Electron Beam Welding, Heat Treatment and Hardening of Beta-Titanium

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Abstract. Analysis of the electron beam welding and different modes of heat treatment such as local heat treatment, furnace annealing, slow speed cooling, water quenching and aging impact on the structure and properties of pseudo-\(\beta\) titanium alloy VT19 welded joints. Microstructure of obtained welded joints in the states after welding and heat treatment were investigated. Using welded joints microsections approximate amount of \(\beta\)-phase has been obtained. Mechanical properties of the welded joints were analyzed and dependency of tensile strength and amount of \(\beta\)-phase were built.

1. Introduction

Pseudo-\(\beta\) titanium alloys are very important commercial materials to a lot of industries, specifically to aircraft construction and rocket science. One of the main advantages of modern pseudo-\(\beta\) titanium alloys are theirs high manufacturability in comparison to alloys with pseudo-\(\alpha\) and (\(\alpha+\beta\))-structure and high strength properties. These advantages of pseudo-\(\beta\) titanium alloys, that has highlyalloyed VT19 alloy as distinctive representative, make this class of titanium alloys very promising for use in new equipment and modernization of existing [1]. Landing gear design of Boeing 777 uses pseudo-\(\beta\) alloy Ti-10V-2Fe-3Al [2]. Its application allows to reduce weight in comparison with high strength low alloy steels, such as 4340 or 300M. One of the latest successful developments was modern commercial pseudo-\(\beta\) alloy Ti-5Al-5Mo-5V-3Cr or Ti-5553, which found its application in constructions of aircrafts and landing gear of Boeing 787 [3]. Pseudo-\(\beta\) titanium alloys constructions strength, including VT19, determined by strength of welded joints. It also can operate in at higher temperatures, than some of high-strength steels [4]. Welds, obtained by electron beam welding, in comparison with TIG-welding or hybrid TIG+CO\(_2\)+Laser welding [5, 6], possesses deeper and much more narrow seams, reduced heat affected zone. Another advantage of EBW is possibility of combining such technological operations, such as welding and heat treatment, which allows to ensure high quality of obtained welds. Therefore, developing technology of electron beam welding and post-welding heat treatment of obtained welds, that allows to ensure phase composition and strength level at 0.9...0.95 of base metal strength, is the main and very important task.

2. The purpose and objectives of the study

Main aims of this work are to determine influence of local heat treatment, furnace annealing and hardening heat treatment regimes on properties of pseudo-\(\beta\)-alloy VT19 welded joints, obtained by electron beam welding. With this purpose research were conducted to determine influence of welding thermal cycle and post-welding heat treatments on structure and properties of welding joints of this alloy.

3. Research methods and materials

Welding of pseudo-\(\beta\) titanium alloy VT19 samples with size 200x100x8 mm was made on this regime: \(U=60\text{kW}, I=120\text{mA}, V=7\text{mm/s}\) [7].

Local heat treatment, as electron beam welding itself, in comparison with TIG-welding, performed in vacuum chamber [8]. Scheme of local heat treatment given in work [9]. Width of local heat treatment zone is 20 mm. Power of electron beam in LHT process is near 3 kW and was adjusted to maintain temperature in the treatment area on level of 750°C.

Furnace annealing of welded joints performed on regime that presumes heating up to 750°C and exposure for 1 hour.

Modes of hardening heat treatment are shown in Table 1.
Table 1. Modes of hardening heat treatment of VT19 welded joints

| Mode # | Heat treatment | Note |
|--------|----------------|------|
| 1      | Heating to 760°C, slow cooling with speed of 1 °C/s | Heating and cooling performed in vacuum furnace |
| 2      | Furnace annealing on mode: heating to 750°C and exposing for 1 hour; cooling to 680°C, exposing for 1 hour, cooling to 380°C, exposing for 8 hour, cooling on air; aging at 450°C, exposing for 4 hours, cooling on air | Heating in furnace without protective atmosphere |
| 3      | Heating to 760°C, exposure for 1 hour, quenching in water, aging at 450°C for 4 hours | Heating in furnace without protective atmosphere |

In all samples, obtained by EBW, as per X-ray examination and structural analysis, such defects as pores, lack of penetration, cracks, non-metallic inclusions are absent.

Structural research were made with the optical microscope “NEOFOT-30”, equipped with a digital photography console. Quantification of β-phase in welded joints were conducted via experiments using microsections. For this, the ratio of light and dark areas of the structure, corresponding to β-phase and α-phase respectively, was estimated on the scanned microsections.

Mechanical properties of base metal and welded joints are given in Table 2.

4. Results

4.1. VT19 base metal

The base metal of the VT19 alloy contains equiaxial polyhedral grains with dispersed precipitates of the α-phase, uniformly distributed throughout the grain body (Figure 1, a). The size of α-particle is 1...2 microns and less. The amount of β-phase in base metal in the state after rolling is 44%.

