Peculiarities of microstructure and mechanical behavior of VT8M-1 alloy processed by rotary swaging

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Abstract. This research is focused on the study of the relationship between microstructure and mechanical behavior of two-phase Ti alloy VT8M-1 (Ti-5.7Al-3.8Mo-1.2Zr-1.3Sn) in the ultrafine-grained (UFG) state, which is produced by rotary swaging (RS) as compared to equal-channel angular pressing (ECAP). It is shown that both processing techniques enable forming a UFG structure and enhanced mechanical properties in the alloy. Distinguishing features of the UFG structure produced by RS are conditioned by different stress-strained states in the alloy in comparison with ECAP. The relationship between structure, strength and ductility of the alloy processed by RS and ECAP is discussed.

1 Introduction

Two-phase Ti alloys are widely used as materials for aircraft structures and engines due to their high specific strength and corrosion resistance. VT8M-1 alloy is a two-phase Ti alloy, which has higher heat resistance and thermal stability as compared to popular Ti-6Al-4V alloy [1,2]. Parts of gas-turbine engines (GTE) are exploited in high-load states in the conditions of corrosion, erosion and thermal impacts, therefore enhanced requirements are imposed on them in today’s conditions of engineering development. It is the combination of high strength, ductility, fatigue resistance, fracture toughness and creep rupture at exploitation temperatures, which determine the performance of structural materials.

Formation of ultrafine-grained states in metals and alloys with the help of different severe plastic deformation (SPD) techniques is one of the most promising approaches to improve strength and ductility; it considerably increases the fatigue endurance limit and other performance properties [3-5].

By comparing the results of grain structure refinement in Ti and its alloys via different SPD techniques [6-10], one should note that the deformation scheme, temperature and applied forces impact greatly the peculiarities of the formed UFG structure and mechanical properties. For example, the advantage of high pressure torsion (HPT) [6] over other SPD techniques is that the use of this treatment allows forming grains of a nanometer size (less than 100 nm), but this technique can be implemented on small-sized samples. Equal-channel angular pressing (ECAP) enables producing bulk billets with larger grains (over 200 nm) [8].

Combination of SPD with conventional plastic deformation techniques [8] and creation of new approaches and treatment techniques [8,11] are promising directions in SPD development and implementation of commercial technologies for producing UFG materials. Rotary swaging (RS) is
one of new commercial techniques, which consists in high-frequency deformation of metals with anvils according to the quasi-scheme of all-round compression. Rotary swaging consists in periodic compressions of a rod and reduction its diameter by split dies which simultaneously move along radial, rotational and axial directions relative to the axis of the rod [9]. An important advantage of RS against ECAP is the possibility of upscaling, which is connected with the increase in geometrical sizes (diameter and length) of produced samples. The combination of the two approaches is possible, which will allow creating new technologies for producing UFG materials on a commercial scale.

This work deals with the studies on the peculiarities of UFG structure formation and mechanical behavior of Ti alloy VT8M-1 processed by RS. The aim of this study is to reveal the peculiarities of grain structure refinement in the alloy, as compared to ECAP, and, as a consequence, their impact on its mechanical behavior.

2 Material and experimental procedure
In order to carry out investigations, VT8M-1 (VSMPO-AVISMA Corporation, Verkhnaya Salda, Russia) alloy with the following composition Ti–5.7Al–3.8Mo–1.2Zr–1.3Sn–0.16Fe (wt. %) was used. The β-transus temperature (TPT) in the alloy is 980 ± 5°C. A VT8M-1 rod with a diameter of 70 mm and 1000 mm long was subjected to heat treatment (HT) by heating of the alloy to a temperature of 940°C, subsequent quenching in water, annealing for an hour at 700°C, and cooling in air to obtain a globular-lamellar structure. The ultrafine-grained state was formed via two different techniques. 4 ECAP passes via the Bc route at a temperature of 750°C (ε=2.7 with a strain rate of 4 mm s⁻¹) were applied to produce rods with a diameter of 30 mm (Figure 1a), the angle of channels intersection was ψ=120°. A rod with a diameter of 70 mm was successively processed by rotary swaging to diameters of 60, 50, 40, 30 mm with intermediate annealing at 750°C (ε ~ 1.7, the strain rate was higher than 300 mm s⁻¹) (Figure 1b).

