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Features of wear and friction in titanium

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Abstract. The characteristics of friction and wear during low-frequency reciprocating motion of the indenter in commercially pure titanium with coarse and fine grains are investigated. The role of the microstructure refining and the ratio of grain size and displacement amplitude is shown.

1. Introduction

Fretting wear is considered a special case of friction between two contact surfaces at very low amplitude <0.5 µm and a frequency of 0.001 Hz of cyclic movements [1]. During fretting, the contact surfaces are not removed from the contact area, and, therefore, the fracture products have almost no possibility to get out of the wear zone [2]. Fretting wear results in fretting fatigue, which leads to a decrease in fatigue strength and the number of cycles to failure by tens of percent [3, 4]. The scientific significance of research on fretting wear is associated with an understanding of the nature and mechanisms of friction in conditions of low amplitudes and frequencies of micromovements, as well as the possibility of modeling the wear process. In practical terms, the study of fretting wear is important for the attachment points of the compressor blades of aircraft engines, fuel elements in a nuclear reactor, riveted and bolted joints, bearings, electrical contacts, dental implants and other similar structures. Nevertheless, most of the tribological studies are still carried out in sliding friction mode. Titanium alloys, due to their high performance properties, are often used for the similar designs mentioned above. However, insufficiently high strength, poor thermal conductivity and high friction coefficient C_f lead to their high sensitivity to fretting fatigue. Therefore, studies of fretting wear of titanium alloys were very relevant, however, they were carried out for a material in a traditional coarse-grained state [5-8]. Among the many factors influencing fretting wear, displacement amplitude, test temperature, and grain size seem to be the most important in the study of friction and wear in structural materials. Unfortunately, there are relatively few works devoted to studying the effect of structure refinement [9-11]. Significant progress in understanding the role of structural refinement has been achieved in the study of the friction of ultrafine-grained (UFG) titanium alloys [12-14]. Note that the above studies of UFG and nanostructured (NS) titanium alloys were carried out under traditional friction conditions, far from fretting. As for the role of temperature in fretting, the study of two-phase coarse-grained titanium Ti-Sn-Al-Mo-Zr alloys in the temperature range from 20 to 600°C showed that the formation of oxide films on the surface of the samples contributes to a decrease in the C_f and the wear rate with an increase in temperature [1]. The purpose of this work was to study the effect of

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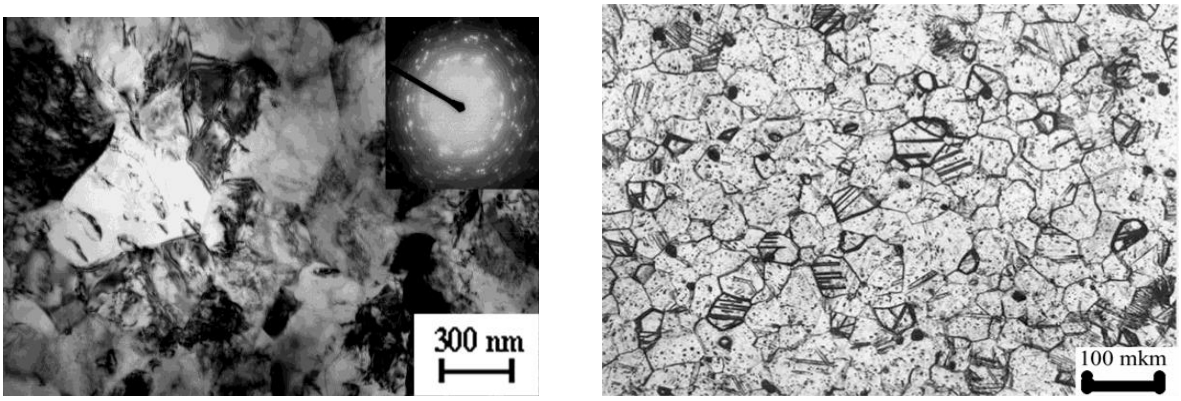
grain size on the fretting behavior of commercially pure titanium at room temperature and a relatively small amplitude of indenter displacement.

