Microstructure and properties of permanent joints of ultrafine-grained titanium alloys produced by linear friction welding

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Abstract. This paper presents the results of a study of the microstructure and mechanical properties of welded joints obtained by linear friction welding of samples from heat-resistant titanium alloys VT8M-1 (Ti-5.4Al-1Sn-12Zr-4Mo-0.15Si) and VT25U (Ti-6.5Al-1.8Sn-4Zr-4Mo-1W-0.2Si). In the VT8M-1 alloy, an ultrafine-grained (UFG) structure was formed prior to welding. The features of the phase and structural transformations in the areas of contact and thermomechanical effect of welding were shown, as well as the microhardness distribution across the width of the welded joints. The obtained values of strength characteristics of a welded joint during short-term and long-term tests at 400 °C indicate their correspondence to the level of the monolithic VT8M-1 alloy with a UFG structure.

1. Introduction

Titanium alloys are widely applied as structural materials in aircraft building owing to their small specific weight and corrosion resistance [1]. In particular, the wheel blades of gas-turbine engines (GTEs) operate in complex operating conditions of high static and dynamic loads, erosive and corrosive action, temperature exposure. Therefore, a whole range of technical requirements are imposed on such products in terms of their static strength, fatigue resistance, long-term strength at operational temperatures, etc. [2].

In today’s GTE compressors, such wheels are used where the blades and the disc do not have a mechanical mounting, but represent a single unit. The only method for producing such joints that can be used in industry is linear friction welding (LFW) [3]. The transition from dismountable wheels to welded monowheels provides an opportunity to produce the blade and disc workpieces separately. For example, to produce blades one can use ultrafine-grained (UFG) alloys with enhanced strength before welding to a disc. In the present work, to produce a solid-phase joint by LFW we used the heat-resistance Ti alloys VT8M-1 and VT25U. The VT8M-1 alloy is widely applied in blades, and the VT25U alloy is intended for the production of large-sized GTE rotor discs [2]. In the VT8M-1 alloy, a UFG structure was formed by high-rate rotary swaging (RS) in order to produce enhanced strength properties [4,5]. The aim of this work is to study the microstructure and mechanical properties of the
solid-phase joint between the VT8M-1 alloy having a UFG structure and the VT25U alloy, imitating the materials of a GTE compressor blade and disc.

2. Material and experimental procedure

For the investigation, we used rods produced by OJSC VSMPO-AVISMA Corporation (Verkhnyaya Salda, Russia) with the following chemical compositions: VT8M-1 (Ti–5.7Al–3.8Mo–1.2Zr–1.3Sn–0.16Fe, wt.%) and VT25U (Ti–6.7Al–3.9Mo–4.2Zr–1.8Sn–1.3W, wt.%) The rotary swaging of the rods from the VT8M-1 alloy was implemented with diameter reduction from 70 to 32 mm at a temperature of 750 °C. The total strain was \( \varepsilon \sim 1.7 \), the strain rate was higher than 300 mm s\(^{-1}\). For implementing LFW, samples were produced from the VT25U alloy rods in the as-received state and the VT8M-1 alloy rod with a UFG structure. The samples had the shape of a parallelepiped with a height of 35 mm and a section of 13×26 mm. LFW was performed by means of reciprocating motion of the welded parts with a frequency of about 50 Hz and an amplitude of up to 2 mm, compressed for a tight contact.

Tensile tests (short-term strength) at an operational temperature of 400 °C were conducted in accordance with the Russian standard GOST 9651-84. Long-term strength was estimated in accordance with the Russian standard GOST 10145-81. For this purpose, samples were produced with a gage portion of \( d = 6 \) mm and a gage length of \( L = 35 \) mm, having threaded heads.

To reveal the microstructure, the sample surface was etched with a solution of hydrofluoric and nitric acids in water. Microstructural studies were performed using an Olympus GX-51 optical microscope and a TescanMira 3 LMH scanning electron microscope. Microhardness was tested using a PMT-3 microhardness tester with a step of 0.5 mm under a load of 2 N applied for 10 s.

3. Results and their discussion

3.1. Microstructure of the VT8M-1 alloy before and after rotary swaging

The microstructure of the alloy in the as-received state had a duplex character and consisted of the primary \( \alpha \)-phase grains with an average size of 3 \( \mu \)m and a volume fraction of about 60%, in the \((\alpha+\beta)\)-regions the thickness of the \( \alpha \)-phase lamellae was on average 0.2 \( \mu \)m (figure 1a).

![Figure 1. Microstructure of VT8M-1 alloy: (a) as-received state; (b) after RS in the transverse section and (c) in the longitudinal section.](image)

After deformation by RS, in the transverse section of the rod we observed the spheroidization of the lamellar \((\alpha+\beta)\)-constituent of microstructure (figure 1b), and in the longitudinal section a typical for RS metallographic texture formed, characterized by the elongation of the primary \( \alpha \)-phase along the deformation direction (figure 1c). The average size of the recrystallized grains of the secondary \( \alpha \)-phase was about 0.3 \( \mu \)m (figure 1b).

