Dry Sliding Wear Characteristics of Ti-6.5Al-3.5Mo-1.5Zr-0.3Si Alloy at Various Sliding Speeds

X.X. LI, Y. ZHOU, Y.X. LI, X.L. JI, and S.Q. WANG

Dry sliding wear behavior of Ti-6.5Al-3.5Mo-1.5Zr-0.3Si (hereafter called TC11) alloy was investigated under various sliding speeds and distances. TC11 alloy presented marked variations of the wear rate with an increase of sliding speed from 0.5 to 4 m/s. Especially at high loads, a severe-to-mild wear transition occurred with the climax at 2.68 m/s, the lower values were at 0.5 to 1.5 m/s, and the lowest point was at 4 m/s. TC11 alloy also presented a mild-to-severe wear transition at 2.68 m/s with an increase of sliding distance, but not at the others. With a thorough examination for worn surfaces, subsurfaces and wear debris, the distinct characteristics were noticed to correspond to the wear behavior in various conditions. The highest wear rate at 2.68 m/s and the lowest wear rate at 4 m/s, respectively, corresponded to no oxides and large wear debris particles as well as more oxides and small wear debris particles. The tribo-oxides formed at room temperature were suggested to be protective, which seemed to be contradictory to the popular view that tribo-oxides of titanium alloys possess no wear-reducing effect.

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I. INTRODUCTION

Ti-6.5Al-3.5Mo-1.5Zr-0.3Si (TC11), typically $\alpha + \beta$ alloy, is widely used in aeronautical industries because of its high specific strength, fracture toughness, and ductility. However, little research has been done concerning the wear property of TC11 alloy. Therefore, it is of much interest to explore the wear behavior of TC11 alloy to evaluate its feasibility of application in sliding-wear conditions. Recently, the wear characteristics of titanium alloys have received increased attention due to the continuous widening applications. However, titanium alloys are not considered to be applicable in sliding applications because they are usually reported to have a low sliding wear resistance.[1–9] In engineering applications, the improvement for the wear performance of titanium alloys is usually made by means of surface modifications. Furthermore, this was suggested to be mainly attributed to no protective role of the tribo-oxide layers formed on the worn surfaces of titanium alloys. In the limited research on the wear of titanium alloys, most of the researchers, such as Molinari *et al.*,[4] Straffelini and Molinari,[5] Alam and Haseeb,[6] and Qiu *et al.*[9] considered that tribo-oxides of titanium alloys were loosened, brittle and thus providing no protection from wear. This seemed to give a reasonable explanation for the poor wear resistance of titanium alloys.

However, Chelliah and Kailas[10] considered that in the dry sliding wear of titanium, tribo-oxides were of protection function. Recently, Gu *et al.*[11] pointed out that TiO_2 could provide lubrication and remarkably improved the load-carrying capacity and antiwearability. In addition, in our recent research on the wear behavior of titanium alloys (Ti-6Al-4V and Ti-5.84Al-3.86Mo-1.57Zr-0.32Si alloys) as a function of temperature, we found that titanium alloys presented excellent high-temperature wear resistance, and more importantly, this was attributed to the protective function of tribo-oxides.[12–15] As for the wear resistance of titanium alloys and the function of their tribo-oxides, the abovementioned results seem to be contradictory. Hence, the wear behavior and mechanism of titanium alloys need further exploration and clarification.

In the current investigation, the dry sliding wear tests were carried out for TC11 alloy at room temperature and various sliding speeds; the wear behavior of TC11 alloy was investigated by a thorough analysis for worn surfaces, subsurfaces, and wear debris, especially for tribo-layers. The wear characteristics and wear mechanisms of TC11 alloy under various conditions were explored and the function of tribo-oxides was further clarified.

II. MATERIALS AND EXPERIMENTAL PROCEDURE

A commercial TC11 alloy was taken from a hot-extruded rod of 70 mm in diameter and machined to pins in a cylinder form with a diameter of 5 mm and a length of 22 mm. Its chemical composition (wt pct) was 5.84 Al, 3.86 Mo, 1.57 Zr, 0.32 Si, and balance Ti. A

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commercial AISI 52100 steel was chosen as disks with the dimensions of 40 mm diameter and 8 mm thickness. The TC11 alloy was solutionized at 1228 K (955 °C) for 2 hours, water quenched and subsequently aged at 813 K (540 °C) for 4 hours, and cooled in air (32 HRC). Its microstructure consists of equiaxed α particles in an aged β matrix. AISI 52100 steel was austenitized at 1123 K (850 °C), and then oil quenched and tempered at 673 K (400 °C) for 2 hours to achieve an average hardness of 50 HRC.

The dry wear tests were performed on a pin-on-disk wear tester (MPX-2000 type) at room temperature. The test parameters were selected as follows: the normal load of 10 to 50 N, the sliding velocity of 0.5 to 4 m/s, and the sliding distance of 600 to 3600 m. All experimental data of the wear tests came from the measurement of pin specimens. The wear was determined by measuring the mass loss of the pins in an electronic balance with an accuracy of 0.01 mg. The wear rate was calculated through the volume loss divided by the sliding distance, where the volume loss was defined as the mass loss of unit density. At least three tests were performed for each experimental point.

The morphology of worn surfaces, subsurfaces, and wear debris was examined using a JSM-7001F type scanning electron microscope (SEM), and the related compositions and phases were examined by means of an energy dispersion spectrometer (EDS) and a D/Max-2500/pc type x-ray diffractometer (XRD) with Cu K_α radiation. The hardness of the alloys after heat treatment was determined by an HR-150A type Rockwell apparatus. To evaluate the property of tribo-layers, the microhardness distributions at subsurfaces were also measured using an HVS-1000 type digital microhardness tester with a load of 0.49 N and a hold time of 15 seconds.

