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Artificial oxide-containing tribo-layers and their effect on wear performance of Ti-6Al-4V alloy

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

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

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ABSTRACT

Artificial oxide-containing tribo-layers were in situ fabricated by supplying the particles of MoS_2, Fe_2O_3 or their mixtures onto the sliding interface of Ti-6Al-4V alloy/AISI 52100 steel. Both of MoS_2 and Fe_2O_3 particles were noticed to directly partake in the formation of tribo-layers. Insert-type and cover-type tribo-layers were artificially fabricated by MoS_2-rich additives and Fe_2O_3-rich ones, respectively; the latter presented more marked reduction of wear. The friction and wear of titanium alloy were substantially improved because of the artificial tribo-layers. The artificially fabricated oxide-containing tribo-layers would be expected for titanium alloys to directly apply in rigorous sliding conditions without any use of surface engineering means.

1. Introduction

The wear of metallic alloys is a complicated process. The cooperative effect of thermal, mechanical and chemical actions often leads to abundant changes of sliding surfaces and subsurfaces [1–3]. A tribo-layer is widely formed on worn surfaces of various metallic alloys [4–9]. Actually, the tribo-layers can be classified into tribo-oxide layers or no-oxide tribo-layers [10–12]. As tribo-layers, especially tribo-oxide layers, exist on worn surfaces, wear behavior and wear mechanism would be changed.

Owing to the existence of oxides, tribo-oxide layers possess considerably high hardness compared to bulk materials, which can be regarded as a load-bearing medium during sliding [13–15]. In this case, the wear mainly relies on the formation and delamination of tribo-oxide layers, whereas the substrate materials merely provide a support. As tribo-oxide layers exist on worn surfaces, the severe wear of metal would be delayed, or even suppressed, and the severe-to-mild wear transition occurs simultaneously. Thus, the tribo-oxide layer is a decisive factor for wear behavior as well as wear mechanism of the sliding system. On the contrary, no-oxide tribo-layers' compositions are similar to sliding and counterface materials, thus still metallic in essential. In this case, they provide no or little protection [10–12]. Clearly, tribo-oxide layers, rather than no-oxide tribo-layers, are considered to be protective in wear-reducing effect.

The existence of protective tribo-oxide layers essentially improves the wear resistance of metals and simultaneously transforms the mechanism from adhesive wear (even seizure) into oxidative mild wear. This is a common phenomenon during dry sliding. Rigney generalized that dry sliding wear of metals is related to the plastic deformation, removal, transfer, reaction with the environment and mechanically mixing of material [2]. It is implied that the formation of tribo-layers is a mechanically alloying of wear particles. Jiang et al. stated meticulously the forming process of tribo-layers and asserted that the characteristics of tribo-layers depend on their chemical ingredient, i.e., the amount of oxidative particles [15]. In addition, the significance of wear particles was also extensively confirmed in other works [16–19].

However, for the formation and function of the tribo-oxide layer, there are three unfavorable drawbacks for engineering applications, as is summarized in the following. (1) The protective tribo-oxide layers are formed from wear debris particles through consuming the underlying substrate materials. This implies that there is a severe "running-in" in earlier period. (2) The forming process needs a harsh sliding condition to oxidize metallic debris, such as faster speeds and/or higher temperatures. This means that the protective tribo-oxide layers cannot be spontaneously generated in a moderate condition. If so, the metal substrate should undergo severe wear firstly. (3) The protective tribo-oxide layers can ameliorate the wear resistance, but do not always reduce friction. According to previous works [19], hard oxides increased friction coefficients and brought about a loud whistle.

In term of three drawbacks mentioned above, the rapid formation of protective tribo-layers can be induced without an unprovoked waste of substrate by artificially supplying particles onto the sliding interface. Their protective function is commonly believed to be derived from the load-carrying capacity of oxidative particles in tribo-layers. If some oxides directly participate in the process, the harsh sliding condition

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* Corresponding author.
E-mail address: shuqi_wang@ujs.edu.cn (S.Q. Wang).

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would not be needed. Fe_2O_3 is a common tribo-oxide in the sliding system of titanium alloys and steels [10–12], which can act as a good load-carrying component because of high Mohs scratch hardness of 5.5 [20]. To reduce friction coefficient, MoS_2 as a lubricant would be better. However, like other lubricants, MoS_2 cannot improve the wear resistance of titanium and titanium alloy [21,22]. A preliminary work were performed to improve wear performance of the titanium alloy by addition of Fe_2O_3 and TiO_2 nano particles, which simulate Ti alloy/ steel sliding system [23]. The additions of TiO_2 and Fe_2O_3 nano particles were confirmed to accelerate the formation of tribo-layers. Especially, the functions of TiO_2 and Fe_2O_3 were distinguished in the first time. The latter was noticed to present a predominated protective function in Ti alloy/ steel sliding system. In present studies, a scheme was designed to induce a rapid formation of protective and lubricative tribo-layers on a titanium alloy, which are expected to possess a load-bearing capability of Fe_2O_3 and a lubricative function of MoS_2 through artificially supplying particles onto the sliding interfaces. The formation and function of the artificial tribo-layers were explored. As a comparison, the respective role of Fe_2O_3 and MoS_2 in the formation of tribo-layers and effect on friction and wear behavior of titanium alloys were also investigated.

2. Experimental procedures

The ferric oxide (α-Fe_2O_3) and molybdenum disulfide (MoS_2) with a diameter of 30–50 nm and 1000 nm respectively, provided by Jing Rui New materials Co., Ltd. (Xuancheng, China), were used as raw materials of artificial tribo-layers. The additives were prepared by mechanically mixing MoS_2 and different-content Fe_2O_3 (0, 20, 50, 80, 100 wt%). Thereinto, Fe_2O_3 has a higher Mohs scratch hardness of 5.5, whereas MoS_2 ones possess a layered structure with the value below 1.5 [20]. Because of the transformable shape, larger MoS_2 particles were expected to enfold nano-Fe_2O_3 during sliding.

