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Effect of laser shock peening on wear behaviors of TC11 alloy at elevated temperature

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Titanium alloy is regarded as a high performance material which has wide application prospect in aerospace and medical field. However, their poor wear properties may lead to failures in early service stages. In this paper, the microstructure, micro-hardness and residual stress of TC11 alloy treated by laser shock peening (LSP) are investigated. The sliding wear experiments are performed to study the influence of various temperature and applied load on the wear behaviors of TC11 alloy with and without LSP. The results indicate that the LSPed specimen has a superior wear properties to that of as-received specimen under the same wear test conditions. The tribological properties are greatly dependent on wear testing temperature and applied load. For the specimens tested under 15 N, the variation trend of friction coefficient and wear rate reduces first (25–500 °C) and then increases (500–600 °C) with increasing the test temperature. When the sliding wear test conducted at 400 °C, the larger the applied load, the more the friction coefficient and wear rate. The prominent tribological performances of LSPed TC11 alloy is ascribed to the high compressive residual stress and grain refinement induced by LSP.

1. Introduction

Titanium alloy has a wide range application in various engineering fields including aerospace, marine, medicine and chemical industry because of their outstanding performances such as strength-to-density ratio, high temperature corrosion resistance, high fatigue resistance and biocompatibility [1–5]. However, the tribological properties of titanium alloys are poor at room temperature due to their lower resistance to work hardening ability and plastic shearing [6]. Besides, the tribo-oxides cannot act as protective mechanism due to the frictional heating during sliding friction [7]. Some researchers found out that titanium alloys has excellent tribological properties at elevated temperature. This phenomenon can be explained that the oxide films formed in the worn surface plays an important role on protecting the substrate during sliding wear at elevated temperature. Therefore, studies on tribological properties at high temperature of titanium alloys have attracted more attention. Chen et al. [8] studied the influence of various test temperature and applied load on tribological properties of titanium alloy. They demonstrated that the wear rate of titanium alloy at 400–600 °C was lowest, and was ascribed to the formation of oxide tribo-layers between the friction pairs during sliding wear. That is to say titanium alloys have excellent high temperature wear performance when the temperature of work condition exceeds the critical value. However, the tribological properties of titanium alloys are weaker than other metals or alloy materials under high temperature sliding friction conditions, which limit their further applications.

To meet the application requirements of titanium alloys under the friction and wear conditions, many surface strengthening technologies including laser surface texturing (LST) [9], thermal oxidation [10,11], laser cladding [12,13], and surface mechanical attrition treatment (SMAT) [14,15] have been employed to enhance the wear resistance of Ti alloys. LST is an advanced method for manufacturing micro-scale structures on the surface to enhance tribological behaviors of metal material effectively under different conditions. Sun et al. [6] used laser surface texturing (LST) to fabricate the micro-textures on the surface of Ti alloy to improve tribological properties. They found that the surface with regular micro-textures had the best wear resistance, which attributed to the regular micro-textures was helpful to increase the oxygen content on the surface that was beneficial to form oxide tribo-layers during sliding friction.

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Laser shock peening (LSP) can generate a high pressure plasma that can impart surface compressive residual stress, increase surface micro-hardness and refine grain of metal materials to improve properties of fatigue, anti-wear, tensile and corrosion cracking resistance [16,17]. LSP is an innovative way to optimize the contact surface between the friction pairs to enhance the tribological performances [18,19]. Trdan et al. [20] investigated the wear properties of 6082 Al alloy subjected to massive LSP without coating, they found that the massive LSP with optimized process parameters could effectively avoid ablation and melting of material surface by laser beam, and the compressive residual stresses and dislocation structure could remarkably increase the wear resistance.

Based on the above mentioned, LSP can be applied to enhance wear resistance and weaken harmful wear mechanisms on the surface of titanium alloys. However, there are inadequate studies on tribological performances and wear mechanisms of LSPed TC11 alloy under elevated temperature and different applied load. The present work investigates the influence of various temperatures and applied loads on wear characteristics and mechanisms of TC11 alloy with and without LSP.

