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Tribological properties of dimple-textured titanium alloys under dry sliding contact

Ze Wu *, Youqiang Xing, Peng Huang, Lei Liu

School of Mechanical Engineering, Southeast University, Nanjing 211189, PR China

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ABSTRACT

Textured dimples are fabricated on the Ti-6Al-4V alloy surfaces by an LD side-pumped solid-state laser. The friction and wear properties of the textured surfaces as well as the relationship between the tribological properties and the texture parameters are investigated by high-speed dry sliding tests. The results show that the dimple-textured titanium surfaces filled with molybdenum disulfide solid lubricants can effectively reduce the friction coefficient as well as its fluctuation compared with the un-textured samples and textured samples without lubricants. The textured surfaces filled with solid lubricants can also reduce the wear loss of the titanium samples and the adhesion on the counterpart steel balls by forming a thin lubricating film at the friction interface. The dimple-distance has a remarkable effect on both the average friction coefficients and the wear rates of titanium surfaces, while the depth of dimple only has an effect on the wear rates within just 90% confidence level. The decrease of the dimple-distance seems to be beneficial to improving the anti-friction and anti-wear properties of the textured surfaces filled with solid lubricants.

1. Introduction

Over the past decades, titanium alloy production practices have matured more rapidly than any other metal materials. Due to their good mechanical and chemical properties, including high strength, low density, excellent corrosion resistance and favorable biocompatibility, titanium alloys are widely used in the fields of aerospace, transportation, chemical industry and medical science [1–3]. Among numerous titanium alloys, Ti-6Al-4V is most popular as a general-purpose alloy. However, the Ti-6Al-4V alloy is also known for its notoriously poor tribological properties which can be ascribed to low resistance to plastic shearing, low work hardening and low protection exerted by surface oxide [4,5]. Accordingly, in the applications where wear resistance is required, the Ti-6Al-4V alloy can be used as structural material only after a specific surface treatment aimed at improving its tribological behavior. To obtain the improved surface, a series of treatments including anodizing [6–8], ion implantation [9,10], nitriding [11], physical vapour deposition [12] and laser alloying [13–15] have been applied.

In recent years, surface texturing which involves flat and smooth lands interrupted by local depressions has been well known in improving wear resistance, friction coefficient and load capacity of lubricated machine components [16–20]. It has also been proved that textured surfaces exhibit good performance from boundary lubrication to fluid film lubrication. Many studies have shown the outstanding performance of surface texturing technology in improving tribological properties of titanium alloys. Hu et al.. [21,22] had reported the effect of laser surface texturing on the tribological performance of Ti-6Al-4V alloys under oil lubricating and solid lubricating, respectively. It was found that the beneficial effects of the textured dimples were more pronounced when lubricated with higher viscosity oil, and the excellent tribological performance could be also achieved when combining the solid lubricants with surface texturing. Amanov [23] and He [24] had reported that the tribological properties of titanium alloy substrate could be improved effectively by combining laser surface texturing and diamond-like carbon film. Its action mechanism was interpreted as the entrapment of wear particles in the textured dimples and dimple-induced graphitization during sliding motions. It was also approved by Qin et al. [25] that the laser surface textured and plasma electrolytic oxidation duplex-treated Ti-6Al-4V alloys deposited with MoS_2 film could sustain low friction coefficient for a long period. In high-temperature environment, the anti-wear ability of titanium alloy can also be enhanced by the formation of more tribo-oxides on the textured surface compared to the untextured one, which was confirmed by Sun et al. [26]. It was reported [27] that the contact angle value of elliptical-dimple textured titanium decreased whilst the wettability was improved significantly, which led to the increased interlocking between the porcelain and titanium.

The study of bioactivity is also important for applications of the surface textured titanium. It was reported by Xiong et al. [28] that the biotribological properties of ultra-high molecular weight polyethylene against surface modified titanium alloy could be improved by improvement of wettability of the alloy surfaces. Kumari and Pfleging [29,30] investigated the characterization and bio-compatibility of laser surface

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* Corresponding author.
E-mail address: wuze@seu.edu.cn (Z. Wu).

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textured Ti-6Al-4V alloy. The results indicated that the wettability and nano-hardness of the Ti-6Al-4V alloy were increased whilst a significant improvement in bioactivity was achieved after laser texturing. Liang et al. [31] investigated the electrochemical construction of a bio-inspired micro/nano-textured structure on the surface of biomedical titanium, and reported that the textured structure possessed a favorable interfacial environment to enhance attachment and proliferation of human osteoblast. It was also approved that the adhesion strength between bone and titanium implant can be improved by surface texturing or roughening [32,33]. In the past, surface texturing had been applied to improve tribological behavior and bio-compatibility of titanium alloy.

Surface texturing is an effective way to improve the tribological performance of titanium alloys. However, the in-depth and systematic researches on the tribological properties of surface textured Ti-6Al-4V alloy at high sliding speeds are insufficient. In the present work, the laser beam machining was selected to fabricate surface textures on Ti-6Al-4V alloys, and the tribological performance of the textured surfaces was assessed in terms of friction coefficient, wear loss and worn-out appearance. Taguchi method was applied to investigate the influence of the dimple-distance, the depth of dimple as well as the applied load on tribological performance. This study aims at investigating the tribological performance of the surface textured Ti-6Al-4V alloys at high sliding speeds as well as the relationship between the tribological properties and the surface texture parameters, which will help to extend their tribology applications in the situation of high-speed friction.