Sliding wear tests were carried out in air on a MPX-2000 pin-on-disc type wear tester. The pin and disc specimens made from Ti-6Al-4V alloy and AISI 52100 steel were cut into the dimensions of $\Phi 5$ mm×22 mm and $\Phi 34$ mm×10 mm, respectively. Ti-6Al-4V alloy pins were solution-treated at 955 °C for 2 h, water quenched, subsequently aged at 540 °C for 4 h and cooled in air to achieve a hardness of 38 HRC, while AISI 52100 steel discs were austenitized at 850 °C for 20 min, oil quenched and tempered at 400 °C for 2 h to achieve an average hardness of 50 HRC. Prior to every sliding, the specimens were polished to achieve an average roughness of 1.5 μm in *Ra* by a surface-grinding machine and 400# silicon carbide papers, respectively.

Fig. 1 illustrates the schematic diagram of the wear tester. The pin and disc specimens were fixed on a rotating upper shaft by a holder and on the static lower shaft by mechanical fasteners, respectively. The dead weight was imposed onto the disc through the lower shaft. The wear tester was further modified to supply the additives onto the sliding interface of specimens in a dashed rectangle area. The adhesive tapes and foam plastics were applied to enclose and center the lower disc, respectively, to retain the additives within wear tracks.

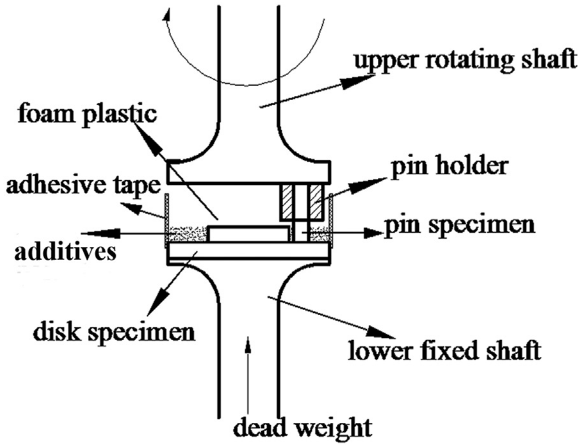

Fig. 1. Schematic diagram of wear tester.

In current study, the sliding wear tests were divided into two parts. The first was to induce the rapid formation of artificial tribo-layers under low loads, while the second was to evaluate their load-carrying capability under high loads. In the first part, the sliding wear tests were performed at 0.5 m/s for a total sliding distance of 840 m at room temperature in the load range of 10–50 N. Prior to the starting of sliding, 0.5 g additives were firstly supplied onto wear tracks. To guarantee the sufficient replenishment, 0.2 g additives were repeatedly added every 168 m sliding until the termination of test. After four supplements, the total weight of additives was about 1.3 g for each test. The detailed procedure was presented elsewhere [23]. In second part, to evaluate the load-bearing capability of artificial tribo-layers, merely 0.5 g additives were supplied before testing under higher loads of 50–250 N with no other changes in sliding parameters and no successive replenishment during sliding.

The wear was determined by measuring the mass loss with an electronic balance (0.01 mg). Each measurement was preceded by an ultrasonically washing in acetone and drying. The wear rate was defined as the volume loss of unit sliding distance (mm^3/mm), where the volume loss was achieved by the mass loss divided by the density of the specimens. Each data point presented the mean value of several repeated wear tests. Additionally, the dry sliding wear test without any additives was also performed as a comparison. During sliding, the coefficient of friction was consecutively recorded with a digital data acquisition system.

The phase, morphology and composition of the worn surface were investigated by a D/Max-2500/pc type X-ray diffractometer (XRD) with Cu Kα radiation, a JSM-7001F type scanning electron microscope (SEM) and an Inca Energy 350 type energy dispersion spectrometer (EDS), respectively. Then, the specimens were cut parallel to the sliding direction and perpendicular to the worn surface. Through being mounted, polished and eroded, the cross-section features of tribo-layers were also characterized by SEM and EDS. Simultaneously, the regional thickness and the shear angle of plastic flow at worn subsurfaces was measured by the matched software of SmileView in SEM, so as to evaluate the function of artificial tribo-layers. The hardness of Ti-6Al-4V alloy and AISI 52100 steel was determined by an HR-150A type Rockwell apparatus.

3. Results and analysis

3.1. Characterization of tribo-layers

Figs. 2 and 3 exhibit the morphological characteristics of artificial and original tribo-layers of Ti-6Al-4V alloy with continuously-supplied additives and no additive. The tribo-layers were presented as two kinds of typical characteristics, i.e., covering the worn surface (cover-type) or being inserted into the subsurface (insert-type).

As Ti-6Al-4V alloy slid against AISI 52100 steel without any additive, the tribo-layer formed in situ was loosely and sporadically distributed in some regions of worn surfaces, as shown in Fig. 2a. This original tribo-layers composed by metallic particles was buried into the substrate of Ti-6Al-4V alloy. As MoS_2 and MoS_2-rich (MoS_2+20 wt% Fe_2O_3) additives were supplied onto the sliding interface, the artificial tribo-layers, made up of lamellar MoS_2 with additional Fe_2O_3 particles or not, were different from that of no additive. Through many-field observation, they were loose and non-homogenous in thickness. Under a load of 10 N, the tribo-layers adhered to the asperities of titanium alloy and covered the worn surface, called as the cover-type tribo-layers, as shown in Fig. 2b and e. As the load increased, the tribo-layers became thick and compact. The cover-type tribo-layers were trans-