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Modifying tribological performances of AISI 316 stainless steel surfaces by laser surface texturing and various solid lubricants

Rong Meng, Jianxin Deng*, Ran Duan, Yayun Liu, Guiliang Zhang

Key Laboratory of High Efficiency and Clean Mechanical Manufacture of MOE, School of Mechanical Engineering, Shandong University, Jinan 250061, PR China

HIGHLIGHTS

- Different kinds of solid lubricants were burnished into the textured samples.
- The textured sample burnished with WS_2 solid lubricants exhibited the best performance.
- The lubricating tribofilm can protect the contact surface from further wear damage.

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ABSTRACT

Severe wear is the primary failure mechanism of AISI 316 stainless steel in tribological applications. The use of surface textures is a well-known method to improve mechanical property of contact surfaces. In this paper, micro-textures were produced on the steel surface by laser ablation process. Different types of solid lubricants were filled into the micro-scale textures, including CaF_2, h-BN, WS_2, and graphite. Dry sliding tests were conducted to examine the tribological performance of the prepared samples. Results showed that severe plastic deformation occurred on both patterned and flat samples. The patterned sample burnished with CaF_2 solid lubricants did not show any apparent decrease in average friction coefficient. Almost all h-BN solid lubricants were squeezed out of the contact area, causing a high friction coefficient. Both patterned samples burnished with WS_2 or graphite solid lubricants showed a relatively low friction coefficient. The lubricating tribofilm existed on the worn area can protect the prepared samples from further wear damage. This study provides a basis for the proper selection of solid lubricants in industrial applications.

1. Introduction

Austenitic stainless steels provide high corrosion resistance, reasonable weldability and excellent mechanical properties [1,2]. Because of these attributes, austenitic stainless steels are widely used in industrial applications, such as aerospace components, medical devices, and apparatus for critical chemical environments [1,3]. However, austenitic stainless steels have low hardness and poor wear resistance [4,5]. These properties can lead to severe adhesive wear, and a short wear life for industrial applications under dry sliding conditions. The inherently poor mechanical behavior becomes a barrier to a wider use of austenitic stainless steel [6]. Therefore, many attempts have been made to enhance the mechanical performance without deteriorating the corrosion resistance. Surface engineering method is a promising way to improve tribological performances of austenitic stainless steels. The commonly used surface treatment methods include laser surface remelting [7], film deposition [8], nitriding [9], and laser surface texturing [10].

Among these surface engineering treatment techniques, surface texturing can significantly affect tribological properties of contact surfaces. Surface texturing involves the introduction of a periodic geometry or pattern on the sliding surface [11]. Various texturing techniques have been used to create the depressions, including machining [12,13], lithography techniques [14,15], ion beam texturing [16], and laser surface texturing (LST) [17]. It seems that the laser surface texturing (LST) is one of the most developed techniques. This is because LST provides precise control of the geometry of the patterns [18], excellent flexibility [19], good repeatability [19], and fast machining speed [20]. These periodic patterns of the textured surface can trap wear particles [21,22], act as reservoirs storing lubricants [23,24], and generate the hydrodynamic pressure [25]. Several early studies showed the influence of surface texture spacings [26], orientations [27], and

* Corresponding author.
E-mail address: jxdeng@sdu.edu.cn (J. Deng).

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geometries on friction and wear [28]. Very recently, Wang et al. [26] fabricated micro-grooved textures on steel surface by a picosecond laser. The textured surfaces showed superior friction and wear performances if the groove spacings were distributed in a proper way. Gachot et al. [27] emphasized that the relative alignment of textures had a significant influence on the contact area. They also fabricated Penrose-like patterns on polyamide surfaces by direct laser inference patterning (DLIP) [28]. The novel Penrose-like patterned samples showed a noticeable reduction of friction coefficient.

A combination of surface texturing and solid lubricant can enhance remarkably the tribological performances of textured surfaces. For example, Ripoll et al. [29] fabricated microscale textured titanium alloy surfaces and coated them with MoS_2. They concluded that the formation of a MoS_2 film could significantly reduce the friction coefficient of titanium alloys. Rapoport et al. [17] also applied MoS_2 films on the textured surfaces. They reported that the textured surfaces with half of the bulge's height showed enhanced MoS_2 storing capability. Shi et al. [30] prepared a few layer graphene on the textured surface. They evidenced an improved wear resistance in textured surfaces when compared with bare steel components. Su et al. [31] burnished $BaSO_4$ solid lubricants on the textured Al_2O_3/Mo ceramic surfaces. They reported a continuous decrease in friction with increasing temperature.

Based on the literature review, solid lubricants can be spread over the textured surface to provide a significant reduction in friction and wear. The most commonly used solid lubricants include WS_2, MoS_2, graphite, CaF_2, and silver. They are used in the form of powers [17], plasma deposited coatings [32], and alloying additions in the matrix [33]. However, the influences of various solid lubricant types on the tribological behavior of textured surfaces have not been studied extensively [25,34,35]. In the present study, we developed micro-textures on austenitic stainless steel surfaces. The textured samples were filled with solid lubricant powders like WS_2, graphite, CaF_2, and hBN. The purpose of the present study was to explore the influences of various solid lubricants on the tribological behavior of textured austenitic stainless steel surfaces. We can further understand the basic mechanism of powder lubrication on the textured surfaces.

