Microstructure and mechanical properties of workpieces of the ultrafine-grained two-phase Ti alloy produced by die forging

T V Yakovleva, G S Dyakonov, A G Stotskiy and I P Semenova
Institute of Physics of Advanced Materials, Ufa State Aviation Technical University, 12 K. Marx street, Ufa, 450008, Russian Federation
E-mail: yakovleva_tatyana93@mail.ru

Abstract. The paper presents the results of studies of the microstructure and mechanical properties of experimental workpieces of the ultrafine-grained (UFG) VT8M-1 (Ti–5.7Al–3.8Mo–1.2Zr–1.3Sn in wt%) alloy produced by isothermal die forging (IDF). The UFG structure in the VT8M-1 alloy was formed by a high-performance method, namely rotary swaging (RS). The structural parameters (the shape and size of the α- and β-phases) and the homogeneity of the UFG structure were analyzed in different sections of forgings. It was shown that the fraction of the primary α-phase decreases, and the size of the secondary equiaxed grains of the α- and β-phases increases from 0.3 to 0.9 µm as a result of recrystallization during IDF. The relationship between the microstructure and mechanical properties of the forged workpieces of the UFG VT8M-1 alloy is discussed.

1. Introduction
Among structural materials, titanium alloys are widely applied in aviation and engine building due to their high specific strength, corrosion resistance and specific hot strength [1]. In particular, the two-phase Ti alloy VT8M-1 (Ti–5.7Al–3.8Mo–1.2Zr–1.3Sn in wt%) is applied in modern engine building for the production of compressor blades, which operate under the severe conditions of high static and dynamic loads, corrosive attack and temperature exposure. In this connection, a higher set of requirements is imposed on them, such as a combination of high strength, ductility, fracture toughness and fatigue resistance.

The conventional technology for the fabrication of blade workpieces from Ti alloys, having a rather complex surface configuration, is die forging [2]. It is known that the temperature of isothermal forging for coarse-grained Ti-based materials is about 950 ºC, and the use of UFG billets in the shape-forming of blades creates an opportunity to implement isothermal forging at lower temperatures of 750-780 ºC. The decrease in the forging temperature is related to the manifestation of superplasticity in UFG materials at lower temperatures and higher strain rates [3]. Such a temperature range makes it possible to preserve a homogeneous UFG structure, which ensures a higher level of properties in an experimental item. In this connection, the aim of the present paper is to study the effect of isothermal forging at lower temperatures on the microstructure of the UFG VT8M-1 alloy, and also to evaluate the mechanical properties of the produced workpiece.
2. Material and experimental procedure

For the investigation, we used the VT8M-1 alloy (VSMPO-AVISMA Corporation, Russia) with the following composition: Ti–5.7Al–3.8Mo–1.2Zr–1.3Sn–0.16Fe (wt.%). The β-transus temperature (TPT) in the alloy is 980 ± 5 °C. The ultrafine-grained structure of the VT8M-1 alloy was formed by rotary swaging (RS) at 750 °C with a gradual reduction along the diameter of the billets from 70 to 32 mm (true strain ε ~ 1.56, the strain rate was higher than 300 mm s⁻¹).

An experimental forging simulating a compressor blade was produced by IDF at a temperature of 780±10 °C. Specimens for metallographic studies and testing of mechanical properties were cut out from the airfoil and root of the experimental forging (figure 1).

![Figure 1](image1.png)  
**Figure 1.** (a) Experimental forging produced from the UFG alloy VT8M-1; (b) scheme of cutting out of the specimens from the experimental forging.

The microstructure was characterized by scanning electron microscopy (SEM) using a JSM 6390, and by transmission electron microscopy (TEM) using a JEM-2100. Tensile mechanical tests of flat specimens with a gage length of 16 mm and a width of 3 mm, cut out from the root and airfoil of the experimental forging, were performed using an Instron universal testing machine at room temperature with a strain rate of 1×10⁻³ s⁻¹ in compliance with ASTM E8/E8M.

3. Results and discussion

3.1. Microstructure and mechanical properties of the VT8M-1 alloy billet produced by RS

The initial structure of the VT8M-1 alloy rod (figure 2a) was a duplex microstructure. The average size of the primary α-phase is 3 µm, and its fraction in the alloy is 60%, the thickness of the lamellae is 0.2 µm. Deformation by RS led to the spheroidization of the lamellar (α+β)-constituent (figure 2b) and the elongation of the primary α-phase along the draw direction (figure 2c) [4]. In the cross section, the primary α-phase was bent in accordance with the flow direction during rotary swaging, its average width decreased from 3 µm to 1.5 µm (figure 2b). The electron-microscopic images show that after the deformation the (α+β)-structure consists of fragments of severely distorted plates, as well as the small globular grains of the α- and β-phases with an average size of 0.3 µm (figure 2b). In the interiors of the primary α-phase grains, an increase in dislocation density with the formation of a developed substructure is observed (figure 2c).