![Figure 1. VT8M-1 rods: (a) after ECAP; (b) after rotary swaging.](image)

The microstructure characterizations were carried out using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The TEM micrographs were obtained using a JEOL JEM-2100 microscope operating under an accelerating voltage of 200 kV. Thin foils for TEM were prepared by spark cutting of plates with a thickness of 0.8-1 mm, mechanical thinning with subsequent electrolytic polishing at subzero temperatures. The average grain size was estimated according to the obtained images according to GOST 5639-82 by “Method of counting grain boundary intersections” with the help of the special software “Graine-size”. The volume fraction was evaluated with the help of the “Image J” software. The stress-strain curves were recorded using an initial strain rate of 1.0 x 10⁻³ s⁻¹ with an Instron universal testing machine. Three samples were tested for each state.

3 Results and their discussion

3.1 Microstructure of VT8M-1 in the as-received state
The initial structure of the VT8M-1 alloy rod (Figure 2a) is a mixed globular-plate structure. The average size of the primary α-phase is 5 µm, and its fraction in the alloy is 50%, the thickness of α lamellas is 0.2 µm.
To ensure the conditions of plastic deformation of hard-to-deform Ti alloys, preliminary heat treatment (HT) was performed with the aim to form a duplex microstructure consisting of a primary α-phase not over 25% and a thin plate α+β structure. This approach to grain structure refinement efficiency enhancement was successfully applied earlier to Ti-6Al-4V [12]. The microstructure after HT (Figure 2b) is a globular platelike structure, which consists of lamellas of the α-phase with a thickness of 0.12 µm, divided by β-phase interlayers and 25% of a globular primary α-phase with an average size of globules of 2.7 µm.

![Figure 2. Microstructure of the VT8M-1 alloy: (a) in as-received (b) after HT.](image)

3.2 Microstructure of VT8M-1 after SPD processing

As it follows from the scanning electron microscopy data (Figure 3), after ECAP and RS the plate component of VT8M-1 practically totally transforms into a globular one. The average size of globular grains of the primary α-phase after both deformation techniques is about 3 µm. Part of grains is elongated along the deformation direction. Their length in the structure achieves 7 µm after ECAP (Figure 3a), whereas after RS the shape of grains of the primary α-phase was close to an equi-axed one (Figure 3b).

![Figure 3. Microstructure of the VT8M-1 alloy: (a) after HT+ECAP (b) after HT+RS.](image)

As it is seen in the images of the structure taken on TEM (Figure 4), the deformation of structure components occurred non-uniformly. In particular after 4 ECAP passes the average size of grains and subgrains after ECAP was about 0.48 µm (Figure 4a). Weakly deformed fragments of α-phase plates were found in the microstructure, which testified to incompleteness of globularization of the plate component [14]. New low-angle dislocation boundaries form inside the primary globular α-phase, separate fragments with a size from 0.5 to 1 µm are observed (Figure 4b). According to the results of TEM, the average size of subgrains in the structure of HT+RS samples as a result of deformation and fragmentation of plates of the α-phase was much lower and varied from 0.2 to 0.3 µm (Figure 4c). The grains of the primary α-phase as well as after ECAP were fragmented by new subgrain boundaries (Figure 4d).
The differences in the UFG structure formed in the alloy after ECAP and RS are evidently connected with different stress-strain states in the billet, which are conditioned by such parameters as rate and accumulated degree of strain. The alloy's microstructure produced at the initial stages of ECAP processing at \( T = 750 \, ^\circ C \) [13] indicates the development of spheroidization of the lamellar constituent. This process was accompanied by the fragmentation of lamellae by shear bands or by the formation of dislocation boundaries [14]. The deformation by RS led to the formation of a more homogeneous refined structure as compared to the ECAP processing (Figures 4a and 4c). The high deformation rate during RS (75 times higher than in the ECAP process), apparently, may promote the development of dynamic recrystallization, which is confirmed by the type of the formed structure (Figures 4a and 4c).