2. Experimental procedures

2.1. Materials

A commercially available AISI 316 stainless steel was used as substrate material. A 5 mm thick sheet of AISI 316 stainless steel was cut into square pieces of 17 mm × 17 mm. The blocks were subsequently polished (Ra = 0.05 µm). The specimens were cleaned with ethanol in an ultrasonic bath for 30 min. After rinsing with ethanol, the specimens were dried in a vacuum oven.

2.2. Laser surface texturing

The surface texturing was applied to the samples with a Nd:YAG pulsed laser (wavelength λ = 1064 nm). The samples surface was processed with a laser power of 12 W, a frequency of 30 KHz, and a scanning speed of 130 mm/s. Equally spaced grooves covered the entire sample surface. The density of the grooves (D_{groove}) can be calculated by the ratio of the total groove area to the total area. The groove density was chosen to be 0%, 1%, 2%, 4%, 7%, 14%, 29%, and 57%, respectively. The textured surface was then lightly polished to reduce the burrs around the boundary of the groove. Solid lubricant films were applied to the textured surface by a rubbing process. The micro-textures were filled with solid lubricants. Various types of lubricants were used in this study, including calcium fluoride (CaF_2), hexagonal boron nitride (h-BN), tungsten disulfide (WS_2), and graphite (see Fig. 1).

2.3. Friction and wear test

Tribological tests were performed using a ball-on-disk tribometer (UMT-2, USA). The experiments were carried out in a reciprocating sliding motion. The microscale patterns were aligned perpendicular to the sliding orientation. The ball counterpart was an AISI 316 steel ball (9.525 mm in diameter). The experiments were conducted at a normal load of 20 N, a sliding speed of 10 mm/s, and a stroke length of 10 mm. Each experiment lasted for 60 min at room temperature. Some of the tests were repeated several times to establish reproducibility.

The surface morphology of the specimens was tested by scanning electron microscope (SEM). Energy-dispersive X-ray spectrometry (EDS) was applied to examine the chemical composition of damaged surfaces. The 3D surface profile of the wear track was measured by a laser microscope (Zeta-20, USA). The wear rate was then calculated as the ratio of the worn volume to the normal load and the distance.

3. Results and discussion

3.1. The characterization of micro-textures

Fig. 2 shows a typical micro-patterned surface topography. Laser beam machining involves the delivery of high-energy laser pulses to vaporize materials. The melting and vaporization of the target material lead to the formation of a microscale groove. The microscale grooves are evenly spread over the surface (see Fig. 2(a)). The laser micromachining causes small bumps of resolidified material around the edge of the grooves (see Fig. 2(b)). The microchannel in Fig. 2 has a depth of about 22 µm and width of about 57 µm.

Various types of solid lubricants are applied to the textured surfaces. The solid lubricants used in this study include CaF_2, h-BN, WS_2, and graphite. Solid lubricant powders are manually burnished onto the textured surface. Fig. 3 displays the characteristic shape of the WS_2 powders burnished on the ablated surface. The micro-groove is filled with WS_2 powders. A minor portion of the WS_2 powders exists on the surfaces around the groove. The top surface of the WS_2 powders is higher than the rest of the textured surface. The difference between measured heights could be due to the bulges around the rim of the groove.

3.2. Tribological properties of patterned surfaces

The graphs in Fig. 4(a) and (b), shows the time evolution of the friction coefficients for the flat and patterned surfaces, respectively. In both cases, the test results for the friction coefficient show a similar trend. In the beginning, both the non-patterned and patterned surfaces show a low friction coefficient of about 0.2. Then the friction coefficient increases rapidly to a maximum of about 0.96 in less than 10 s. Afterwards, the friction coefficient gradually decreases with time. In the final stage, the value of the friction coefficient levels off.

Fig. 4(c) presents a comparison of the steady-state friction coefficient of the non-patterned and patterned surfaces. The patterned surface with a groove density of 14% shows a lower friction coefficient value in the steady state than that of the non-patterned surface. The error bar represents the random scatter of the friction coefficient data. In addition, the surface texture can lead to a decrease in the amplitude of oscillations. However, the presence of micro-scale grooves results in a slight increase in the wear rates (see Fig. 4(d)).

Fig. 5 shows the wear tracks of the non-patterned and patterned surfaces, respectively. In both cases, the AISI 316 stainless steel samples suffer from poor metallic wear. Significant amounts of debris particles remain in the wear track. EDS analysis of the debris particles located at points A and B reveals a considerable amount of Fe, Cr, and oxygen. A pronounced signal from oxygen shows severe oxide formation during the sliding process (see Fig. 5(c) and (f)). The relatively low hardness and low fracture toughness of the AISI 316 stainless steel could