The conducted studies of the joints structure in the state after welding led to the conclusion, that in the weld metal and the HAZ, obtained with a welding speed of 7 mm/s, the structure is non-equilibrium and requires the use of heat treatment to obtain a uniform structure. Large, equiaxed polyhedral β-grains predominate in this welded joint. The weld metal consists of practically pure β-phase (see Figure 1, b) with hair-like borders, the amount of β phase is 99%. The strength of welded joints made by EBW in the state after welding is at the level of 91% (Table 2).

4.2. Local heat treatment

In the weld metal made by EBW using LHT (Local Heat Treatment) at 750°C for 10 min, the amount of dispersed excretions of the metastable α’-phase increases (Figure 2, a). The amount of β-phase as a result of the application of preheating has decreased to 53%. The strength of welded joints is at 99% of the strength of the alloy itself.

Thus, the use of local heat treatment makes the structure more uniform across the entire width of the welded joint in comparison with the structure of the samples without using LHT, which allows to ensure uniform strength of the welded joint and mechanical properties at 99% of the strength of the alloy in the condition after rolling. A further increase in the strength of welded joints is limited by the strength of the base metal.

Figure 1. Microstructure of VT19 welded joint, obtained by EBW in the state after welding:

a – base metal, x20; b – seam metal, x20;
4.3. Furnace annealing

Studies of welded joints subjected to furnace annealing at 750°C showed that in this case the weld metal consists of primary β-grains that are elongated in the direction of heat removal and have uniform, two-phase structure (Figure 2, b), consisting of α- and β-phase particles. The α-phase particles have a lamellar morphology, the length of the α-plates is 1...5 μm, with a thickness of 0.5...0.8 μm. The amount of β-phase as a result of furnace annealing is minimal for welded joints and is at 35%. The strength of welded joints in this case is maximum at 105...107% of the alloy strength in the state after rolling. It should be noted that VT19 alloy allows the use of heat treatments at lower temperatures compared to high-strength two-phase titanium alloys, such as VT23, T110 or T120 [10]. Therefore, the annealing temperature is 750°C, which is lower than the LHT temperature of 850°C or the temperature of the recommended vacuum annealing of 900°C for alloy T120.

Figure 2. Microstructure of VT19 welded joint, obtained by EBW: a – after local heat treatment at 750°C, 10 minutes, x20; b – after furnace annealing at 750°C for 1 hour, x20

4.4. Regulated Step Annealing

The weld metal and HAZ consists of elongated in the direction of the heat sink and equiaxed grains located along the axis of the weld (Figure 3).

It should be noted that the dendritic structure of the electron-beam weld after heat treatment almost did not appear, apparently because cooling of the weld metal of a small volume occurred so quickly that diffusion processes did not find such development as, for example, during TIG-welding. The size α of plates in the weld metal made by EBW is 1...6 μm with a thickness of up to 1 μm. The amount of β-phase in the weld metal was 43%.

Figure 3. Microstructure of VT19 welded joint, obtained by EBW after regulated step annealing

4.5. Slow cooling with regulated speed

The microstructure of the weld metal of this welded joint is shown in Figure 4. In the upper part of the weld, made by EBW, crystallite accretion occurs along the weld axis, equiaxial or elongated grains grow in the middle and root parts along the axis. Heat treatment in the weld metal causes the decomposition of the β-phase with the release of α- and β-particles of different sizes. Along with finely dispersed decay products with a size
of less than 1 µm, on the background of the β-matrix there are α-plates 2…5 µm long and less than 1 µm thick, that predominate in the structure.

In the HAZ there are dispersed particles with a size of about 1 µm or less, as well as lamellar α-particles 2…4 µm long and 1…1.5 µm thick with the β-matrix in background. The amount of β-phase in the weld metal after this heat treatment mode was 41%.

![Figure 4](image1.png)

**Figure 4.** Microstructure of VT19 welded joint, obtained by EBW after slow cooling with regulated speed

4.6. **Hardening and aging**

Studies of the microstructure of welded joints with hardening heat treatment - quenching and subsequent aging showed that the intragranular structure of the weld metal is finely dispersed, the size of decomposition products most often does not exceed 1 µm (Figure 5). In individual grains of the weld metal, a substructure is observed.

The HAZ metal consists of equiaxed polyhedral grains. In the HAZ, fine-dispersed decomposition products are also formed, mainly with the size of 1…1.5 µm and less, in some grains individual particles reach 2…3 µm. The fine structure in all zones of the welded joint should provide it with high strength. The amount of β-phase in the weld metal was 32%.

