Mechanical behavior and impact toughness of the ultrafine-grained VT8M-1 alloy

Iu M Modina, V V Polyakova, G S Dyakonov, A V Polyakov, I P Semenova and A G Raab

Institute of Physics of Advanced Materials, Ufa State Aviation Technical University, 12 K. Marx st., Ufa, 450008, Russian Federation

E-mail: modina_yulia@mail.ru

Abstract. This paper reports on a study of the relationship between the microstructure, mechanical behavior and impact toughness of the two-phase Ti alloy VT8M-1 (Ti-5.7Al-3.8Mo-1.2Zr-1.3Sn) in the ultrafine-grained (UFG) state, which was produced by two different techniques – equal-channel angular pressing (ECAP) and rotary swaging (RS). It is shown that both processing techniques enable forming a UFG structure and enhanced mechanical properties in the alloy. The UFG structures formed in the billets are characterized by different shapes and sizes of the α- and β-phases. The relationship between the structure, strength, ductility and impact toughness of the alloy processed by RS and ECAP is discussed.

1. Introduction

Two-phase titanium alloys are widely used for producing complex-loaded parts of a gas-turbine engine (GTE). Therefore, high requirements are imposed on them not only in terms of strength, fatigue resistance, but also ductility-related properties, such as fracture toughness and impact toughness, which characterize a material’s resistance to brittle fracture.

To date, one of the most promising approaches to drastically modify and enhance the mechanical properties of metals and alloys is to produce ultrafine-grained (UFG) states using various severe plastic deformation (SPD) techniques [1]. This type of treatment, applied to two-phase Ti alloys, enabled considerably increasing both strength and endurance limit, implementing high-speed and/or low-temperature superplasticity [2,3]. However, recent studies show that the formation of UFG structures in metals and alloys often leads to a decrease in both fracture toughness and impact strength [4]. Many investigators attribute this trend to the decline in the capacity of UFG metals to strain hardening [4]. As a result, the practical application of high-strength UFG Ti alloys as engineering materials can be severely limited.

In this work, two different techniques were used to form the UFG structure in the VT8M-1 alloy under study: equal-channel angular pressing (ECAP) and rotary swaging (RS). RS consists in the high-frequency deformation of metals with anvils according to the quasi-scheme of all-round compression and it is new to the processing of titanium alloys [5,6]. RS can be seen as an alternative to ECAP methods, and a combination of the two approaches is possible, which will allow creating new technologies for producing UFG materials on a commercial scale. To compare the potential of two alternative methods, the present paper is devoted to the study the relationship between the
microstructure, mechanical behavior and impact toughness of the VT8M-1 alloy subjected the two techniques.

2. Material and experimental procedure

The experiments were conducted using the VT8M-1 alloy (VSMPO-AVISMA Corporation, Verkhnaya Salda, Russia) in the form of hot-rolled rods with a diameter of 70 mm. The alloy had the following chemical composition (in wt.%): 5.7% Al, 3.8% Mo, 1.2% Zr, 1.3% Sn and Ti – base. The initial structure of the rod made of the VT8M-1 alloy was a mixed globular-plate structure. The average size of the primary α-phase was 5 µm, and its fraction in the alloy was 50%, the thickness of α-lamellae was 0.2 µm [7]. To ensure the conditions of plastic deformation of hard-to-deform Ti alloys, preliminary heat treatment (HT) was performed by heating the alloy to a temperature of 940 °C, subsequent quenching in water, annealing for one hour at 700 °C, and cooling in air [7]. The UFG state was formed via two different techniques. Four ECAP passes via B_C route at a temperature of 750°C (e=2.7 with a strain rate of 4 mm s⁻¹) were applied to produce rods with a diameter of 30 mm [8]. A rod with a diameter of 70 mm was successively processed by RS to a diameter of 30 mm with intermediate annealing at 750 °C (e ~ 1.7, the strain rate was ~300 mm s⁻¹).

The metallographic study was conducted using a JEOL JEM-2100 microscope (TEM) and a JEOL JSM 6390 microscope (SEM). 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. The samples with cross-sectional dimensions of 10 × 10 mm and a V-notch were tested using an Instron CEAST 9350 impact tester at room temperature in accordance with ASTM E23-16. At least three samples were used per experimental point.

3. Results and their discussion

3.1. Microstructure and mechanical properties of VT8M-1 after SPD processing

The microstructure after HT (figure 1a) is a globular plate-like structure, which consists of 0.12 µm thick α-phase lamellae divided by β-phase interlayers, and 25% of the globular primary α-phase with an average grains size of 2.7 µm.

![Figure 1](image-url)

Figure 1. Microstructure of the VT8M-1 alloy: (a) after HT; (b) after HT+ECAP; (c) after HT+RS; (d) after HT+RS (TEM).

According to the SEM data (figures 1b and 1c), in the structures after ECAP and RS, the lamellar constituent is almost fully transformed into the equiaxed one, the grain size of the primary α-phase is ~3 µm. Part of the grains of the primary α-phase after RS is elongated along the deformation direction, their length is 7 µm (figure 1c), whereas after ECAP the grain shape of the primary α-phase is close to the equiaxed one (figure 1b).

According to the TEM data, after ECAP, the average size of grains and subgrains in the (α+β) areas was 0.48 µm, and after RS it was 0.25 µm (figure 1d). The features of the UFG structure formation resulting from ECAP are considered in more detail in [8].