In the metallographic images from a section of the welded joint (figure 2) one can distinguish four characteristic zones. Zones 1 and 4 correspond to the structure of the samples, respectively, from the UFG VT8M-1 alloy (1) and from the VT25U alloy (4) with a coarse-grained (CG) duplex structure, which did not undergo any changes in the course of welding (figure 2 a,b,d). Regions 2 and 3 are the thermo-mechanical affected zones, zone 2 refers to the UFG VT8M-1 alloy, and zone 3 refers to the VT25U alloy (figure 2a). In Fig. 2d distinctly visible is a pronounced metallographic texture oriented...
in the direction of the deformation flow of the material, which is apparently related to the thermomechanical effect of friction welding. In zone 2, from the side of the UFG alloy, this type of texture is weakly expressed (figure 2b). The images of the microstructure in the area of contact between zones 2 and 3 are characterized by recrystallized grains of the β-phase with a martensitic structure and sizes ranging from 5 to 15 µm (figure 2a and c), which is related to local heating to temperatures above the β-transus temperature of the welded alloys and subsequent rapid cooling of the sample.

Figure 2. Microstructure of the solid-phase joint between the UFG VT8M-1 alloy and the VT25U alloy: (a) general view; (b) zones 1 and 2 – UFG VT8M-1; (c) zones 2 and 3 – welded seam; (d) zones 3 and 4 – VT25U.

Figure 3 shows the HV microhardness distribution across the section of the welded seam. On the whole, these results agree well with the microstructural zones revealed earlier, shown in figure 2.

In particular, in the contact area (zones 2 and 3) the formation of a martensitic structure resulted in higher microhardness values, up to 4500 MPa on average, as compared to zones 1 and 4 with the initial (before welding) structure. We should also note the small difference in the microhardness of VT25U (HV 3200 MPa) and VT8M-1 with a UFG structure (HV 3500 MPa). The increased microhardness values are characteristic for a rather extensive region with a length of 1200 µm (areas 2 and 3). It should be noted that in [6] a more narrow interval of increased hardness (about 500 µm) was observed in the samples of the CG alloy Ti-6Al-4V, as compared to the joint of UFG samples [6]. Apparently, the smoother distribution of microhardness across the width of the welded seam of the UFG samples was promoted by the presence of the residual α-phase in the martensitic matrix [6].

In the present work, to produce a solid-phase joint we used different alloys, where the more heavily-alloyed VT25U alloy is noticeably stronger than the VT8M-1 alloy in the initial CG state [2]. The UFG structure formation in the VT8M-1 alloy enabled, first, increasing its microhardness and equalizing it with the strength of VT25U, and second, forming a practically full-strength joint without local “jumps” in microhardness in the contact area (figure 3).
3.2. Short-term and long-term strength

To evaluate the strength of the obtained solid-phase joint, we performed the tensile mechanical testing of the samples at a temperature of 400 °C, corresponding to the operational temperature. It can be seen from Table 1 that the short-term strength of the VT8M-1 alloy in the case of UFG structure formation increases from 800 to 1100 MPa, while the short-term strength of the VT25U alloy at this temperature is ~ 860 MPa [2]. For testing long-term strength, specimens were cut out from the solid-phase joint so that their welded seam was in the middle. The 100-hour strength at 400 °C was 850 MPa, and the fracture took place far from the junction, in the area of the VT25U.

| Alloy/state                      | Short-term strength at T=400 °C, σ\textsuperscript{400}, MPa | 100-hour long-term strength at T=400 °C, σ\textsuperscript{400}, MPa |
|---------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| VT25U CG                        | 860*                                                          | 850*                                                          |
| VT8M-1 CG                       | 800                                                          | 720                                                          |
| VT8M-1 UFG                      | 1100                                                         | 850                                                          |
| UFG VT8M-1/VT25U welded joint   | 900                                                          | 850                                                          |

* according to the data given in [2].

The obtained values of the strength characteristics of the welded joint under short-term and long-term tests indicate that they correspond to the level of the monolithic VT8M-1 alloy having a UFG structure, which is higher than the strength properties of the alloys in the CG state.

4. Conclusions

The following conclusions can be drawn from the results of the conducted studies:

1. The main characteristic zones have been revealed in the section of the welded joint of samples differing in terms of composition and microstructure, namely the VT8M-1 alloy with a UFG structure and the VT25U alloy. It has been shown that the contact area of the alloys (welded seam) is characterized by recrystallized grains of the β-phase with a martensitic structure, which is related to local heating to temperatures above the β-transus temperature of the welded alloys and subsequent rapid cooling after LFW.

2. Microhardness across the width of the welded joint varies uniformly without any sharp jumps, which characterizes the full-strength joint. This is also confirmed by the mechanical test results of the welded joint between the UFG VT8M-1 alloy and the VT25U alloy at a temperature of 400 °C, which revealed a 100-hour long-term strength of 850 MPa, corresponding to the level of the monolithic material with a UFG structure. This allows us to talk about the possibility of using this approach in production of high strength welded joints.

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