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Manipulation of tribological properties of stainless steel by picosecond laser texturing and quenching

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ABSTRACT

We reported on the manipulation of tribological properties of stainless steel by picosecond laser texturing and quenching. The micro-grooved textures were formed on the steel surface, accompanied with the appearance of nanostructures with grain sized of 80–400 nm, oxides thin film (Fe_2O_3 and Cr_2O_3) and martensite during picosecond laser surface texturing process. The tribological tests indicated that the average friction coefficients and wear rates of textured surfaces initially increased then decreased with the increase of spacing of micro-grooves. The well-controlled friction and wear properties are attributed to the combined effects of induced micro-/nanostructures, martensitic transformation and oxides thin film in the local quenched zone of stainless steel samples.

1. Introduction

The improvement in tribological properties by laser-texturing of materials has received great attention in the past few years [1–6]. These laser-machined surface textures, such as micro-dimples and micro-grooves, can act as traps for wear debris [7,8], as lubricant reservoirs for feeding lubricant [9,10], and as micro-hydrodynamic bearings for increasing load-carrying capacity [11,12]. To date, laser surface texturing has been used in many fields to modulate the tribological performances of interfaces, such as mechanical seals, piston rings, drill bits, cutting tools, and magnetic storage devices [13–18].

Recently, the femtosecond pulsed laser technology becomes one of the most promising ways to achieve micromachining in the field of tribological applications, which is owing to its ultrashort pulse width and ultrahigh peak power that can process almost all material. Moreover, femtosecond laser processing is expected to minimize the melt ejection and heat-affected effects for surface texturing in tribological applications [19–25]. It has been demonstrated that the femtosecond laser-textured surface without heat-affected effects is beneficial to improving tribological properties of material surfaces [20,21]. However, the heat-affected effects during laser surface texturing process maybe have positive influence on tribological performances of material surfaces [26]. During the interaction between incident pulsed laser beam and the material surfaces, such a high energy is deposited only in a very thin layer within a short time, causing super-fast processes including super-fast melting and solidification, accompanied with surface oxidation as well [27]. The super-fast cooling and solidification (laser quenching effects) can result in microstructural changes such as a reduction in grain size or phase transition [28–30]. The increase of surface hardness due to grain refinement or phase transition and the formation of oxides are possible to enhance tribological properties. For these reasons, searching lasers with pulse width within femtosecond and nanosecond, which can form surface textures accompanied with heat accumulating, becomes an urgent need. Lasers with few of picosecond pulse width are expected to meet the requirement. Picosecond lasers surface texturing is accompanied with local quenching effect on the metal surface [31,32], which maybe results in grain refinement or phase transition in the laser heat-affected zone.

In this study, we choose a picosecond pulsed laser with pulse duration of 100-ps to induce micro-groove textures, accompanied with local quenching effect simultaneously on the surface of stainless steels. To our best knowledge, no study has been reported with regards to the effect of the combined action of geometric patterns (micro-grooves) and local quenching effects on tribological properties of stainless steels by picosecond laser surface texturing. It was found that the tribological properties of the AISI 304L steel can be tuned by picosecond laser surface texturing.

2. Experimental procedures

2.1. Material and laser surface treatment

AISI 304L stainless steel plates with dimensions of 25 mm × 15 mm × 6 mm were used for experiments and its main properties

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were listed in Table 1. As a comparison, the properties of friction test material, GCr15 steel ball, were also listed in Table 1. Before laser surface texturing, the steel samples were ground and polished to a mirror finish using a 0.5-μm diamond polishing agent. The final surface roughness R_a before texturing was 0.030 ± 0.006 μm (smooth surface). The GCr15 steel balls had a diameter of 3 mm, and their surface roughness was less than R_a 0.02 μm.

The 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 picosecond laser (Fianium Ltd.) that generates 532-nm, 100-ps laser pulse at a repetition rate of 500 kHz was used for the laser surface modification. Some reflective mirrors placed in the optical path were used to guide the laser beam toward the surface of samples. The laser pulse with an average power of 700 mW was focused via a microscope objective (10 ×, NA=0.3) onto the surface of samples. The scanning speed of the stage was set as 200 μm/s. Micro-grooved textures consisting of regularly repeating features were then produced with varied spacing ranging from 5 to 300 μm. Table 2 lists the geometric parameters of picosecond laser textured surfaces (PLTSs). The width of grooves was about 5 ± 0.12 μm, and the depth was about 0.42 ± 0.05 μm. The SS was a smooth surface (untextured surface) used for comparison with textured ones. Fig. 1 shows the schematic diagram of picosecond laser textured surfaces.