2. Experimental methods

2.1. Specimen preparation and LSP experiment

The TC11 titanium alloy is used in this work and the chemical composition is shown in Table 1. The samples were processed into a rectangular block with dimension of $20 \times 20 \times 5$ mm^3. Before the LSP treatment, all specimen surfaces were ground by SiC sandpapers from 160 to 2400 grade, and subsequently cleaned in deionized water. All the specimens were degreased by ultrasound in ethanol. Laser shock peening experiments were carried out by a Q-switched Nd: YAG laser system with a 1064 nm wavelength, 10 ns laser pulse width and 5 Hz repetition rate. The LSP parameters are shown in Table 2. A water layer with 1–2 mm in thickness was employed to restrain the diffusion of plasma that was induced by laser beam during the LSP experiment, and a 0.12 mm thick aluminum tape was used as an absorbing layer.

2.2. Measurements of micro-hardness and residual stress

The micro-hardness profile on the cross-section of LSPed specimen was obtained by an automatic micro-hardness tester for a load of 2.942 N with duration of 15 s. In order to ensure the accuracy of the measurements, each value of micro-hardness was measured at least three times.

The residual stress along depth direction of LSPed specimen were measured by the XRD with the $\sin^2\psi$ method. The X-ray source was Cu-kα and the diffraction plane was {2 1 3} plane with a diffraction angle (2θ) from 137 to 145°. The electro-polishing method was carried out to remove the surface material, and then measured residual stress in the depth direction of the LSPed specimen. The solution used in the electrolytic polishing was a 3.5% saturated sodium chloride.

Table 1
Chemical composition of TC11 alloy.

Elements	Al	Mo	Zr	Zr	Ti
wt%	6.5	3.5	1.5	0.3	Balanced

Table 2
The laser shock peening parameters.

Parameters	Value
Pulse energy (J)	8
Beam diameter (mm)	3
Power intensity (GW/cm^2)	11.2
Overlapped rate (%)	50
Laser impact times	5

2.3. Wear and frictions tests

The friction and wear properties were conducted on a ball-on-disk tribo-meter (UMT-2, CETR, USA) under dry sliding conditions. An Al_2O_3 ceramic ball of 10 mm diameter was employed as the counter ball. The test parameters are listed in Table 3. The values of the friction coefficient was automatically recorded by an acquisition system. The wear volume (ΔV) was assessed with the formula below [21]:

$$\Delta V = \frac{h}{6b}(3h^2 + 4s^2)2\pi r \quad (1)$$

where ΔV is the wear volume, b is the width, h is the depth and r is the radius of the wear track. The wear rate can be estimated as follows [12]:

$$\mathrm{w} = \frac{\Delta V}{Ls} \quad (2)$$

where W is the wear volume rate, L is load, s is the total sliding distance.

2.4. Microstructure observations

The worn surfaces of specimens after wear test were characterized via scanning electron microscopy (SEM) and energy-dispersive spectrometer (EDS). A JEM-2100 transmission electron microscopy (TEM) was employed to observe microstructural evolution of the plastic deformation layer induced by LSP. The thin foils were cut out from the topmost side of treated layer of the LSPed specimen and the thickness of thin foils was less than 100 μm. The untreated sides of the thin foils were polished and until it reached to about 30 μm in thickness, and then the electrochemical polishing was employed to complete the preparation of sample for TEM observations. The size of crystalline grain was measured by Image Pro-Plus 6.0 software [22].

3. Results and discussion

3.1. Characterization of microstructures of LSPed specimens

Fig. 1 are the TEM observations in the top surface layer of the specimen after multiple LSP. Four kinds of microstructure characteristics exist in the plastic deformation layer, such as deformation twin (Fig. 1(a)), dislocation tangle (Fig. 1(b)), dislocation wall and dislocation cell (Fig. 1(c)). It can be seen from Fig. 1(a) that the width of deformation twin is about 30 nm and the distance between two adjacent twins is about 110 nm. The twins are along one direction in the plastic deformation layer and the twin boundaries can be identified clearly. The coarse grains is separated into twin-matrix (T-M) lamellae by the deformation twins and then the T-M lamellae evolve into homogeneous and equiaxed refined grains [23]. From Fig. 1(b) and (c), there are some dislocation lines and dislocation tangles in the grain. The dislocation cells with size of 300–900 nm and the dislocation wall is also observed in the grain. The dislocation cells and dislocation tangles are as a result of the accumulation and rearrangement of dislocation lines, which will accommodate the energy induced by severe plastic deformation [23]. The coarse grains in the treated surface is refined due to the dislocation tangles and dislocation walls develop into low-angle sub-grain boundaries [24]. Fig. 1(d) shows that the nano-