Mechanical behavior of titanium alloy Ti-6Al-4V with vacuum-plasma protective coating V+(Ti-V)N at elevated temperatures

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Abstract. This work is devoted to improving the performance properties of the titanium alloy Ti-6Al-4V due to hardening by forming an ultrafine-grained structure (UFG) using severe plastic deformation (SPD) by equal channel angular pressing (ECAP) and then applying a protective coating V+(Ti-V)N on its surface by vacuum-plasma deposition. The effect of the coating on the increase in the strength characteristics of the UFG material is demonstrated in comparison with the CG and UFG state without coating.

1. Introduction
The titanium alloy Ti-6Al-4V is widely used as a structural material in aerospace and aircraft engine building due to its high specific strength and corrosion resistance. However, more and more strict requirements regarding the structural strength are imposed on products and parts of gas turbine engines due to their operation under high static and dynamic loads, temperature, erosion and corrosive effects. One of the most promising approaches to dramatically improve the mechanical and fatigue characteristics of metals and alloys is the formation of an ultrafine-grained (UFG) structure in them by the methods of severe plastic deformation (SPD) [1]. While the use of ionic surface modification by the vacuum plasma deposition of a protective coating provides resistance to wear, erosion and corrosive effects [2,3].

It is known that the most favorable combination of physico-chemical and mechanical properties is possessed by coatings based on titanium nitrides [2,3]. In our recent works [4, 5], a comprehensive analysis of the Ti+(Ti-V)N protective coating, which was deposited on the surface of the UFG titanium alloy T-6Al-4V, was carried out, where commercially pure Ti was used as the first sublayer. The results of this analysis showed that the use of such a combined approach increases the wear resistance and operational stability of two-phase titanium alloys. However, the use of V as the first sublayer can give an additional increase in erosion resistance, since this element has good viscosity [6]. Therefore, the purpose of this work is to study the mechanical properties of the V+(Ti-V)N vacuum-plasma protective coating at operating temperatures.
2. Material and experimental procedure
The titanium alloy Ti-6Al-4V was used as the material for investigation. The chemical composition of the alloy was (in wt%): 6.2% Al, 4.3% V, 0.02% Zr, 0.039% Si, 0.16% Fe, 0.06% C, 0.168% O, 0.015% N, 0.003% H, Ti-base. To ensure the conditions for plastic deformation of hard-to-deform materials, workpieces with a length of 20 mm were subjected to preliminary heat treatment (HT) by quenching in water at a temperature of 960 °C for 1 h and subsequent annealing at 600 °C for 4 h with air cooling to form a duplex α+β structure with a fraction of the primary α-phase no more than 25% [7].

The ultrafine-grained state was obtained by the SPD method of equal-channel angular pressing (ECAP), 4 passes according to the route Bc with an angle of intersection of the channels of 120° at a temperature of 750 °C (e=2.7 with a strain rate of 4 mm s⁻¹).

Prior to the coating deposition, the samples were subjected to electrolytic-plasma polishing (EPP), which is used to polish complex-profile parts from titanium alloys and other structural materials [8]. Then, the vacuum-plasma coating V+(Ti-V)N was deposited on the surface of all samples according to the technique described in [4, 5].

The microstructure of the samples was investigated using scanning and transmission electron microscopy (SEM and TEM, respectively). Investigations of the coating on substrates with different microstructures included the measurement of hardness at a load of 300 g for 15 s on a Struers Duramin instrument; the measurement of the coating thickness was carried out on a Calotest instrument, which made it possible to prepare a spherical cut of the coating to the base material (substrate). Cylindrical specimens with a diameter of 3 mm and a gauge length of 15 mm were used for the tensile tests. The tensile testing was performed at an initial strain rate of 10³ s⁻¹ at room and elevated temperatures on an Instron testing machine.

3. Results and their discussion
3.1. Microstructure of Ti-6Al-4V
The microstructure of the coarse-grained titanium alloy Ti-6Al-4V was a duplex structure (Figure 1a) with a primary α-phase size of ~ 7 µm and its volume fraction 65%, as well as a lamellar α+β phase.

Figure 1. Microstructure of Ti-alloy (a) in-received state, SEM-image; and after ECAP-processing: (b) SEM; (c) TEM.

SPD by ECAP completely transformed the lamellar component of the structure into a globular one (Figure 1b), with a grain / subgrain size of ~ 0.48 µm (Figure 1c).

3.2. Architecture and mechanical behaviour of vacuum-plasma protective coating V+(Ti-V)N
The architecture of the deposited coating with a total thickness of ~ 6 µm (Figure 2) consisted of the first sublayer V deposited on the UFG substrate of the Ti-6Al-4V alloy, the first functional layer (Ti-V)N, the second sublayer (Ti-V), and the second functional layer (Ti-V)N. Sublayers are not visible in the image due to their small thickness ~ 0.2 µm.
Figure 2. SEM-image of the Ti-alloy with the deposited vacuum-plasma coating V+(Ti-V)N.

Figure 3 shows the results of mechanical tensile tests at room and elevated temperatures, the scale on the left shows the dependence of the ultimate strength (UTS), and on the right, the dependence of the total elongation (δ). It is noted that the formation of the UFG state increases the ultimate strength of the titanium alloy Ti-6Al-4V by 30%, and the deposition of a protective coating gives an additional increase in strength by ~ 5% for UFG specimens in this temperature range. With an increase in temperature, a decrease in UTS is observed for all states, however, the V+(Ti-V)N coating restrains the softening of the UFG alloy in the temperature range of 350-400 °C, the total elongation of which was 25% with the coating and 35% without the coating.

Figure 3. Dependence of UTS and Total elongation on tensile test temperature of Ti-6Al-4V titanium alloy specimens in the CG, UFG states and V+(Ti-V)N coated.

Thus, it was found that the V+(Ti-V)N coating has a positive effect on the strength of the UFG alloy at room temperature and elevated temperatures up to 400 °C. This behavior is typical for vacuum-plasma coatings deposited on titanium alloys [4, 9], which is due to a change in the mechanism of crack initiation in the surface and the creation of a barrier effect in a coating with a higher modulus of elasticity than a substrate [4, 9].

The presented experimental data demonstrate the principal possibility of increasing the strength properties of the Ti-6Al-4V alloy with an ultrafine-grained structure at operating temperatures (up to
400 °C) by deposition of a high-strength and wear-resistant coating of the V+(Ti-V)N system by the plasma-vacuum method.

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