III. RESULTS AND ANALYSIS

A. *Wear Rates and Frictional Coefficients*

The wear rates of TC11 alloy as a function of the sliding velocity are shown in Figure 1. It can be observed that TC11 alloy presented the variation of wear rate with an increase of sliding speed from 0.5 m/s to 4 m/s. For each speed, the wear rates increased with the increase of the applied load. In detail, the wear rates of TC11 alloy underwent two substantial transitions. When the sliding velocity increased from 0.5 to 4 m/s, the wear rate first decreased, experienced an inflection point at 0.75 m/s, then rapidly increased to reach another inflection point at 2.68 m/s, and finally substantially decreased to the lowest point at 4 m/s. Especially at high loads, a severe-to-mild wear transition occurred with the climax at 2.68 m/s, the lower values were at 0.5 to 1.5 m/s, and the lowest point was at 4 m/s. To interpret in depth this large variations of the wear rate *vs* velocity curve, the wear behavior as a function of sliding velocity is worthy to be explored, especially the wear characteristics at 0.75, 2.68, and 4 m/s.

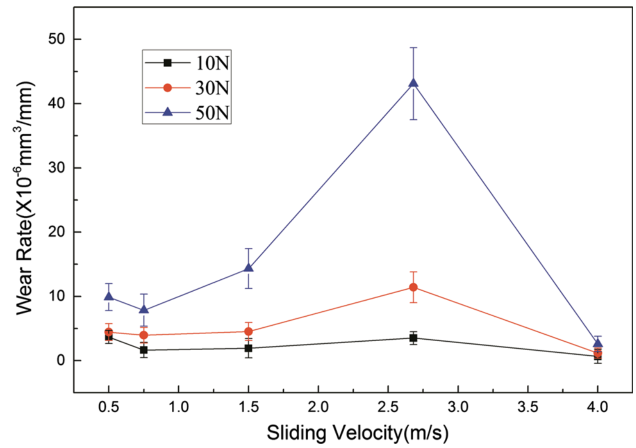

Fig. 1—Wear rates as a function of sliding velocity under various loads.

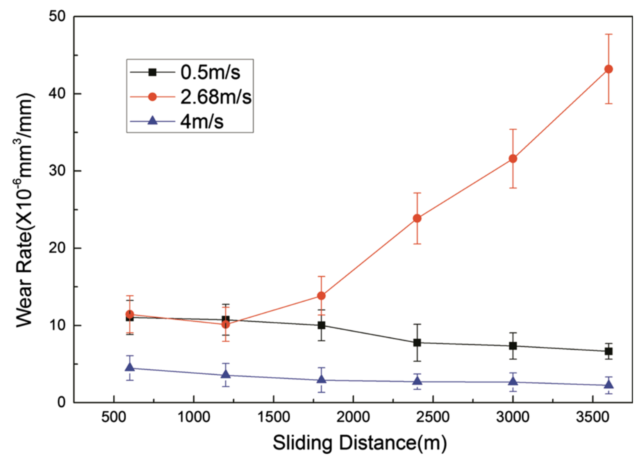

Fig. 2—Wear rates as a function of sliding distance under at various loads,sliding speeds, and a load of 50 N.

The wear rates of TC11 alloy as a function of the sliding distance at 0.75, 2.68, and 4 m/s are shown in Figure 2. At 2.68 m/s, the wear rate slowly increased before 1800 m, and then it rapidly increased. At 0.75 and 4 m/s, the wear rates marginally decreased at first with an increase of distance, and then subsequently stabilized after 1800 m. It is clear that TC11 alloy presented two changed trends in the wear rate *vs* distance curve. TC11 alloy also presented a mild-to-severe wear transition at 2.68 m/s with the increase of sliding distance, but not at the others.

The average friction coefficients as a function of the sliding speed at 10 and 50 N were illustrated in Figure 3. It can be observed that the variation trend of the friction coefficient with the sliding velocity and load is roughly similar to that of the wear rate. The wear rates and the average friction coefficients shared two transition points at 0.75 and 2.68 m/s, irrespective of the load. At 2.68 m/s, TC11 alloy possessed high wear rates and friction coefficients. Conversely, at 0.75 and 4 m/s, the wear rates and friction coefficients were substantially reduced.

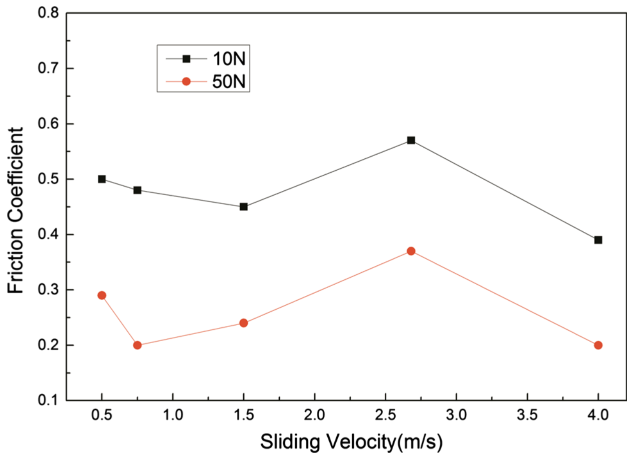

Fig. 3—Average friction coefficients of TC11 alloy as a function of sliding velocity at 10 and 50 N.

B. *Phases and Morphology of Worn Surfaces*

The phases of worn surfaces at various sliding speeds and a load of 50 N for a sliding distance of 1800 and 3600 m are illustrated in Figure 4. It can be noticed that the phases on worn surfaces were different under various conditions. Besides titanium as main phase, oxides started to appear at 0.75 and 4 m/s. At 0.75 m/s, trace oxides TiO and TiO_2 existed on worn surfaces. As the sliding distance increased, the amount of oxides remained the same. At 4 m/s, a small amount of oxides TiO and TiO_2 appeared on worn surfaces. As the sliding distance increased, the amount of oxides slightly increased. Interestingly, at 2.68 m/s, there were almost no oxides on worn surfaces.

