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High friction and low wear properties of laser-textured ceramic surface under dry friction

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ABSTRACT

Two kinds of grooved textures with different spacing were fabricated on Al_2O_3/TiC ceramic surface by an Nd:YAG laser. The dry tribological properties of the textured samples were investigated by carrying out unidirectional rotary sliding friction and wear tests using a ball-on-disk tribometer. Results show that the laser textured samples exhibit higher friction coefficient and excellent wear resistance compared with the smooth sample under dry friction conditions. Furthermore, the texture morphology and spacing have a significant influence on the tribological properties. The sample with small texture spacing may be beneficial to increasing the friction coefficient, and the wavy-grooved sample exhibits the highest friction coefficient and shallowest wear depth. The increasing friction coefficient and anti-wear properties are attributed to the combined effects of the increased surface roughness, reduced real contact area, micro-cutting effect by the texture edges and entrapment of wear debris.

1. Introduction

Due to a unique combination of excellent intrinsic properties of low density, high hardness, high melting point, and excellent wear and corrosion resistance, Al_2O_3 based ceramics are widely used in engineering applications, such as cutting tools, brake systems, mechanical seals and bearings [1–4]. Although ceramics can be used much more successfully than metals under dry conditions, the dry friction and wear tests on self-mated Al_2O_3 based ceramics or Al_2O_3 based ceramics mated to other ceramics and metallic materials show low resistance to abrasive wear and adhesions [5,6]. This reduces the wear life of the ceramics and limits their applications in engineering. Therefore, considerable methods have been introduced to improve the tribological properties of ceramic surfaces, including laser pretreatment [7], laser-induced alloying [8], lamination [9], deposition coatings [10], ion-plasma treatment [11] and an addition with solid lubricants [12].

It is well known that the surface topography has an important influence on the friction and wear properties [13,14]. Laser surface texturing is a well-known surface engineering process and it has attracted increasing attentions in improving the friction and wear properties of materials in the past few years, and they have been used in many fields to modulate the tribological performance of the interfaces, including piston rings [15], cutting tools [16], bearings [17], cylinder liners [18] and mechanical seals [19]. The main mechanism of the surface textures can be summarized as trapping wear particles, acting as reservoirs of lubricants, and increasing load carrying capacity [20–22].

Fundamental researches on tribological properties of surface textures with different geometries and lubricated conditions have been carried out, and experiments under different conditions exhibit different results. For examples, Wang et al. [23] investigated the effect of groove spacing on dry tribological property of textured stainless steel sliding against Al_2O_3 ceramic ball, and found that the groove spacing had an influence on the friction and wear properties. The average friction coefficient can be reduced or increased by modulating the groove spacing. Afterwards, they reported that the friction and wear of stainless steel were reduced under starved oil lubricated conditions, and the spacing and angle of grooves significantly affected the tribological property [24]. Rosenkranz et al. [25] studied the alignment and wear debris effects between laser-patterned steel surfaces under dry sliding conditions. Results showed that all textured samples exhibited a lower kinetic friction coefficient than the smooth samples, and the alignment and period of surface textures were well correlated with the evolution of the friction coefficient and wear. Suh et al. [26] reported that the friction reduction can be achieved by crosshatched micro grooves under lubricated sliding friction, and the crosshatch angle and

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aspect ratio of grooves were important parameters [27]. Experiments and theoretical researches by Tang et al. [28] indicated that the surface texturing was important for reducing friction and wear under lubricated sliding contact, and the dimple area fraction had an important influence on the reduction of friction and wear. Wu et al. [29] investigated the influence of applied load, sliding speed and area density of dimpled and linear textures on sliding friction and wear properties of cemented carbide based on the Taguchi method. They found that the textured surface filled with MoS_2 lubricants decreased the friction coefficient and adhesions, and the linear grooves exhibited better tribological performance. They also found that the textured cemented carbide without solid lubricants increased the friction and adhesions [21]. Rapoport et al. [30] studied the effect of incorporation of solid lubricants into dimples on the tribological properties of hardened steel. Results showed that the reduction of friction and wear depended greatly on the density of the dimples. The authors' previous studies showed that, under dry and solid lubricated conditions, the textured surface with wavy grooves exhibited lower friction and wear compared with the linear grooved and untextured surfaces; meanwhile, the texture spacing, sliding speed and load had an important influence on the friction and wear properties [31,32].

As mentioned above, surface textures can reduce the friction and wear in both liquid and solid lubricated conditions, however, they not only can reduce the friction coefficient but also can increase the friction coefficient under dry friction condition. Though most studies on surface textures focus on the benefits of the reduction of friction coefficient in applications, the enhancement of friction coefficient is expected to our life in some conditions. Unfortunately, until now only few researches are reported with regards to the increasing friction coefficient by surface textures [33–35].