2. Material and research methods

The starting material was commercially pure titanium Grade 4 in the form of a bar 20 mm in UFG state (grain size d_z = 0.45 μm), obtained by equal channel angular pressing. Two plates 2 x 6 x 43 mm^3 were cut from the bar along the longitudinal axis, one of which was subjected to annealing (680°C, 1 hour) to obtain a coarse-grained (CG) state (d_z = 45 μm). To prevent the possible influence of roughness, the sample plates were polished before testing for fretting wear so that the surface roughness would be Ra ≤ 0.15 μm. Fretting wear tests were carried out without lubrication on a CETR UMT-3M tribometer using a reciprocating motion in a direction parallel to the pressing axis of the sample with a displacement amplitude of A = 300 μm and a frequency of 13 Hz (3.9 $mm{\cdot}s^{-1}$). The experiment was carried out in air, at a room temperature of 20°C, for 128 min. Tungsten carbide ball of ∅6 mm as counter body was used, the load was 3 N. The choice of the force value is based on the capabilities of the device (on the one hand) and the idea of the independence of C_f on the normal force [15]. The total linear wear of the sample and the indenter was recorded by a stepping motor. For greater reproducibility of the wear test results for each mode, measurements were made at three points. The morphology of the wear places was examined using an Olympus SZ microscope. Fretting behavior was assessed by the dependences of wear and C_f on time, as well as by the wear morphology of contact points.

3. Results

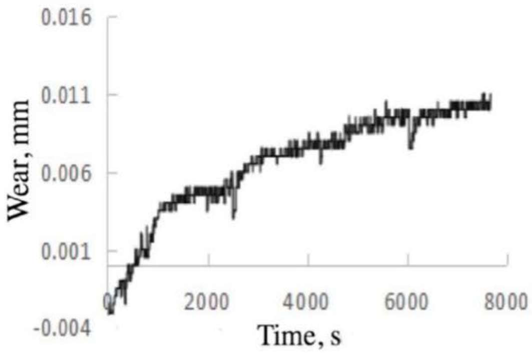
Figure 1 shows the microstructures of UFG titanium (figure 1 (a)) and CG titanium (figure 1 (b)).



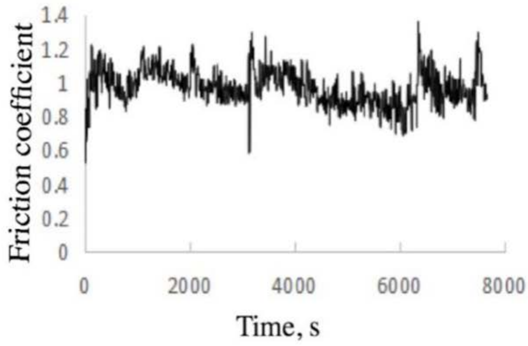
(a) (b)

Figure 1. Microstructures of ECAP titanium before (a) and after (b) high temperature annealing.

Figure 2 shows typical dependences of wear and C_f on time for CG titanium at room temperature. It is noted that, with the exception of the initial stage, the wear is positive and increases exponentially with time (figure 2 (a)). In this case, C_f has a wave-like dependence in time and high values in the range from 0.8 to 1.2 (figure 2 (b)).



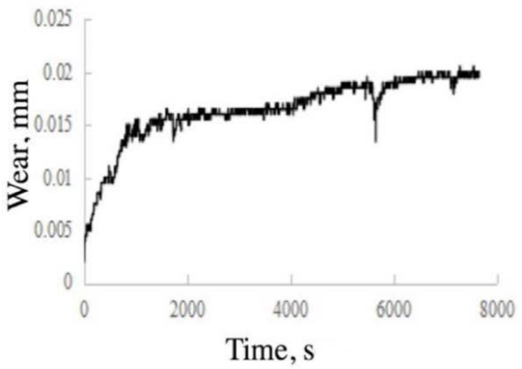
(a)



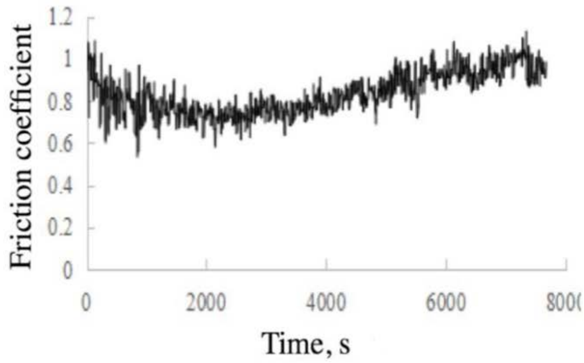
(b)

Figure 2. Dependence of linear wear (a) and coefficient of friction (b) on time for SC titanium at 20°C and A = 300 μm.

Figure 3 shows typical dependences of wear and C_f on time for UFG titanium at room temperature and amplitude of 300 microns. For UFG titanium, wear over time is characterized by a decrease in the initial wear rate to 5 $\mu m \cdot hour^{-1}$ (figure 3 (a)). The C_f curve has stages of decrease, reaching a stationary stage (plateau), followed by its increase (figure 3 (b)).