The morphology of worn surfaces at various sliding speeds for a sliding distance of 1800 and 3600 m is shown in Figure 5. All the worn surfaces presented delamination characteristics with many cracks and some oncoming delamination places. Based on the XRD patterns of worn surfaces, their delamination characteristics were different. At 2.68 m/s, pure metallic delamination prevailed because of no oxide on worn surfaces. At 4 m/s, the delamination pattern was an oxide-predominated characteristic due to the existence of more oxides. At 0.75 m/s, the delamination pattern can be classified into partly metal and partly oxide delamination. Cracks and delaminated traces were found on worn surfaces at 0.75 m/s, as shown in Figures 5(a) and (b). At 2.68 m/s, the tribo-layer formed at the earlier sliding was made of metal wear debris, but not compacted (Figure 5(c)). As the sliding distance increased, the pure metal tribo-layer seemed to be readily delaminated in a shape of large platelike, as shown in Figure 5(d). At 4 m/s, the worn surfaces displayed different features from those at 2.68 m/s. At the earlier sliding, a smooth compacted tribo-oxide layer started to form and almost covered the worn surface (Figure 5(e)). As the sliding distance reached 3600 m, the typical characteristics of oxidative mild wear were represented with compacted tribo-oxide layer and some delaminated regions, as reported by Wang *et al.*[15]

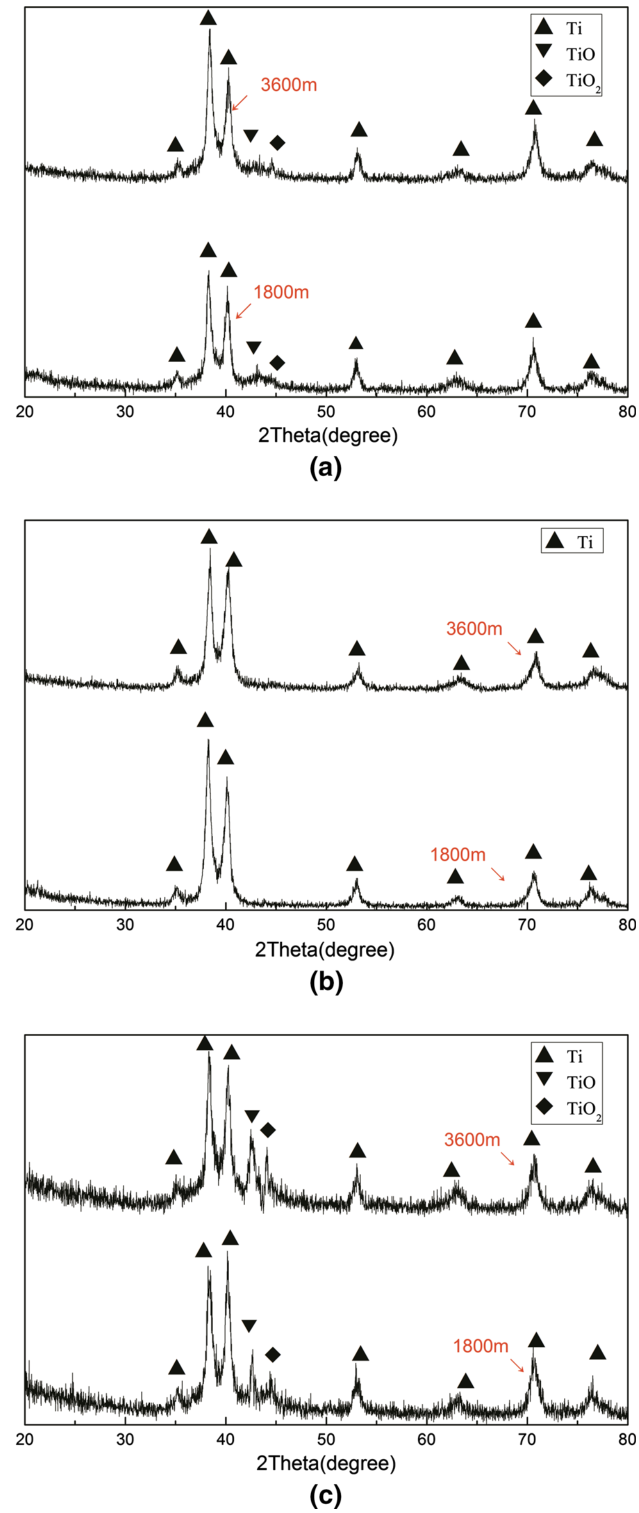

Fig. 4—X-ray diffraction patterns for worn surfaces of TC11 alloy sliding under various conditions: (*a*) 0.75 m/s, (*b*) 2.68 m/s, and (*c*) 4 m/s.

