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Dry sliding wear of Ti-6Al-4V alloy in air and vacuum ①

LIU Yong(刘 勇), YANG De-zhuang(杨德庄), HE Shi-yu(何世禹), WU Wan-liang(武万良)
(Space Materials and Environment Engineering Laboratory,
Harbin Institute of Technology, Harbin 150001, China)

Abstract: Differences in wear rate, morphology of the worn surface and debris, and the microstructure in subsurface of the Ti-6Al-4V alloy after wear in air and vacuum were compared. The wear rate of Ti-6Al-4V alloy in air is higher than that in vacuum in all the ranges of sliding velocities and applied loads. The wear of Ti-6Al-4V alloy in air is controlled by a combination of abrasion, oxidation and delamination with micro-cracks remaining in subsurface. Under the vacuum condition, the surface layer of Ti-6Al-4V alloy experiences a severe plastic deformation on a great scale, which results in an ultra-fine microstructure.

Key words: dry sliding; titanium alloy; delamination; adhesion; deformation
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1 INTRODUCTION

Titanium and its alloys are ideal materials for aerospace and space industries because of their high specific strength and excellent corrosion resistance[1]. The vacuum environment must be considered in space applications where wear resistance is required. The absorption, stains and oxides may be totally or partially removed from the solid surface in vacuum[2]. Thus, a relatively clear surface can be formed, which might result in an adhesion or even cold welding due to the strong attractive forces between molecules of the contacting surfaces[3]. This would lead to a faulty spread of solar arrays with its pins made of Ti-6Al-4V alloy, a decrease in the life of bearings, and a bad contacting of electric brushes[4, 5].

Despite having good mechanical and chemical properties, the use of Ti-6Al-4V alloy is prevented from its poor sliding wear resistance attributed to the low resistance to plastic shearing and low protection exerted by the surface oxides[6]. Molinari et al[7, 8] showed that the dry sliding wear of Ti-6Al-4V alloy in air was controlled by oxidation and delamination. The maximum wear resistance was found at the velocity at which a transition from the oxidation to delamination wear occurred. Other researches showed that the pressure and composition of atmosphere would influence the wear of Ti-6Al-4V alloy[9, 10]. Under vacuum condition, an $\alpha \Leftrightarrow \beta$ transformation with the formation of extremely hard secondary martensites occurred in the titanium alloys at a critical value of sliding velocity, leading to a high wear resistance and low friction coefficient[11].

The objective of the present investigation is to study the dry sliding wear behavior of Ti-6Al-4V alloy in both air and vacuum, and provide a basis for its surface modification.

2 EXPERIMENTAL

The composition of the Ti-6Al-4V alloy was: 5.5%-6%Al, 3.5%-4.5%V, 0.3%Fe, 0.15%O, and balance Ti(mass fraction). The as-hot-rolled bar of the Ti-6Al-4V alloy was annealed at 760 ℃ for 1 h and then cooled in the furnace, and an average hardness of HRV 345 was obtained.

Wear tests were carried out using a pin-on-disc scheme and pure sliding was obtained by keeping the disc rotating and the counter pin fixed. The Ti-6Al-4V alloy specimens were made as the pins with a shape of cylinder, and size of d9 mm × 20 mm. The discs with the size of d70 mm × 10 mm were made of GCr15 steel(approximately 1.0%C, 1.5%Cr (mass fraction)), and quenched in water from 840 ℃ with subsequent tempering at 150 ℃ to reach the hardness of HRC 62.

The applied load varied from 30 N to 90 N, and the sliding velocity ranged from 0.2 m/s to 1.2 m/s. Vacuum wear tests were performed under the pressure of 10 Pa. Wear results were characterized in terms of the mass loss per kilometer of the pin using a Sartius Micr electronic precision balance ($\pm 10^{-5}$ g). The worn surfaces of Ti-6Al-4V alloy specimens and the wear debris were examined by means of a Hitachi S-570 type scanning electron microscope. The debris were analyzed using a D/max-γB of XRD spectrome-

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Correspondence: LIU Yong, PhD; Tel: +86-451-86412462; Fax: +86-451-86415168; E-mail: yongliu@public.hr.hl.cn

ter. A Philip 22 type transmission electron microscope was used to observe the subsurface change of the Ti-6Al-4V alloy after wear. The TEM specimens were cut along the direction parallel to the sliding surface, and the foils were prepared by ion-thinning. The observing spot was about 50 μm from the worn surface.

