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Angle-dependent lubricated tribological properties of stainless steel by femtosecond laser surface texturing

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ABSTRACT

Lubricated tribological properties of stainless steel were investigated by femtosecond laser surface texturing. Regular-arranged micro-grooved textures with different spacing and micro-groove inclination angles (between micro-groove path and sliding direction) were produced on AISI 304L steel surfaces by an 800 nm femtosecond laser. The spacing of micro-groove was varied from 25 to 300 µm, and the inclination angles of micro-groove were measured as 90° and 45°. The tribological properties of the smooth and textured surfaces with micro-grooves were investigated by reciprocating ball-on-flat tests against Al_2O_3 ceramic balls under starved oil lubricated conditions. Results showed that the spacing of micro-grooves significantly affected the tribological property. With the increase of micro-groove spacing, the average friction coefficients and wear rates of textured surfaces initially decreased then increased. The tribological performance also depended on the inclination angles of micro-grooves. Among the investigated patterns, the micro-grooves perpendicular to the sliding direction exhibited the lowest average friction coefficient and wear rate to a certain extent. Femtosecond laser-induced surface texturing may remarkably improve friction and wear properties if the micro-grooves were properly distributed.

1. Introduction

Laser surface texturing (LST) is a well-known surface engineering process applied to improve surface tribological properties by fabricating artificial topography on the surfaces of materials [1–3]. The dimples and grooves are the most common geometric features used for laser-textured tribo-surfaces. These textured surfaces can act as lubricant reservoirs that can feed the lubricant directly into the contact zone of the sliding surface under starved oil lubrication [4,5]. Another critical function of the textured surfaces is trapping of wear particles. The elimination of wear particles from the interface reduces friction and wear in both lubricated and dry sliding [6,7]. Furthermore, the textured surfaces can also promote occurrence of hydrodynamic lubrication conditions and increase load-carrying capacity [8–10]. To date, laser surface texturing has been used in many fields to improve the tribological performances of interfaces, such as mechanical seals [11–13], piston rings [14], cutting tools [15–18], thrust bearing [19,20], and magnetic storage devices [21].

Femtosecond pulsed lasers, owing to their ultrashort pulse width and ultrahigh peak power, are among the most promising tools to achieve micromachining in the field of tribological applications [22–27]. Due to the very short time scales involved in the ablation with femtosecond laser pulses the ablation process can be considered as a direct solid-vapor transition [28,29]. Therefore, almost all materials can be accurately micro-textured in a controlled and reproducible way, and with minimal collateral damage. Tagawa et al. [22] described the development of contact sliders with nanotextures by means of femtosecond laser processing. It is found that the friction coefficients of contact head-disk interface could be decreased remarkably by the nanotextures fabricated on the contact slider surfaces. Bathe et al. [27] investigated the influence of laser-textured surface produced by different laser sources on the tribological behavior of gray cast iron. They proved that surface texturing using femtosecond pulse duration resulted in significant improvement in tribological performance in comparison to the untextured as well as millisecond and nanosecond laser-textured surface under dry condition.

The textured surfaces features also have great influence on tribological properties under lubricated conditions. He et al. [30] studied the effects of dimple spacing on tribological properties, and their results showed that small texture spacing is beneficial for the reduction of friction coefficients of textured surfaces.

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However, the results of Shun et al. [31] and Xiong et al. [32] indicated that the friction coefficients and wear rates of textured samples do not monotonically decrease as the dimple spacing is reduced. Yuan et al. [33] investigated the effects of micro-groove orientation on sliding performances, showing that the merits of different micro-groove inclination angles may swap under various contact conditions. Thus, the tribological properties of textured surfaces may be relatively sensitive to the spacing and inclination angle, which should be further investigated.

In the current study, micro-grooved textures with different spacing and inclination angles were fabricated by femtosecond laser-induced surface texturing on AISI 304L steel surfaces. The effects of textures on the tribological properties were investigated by reciprocating ball-on-flat tests against Al_2O_3 ceramic balls under starved oil lubrication. In comparison of other laser-textured surface, there is very minimal resolidified and spatter particles on the femtosecond laser-textured surface due to its ablation mechanism. During sliding wear test, the resolidified and spatter particles on the metal surface is collapsed readily, which is probably detrimental to the tribological properties [27]. To the best of our knowledge, few studies have used femtosecond laser-induced surface texturing on the stainless steel surface to determine the effects of different micro-groove spacing and inclination angles on tribological properties under starved oil lubrication. Consequently, we applied femtosecond laser-induced surface texturing under starved oil lubrication to investigate the effects of micro-grooved textures on tribological properties.