![Figure 4. TEM images of the VT8M-1 alloy microstructure: (a) after HT+ECAP; (b) weakly deformed primary \( \alpha \)-phase after HT+ECAP; (c) after HT+RS; (d) weakly deformed primary \( \alpha \)-phase after HT+RS.](image)

3.3 **Mechanical properties of VT8M-1 after SPD processing**

It is seen from Table 1 that the grain structure refinement in the alloy achieved by RS and ECAP techniques increases the ultimate tensile strength of the VT8M-1 alloy. It should be noted that RS leads to more considerable hardening (from 1030 to 1220 MPa) as compared to ECAP (from 1030 to 1160 MPa) (Table 1). The difference in the UTS values of the investigated states is primarily conditioned by a more homogeneous and fine structure in the alloy after rotary swaging (0.25 and 0.48 \( \mu m \) for RS and ECAP, respectively).

**Table 1.** Mechanical properties of the VT8M-1 alloy before and after SPD-processing.

| State   | Average grain size of primary \( \alpha \)- | Average size \( UTS, \) MPa | \( YS 0.2, \) MPa | Elong., % | Uniform elongation, % |
|---------|------------------------------------------|-----------------------------|------------------|-----------|----------------------|
|         |                                           |                             |                  |           |                      |
Moreover, judging by the shape of tensile curves, RS changes the mechanical behavior of the alloy against ECAP (Figure 5). In particular, the alloy after RS demonstrates uniform elongation of about 4% in comparison with ECAP, which was 1.2%, the total relative elongation was practically the same and was found in the error range (11 and 10%, respectively) (Table 1). The higher value of uniform elongation in the alloy after RS as compared to the ECAP-processed condition can be attributed to a lower dislocation density inside grains/subgrains (as it can be seen from Figure 4c), and also to a more equilibrium state of the boundaries.

As it is known the uniform elongation value during tension indirectly points to the material ability for strain hardening and tendency to strain localization [15]. First of all it is connected with fracture toughness of material, i.e. the ability to resist brittle failure, which is one of the important properties of structural materials applied in aviation [16].

|                  | D, µm | phase, µm |
|------------------|-------|-----------|
| As-received      | 5±1   | 5±1       |
| HT+ECAP          | 0.48±0.08 | 2.7±0.2 |
| HT+RS            | 0.25±0.05 | 3.0     |

**Figure 5.** Typical tensile mechanical curves of Ti alloy VT8M-1 in different states.

Thus, the rotary forging ensures enhanced strength and ductile properties in the VT8M-1 alloy against ECAP processing due to formation of a UFG structure with a size of grains/subgrains of less than 0.3 µm. This technique is the most efficient way of producing rods in commercial scales as compared to ECAP. Alongside, the combination of these techniques could be the basis of creating a new technology for producing high-strength rods from Ti alloys with an increased set of exploitation properties, which is the subject of our future studies.

4 Conclusions
The results of the comparative studies of the VT8M-1 alloy processed by ECAP and rotary swaging at a temperature of 750°C enables stating that:
1. The RS treatment allows forming a bulk ($\alpha+\beta$) UFG structure with an average size of grains/subgrains of 0.25 $\mu$m in the VT8M-1 rod unlike ECAP, as a result of which an average size of the $\alpha$-phase achieved approximately 0.5 $\mu$m. In both cases during deformation primary grains of the $\alpha$-phase retained their initial sizes (~3 $\mu$m) with formation of subgrain boundaries. The grain and subgrain size reduction after RS as compared to ECAP is probably connected with a very high strain rate, which suppresses the static recrystallization at high temperatures.

2. The formation of the UFG structure with a finer grain size during RS as compared to ECAP (0.25 and 0.48 $\mu$m, respectively) results in a higher ultimate tensile strength (1220 and 1160 MPa, correspondingly).

3. The UFG VT8M-1 alloy after RS demonstrates a higher uniform elongation as compared to the samples produced by ECAP (4 and 1%, respectively), which can be attributed to a lower dislocation density inside grains/subgrains, and also to a more equilibrium state of grain boundaries.

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