3 RESULTS AND DISCUSSION

3.1 Wear rates

Fig. 1 shows the wear rate of Ti-6Al-4V alloy as a function of sliding velocity under different applied loads. In air, the wear rate is increased with increasing the load in the range of the tested velocities. With increasing the sliding velocity, the wear rate is decreased to a minimum and then increased. The wear rate curves show the minimum values at some sliding velocities. In the case of vacuum condition, the wear rate is increased slightly with increasing the sliding velocity and load. The calculated results show that the wear rate of Ti-6Al-4V alloy in air is higher than that in vacuum in all the ranges of sliding velocity and applied load.

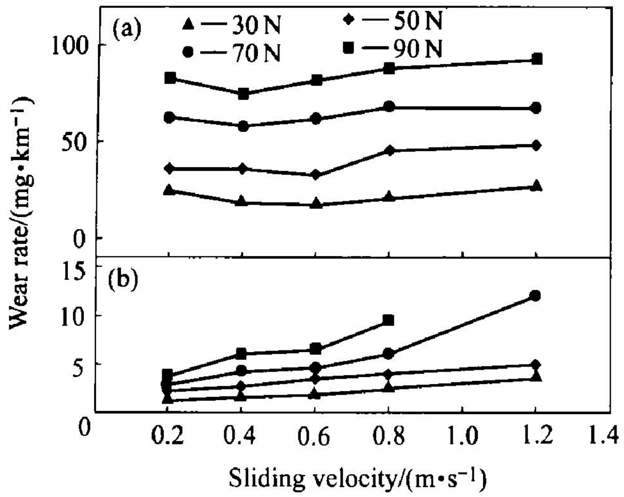

Fig. 1 Wear rates of Ti-6Al-4V alloy as a function of sliding velocity under varied loads
(a) —In air; (b) —In vacuum

3.2 Worn surface

Different surface characteristics of Ti-6Al-4V alloy specimens worn in air and vacuum are shown in Fig. 2. Many fine particles of wear debris remain on the surface worn in air, as shown in Fig. 2(a). On the contrary, they were not observed on the surface worn in vacuum, as shown in Fig. 2(b). Typical furrows produced by the micro-cutting process in air are formed along the sliding direction, suggesting an abrasion process occurred[7]. Further examination of the worn surface in air in Fig. 2(a) shows that there are many micro-cracks at the edges of furrows.

In the case of the worn surface in vacuum, the adhesive characteristic can be observed. Typical plowing tracks along the sliding direction and tongue-shaped wedges forming a layered microstructure are observed, as shown in Fig. 2(b). The layered wedges present a characteristic of plastic deformation. During the wear process in vacuum, the material at the contacting spots is pushed up and over the surface of Ti-6Al-4V specimens, forming a "tongue". The subsequently formed tongues will be squeezed and repressed onto the former tongues due to the pressure exerted by the counter. As such a process is continuously developed, the tongues will be overlapped against each other, forming layered wedges on the worn surface of Ti-6Al-4V alloy. In the course of repeating new encounters, the growing wedge will become higher normal to the average sliding plane, which will crowd out neighboring contact spots as described in Ref. [12]. As a result, in some areas which are lower than the average sliding plane, large layered tongue-shaped wedges will be formed.

3.3 Wear debris

Fig. 3 shows the SEM micrographs of wear debris stripped in air and vacuum. The wear tests