Table 1 shows that the UFG structure formation by ECAP and RS leads to an increase in the ultimate tensile strength (UTS) and yield stress (YS) (by 10% for ECAP and 20% for RS). The difference in the UTS values of the investigated states is primarily conditioned by a finer structure in the alloy after rotary swaging (0.25 and 0.48 µm for RS and ECAP, respectively).
In particular, a higher value of uniform elongation in the alloy after RS (4%) as compared to the ECAP-processed condition (1.3%) (table 1) can be attributed to a lower dislocation density inside grains/subgrains, and also to a more equilibrium state of the boundaries [7]. The total elongation was practically the same and was found to be within the error range (11 and 10%, respectively).

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

| Condition | UTS, MPa | YS, MPa | Elong., % | Uniform elongation, % |
|-----------|----------|---------|-----------|-----------------------|
| As-received | 1040±20 | 970±20 | 15±2 | 5.0±0.9 |
| HT+ECAP | 1150±10 | 1080±20 | 10±1 | 1.3±0.5 |
| HT+RS | 1230±10 | 1150±15 | 11±1 | 3.8±0.5 |

3.2. Impact toughness of VT8M-1 after SPD processing

Table 2 presents the results of impact tests of the samples with different types of microstructure. A tendency is observed for an almost 2-fold decrease in absorbed energy for UFG VT8M-1 as compared to the CG alloy, which is primarily conditioned by the increase in yield stress both after ECAP and after RS (table 1). Such a tendency is typical for many metals [4]. The absorbed energy values after impact tests of the ECAP-processed and RS-processed samples are practically identical and on average amount to ~0.25 MJ/m² (table 2). The RS-processed samples exhibit a smaller spread in the Kcv values as compared with the ECAP-processed samples.

The appearance of the fracture surfaces of the VT8M-1 alloy (figure 2) after testing is typical for titanium alloys, it has a flat area, which is characterized by a fibrous zone and shallow fracture dimples, and also has a shear lip, but also some differences are observed related to the features of the microstructure of the alloy. The rupture area in the RS-processed sample, in contrast to the CG and ECAP-processed samples, is located at an angle of 45° with respect to the fracture plane (figure 2g), which may be related to inhomogeneity and the formation of a specific texture by rotary swaging [6].

In the case of fracture in the CG alloy, the microrelief consists of comparatively large (~6 μm in size, table 2) and deep, slightly elongated dimples, which are typical for conventional CG Ti alloys (figure 2c). On the fracture surfaces after ECAP and RS (figures 2f and 2i), the dimples are smaller with sizes ~ 4 and 2 μm, respectively (table 2), and the fraction of dimples with a size of less than 1 μm is much larger, which indicates the predominantly intercrystalline character of the fracture, in contrast to the CG sample, where the transcryrstalline character of the fracture prevails. Thus, the conducted study shows that producing an ultrafine grain size in the VT8M-1 alloy by ECAP and RS leads to a decline in the impact toughness Kcv from 0.5 MJ/m² in the CG state to 0.25 MJ/m² due to an increase in yield strength. At the same time, the RS-processed sample with a higher yield stress in comparison to the ECAP-processed condition (1150 and 1080 MPa, respectively) exhibits the same level of impact toughness. Apparently, this could be attributed to the higher values of the uniform elongation of the samples after RS (4%) in comparison to the ECAP-processed samples (1.3%), which characterizes the greater ability of the material to strain hardening [4]. Achieving in the UFG VT8M-1 alloy a combination of high strength (UTS 1230 MPa) and impact toughness (0.25 MJ/m²) creates prospects for its successful application as a structural material in aviation and mechanical engineering.

### Table 2. Impact toughness of the VT8M-1 alloy in different structural states.

| Condition | Average grain size, D, μm | Kcv, MJ/m² | Dimple size, μm |
|-----------|--------------------------|------------|----------------|
| As-received | 5±1 | 0.510±0.010 | 6.40±0.38 |
| HT+ECAP | 0.48±0.08 | 0.254±0.040 | 3.86±0.18 |
| HT+RS | 0.25±0.05 | 0.246±0.005 | 2.35±0.18 |
4. Conclusions
The following conclusions can be drawn from the conducted studies of the mechanical behavior and impact toughness of the UFG VT8M-1 alloy produced by two different techniques – RS and ECAP:

1. The formation of the UFG structure with a finer grain size during RS as compared to ECAP (0.25 and 0.48 μm, respectively) results in a higher ultimate tensile strength (1230 and 1150 MPa, respectively) and uniform elongation (4 and 1.3%, respectively).

2. It is shown that the impact toughness of the alloy in the UFG state produced by the two techniques (RS and ECAP) decreases almost 2-fold in comparison to the coarse-grained state due to an increase in yield stress. The UFG RS-processed samples, having a higher yield stress and uniform elongation than the ECAP-processed samples, exhibit identical Kcv values (0.25 MJ/m²).

Acknowledgements
This work was supported by the Ministry of Education and Science of the Russian Federation in the scope of the State Assignment. The authors are grateful to I. Ramazanov for performing the impact toughness tests at the Center for Common Use of the Research and Educational Center “Nanostructured Materials and High Technologies” of Ufa State Aviation Technical University.

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