C. *Phases and Morphology of Wear Debris*

XRD spectra of the wear debris at various speeds are shown in Figure 6. It is clear that more or less oxides appeared in wear debris besides titanium as the

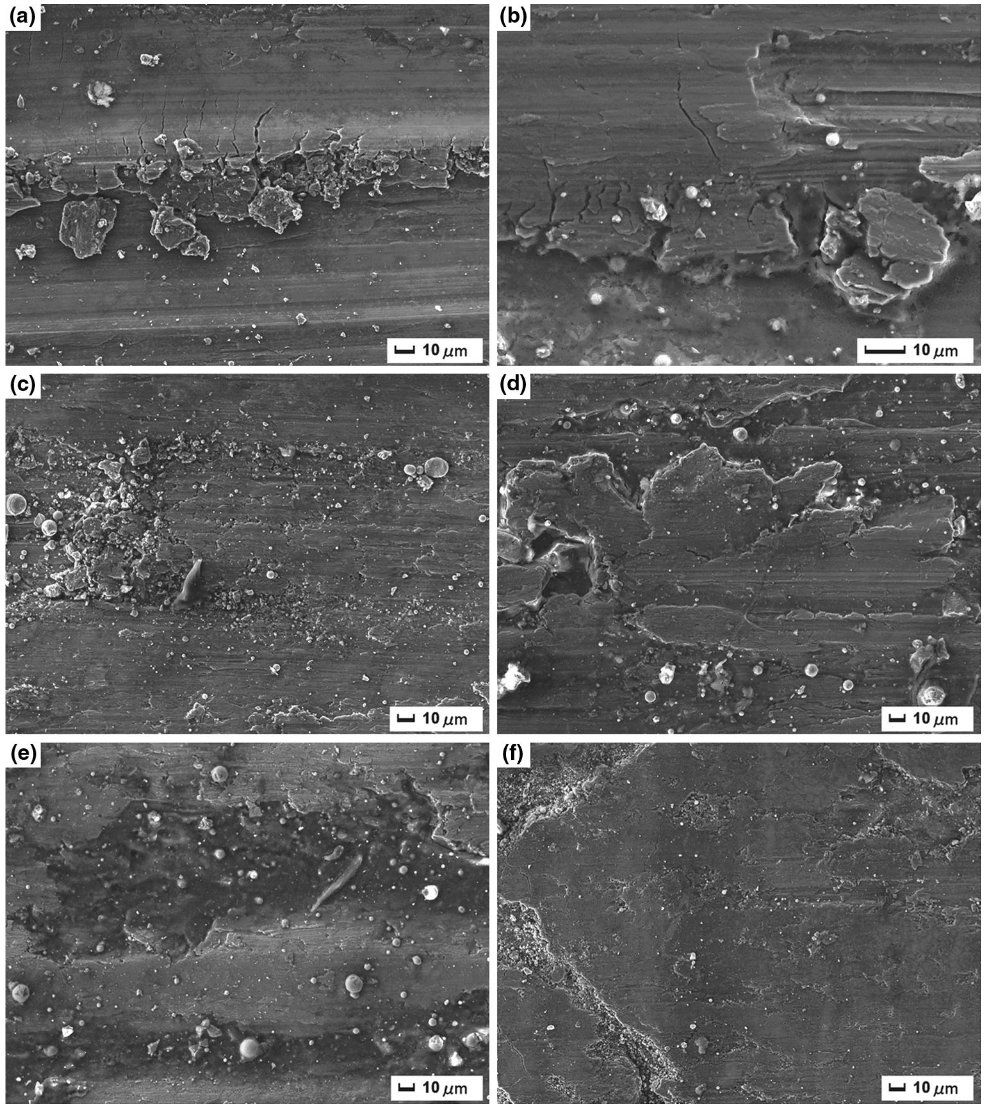

Fig. 5—Morphology of worn surfaces of TC11 alloy under various sliding speeds and distances: (*a*) 0.75 m/s, 1800 m; (*b*) 0.75 m/s, 3600 m; (*c*) 2.68 m/s, 1800 m; (*d*) 2.68 m/s, 3600 m; (*e*) 4 m/s, 1800 m; and (*f*) 4 m/s, 3600 m.

predominated phase. It appeared that the amount of oxides changed with the variation of the sliding speed. At 0.75 m/s, more oxides (TiO and TiO_2) appeared. In addition, the peaks of Fe_2O_3 and Ti_7O_{13} were identified. At 4 m/s, the wear debris presented the same oxides but more amount. At 2.68 m/s, merely trace oxides (TiO and TiO_2) existed. These hinted that the wear debris was almost metallic at 2.68 m/s, and the mixture of metal and oxides at 0.75 and 4 m/s.

The morphology of the wear debris at various sliding speeds is shown in Figure 7. The wear debris represented different morphologies in various conditions. At 2.68 m/s, large, plate-like wear debris reached 100 to 1000 μm. On the contrary, the wear debris at 4 m/s represented powder particles with a size of about 10 μm and trace plate-like fragments. At 0.75 m/s, small, plate-like wear debris reached 20 to 100 μm. It is clear that the wear debris at 0.75 and 4 m/s included oxides and metal fragments. But at 2.68 m/s, the large, plate-like wear debris was almost metallic.

D. *Characterization of Tribo-Layers*

By examining the cross-section morphology of worn surfaces, a special layer was noticed to exist on worn surfaces. It is obviously different from the matrix, usually termed as tribo-layers. The longitudinal cross-section morphology and EDS line analysis of worn surfaces of TC11 alloy at various sliding speeds are shown in Figure 8. It was noticed that tribo-layers indeed formed at room temperature and various sliding speeds. At 0.75 and 4 m/s, the tribo-layers were thick, contained oxygen, and were relatively compacted. The tribo-layer at 0.75 m/s contained less oxygen and coarser cracks than at 4 m/s. Conversely, at 2.68 m/s, the tribo-layer was obviously thin, did not contain oxygen and was uncompacted.