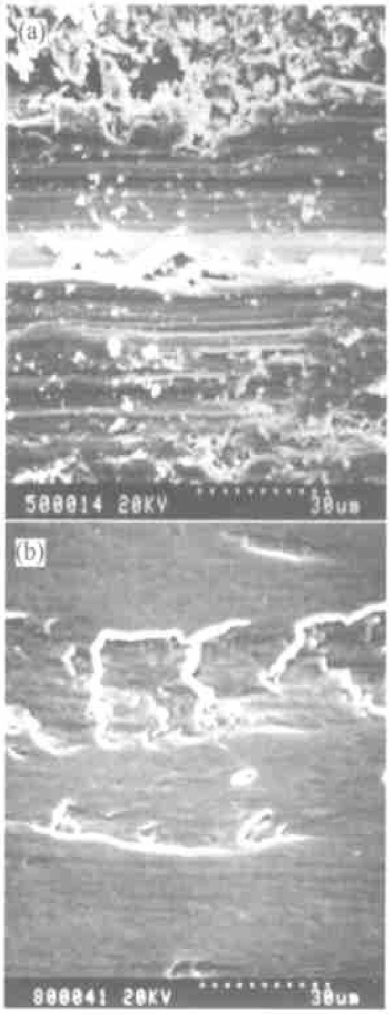

Fig. 2 SEM micrographs of surface of Ti-6Al-4V alloy worn under 0.6 m/s and 70 N in air(a) and vacuum(b)

Fig. 3 SEM micrographs of debris stripped under 0.6 m/s and 70 N in air(a) and vacuum(b)

were performed under a given sliding velocity as well as applied load, in order to facilitate the comparison of results. The debris collected at the end of the tests in air are in the form of plate-like fragment, as shown in Fig. 3(a). The morphology of debris stripped in air shows a typical delamination characteristic. Under the testing condition of vacuum, the debris is collected at the tail areas of the friction interface, as shown in Fig. 3(b). A large monolithic debris might be build up by many extended tongue-shaped fragments overlapping with each other, as described in paragraph 3.2.

The XRD spectra of wear debris stripped in air and vacuum are shown in Fig. 4. It is found that TiO exists in the debris stripped in air. The debris stripped in vacuum consists of α-Ti and a little amount of β-Ti. It implies that an oxidation wear occurs during the test in air. Combined with the results described in paragraph 3.2, the wear of Ti-6Al-4V alloy in air would be controlled by a combination of abrasion, oxidation and delamination. Previous studies[7, 8] showed that, the wear of the Ti-6Al-4V alloy in air is controlled by abrasion and oxidation at lower sliding velocities. Increasing the sliding velocity, the oxidation rate is decreased and the wear rate of Ti-6Al-4V alloy is also decreased. Under higher sliding velocities, the contribution of metallic delamination is prevailed, leading to the increase of wear rate with sliding velocity. As a result, a minimum will appear on the wear rate versus sliding velocity curves in air.

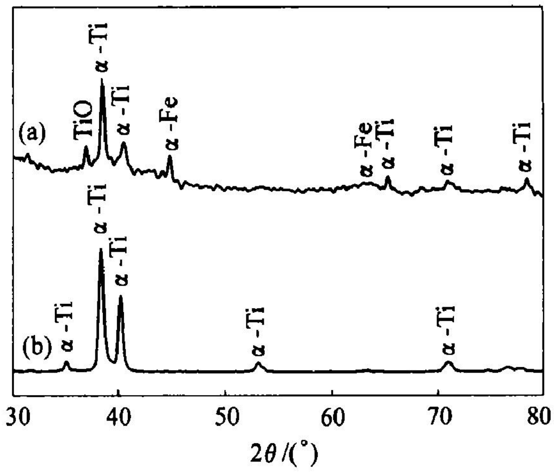

Fig. 4 XRD spectra of debris stripped under 70 N and 0.6 m/s in air(a) and vacuum(b)

3.4 Microstructure in subsurface

Micro-cracks are found in the subsurface of Ti-6Al-4V alloy specimens after wear in air, as shown in Fig. 5(a). This phenomenon may be related to characteristic delamination. According to the delamination theory, the micro-cracks often form in the areas with a certain depth from the surface. Fig. 5(b) shows the microstructure of the subsurface of Ti-6Al-4V alloy after wear in vacuum. An ultra-fine microstructure with the gain size of 50 − 100nm is formed, and the substructure has high density of dislocations. The refining of microstructure in the subsurface after wear in vacuum illustrates that a more intensive plastic deformation takes place.