![Figure 5](image2.png)

**Figure 5.** Microstructure of VT19 welded joint, obtained by EBW after water quenching and hardening

5. **Discussion**

The use of local heat treatment to a welded joint obtained by EBW reduces the amount of metastable β-phase in the weld metal and HAZ, which allows obtaining equal strength welded joints of titanium pseudo-β-alloy VT19. At the same time, in order to obtain a uniform structure in all zones of the welded joint, it is possible to use furnace annealing at 750°C for 1 hour.

Step annealing leads to the formation of larger elements in weld metal and HAZ, so that the size of the α-plates in the weld metal is 1…6 µm with a thickness of up to 1 µm. In the HAZ the α-phases inside the grain have a length of 1…4 µm 1.5 microns. The amount of β-phase in the weld metal after step annealing is 43%, and slow cooling reduces the volume of β-phase in the weld metal to 41%. The smallest amount of β-phase obtained after quenching and aging is at 32%. It is due to the decomposition during aging of quenching structures formed during the quenching process. In the process of aging, the final decay products are the dispersed α- and β-phases in close to the equilibrium state, the formation of which causes dispersion hardening of the alloy [11, 12].
The study of the mechanical properties of titanium pseudo-β VT19 alloy welded joints made by EBW in mode No. 1, which were subjected to such types of thermal hardening as quenching in water and aging, regulated step annealing, slow cooling at a regulated rate of 1°C/s, showed that the highest strength values are welds subjected to quenching in water followed by aging and are at 1.285 MPa (Table 2).

Studies have led to the conclusion that because of quenching and subsequent aging, the finest intragranular structure of the weld metal in which the size of the decomposition products most often does not exceed 1 µm is formed. In the HAZ size is 1...1.5 µm. The fine structure in all zones of the welded joint of the VT19 alloy provides it with high strength reaching $\sigma_B = 1285$ MPa, with high impact toughness $KCV = 23$ J/cm$^2$. It should be noted that for welded joints of titanium pseudo-β alloy VT19 effective hardening heat treatment is quenching in water with subsequent aging, which ensures the strength of joints at 130% of strength level of the alloy in the rolled state.

Table 2. Mechanical properties of pseudo-β-titanium alloy VT19 base metal and welded joints, obtained by EBW in the state after heat treatments

| Mode # | Sample type, Type of heat treatment | Tensile strength $\sigma_B$, MPa | Yield strength $\sigma_{0.2}$, MPa | Elongation $\delta_s$, % | Reduction of area $\Psi$, % | Impact toughness $KCV$, 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, LHT 750°C - 10 minutes. | 937                             | 868                              | 5.3                    | 19                        | 20                          |
| 4      | Welded joint, Annealing at 750°C - 1 hour | 1026.7                         | 985.7                            | 12.0                   | 31.5                      | 26                          |
| 5      | Welded joint, Regulated step annealing 750°C, 680°C, 380°C, aging 450°C | 1047                             | 985                              | 6.0                    | 25.4                      | 28                          |
| 6      | Welded joint, Slow cooling with 1°C/s speed | 1068                             | 1012                             | 11.3                   | 36                        | 22.5                        |
| 7      | Welded joint, Water quenching and aging at 450°C | 1285                             | 1234                             | 4.7                    | 20.6                      | 23                          |

Figure 6. Dependency of welded joints strength on β-phase quantity in weld metal of titanium alloy VT19

$\sigma_B = 1235 - 3.8(\beta)$
Studies of the microstructure and it comparison with mechanical properties of the joints, allowed us to establish an inversely proportional dependence of the titanium pseudo β-VT19 alloy welded joints strength on the amount of β-phase in the weld metal (see Figure 6) in the form $\sigma = 1235 - 3.8 (\beta, \%)$, according to which the minimum strength values $\sigma = 881$ MPa of welded joints are fixed at the β-phase content of 99%, and the maximum $\sigma = 1285$ MPa at the β-phase content of 32%.

6. Discussion
EBW in combination with local heat treatment allows to adjust the ratio between α- and β-phases in the weld metal and reducing the β-phase content in the weld metal of the VT19 alloy from 91% to 53%, as well as increasing the strength of the welded joints from 876 MPa to 937 MPa and as a result ensuring equal strength of welded joints to the base metal. To form a homogeneous structure, increase the strength of the base metal and welded joints to the level of 1020 MPa, complete decomposition of the metastable phases in VT19 alloy welding joints, it is necessary to subject them to furnace annealing at 750°C for 1 hour, as a result of which the strength level of the joints increases to 105...107 % compared to the strength of the alloy after rolling. As a result of heat treatment of hardening and subsequent aging, in welded joints of VT19 alloy, made by EBW, the amount of β-phase in the weld metal decreases from 99% in the state after welding to 48% in the state after hardening heat treatment. The smallest intragranular structure of the weld metal formed in the seam. This structure provides the welded joint with high strength, which is 1285 MPa.

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