A compacted tribo-layer with some oxides had a lower thermal conductivity and high load-bearing capability, thus the temperature at subsurfaces would be lower and the force was prevented to be transferred to the matrix. In this case, a relatively slight plastic deformation region

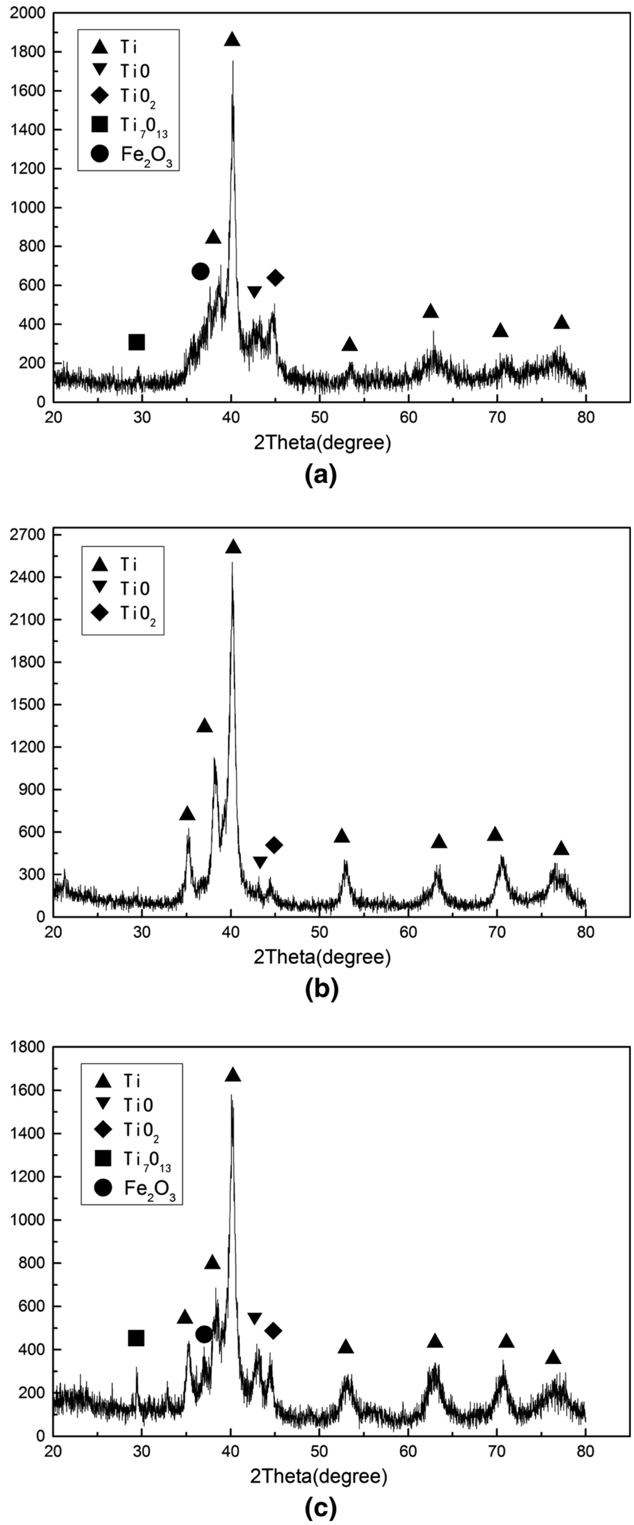

Fig. 6—X-ray diffraction patterns for the wear debris of TC11 alloy at various sliding speeds and a load of 50 N: (*a*) 0.75 m/s, (*b*) 2.68 m/s, and (*c*) 4 m/s.

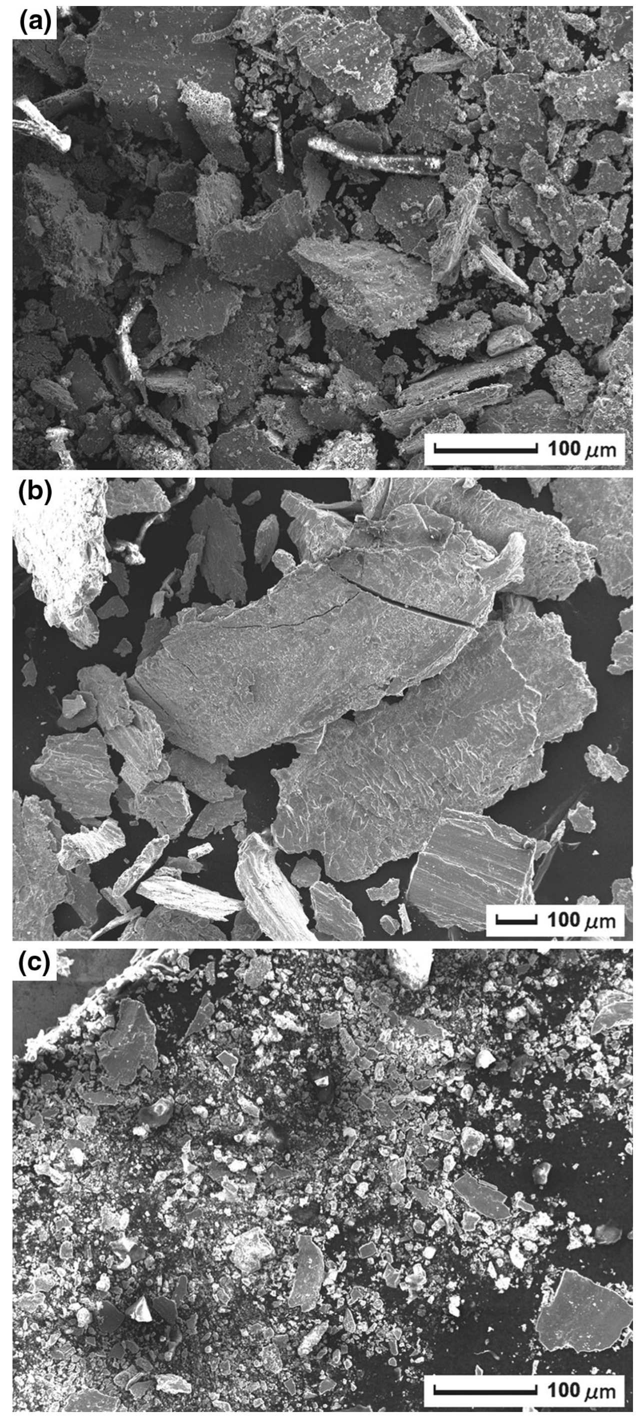

Fig. 7—Morphology of the wear debris of TC11 alloy at various sliding speeds and a load of 50 N: (*a*) 0.75 m/s, (*b*) 2.68 m/s, and (*c*) 4 m/s.