2. Experimental details

2.1. Material and laser-induced surface texturing

AISI 304L stainless steel is the material used for the tests, and its main properties are listed in Table 1. For comparison, the properties of the friction test material, Al_2O_3 ceramic ball, are also listed in Table 1. The plane AISI 304L steel samples with dimensions of 25 mm × 15 mm × 6 mm were cut from the as-received state steel plates. Prior to laser texturing, the plane steel surfaces were ground and polished to a mirror finish with 0.5 μm diamond polishing agent. The final surface roughness Ra before texturing was about 0.1 ± 0.01 μm. The Al_2O_3 ceramic balls showed a diameter of 9.525 mm, and their surface roughness was less than Ra 0.05 μm.

The plane steel samples were mounted on a xyz stage with a resolution of 1 μm, which was precisely controlled by a computer for laser micromachining. A regeneratively amplified 800 nm Ti: sapphire laser emitting a train of 130 fs, 1 kHz mode-locked pulses was used for laser-induced surface texturing. The output beam diameter of the used femtosecond laser is 5.4 mm, which was focused via an objective with ten time magnification and a numerical aperture of 0.3. When the laser is 125 μJ, the focusing enegy density (fluence) of 70.8 J/cm^2 can be achieved. The laser fluence we used is higher than the ablation threshold (~0.1 J/cm^2) of the stainless steel.

Textures were produced with varied spacing ranging from 25 μm to 300 μm. The dimensions of the textures are shown in Table 2. The values of the width and the depth are the mean values of ten data with a standard error of mean (SE).

Table 2
Geometric parameters of textured surfaces.

Untextured/ textured	Width/μm	Depth/μm	Spacing/μm	The abbreviated form of surfaces	The abbreviated form of surfaces
Smooth	–	–	0	SS	SS
Textured	15 ± 0.06	12 ± 0.04	25	ST-90-25	ST-45-25
Textured	15 ± 0.06	12 ± 0.04	35	ST-90-35	ST-45-35
Textured	15 ± 0.06	12 ± 0.04	50	ST-90-50	ST-45-50
Textured	15 ± 0.06	12 ± 0.04	75	ST-90-75	ST-45-75
Textured	15 ± 0.06	12 ± 0.04	100	ST-90-100	ST-45-100
Textured	15 ± 0.06	12 ± 0.04	150	ST-90-150	ST-45-150
Textured	15 ± 0.06	12 ± 0.04	200	ST-90-200	ST-45-200
Textured	15 ± 0.06	12 ± 0.04	300	ST-90-300	ST-45-300

The samples with smooth surfaces, micro-grooves of 90° groove inclination angles, and micro-grooves of 45° groove inclination angles are named SS, ST-90, and ST-45, respectively. The surface morphologies of textured surface were imaged by a scanning electron microscope (SEM, JSM-7600F). The topographies of textured surfaces were measured by an optical profilometer (Veeco Wyko NT9100).

2.2. Friction and wear test

Reciprocating ball-on-flat tests based on ASTM G133 standards were conducted using a tribometer (UMT-2) to investigate the friction and wear performances of textured and smooth AISI 304L stainless steel surfaces sliding against the Al_2O_3 ceramic balls. AISI 304L stainless steel samples were mounted flat, whereas the Al_2O_3 ceramic balls were fixed on a fixture reciprocated at a speed of 10 mm/s. The angles between the sliding orientations of the Al_2O_3 ceramic balls and the micro-groove path were 90° and 45°, respectively. For each test, the stroke length was 10 mm and the normal load was 3N. The tests were conducted at room temperature of 25 °C with 30% relative humidity. Before each test, the balls and surfaces were cleansed with acetone and ethanol then blown dry with nitrogen to remove residual dust, grease, and other solid contaminants, thereby keeping the surface conditions constant as possible. KUNLUN diesel oil 10W-30 was used as lubricant in the tests. Prior to each test, sufficient lubricant was dropped on the contact surface, and excessive lubricant was removed from the surfaces by using a rubber blade. After the removal, only a thin layer of lubricant appeared on the surface to keep the starved oil lubrication condition [34]. The friction test was conducted three times for each sample in order to minimize data scattering. The wear tracks of smooth and textured surface were imaged by a scanning electron microscope (SEM, JSM-7600F) and an optical microscope (OM, Leica MEF4A). The line profiles of wear tracks of smooth and textured surface were measured by an optical profilometer (Veeco Wyko NT9100).

The variation of friction coefficient with time can be obtained directly by the software on the UMT-2 tribometer. Average friction coefficients can then be calculated on the basis of average values in the stable curve stage. The wear rate is calculated as follows:

Table 1
Properties of AISI 304L steel and Al_2O_3 ceramic ball.

Material	Density/g cm^{-3}	Young's Modulus/GPa	Poisson's ratio	Hardness/HV	Compressive strength/MPa	Tensile strength/MPa
Steel	7.93	195	0.28	198	–	590
Al_2O_3	3.92	340	0.22	1650	2200	–