2.2. Analysis and characterization

The field emission scanning electron microscopy (FESEM) micrographs were obtained on a JSM-7600F scanning electron microscope equipped with energy-dispersive spectrum (EDS, OXFORD INCA). The topographies of picosecond laser textured surfaces were measured by an optical profilometer (Veeco Wyko NT9100). The grazing incidence X-ray diffraction (GI-XRD) patterns were measured by a Rigaku SmartLab X-ray diffractometer with Cu Kα radiation (λ=1.54056 Å) in 2θ mode. X-ray photoelectron spectroscopy (XPS) was performed on a Kratos AXIS Ultra DLD spectrometer. The surface hardness (HV) was measured on Fischerscope H100 VP nanoindention device. The penetration load employed in the experiment was 10 mN and the values for each sample were average of at least ten measurements, with standard deviations.

2.3. Friction and wear test

Reciprocating ball-on-flat tests based on ASTM G133 standards were conducted using a tribometer (CETR UMT-2) to investigate the friction and wear performances of smooth and textured AISI 304L stainless steel samples sliding against the GCr15 steel balls. The samples were mounted on the flat, and the GCr15 steel balls fixed on a fixture reciprocated the surfaces at a speed of 5 mm/s. The sliding direction of the GCr15 steel balls was perpendicular to the orientation of the micro-grooves. For each test, the stroke length was 5 mm and the normal load was 0.4 N. The tests were conducted at room temperature of 25 ± 1 °C with $30 \pm 1\%$ relative humidity. Before each test, the balls and surfaces were cleaned 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. All tests were repeated under the same conditions 6 times in order to acquire a reliable data set, with standard deviations.

Table 1
Properties of AISI 304L steel and GCr15 steel ball.

Material	Density (g cm^{-3})	Young' s modulus (GPa)	Poisson' s ratio	Hardness (HV5)
AISI 304L	7.93	195	0.28	198
GCr15	7.81	201	0.3	660

The variation of the friction coefficient with time was directly determined using 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. Worn surfaces were observed by the FESEM and their cross-sectional areas were measured by the optical profilometer. The wear rate was calculated as follows:

$$K = \frac{A \times L - \frac{B \times W \times L}{S}}{F \times D} \qquad (1)$$

where A is the cross-sectional area of worn tracks (μm^2), B is the cross-sectional area of micro-grooves (μm^2), L is the length of worn tracks (mm), W is the width of worn tracks (μm), S is the spacing of micro-grooves (μm), F is the normal load (N), and D is the sliding distance (m), respectively.

3. Results and discussion

3.1. Morphology of picosecond laser textured surfaces

Fig. 2 shows the SEM micrographs of smooth surface (SS) and picosecond laser textured surfaces (PLTSs). The original grain of SS is etched by 10% oxalic acid and its average grain size of austenite (γ) is larger than 20 μm as shown in Fig. 2(a). The α-ferrite also can be observed in this image. Fig. 2(b) and (c) illustrate the laser-textured structures with 5 μm and 50 μm spacing. Micro-cracks appear in the local quenched zone, which is attributed to the formation of stress in the process of picosecond laser quenching. Fig. 2(d) shows the higher magnified image of the local quenched zone. It can be seen that the local quenched zone consists of nanostructures with grain sizes of 80-400 nm. Compared with the smooth surface (Fig. 2(a)), the local quenched zone has a significant grain refinement. As well-known that the time scale for a considerable energy transfer from electronics to the lattice is about 1 ps during the interaction of laser pulse with metal targets [33,34]. In other words, the thermal wave will propagate into the metal target and the thermal diffusivity cannot be neglected if the duration of laser pulse is more than 1 ps. In our case, the high energy is deposited only in a very thin layer within 100 ps, which causes super-fast heating, melting, and evaporation, followed by super-fast solidification of the laser quenched layer. Such a non-equilibrium process (rapid cooling) significantly increases the nucleation rate on the melted layer. Once a large number of nuclei are formed, the growth of crystals is finally restrained by neighboring crystals, which is easy to form fine grains, i.e., nanostructures [28]. Therefore, the grain size on the local quenched zone (Fig. 2(d)) is far less than the original grain size of untreated surface (Fig. 2(a)). This is also suitable for other textured samples.

In the current research, the length of heat-diffusion in the stainless steel is very short because the pulse width of the selected laser is only 100 ps (10^{-10} s) [35]. Therefore, no interference occurs between the adjacent laser ablated lines as the length of

Table 2
Geometric parameters of picosecond laser textured surfaces.

Sample	SS	PLTS -5	PLTS -10	PLTS -15	PLTS -25	PLTS -35	PLTS -50	PLTS -75	PLTS -100	PLTS -150	PLTS -200	PLTS -300
Spacing (μm)	–	5	10	15	25	35	50	75	100	150	200	300