7), which meets the requirements of IS.

![Figure 7. Microstructure of the main material (away from the weld and the heat affected zone), x500](image)

![Figure 8. The microstructure of the welded joint: a - with the interface of large grains; b - (α + β) -phase in the grain field, x500; c - (α + β) phase, x1000](image)
For welded joints, this standard does not apply. The microstructure of the welded joint was investigated based on the transformation diagrams of the titanium-aluminum-vanadium (Ti-Al-V) system at various temperatures. Researches have shown that the microstructure of the welded joint is coarse-grained, which is the $(\alpha + \beta)$-phase of multidirectional needle orientation, delimited by the $\alpha$-phase (Figure 8). In the heat affected zone, there is a decrease in grain, which also consists of $(\alpha + \beta)$ phases (where the $\beta$ phase is represented by martensite [3] after transformations during annealing), limited by the $\alpha$ phase (Figure 9).

![Figure 9. The microstructure of the heat affected zone, x500](image)

Different sources discuss the theory of reducing the required parameters of mechanical properties in the presence of large grains, namely, the loss of plasticity, which leads to cold brittleness in cryogenic conditions. But there are works [4] that, for annealing in titanium alloys in the regions of $\alpha + \beta$ transformations, no unique relationship between grain size and toughness of titanium was found. On the contrary, impact toughness values during the -196°C tests increase.

3.2.2. Hardness. The hardness (microhardness), measured by the Vickers method, was determined in the cross-sectional slice in the fractional direction: the main material – the heat-affected zone – the welded joint - the heat-affected zone – the main material. The microanalysis of the location of the prints after the measurement showed that the values of hardness (microhardness) vary within the measurement errors, there are no sharp changes (gradients), therefore, the hardness in the zones of the weld and heat-affected zones is within the hardness of the base material (the values are shown in Figure 10).

It should be considered that the hardness of the base material does not have a strictly uniform value. The variation in the values is associated with the entry of the imprint of the identifier (diamond pyramid of the hardness tester) into different structural components ($\alpha$ or $\beta$).

![Figure 10. The distribution of hardness (microhardness, average values) according to Vickers in different zones of the welded joint: under the values, in brackets are the errors for measurements of this method](image)
3.2.3. Gas saturated layer. Since the base of the Ti-6Al-4V alloy contains a metal that is chemically active in nature (titanium - Ti), which actively interacts with air, especially at elevated temperatures, the use of a vacuum medium in an EBW and subsequent annealing in a vacuum furnace is mandatory.

The presence of a gas-saturated layer is detected by the overestimated values of hardness (microhardness) from the surface. For the depth of the gas-saturated layer, consider the value equal to the distance of the nearest print with microhardness corresponding to the microhardness of the core. In our case, hardness (microhardness) was measured in the zones of the weld from the surfaces of the root of the weld and the reinforcement zone. The hardness was checked also from the surface of the heat-affected zone: from the root of the weld (considered the inner surface of the part) and from the reinforcement (outer side of the part).

The microresearch found that the microstructure from the surfaces of the weld in the reinforcement zone, on the root side, in the heat affected zones has a structural (α + β) -phase composition, no alpha layer consisting of the α phase (non-etching layer) was found (Figure 11).

![Figure 11](image)

Figure 11. Microstructure from the surface: a - zone of reinforcement of the weld; b - the root of the welded joint; c - heat affected zone; x500

By measuring microhardness (hardness in Vickers units, HV₀₀₅) it was confirmed that the obtained values of HV₀₀₅ are within the measurement errors (the first value is at a distance of 15-20 μm from the surface, the following ones are the distance of at least 3 diagonals of the fingerprint of the identifier to 50 μm (according to the manual for the device), given in table 1). So, there is no gas-saturated layer.

3.2.4. Mechanical properties. The test results of the controlled parameters of the mechanical properties for welded joints of Ti-6Al-4V material are satisfactory, meet the requirements of the design documentation for titanium balloons and are shown in table 2.

| №            | Hardness, HV₀₀₅       |
|--------------|----------------------|
|              | 1         | 2         | 3         | 4         | 5         |
| Welded joint reinforcement | 307 (±31) | 325 (±33) | 303 (±30) | 293 (±29) | 319 (±32) |
| Welded joint root            | 272 (±27) | 296 (±30) | 304 (±30) | 307 (±31) | 285 (±29) |
| Heat affected zone*        | 323 (±32) | 309 (±31) | 343 (±34) | 337 (±34) | 289 (±29) |

*a the values of the heat affected zone are given on average from different zones
Table 2. Mechanical properties

| Parameters                                     | +20°C | -196°C |
|------------------------------------------------|-------|--------|
| Strenght, $\sigma_b$, kgf/sm²                 |       |        |
| Bending angle, $\alpha$, degree               |       |        |
| Impact strenght, $KCU$, kgsm/sm²              |       |        |
| Strenght limit, $\sigma_b$, kgf/sm²           |       |        |
| Striking viscosity, $KCU$, kgsm/sm²           |       |        |
| Fact                                          | 95    | 6,5    |
| Requirements                                  | ≥77   | ≥3,7   |
| DD                                            | ≥90   | ≥115   |
|                                               | ≥2,5  |        |

4. Conclusion
The researches help to establish that:
- using a change in the shape of the section of edges in front of the EBW, we obtained a welded joint without defects such as lack of penetration, undercuts;
- the macrostructure is dense, the formation of porosity is not detected;
- the microstructure of the weld consists of differently oriented ($\alpha + \beta$) phases in the form of martensite, but, on the whole, the grain limited by the $\alpha$ phase is large, which is typical for titanium alloys annealed;
- when measuring hardness (microhardness) from the base material to the welded joint with a step of ~ 30 μm, sharp changes in values are not observed;
- a gas-saturated layer in the cross section from the surface of the welded joint, including in the zones of thermal influence, was not detected;
- the parameters of the mechanical properties of welded joints, tested at room temperature (20 °C), as well as at low (-196 °C), meet with the requirements of the design documentation.

The manufactured titanium spherical balloon using the modified design of the welded edges of the equatorial joint passed tests at positive and negative temperatures successfully. The changed design of the welded edges for EBW has been introduced into the mass production of titanium spherical balloons of different capacities at our factory.

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