2. Experimental

2.1. Surface texture preparation of Ti-6Al-4V alloy

The selected substrate material was Ti-6Al-4V alloy, which was cut into disks of 62 mm in diameter and 4 mm in thickness. The disks were subsequently polished with a diamond polishing agent to obtain a roughness of $Ra \leq 0.05$ μm. Micro-dimple patterns were then created on the surface of the Ti-6Al-4V alloy substrates by an LD side-pumped solid-state laser. The laser pulse was generated using an Nd:YAG laser system at a center wavelength of 1064 nm, repetition rate of 2 kHz and pulse duration of about 20 ns. Machining was accomplished in air with the average operating voltage of 10 V, the working current of 15 A and the processing speed of 5 mm/s. After laser texturing, a gentle polishing process was carried out to remove bulges or burrs around the rim of the dimples. The diameter of the dimple is about 70 μm and the depth is about 50 μm. Three kinds of dimple patterns with dimple-distance of 150 μm (T-D150), 200 μm (T-D200) and 250 μm (T-D250) were designed and fabricated, respectively. The dimple patterns with different dimple-distances are presented in Fig. 1a–c, and the stereoscopic profile of the pattern T-D150 is presented in Fig. 1d. Some of the textured samples were also polished with molybdenum disulfide solid lubricants (see Fig. 1e, f).

2.2. Tribological evaluation

Rotary ball-on-disk tests were executed using a tribometer (UMT-2, USA) to investigate the friction and wear behavior of textured and untextured titanium alloy samples sliding against GCr15 steel balls with hardness of 60 HRC. The diameter of the GCr15 steel ball is 9.5 mm. The steel ball was fixed, while the titanium alloy disk was rotated. Firstly, single factor tests were conducted with the sliding speeds varied from 5 to 25 m/min, and the normal applied load was 8 N. The used titanium alloy samples in single factor tests were dimple patterns (dimple-distance of 200 μm) without (T-D200) and with solid lubricants (T-D200-L), as well as the un-textured samples (UT) for comparison. Furthermore, Taguchi method was applied to investigate the influence of the dimple-distance, the depth of dimple as well as the applied load on tribological performance. The titanium alloy samples used in Taguchi tests are the textured samples filled with solid lubricants. The dimple-distance is 150–250 μm, the depth of dimple is 15–50 μm, the applied load is 3–15 N, while the sliding speed is fixed at 25 m/min. All tests were conducted in ambient air over a period of 5 min.

Under given friction condition, each test was replicated three times. The three-dimensional surface topography of the wear track on the Ti-6Al-4V alloy surface was measured by an optical profiler (Wyko NT9300), and the wear volume loss was derived from the wear track. As a result, the specific wear rate was calculated as the ratio of wear volume loss over the applied load multiplied by the total sliding distance. The surface topography in the worn regions of the titanium alloy disks as well as the steel balls were studied using a scanning electron microscope (SEM) and an energy dispersive X-ray analysis (EDX). At the same time, variance analysis of factors influencing the average friction coefficient and the specific wear rate obtained in Taguchi tests were conducted.

3. Results and discussion

3.1. Single factor tests

3.1.1. Friction coefficient

Fig. 2a and b show the variations of friction coefficients of the three kinds of samples i.e. un-textured surface (UT), textured surface without (T-D200) and filled with solid lubricants (T-D200-L) wherein the dimple-distance is 200 μm at sliding speeds of 5 m/min and 25 m/min, respectively. As shown in Fig. 2a, a sharp increase of the friction coefficient is observed in the initial sliding time for both the un-textured surface and the textured surface without solid lubricants. For the UT and T-D200 samples, the friction coefficients increase sharply from the initial value of about 0.2 to the stable value of about 0.5–0.6 which are associated with severe fluctuations, whereas the value for the textured sample (about 0.5) is a little lower than that for the un-textured one (about 0.57). In comparison to above situation, the textured surface filled with solid lubricants (T-D200-L) sustains a low friction coefficient below 0.1 with almost no fluctuation for about 1 min and then the value rises to a stable level of about 0.37. It can also be observed that the fluctuation of friction coefficient in the stable period for the T-D200-L sample is relatively milder than that for other two kinds of samples (see Fig. 2a). When the sliding speed is raised to 25 m/min, the values of friction coefficients are a little lower than that for corresponding samples at sliding speed of 5 m/min, in addition, the situation of variations of friction coefficients is similar to that at low sliding speed (see Fig. 2a and b).

The average values of the friction coefficients in sliding process are calculated as average friction coefficients for comparison. The average friction coefficients of UT, T-D200 and T-D200-L samples at different sliding speeds are indicated in Fig. 3. It can be seen that the average friction coefficients present slow downtrend with increasing sliding speeds for all the samples. The values of average friction coefficients for T-200 sample are slightly lower than that for the un-textured one, while the T-D200-L sample has the relatively smaller average friction coefficients. Under the present test condition, textured surface filled with molybdenum disulfide can reduce the average friction coefficients by 40% or so compared to the smooth surface.

3.1.2. Wear morphology

The worn surface of the titanium alloy samples after 5 min sliding time with the speed of 25 m/min and the load of 8 N are presented in Fig. 4. It can be seen that the un-textured sample shows deep plow, adhesive wear and plastic deformation (see Fig. 4a), which indicates the wear is inclement. For the textured sample without solid lubricants (see Fig. 4b), in addition to a little narrower wear scar, no evident difference can be discovered in comparison to the un-textured one. Without filled lubricant, most of the textured dimples are worn out, which can be mainly attributed to the visible distinction of hardness between the titanium alloy sample and the mated steel ball. The hardness of GCr15 steel is about 60 HRC, while the value is just about 35 HRC for Ti-6Al-4V alloy.