was noticed at 4 m/s. It is clear that the EDS line analysis conformed to the XRD results. The tribo-layer possessed less oxides at 0.75 m/s, almost no oxide at 2.68 m/s, and more oxides at 4 m/s. The characteristics of the tribo-layer were expected to have a significant effect on the wear behavior and wear mechanism of TC11 alloy.

IV. DISCUSSION

A. *Mild Wear and Severe Wear of TC11 Alloy*

The wear performance of a material is a systematic property, which depends on sliding and counterface

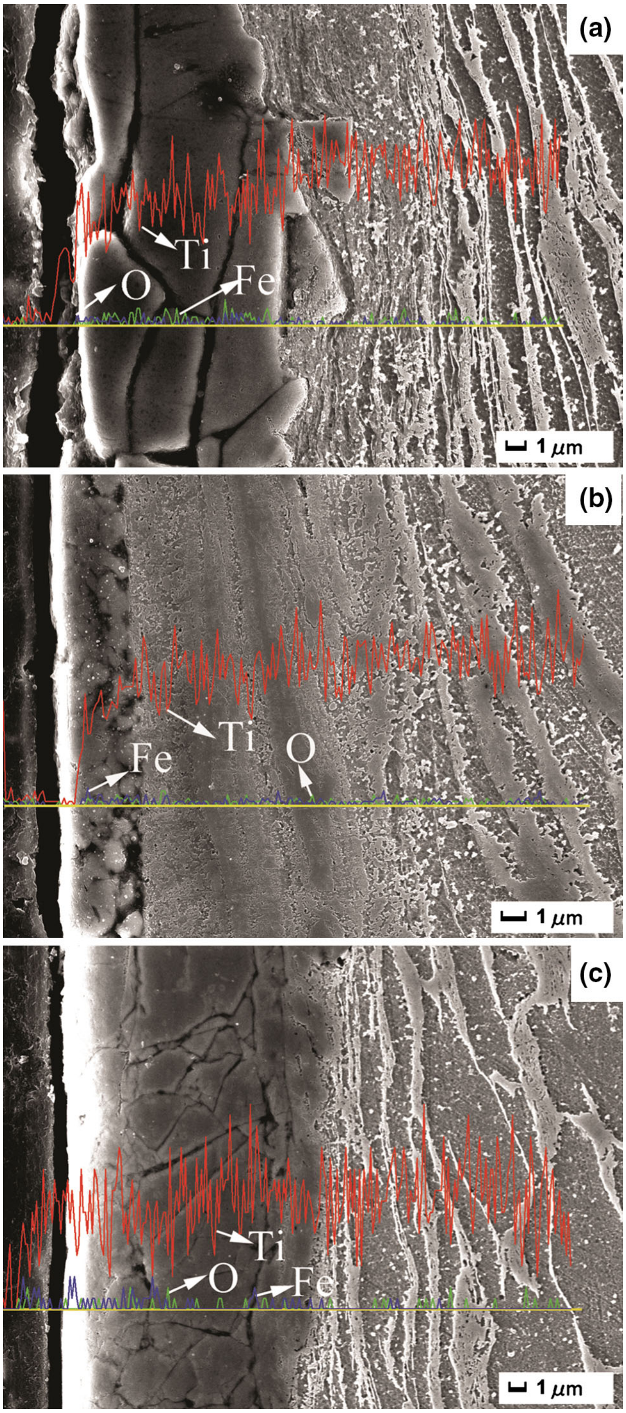

Fig. 8—Cross-section morphology of the worn surfaces of TC11 alloy at various sliding speeds and a load of 50 N: (*a*) 0.75 m/s, (*b*) 2.68 m/s, and (*c*) 4 m/s.

materials and their properties, environments, and sliding conditions, such as load, temperature, sliding speeds, and distance.[16] At the end of last century, Molinari *et al.*[4] summarized the poor wear resistance of titanium alloys based on the previous research. They considered that the poor wear resistance of titanium alloys was attributed to two factors: (1) low plastic deformation resistance and work-hardening ability and (2) low protection of tribo-oxides. Currently, in the field of engineering and scientific research, the notorious poor wear resistance of titanium alloys is a popularly accepted viewpoint. This view seems to impress us that titanium alloys are merely of severe wear. However, Lebedeva and Presnyakova[3] reported that severe wear and mild wear both appeared in the titanium alloy. Qiu *et al.*[9] reported that a mild-to-severe wear transition occurred because of unstable TMML delamination. In our recent study, it was found that there existed a severe-to-mild wear transition as a function of temperature.[14] All the above reports demonstrated that not only severe wear but also mild wear would appear in titanium alloys.