![Figure 2](image2.png)  
**Figure 2.** Microstructure of VT8M-1 alloy: (a) initial state; (b) after rotary swaging in the cross section and (c) in the longitudinal section. The arrow indicates the draw direction.
In the as-received state, the VT8M-1 alloy exhibited the following mechanical characteristics: ultimate tensile strength (UTS) ~1056 MPa and elongation $\delta=13\%$ (table 1). As a result of the UFG structure formation, the alloy’s strength increased by 22% to UTS = 1290 MPa and elongation decreased to $\delta=9\%$, which is typical of the majority of metals and alloys subjected to SPD [5,6,7].

3.2. Microstructure and mechanical properties of the experimental forgings produced from the UFG alloy by IDF

The microstructure of the forged workpieces produced by IDF ($T=780 \, ^\circ C$) is shown in figure 3. Due to a complex geometrical shape of the experimental forgings, different strains are observed in the airfoil and in the root part. The estimation of strain showed that the root part of the experimental forging experienced a lower strain (60%) in comparison to the forging’s airfoil (75%). The SEM study of the microstructure of the forgings revealed a similar character of microstructure in the airfoil part and in the root part. The primary $\alpha$-phase grains are elongated along the deformation direction and their thickness is 2-3 $\mu$m (figure 3a,c). As it was noted above, such an elongated shape formed at the stage of processing by rotary swaging. It was found that forging led to a reduction in the volume fraction of the globular constituent of the $\alpha$-phase due to a decrease in grain length, as compared to the condition after RS (from 65% to 29% in the airfoil zone and to 35% in the root part) (figure 3a,c). TEM study at a larger magnification revealed (figure 3b,d) that the microstructure of the ($\alpha+$$\beta$)-region is represented by equiaxed recrystallized and deformed grains, the average grain size in the root part being larger than that in the airfoil and amounting to 0.9 and 0.7 $\mu$m, respectively. This is related to the fact that in the more massive root part, cooling after forging is slower than in the airfoil, which promotes more intensive recrystallization processes.

The mechanical properties of the specimens cut out from the root and airfoil zones of the experimental forging are listed in table 1. In the longitudinal direction of the experimental forging’s airfoil (specimen 1 in figure 1b) strength declines to 1100 MPa as compared to the condition after RS (UTS = 1290 MPa), but at the same time ductility increases visibly, in particular, the uniform and percentage elongations grow to 7 and 15%, respectively (table 1). Such a decline in strength is conditioned by a decrease in dislocation density, the propagation of recrystallization and an increase in the sizes of small globular grains of the $\alpha$- and $\beta$-phases (from 0.3 to 0.7 $\mu$m) (figure 3). The mechanical properties of the specimens in the longitudinal (specimen 1) and cross sections (specimen 2 in figure 1b) of the airfoil zone have some differences. In particular, the ultimate tensile strength (UTS) in the
cross section of the airfoil is slightly higher (1118 MPa), while the ductility, percentage and uniform elongations are lower. This is apparently conditioned by the presence of the inherited after RS metallographic and crystallographic texture in the forged workpiece. The ultimate tensile strength in the root part of the experimental forging amounts to UTS=1109 MPa with an elongation of δ=10%, and it is close to the level of properties of the alloy in the cross section of the airfoil (specimen 3 in figure 1b and table 1). Thus, the results of this investigation demonstrate a possibility in principle of preserving a UFG structure during the shape-forming of an item by isothermal forging, and correspondingly, of preserving enhanced mechanical properties.

Table 1. Mechanical properties of the Ti alloy VT8M-1 in different conditions.

| Condition                  | UTS, MPa | YS 0.2, MPa | Elong., % | Uniform elongation, % |
|----------------------------|----------|-------------|-----------|-----------------------|
| As-received                | 1056±10  | 967±5       | 13±0.5    | 4.7±0.5               |
| RS                         | 1290±5   | 1195±10     | 9±1       | 3.4±0.5               |
| IDF 780 °C specimen 1 airfoil | 1100±30  | 947±25      | 15±1      | 7.0±0.5               |
| IDF 780 °C specimen 2 airfoil | 1118±10  | 1048±20     | 10±0.6    | 0.7±0.2               |
| IDF 780 °C specimen 3 root | 1109±15  | 1105±15     | 10±0.5    | 0.2±0.1               |

4. Conclusions
1. As a result of processing by rotary swaging, a UFG structure is formed in the VT8M-1 alloy, characterized by the primary α-phase grains elongated in the draw direction with a thickness of ~1.5 μm, and ultrafine α- and β-grains ~0.3 μm in size in the two-phase regions. This type of UFG structure leads to an increase in the ultimate tensile strength to UTS = 1290 MPa and some decline in elongation to δ=9%, as compared to the initial condition.
2. It is shown that as a result of isothermal forging at a temperature of 780 °C, the workpiece retains the ultrafine grain size which increased to 0.7 μm in the airfoil and 0.9 μm in the root due to the processes of recovery and recrystallization.
3. The differences in the mechanical properties of the root and airfoil zones are conditioned by different strains accumulated during the forging and the different cooling rates of the massive root and a thin airfoil part.

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