Mechanical behavior at elevated temperatures of the ultrafine-grained titanium alloy VT8M-1 processed by rotary swaging

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Abstract. This paper investigates the mechanical properties at elevated operation temperatures of the Ti alloy VT8M-1(Ti-5.3Al-4.0Mo-1.2Zr-1.3Sn-0.2Si) in the coarse-grained (CG) and ultrafine-grained (UFG) states. The duplex UFG structure was produced by rotary swaging at a temperature of 750 °C. The UFG state was studied in terms of thermal stability during annealing at temperatures 500, 550, 600, 700 °C for a period of 1 hour. It was demonstrated that the recrystallization processes in the UFG structure start after annealing at 550 °C and above. We performed tensile mechanical tests at such temperatures. In a range of 300-450 °C, the ultimate tensile strength of the UFG alloy was stably above that of the CG alloy. Mechanical tests at 500 and 550 °C revealed a more significant decrease in the ultimate tensile strength of the UFG alloy as compared to the CG alloy, conditioned by the intensification of the recovery and recrystallization processes at these temperatures.

1. Introduction
Titanium alloys are applied in aviation and engine building primarily due to their high strength and small weight. In particular, the two-phase (α+β) Ti alloy VT8M-1 (Ti-5.3Al-4.0Mo-1.2Zr-1.3Sn-0.2Si) is used for producing compressor blades of gas-turbine engines (GTE) and is operated at temperatures up to 450 °C. Currently, the demands to modern engines are such that require a material that not only has high strength characteristics at elevated temperatures, but also does not degrade in long-term temperature-stressed conditions. In order to increase the hot-strength characteristics of Ti alloys, alloying with rare-earth elements and heat treatments are used, which have largely exhausted their potential [1].

One of the ways to improve the physical and mechanical properties of metals and alloys is the formation of ultrafine-grained (UFG) structures by means of severe plastic deformation (SPD) processing [2]. However, structures refined by large strains are usually stable at room temperature and at close temperatures, which is conditioned by a high accumulated internal energy leading to fast relaxation and a decrease in the recrystallization onset temperature [3]. Correspondingly, a question arises about the applicability of these methods for engineering materials operating at elevated temperatures.
The possibility in principle to produce a UFG structure in the VT8M-1 alloy by rotary swaging was demonstrated earlier [4]. The deformation by rotary swaging is implemented by a gradual slight swaging of a billet with a very high frequency, as a result of which a very high strain is introduced in a material and a rather uniform deformation takes place [5]. As a result of such a processing, a UFG structure with a grain size of 0.3 μm was produced in a bulk billet of the VT8M-1 alloy [4]. This method enables producing long-length billets, which is an undoubted advantage for industrial application. In this connection, the aim of the present work is to study the stability of the mechanical properties of the VT8M-1 processed by rotary swaging, at temperatures close to the operation ones.

2. Material and experimental methods
As the material for the study, we used the VT8M-1 (Ti-5.3Al-4.0Mo-1.2Zr-1.3Sn-0.2Si) alloy in the form of hot-rolled rods with a diameter of 70 mm (produced by VSMPO-AVISMA Corporation, Verkhnaya Salda, Russian Federation).

Rotary swaging (RS) was conducted at a temperature of 750 °C with a gradual reduction in the diameter from 70 mm to 32 mm. This allowed to introduce in the material a true strain of 1.56. The strain was calculated according to the relation \( e = \ln((S_0-S_i)/S_i) \), where \( S_0 \) and \( S_i \) are the cross-sectional areas of the billet before and after deformation, respectively.

Tensile mechanical tests were performed using an Instron universal testing machine at elevated temperatures (300, 400, 450, 500, 550 °C) with a strain rate of \( 1 \times 10^{-3} \) s\(^{-1} \) in compliance with the Russian standard GOST 9651-84. For the tests, we used cylindrical samples cut out in the longitudinal direction of the billet.

The microstructure of the samples was studied in the cross section using a JEOL JSM 6390 scanning electron microscope.