(a)



(b)

Figure 3. Dependence of linear wear (a) and friction coefficient (b) on time for UFG titanium at 20°C and A = 300 μm.

Table 1 summarizes the results of measuring the average values of wear, C_f, the initial size of the contact spot for CG and UFG titanium at a temperature of 20 °C and a displacement amplitude of 300 μm at the end of the tests. Maximum wear has positive values and corresponds to UFG titanium. At displacement amplitude of 300 μm, this value is twice that for CG titanium.Structure refinement did not affect the friction coefficient, the maximum value of which is 1.

The mechanism of friction and its features in UFG and KZ titanium, the morphology of contact spots of the samples with the indenter were studied using an optical microscope. The general view of the contact spots after tests at room temperature is shown in figure 4.

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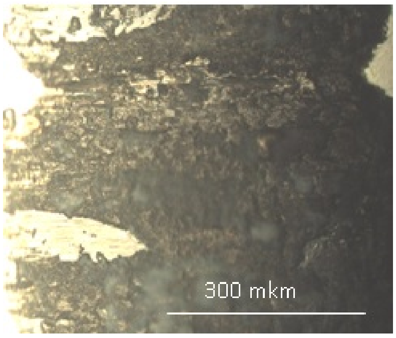
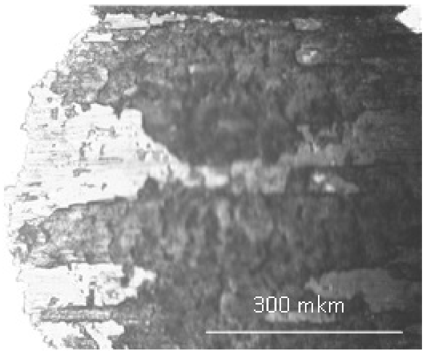


(a)



(b)

Figure 4. General view of the contact spots of CG (a) and UFG (b) titanium after testing at 20°C and A = 300 μm.

It can be seen that the morphology of contact spots for CG and UFG titanium is typical for abrasive wear and practically does not depend on the structure refinement. The linear size of the contact spots at the end of the test exceeds the displacement amplitude by 3 and 2.5 times, respectively. The adhesion zone typical for fretting wear, as well as wear products around the contact patch, are absent.

Table 1. Wear and friction coefficient.

Structure state	Hv, (MPa)	Initial contact area size (R, μm)	Displacement Amplitude (A, μm)	Wear (μm)	C_f
CG	2860	~75	300	10	1.0
UFG	3320	~70		20	1.0

4. Discussion

The results obtained showed a number of features in the tribological behavior of titanium. In both structural states, wear develops over time in two stages, which differ in the wear rate - accelerated at the beginning and slowed down at the end. The deceleration of the wear rate and its stabilization over time indicates the formation of a "third body" between the contacting surfaces.

Despite the higher microhardness of UFG titanium, the total amount of wear in this state is twice that for CG titanium (table 1). This is most likely due to the density of grain boundaries, which in UFG titanium is several orders of magnitude higher than in CG titanium. Since it is known that grain boundaries are a source of defects and places of destruction, their multiple intersections lead to increased wear.

The different sign of the wear in the CG and UFG titanium at the initial stage of testing is due to the different thickness of the oxide film and its subsequent destruction [1]. It is known that the corrosion resistance of UFG titanium is higher than the similar characteristic of CG titanium, which is associated with the high rate of formation of a protective film with a more dispersed structure [17]. The average C_f values for both states were approximately the same and high. A distinctive feature is the presence of wavelike behavior of the time dependence of the friction coefficient for CG titanium (figure 2 (b)). One of the explanations for this phenomenon can be the processes of hardening and softening due to refinement and destruction of the surface layer ("third body") between the indenter and the material. This process also manifests itself for UFG titanium, but with a long period (figure 3 (b)).

The ratio of the displacement amplitude and the size of the contact zone A/R> 1 shows that the conditions for fretting are not realized and the wear process corresponds to traditional friction [2].

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Noteworthy is the many times higher size of the contact spots in comparison with the displacement amplitude. Perhaps this fact is associated with an increase in temperature on the contact surface during the movement of the indenter.

5. Conclusions

1. The tribological behavior of titanium is a complex phenomenon that depends not only on the hardness and corrosion resistance of the surface layer, but also on the structure refinement.
2. Wear in UFG titanium is higher than in CG titanium, while the friction coefficient does not depend on the grain size.
3. The investigated conditions of the experiment, the amplitude and frequency of movement, exclude the possibility of fretting wear.

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