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Investigation on wear characteristics of a titanium alloy/steel tribo-pair

K.M. Chen, Y. Zhou, X.X. Li, Q.Y. Zhang, L. Wang *, S.Q. Wang *

School of Materials Science and Engineering, Jiangsu University, Zhenjiang 212013, China

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ABSTRACT

Dry sliding wear tests of a titanium alloy against AISI 52100 steel as a tribo-pair were performed under 50–250 N at 25–600 °C. The wear characteristics of the titanium alloy and the counterface steel were investigated. The results showed that tribo-layers always existed on the worn surfaces of titanium alloy (pins) and steel (disks) in various test conditions. At 25–200 °C, the titanium alloy presented much higher wear rate than the steel. As the temperature increased to 400–600 °C, the wear rate was substantially reduced to very low values for both of the titanium alloy and steel. For titanium alloy (pins), the severe-to-mild wear transition was attributed to the formation of tribo-layers containing tribo-oxides, especially Fe_2O_3. The tribo-pair of the titanium alloy sliding against AISI 52100 steel was suggested to an ideal sliding system for elevated-temperature applications.

1. Introduction

Since titanium alloys are characterized by low density, high specific strength and good corrosion resistance, they are widely applied in many industrial fields [1–4]. However, titanium alloys were reported to possess poor tribological properties because of their low plastic shearing resistance, work hardening ability and no protection exerted by their tribo-oxides [5,6]. The poor wear resistance severely hinders the applications of titanium alloys. The normal way to improve the wear resistance is to use various surface treatment coatings on titanium alloys. Hence, the research concerning the wear of titanium alloys has been limited till now [5–9].

The widely accepted views on the tribological properties of titanium alloys are mainly based on the wear tests at room temperature [5–9]. However, the research on the wear properties of titanium alloys at elevated-temperature was sparsely reported. Recently, our study indicated that Ti–6Al–4V alloy presented excellent wear resistance at a high temperature of 400 °C [9]. However, it does not mean that this high wear resistance is of universality for all titanium alloys. In order to explore the wear-related engineering applications of titanium alloys, a detailed study on their high-temperature tribological characteristics is needed.

Ti–6.5Al–3.5Mo–1.5Zr–03Si alloy (code-named TC11), a typical dual phases ($\alpha + \beta$) titanium alloy, is widely applied as advanced structural material in aeronautic gas turbine components, such as disks and blades of compressor, which works at elevated-temperature around 500 °C [10–12]. Due to the additions of beta isomorphous element Mo, neutral element Zr and beta eutectoid element Si into Ti–6Al base, TC11 alloy has a higher strength, better creep resistance and more excellent thermal stability, especially at elevated temperatures compared with Ti–6Al–4V alloy [10–12]. Hence, an investigation on the dry sliding wear behavior of TC11 alloy at various temperatures is of important engineering and theoretic significances.

The purpose of this study is to explore the wear characteristics of a titanium alloy/steel tribo-pair at various temperatures. In the present test, TC11 alloy was subjected to dry sliding wear against AISI 52100 steel; the wear performance and mechanism of TC11 alloy and AISI 52100 steel were investigated as a function of the temperature and load. Especially, the wear resistance of TC11 alloy and the function of tribo-oxide layers were focused on to be studied.

2. Experimental procedure

2.1. Material preparation

TC11 alloy and AISI 52100 steel were selected as the pin and disc of a tribo-pair, respectively. The chemical compositions of TC11 alloy are 5.84 Al, 1.57 Zr, 3.86 Mo, 0.32 Si and balance Ti (wt.%). TC11 alloy was machined into the pins with a diameter of 6 mm and a height of 12 mm. Then it was solid dissolved at 955 °C for 2 h, water quenched and subsequently aged at 540 °C for 4 h and cooled in air to achieve the microstructure consisting of equiaxed α particles in an aged β matrix (about 36 HRC).

* Corresponding authors. Tel.: +86 51188797618.
E-mail addresses: 929620176@qq.com (L. Wang), shuqi_wang@ujs.edu.cn (S.Q. Wang).

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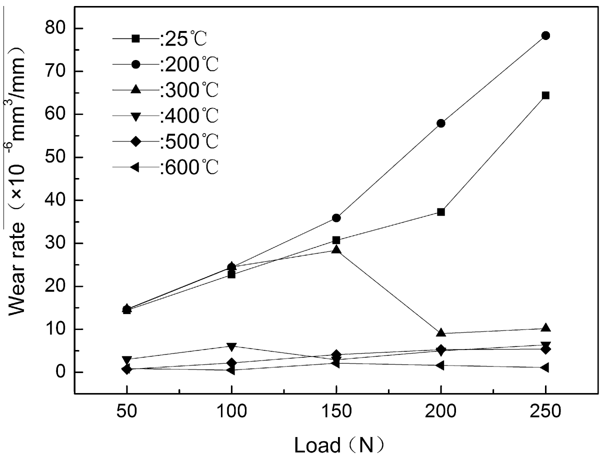

Fig. 1. Wear rate of TC11 alloy as a function of temperature and load.

Commercial AISI 52100 steel was machined to the discs with the dimensions of 70 mm diameter and 10 mm thickness. AISI 52100 steel was austenitized at 850 °C, oil quenched, then tempered at 600 °C for 2 h to achieve the hardness of 38–40 HRC.