Figure 1 presented marked variations of the wear rate with an increase of sliding speed from 0.5 to 4 m/s. Even the variations of the wear rate would surpass more than one order of magnitude. This meant that TC11 alloy did not always have high wear rates; in some cases, mild wear prevailed. More importantly, it can be deduced that the wear of titanium alloys would be controlled by changing sliding conditions. Zhang and Alpas[17] considered that 1×10^{-6} mm^3/mm entered mild wear and the boundary line between mild and severe wear is 4×10^{-6} mm^3/mm for aluminum alloys. The wear rates were 10^{-6} to 10^{-7} mm^3/mm as mild oxidative wear prevailed in steels.[18] Wang *et al.*[19] considered that there was no strict dividing line between mild wear and severe wear. They argued that the dividing line for mild and severe wear corresponded to the cases, in which the worn surfaces became obviously rougher, and the number and size of wear particles rapidly increased with a variation of normal load or sliding speed. It is clear that for various metal alloys, mild and severe wear should be distinguished in the similar standard. Therefore, for titanium alloys, 4×10^{-6} mm^3/mm can be roughly considered to be the boundary line between mild and severe wear.

According to the above classification of mild and severe wear, in the current test, the wear rates at 4 m/s and various loads as well as at 0.5 to 2.68 m/s and a low load of 10 N remained in mild wear. The wear rates of the other cases were considered to be beyond mild wear. In other words, with the increase of load and the variation of speed, TC11 alloy entered severe wear. Particularly, at 2.68 m/s and 50 N, the wear rate reached higher than 4×10^{-5} mm^3/mm, which was more than one order of magnitude than the boundary line. This meant that TC11 alloy does not always possess poor wear performance at room temperature. It is clear that the above results are totally against the traditional view of the poor wear resistance of titanium alloys. Similarly, Straffelini and Molinari[20] noticed that the titanium alloy possessed a severe-to-mild wear transition as a function of sliding distance and pointed out that the titanium alloy did not conform to the criterion of the critical surface temperature for mild-to-severe wear transition, put forward by Wilson and Apas.[17] This also forecasted that titanium alloys should possess different wear performances from other metal alloys.

Table I. Thickness, Feature, and Hardness of Tribo-Layers

Sliding Conditions	0.75 m/s 0.51 MPa	0.75 m/s 2.55 MPa	2.68 m/s 0.51 MPa	2.68 m/s 2.55 MPa	4.00 m/s 0.51 MPa	4.00 m/s 2.55 MPa
Thickness (μm) and feature of tribo-layer	5 to 10 continuous	10 to 15 continuous	10 to 15 relatively continuous	2 to 5 discontinuous	15 to 20 continuous	15 to 20 continuous
Microhardness of tribo-layer (HV)	550	630	563	400	800	880
Microhardness of matrix (HV)	300 to 330	330 to 350	300 to 325	340 to 360	275 to 300	310 to 355

B. *Formation of Tribo-Layers and Their Characteristics*

Through an investigation and a microhardness measurement of tribo-layers, the average thickness and hardness as well as the feature of tribo-layers are summarized in Table I. At 0.75 m/s, the tribo-layer was continuous; as the load increased, it thickened from 5 to 10 to 10 to 20 μm, and its hardness increased from 550 to 630 HV. At 2.68 m/s, as the load increased, the relatively continuous tribo-layer became discontinuous, and the thickness decreased from 10 to 15 μm to 2 to 5 μm and its hardness decreased from 563 HV to 400 HV, which approached the hardness of the matrix. At 4 m/s, the tribo-layer was continuous and reached 15 to 20 μm; as the load increased, its hardness increased from 800 to 880 HV, which is much higher than the hardness of the matrix. It can be deduced that the increase of hardness was attributed mainly to the existence of TiO_2 and TiO in tribo-layers.

It is understandable that in the initial stage of sliding, some small or large fragments were detached from the worn surface by adhesion or delamination. They might be entrapped and further fragmented, oxidized, and agglomerated to form a tribo-layer, or they might escape from the sliding system to produce wear debris. As the sliding continued, the tribo-layers were detached to produce new wear debris. The above-mentioned analysis for worn surfaces, subsurfaces, and wear debris demonstrates that tribo-layers and wear debris at various loads and speeds presented different characteristics. During the dry sliding, frictional heat was produced to heat worn surfaces and subsurfaces. As the sliding speed increased, more frictional heat was released to substantially elevate the temperature of worn surfaces. On the one hand, higher temperature readily caused the oxidation of worn surfaces and wear debris. Thus, more tribo-oxides were produced on worn surfaces and in wear debris. On the other hand, a higher temperature softened the subsurfaces matrix, thus resulting in the delamination of tribo-layers.[21]

Moreover, different sliding speeds affect the formation of tribo-layers. At different sliding speeds, wear debris would escape away from the sliding system or be entrapped. At a lower sliding velocity of 0.75 m/s, the wear debris was readily entrapped and slightly oxidized due to a small elevation of temperature on worn surfaces, thus forming a continuous, thick tribo-layer with less tribo-oxides (as shown in Figure 4). At a higher speed of 4 m/s, a higher flash temperature not only would suppress the escape of wear debris but also would oxidize massively the wear debris. Despite high speed, small wear debris were readily entrapped because of low momentum (Figure 7(c)). Meanwhile, small wear debris was readily pressed and sintered on the worn surfaces at higher flash temperature. Because of high temperature and small wear debris, more oxides would appear on worn surfaces and in wear debris, as shown in Figures 4 and 6, respectively. In this case, a continuous, thick tribo-layer with more tribo-oxides was formed on worn surfaces at 4 m/s.

However, at 2.68 m/s, large platelike wear debris was produced as shown in Figure 7(b). Large wear debris would escape from the sliding system because of high momentum. It can be deduced that as soon as large platelike, metallic wear debris was produced, most wear debris got off away from the sliding system. Because of a short duration of stay in the sliding system, almost no oxides appeared on worn surfaces and in wear debris (Figures 4 and 6). Hence, the retained wear debris made a discontinuous, thin tribo-layer with no tribo-oxides.