When Ti-6Al-4V alloy is sliding against GCr15 steel in vacuum, a remarkable adhesive force will be produced due to micro-contacting and cause the stress in the subsurface of Ti-6Al-4V alloy specimens[12]. Dislocations will generate within the zone where the stress is higher than yield stress, forming a layer with high density of defects. The dislocations will arrange themselves in "walls", which are in fact low-angle misorientation boundaries[12]. The increase in dislocation density will increase the level of lattice energy, and one way to reduce it is to create misorientation boundaries and thus form fragments with a finite dimension. With the further increase in plastic deformation, the dislocation density inside the fragments and the extent of boundary misorientation increase, resulting in the formation of the ultra-fine microstructure with high density of dislocations. In the case of wear in air, the formed tongue-shaped wedges will be separated by oxides and be easy to be fractured[8]. Also, the ductility of the formed tongue-shaped wedges and even the whole surface layer will be de-

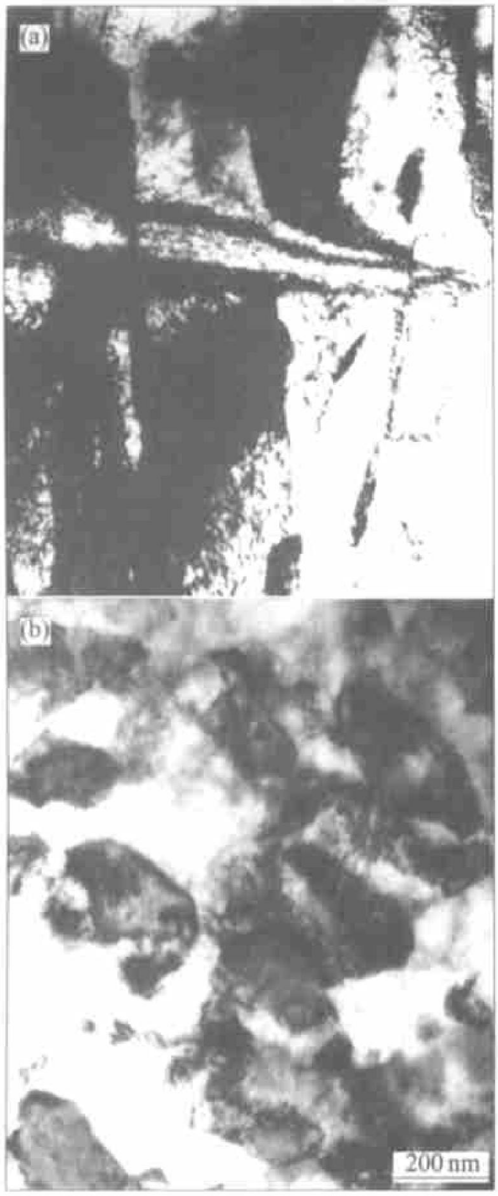

Fig. 5 TEM micrographs of subsurface of Ti-6Al-4V alloy after wear under 70 N and 0.6 m/s in air (a) and vacuum (b)

creased. As a result, micro-cracks are formed on the worn surface and in subsurface of the Ti-6Al-4V alloy specimens, as shown in Fig. 1 and Fig. 5(a), respectively.

The thermal effect induced by friction is more remarkable during the wear tests of Ti-6Al-4V alloy in vacuum than in air. The surface temperature of Ti-6Al-4V alloy specimens increases with increasing the load and sliding velocity. The deformation process in subsurface is easier to be developed with increasing the temperature, and thus resulting in the increase of wear rate of Ti-6Al-4V alloy with increasing the load and sliding velocity, as shown in Fig. 1.

4 CONCLUSIONS

1) The wear rate of Ti-6Al-4V alloy shows a minimum on the curve of wear rate versus sliding velocity in air, while slightly increases with increasing the sliding velocity in vacuum. The increasing of the applied load increases the wear rate of Ti-6Al-4V alloy in both wear environments.

2) The wear rate of Ti-6Al-4V alloy in air is higher than that in vacuum in all ranges of tested sliding velocities and loads.

3) The wear of Ti-6Al-4V alloy in air is controlled by a combination of abrasion, oxidation and delamination. Severe plastic deformation occurs in the subsurface during the wear in vacuum.

4) After the wear in air and vacuum, micro-cracks and microstructure with ultra-fine grains are formed in the subsurface of Ti-6Al-4V alloy, respectively.

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