2.2. Wear test

Dry sliding wear tests were carried out on an MG-2000 type pin-on-disc high temperature wear tester. All wear tests were performed in air with the following parameters: 25, 200, 300, 400, 500 and 600 °C for the ambient temperature; 50–250 N in a step of 50 N for the normal load; 1 m/s for the sliding speed; 1.2×10^3 m for the total sliding distance. Before each test, the contact surfaces of the pins and the discs were prepared by grinding against a 600-grit silicon carbide paper and a grinding machine to attain average surface roughness (R_a) values of about 0.38 and 0.3 μm, respectively, subsequently cleaned with acetone and dried.

The wear data came from the wear loss of the pins and discs, respectively. The wear loss was determined from the mass loss measurements by using an electronic balance with an accuracy of 0.01 mg. Each measurement was preceded by an ultrasonic washing in acetone and then drying. The wear rate (Ws) was calculated in term of the formula: $Ws = \Delta V/L$, where ΔV is the wear volume loss (mm^3) of the pin or disc, which could be calculated from their wear losses and densities (4.5 g/cm^3 and 7.8 g/cm^3) of TC11 alloy and AISI 52100 steel, respectively, L is the sliding distance (1.2×10^3 mm). Three tests were repeated for each test condition.

Morphologies and compositions of the worn surface and its cross-section at subsurfaces were examined by a JSM-7001F type scanning electron microscope (SEM) and an Inca Energy 350 type energy dispersion spectrometer (EDS). Phases on the worn surface were identified by a D/Max-2500/pc type X-ray diffractometer (XRD) with Cu Kα radiation. The microhardness of tribo-layer and matrix was measured by an HVS-1000 type digital microhardness tester with a load of 0.49 N and a hold time of 15 s. The hardness of TC11 alloy and AISI 52100 steel after heat treatment was determined by an HR-150A type Rockwell apparatus.

3. Results and analysis

3.1. Wear rate of the tribo-pair

Fig. 1 shows the wear rate curve of TC11 alloy (pins) as a function of the temperature and the load. At 25 and 200 °C, the wear rate rapidly increased with an increase of load; their wear rate difference was very small under the load of 50–100 N. When the load surpassed 100 N, the wear rate at 200 °C was much higher than that at 25 °C. At 300 °C, the wear rate rapidly increased under the load of 50–150 N, then obviously decreased at more than 150 N not to almost vary at 200–250 N. As the temperature reached 400–600 °C, the wear rates dramatically decreased compared with those at 25–300 °C. At 400 °C, with an increase of load, the wear rate increased slightly under 50–100 N, and had a slight decrease at 150 N, then kept a minor vibration at 200–250 N. The variations of the wear rate at 500 and 600 °C as a function of the load have the same regularity. On the other hand, the wear rate reached relatively low values and had almost no variation with the increase of load. And the wear rates of TC11 alloy at 600 °C were slightly lower than those at 400 and 500 °C and reached extremely low values.

The above results demonstrate that TC11 alloy presented different wear behavior under various temperatures and loads. It is clear that TC11 alloy possessed poor wear resistance at room temperature, which is consistent with the traditional views. However, the wear rates of TC11 alloy at 300 °C and 200–250 N and at 400–600 °C were lower than 10×10^{-6} mm^3/mm. It can be seen that TC11 alloy exhibited excellent wear resistance at elevated-temperature, especially at 600 °C.

In a tribo-system, the wear rates of sliding part (the pin) and counterface (the disc) are equally important. Fig. 2 illustrates the comparison between the wear rates of TC11 alloy and AISI 52100 steel as a function of load at 25 and 600 °C. At 25 °C, compared with the higher and rapidly increased wear rate of TC11 alloy, the wear rate of AISI 52100 steel slightly increased with an increase of load and maintained at a relatively low level ($3.43–5.13 \times 10^{-6}$ mm^3/mm). It is clear that AISI 52100 steel presented a significantly higher wear resistance than TC11 alloy at room temperature. However, both of TC11 alloy and AISI 52100 steel possessed extremely low wear rate (0.26×10^{-6} mm^3/mm) at 600 °C. Therefore, it was suggested that the tribo-pair (TC11 alloy/AISI 52100 steel) is an ideal frictional system at elevated-temperature.

3.2. XRD analysis of worn surfaces

In order to obtain the important message on the formation of tribo-oxides, X-ray diffraction analysis of the worn surfaces was conducted. The XRD results of TC11 alloy (pins) and AISI 52100 steel (discs) in various conditions are illustrated in Figs. 3 and 4, respectively. As for TC11 alloy, there were only characteristic peaks of α-Ti on the worn surfaces at 25–200 °C (Fig. 3a and b); trace TiO_2

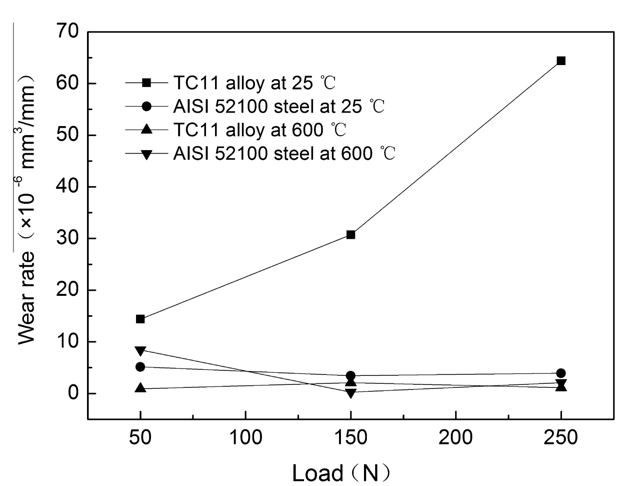

Fig. 2. Wear rate of TC11 alloy and AISI 52100 steel as a function of load at 25 and 600 °C.