3. Results and discussion
The microstructure of the VT8M-1 alloy in the initial condition represented a duplex structure typical for the hot-rolled condition. The average grain size of the primary \( \alpha \)-phase was 3 μm, and its volume fraction was \( \alpha_{\text{glob}} \approx 65\% \) [6]. The VT8M-1 alloy after RS retains a duplex structure, the grains of the primary \( \alpha \)-phase are elongated and twisted, and the lamellar mixture of the (\( \alpha+\beta \)) phases is divided into fragments of a globular shape (figure 1a). The average size of the grains/subgrains of the secondary \( \alpha \)- and \( \beta \)-phases is 0.3 μm [6].

Figure 1. Microstructure of the VT8M-1 alloy after rotary swaging (a) and further annealings for 1 hour: (b) – 500 °C, (c) – 550 °C, (d) – 600 °C, (e) – 700 °C.
In order to evaluate the thermal stability of the alloy’s UFG structure, we performed a series of short-term annealings for 1 hour at 500, 550, 600, 700 °C [7]. Based on the results of the one-hour annealings, it can be seen that the structure after annealings at 500 and 550 °C does not exhibit any changes, which indicates the stability of the UFG structure at these temperatures. After annealing at 600 °C, we observed in the UFG structure growth of the sizes of secondary phases, resulting from the start of recrystallization (figure 1d). At the annealing temperature of 700 °C these processes became more noticeable when the size of the secondary phases reached 0.5 μm (figure 1e). It should be noted that the volume fraction of the primary α-phase practically does not change and remains at a level of 65%, whereas the sizes of the secondary α- and β-phases retain their ultrafine range.

Taking into account the high thermal stability of the UFG structure during static heating at temperatures of 500 and 550 °C, the tensile mechanical tests were performed in a range of 300-550 °C. The test results are shown in figure 2. It can be seen that the UFG alloy VT8M-1 exhibits higher, almost by 200 MPa, values of ultimate tensile strength (UTS) and yield stress (YS) in comparison with the initial CG state up to a temperature of 450 °C. Worth noting are two characteristic slopes of the UTS and YS curves for the UFG state. In a temperature range of 300-450 °C the slope of the curve for the UFG alloy is parallel to the slope of the curve for the CG state (figure 2).

![Figure 2](image)

**Figure 2.** Mechanical tests of the VT8M-1 alloy in the UFG and CG states at temperatures of 300-550 °C: (a) curves showing the variation of UTS and YS with temperature; (b) curves showing the variation of ductility with temperature.

At temperatures of 450-550 °C the slope of the curve for the UFG alloy is much more pronounced than the one for the CG state, which indicates a more intensive softening of the UFG alloy, in spite of the fact that static heating at these temperatures does not lead to a considerable growth of the α- and β-phases (figure 1e). Apparently, the generation of stresses during tensile deformation can promote the development of dynamic recrystallization and a more intensive coarsening of structural elements [8]. After testing at a temperature of 550 °C the UTS and YS values for the UFG and CG states are close, and elongation is visibly higher as compared to the CG state (40 and 18%, respectively) (figure 2b). Such a mechanical behavior of the UFG alloy is an undoubted advantage from the perspective of further processing and shape-forming of items at lower deformation temperatures.

Thus, grain refinement in the structure of the VT8M-1 alloy by means of high-rate rotary swaging leads to the strength enhancement of the VT8M-1 alloy at temperatures of 300-450 °C, i.e. in the temperature range of operation of GTE components [9]. The obtained research results provide grounds to predict an enhanced strength of the UFG alloy under long-term applied stresses at operation temperatures (creep rupture strength), and this will be the focus of our further studies.
4. Conclusions
Based on the results of the study into the stability of the microstructure and mechanical properties at elevated temperatures of the VT8M-1 alloy samples with a UFG structure formed by rotary swaging, the following conclusions can be made:

1. The VT8M-1 alloy produced by rotary swaging is thermally stable during one-hour annealings at temperatures up to 550 °C. Some growth of the secondary α- and β-phases with increasing annealing temperature to 600 and 700 °C is conditioned by the development of recrystallization, while the structure’s ultrafine range is retained.

2. The mechanical behavior of the UFG alloy is characterized by the fact that its UTS and YS values are stably higher by 200 MPa in comparison with the CG alloy up to a temperature of 450 °C, which creates prospects of its successful application for producing GTE components.

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