C. *Influence of Tribo-Layers on Wear Behavior and Mechanism*

Wang *et al.*[19] considered that the wear behavior of alloys was attributed to a competition between strain hardening and thermal softening that might occur concomitantly at the surface of the material as the sliding speed increased. It is absolutely right when there is no tribo-layer formed on worn surfaces. However, in the most cases, tribo-layers were found to always exist on worn surfaces.[12–15] Qiu *et al.*[9] put forward that as frictional heat increased and reached a certain value, a thermal mechanically mixed layer formed. They considered that the wear behavior was decided by thermal mechanically mixed layer, not by the titanium alloy itself.

Whether tribo-layers take a role in wear depends on the types of tribo-layers. Pauschitz *et al.*[22] classified tribo-layers into three types: transfer layer (TL), mechanically mixed layer (MML), and composite layer (CL). The main difference of these three types of tribo-layers is their chemical composition. The chemical compositions of tribo-layers are same as the mating material in TL, between the compositions of the sliding and the mating materials with a low oxygen content for MML, and similar to MML but with a relatively high oxygen content for CL, respectively. Roy *et al.*[23] systematically studied the wear behavior of 253 MA alloy against 100Cr6 steel and PM 1000 alloy at an elevated temperature. No matter what material was used as mating surface, no or a thin TL was formed at ambient temperature, MML was formed at 673 K (400 °C) and CL at higher temperature. They considered that compared with TL and CL, MML represented a protective role.

From the results of XRD and EDS analysis, the tribo-layer of TC11 alloy undoubtedly was MML, which was composed of oxides and metal debris that resulted from sliding and mated materials. For TC11 alloy, MML was formed at room temperature and various sliding speeds. However, most of the limited research on the wear of titanium alloys[4–6,9] considered that tribo-oxides or tribo-layers were loosened and brittle, and thus provided no protection from wear. Hence, the poor wear resistance was considered to be result of loosened tribo-oxide layers.

However, recently, Chellia and Kailas[10] considered that the dry sliding wear behavior of titanium was decided by tribo-oxidation and strain rate response at subsurfaces and pointed out that tribo-oxides or tribo-layers exerted a positive function in the wear process. In our previous study on the wear behavior as a function of temperature, the protective functions of tribo-oxides or tribo-layers were also confirmed.[12–15] It is clear that there were two opposite views on the protection function of tribo-oxides or tribo-layers. In our current research, the protective function of tribo-oxides or tribo-layers formed at various sliding speeds was distinguished through comparing the wear behavior and characteristics of tribo-layers. At various sliding velocities, tribo-layers with different characteristics formed on worn surfaces. It is expected that different-characteristic tribo-layers exert distinct influence on the wear behavior and mechanism. Hence, the wear behavior and mechanism would vary with the characteristics of tribo-layers at various sliding speeds.

At 4 m/s, the continuous, thick MML formed, and especially it contained more tribo-oxides. As the load increased, MML retained its continuous and thickened form. This meant that MML stably existed on the worn surfaces. More importantly, this ceramic-characteristic MML presented higher hardness than the matrix metals. In this case, MML would effectively prevent the metal-metal adhesion and protect the metal from wear, and it became a solid lubricating agent. Thus, the wear rate and friction rate were substantially reduced. Extremely small particles of wear debris meant that the wear was mild. The morphology of worn surfaces demonstrated that typical oxidative mild wear prevailed (Figures 5(e) and (f)). At 2.68 m/s, as the load increased, relatively continuous and thick MML changed to discontinuous and thin MML. This meant that MML did not stably exist on the worn surfaces. In addition, MML presented relatively low hardness approached to that of the matrix because of no oxides. In this case, the metallic MML did not protect the metal from wear. Conversely, unstable MML readily delaminated to cause high wear rates. Hence, a mild-to-severe wear transition occurred at 2.68 m/s with an increase of sliding distance. The morphology of worn surfaces and wear debris demonstrated that metallic delamination was the predominated wear mechanism (Figures 5(c) and (d)). At 0.75 m/s, as the applied load increased, MML slightly thickened and retained continuous form. This meant that the MML stably existed. Moreover, MML presented higher hardness than the matrix due to the existence of trace oxides, although the hardness is lower than that that at 4 m/s. Thus, MML at 0.75 m/s was considered to take a partial protection from wear. The experimental results reported in Section III show that the wear characteristics of 0.75 m/s were in the intermediate state between those of 2.68 and 4 m/s. It is clear that the protective function of MML at 0.75 m/s was higher that at 2.68 m/s, but lower than that at 4 m/s. As illustrated from the morphology of worn surfaces and wear debris, delamination wear and oxidative mild wear simultaneously prevailed.

V. CONCLUSIONS

1. TC11 alloy presented marked variations of the wear rate with an increase of sliding speed from 0.5 to 4 m/s. Especially at high loads, a severe-to-mild wear transition occurred with the climax at 2.68 m/s, the lower values at 0.5 to 1.5 m/s, and the lowest point at 4 m/s. The TC11 alloy also presented a mild-to-severe wear transition at 2.68 m/s with an increase of sliding distance, but not at other speeds.
2. MML always formed on worn surfaces but presented different characteristics at various sliding speeds. Continuous, thick, and oxide-contained MML was considered to be protective.
3. The highest wear rate at 2.68 m/s and the lowest wear rate at 4 m/s, respectively, corresponded to no oxides and large wear debris particles as well as relatively high content of oxides and small wear debris particles. Oxidative mild wear and delaminated wear prevailed at 2.68 and 4 m/s, respectively.
4. TC11 alloy exhibited mild wear and severe wear at room temperature and various sliding speeds, especially mild wear at 4 m/s. Tribo-oxides were noticed to be protective. The results seemed to be contradictory to the popular views that titanium alloys possess notorious poor wear performance and their tribo-oxides have no wear-reducing effect.

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