In this paper, the friction and wear properties of laser textured Al_2O_3/TiC ceramic are studied by dry sliding friction tests aimed to increase the friction coefficient and to reduce the wear. Meanwhile, the effect of geometry of laser surface textures with different spacing and morphologies on tribological properties is studied using different experimental parameters. The results may provide a certain reference value for further research in high friction applications.

2. Experimental details

2.1. Materials and surface texturing

The materials and fabrication of the textures are the same as the authors' previous reports [36]. The specimens used are hot-pressed Al_2O_3/TiC ceramic disks with a diameter of 60 mm and thickness of 5 mm (Zibo Dongtai Co., Ltd., China). The ceramic disks are composed of Al_2O_3 powder with an average particle size of 0.8 μm and TiC particles with an average particle size of 1 μm. The density of the disks is measured by the Archimedes' method. Three-point bending mode is used to measure the flexural strength, and the hardness and fracture toughness are measured using the indentation method with a hardness tester (MH-6, China). The main component and mechanical properties of the ceramic specimens are listed in Table 1. The friction mates used are AISI 1045 hardened steel balls with a diameter of 9.525 mm and a hardness of 40–50 HRC. Prior to the laser texturing, the surfaces of all ceramic specimens are finished by grinding and polishing to the roughness less than *Ra* 0.05 μm, and the roughness of the balls is about *Ra* 0.1 μm. All disks and balls are cleaned twice in an ultrasonic bath by alcohol and each for 20 min and then dried for laser texturing.

The surface textures are created on the ceramic surface by using an Nd:YAG laser (DP-H50, Jinan Xinchu Co., Ltd., China) with a wavelength of 1064 nm and pulse duration of 10 ns. The laser beam is focused on the sample surface by a lens with focal length of 63 mm to give a spot diameter of about 41 μm at the focal plane. The grooves are ablated directly in one step laser machining process, and the experiments are performed under air condition with atmospheric pressure, and laser power of 16.2 W, frequency of 6000 Hz, scanning speed of 5 mm/s and 1 overscan are employed as the processing parameters. Circular textures of 20 mm inner diameter and 45 mm outer diameter consisted of arrayed linear and wavy grooves oriented in a radial direction from the center of the ceramic disks are fabricated. In order to assess the effect of the textures, the smooth samples are tested for comparison. To simplify the nomenclature, the samples with smooth surfaces, linear grooves and wavy grooves are named AS, AT-L and AT-W, respectively. The morphology of the textured samples is observed using an optical microscope (VHX-600E, Japan) and white light interferometer (WYKO NT9300, USA). The optical photos of the ceramic samples with linear and wavy grooves are shown in Fig. 1.

2.2. Friction and wear test

Unidirectional rotary sliding friction and wear tests are conducted in air using a ball-on-disk tribometer (UMT-2, USA). During the friction tests, the upper specimen (an AISI 1045 steel ball) is fixed and the lower specimen (Al_2O_3/TiC ceramic disk) suffers from axial rotation sliding against the upper specimen. The schematic diagram of the friction and wear test is shown is Fig. 2. Effect of the spacing of the grooves and the experimental parameters on friction properties of the textured and smooth surfaces are investigated. The spacing of the grooves is about 100 μm, 150 μm, 200 μm and 250 μm apart at 11 mm, 15 mm, 18 mm and 20 mm from the center of rotation, respectively. The sliding speed is in the range of 40–160 m/min and the load is 5–20 N. Each test is run over a period of 4000 cycles and is repeated twice. Prior to the friction and wear tests, all the textured samples are cleaned in an ultrasonic bath by alcohol for 30 min and then dried.

The friction coefficient is recorded continuously and obtained directly by the software on the UMT-2 tribometer. After the friction and wear tests, the worn topographies of the samples are observed by an optical microscope and a scanning electron microscope (SEM, QUANTA FEG 250, USA). The three-dimensional surface topographies and profiles of the wear scars are measured by the white light interferometer. At the same time, the element distribution on the wear scar is identified by the energy dispersive X-ray (EDX, X-MAX50, UK).

3. Results and discussion

3.1. Morphology of laser-textured surfaces

Fig. 3 illustrates the three-dimensional surface topographies, detected by the white light interferometer (Fig. 3(a) and (b)) and optical microscope (Fig. 3(c)), and schematic diagram of the

Table 1
Properties of Al_2O_3/TiC ceramic.

Composition/wt.%	Density/g·cm^{-3}	Hardness/GPa	Flexural strength/MPa	Fracture toughness/MPa·m$^{1/2}$
Al_2O_3/55%TiC	4.76 ± 0.04	23.5 ± 0.5	900 ± 50	5.04 ± 0.32