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Tribological properties of PTFE/laser surface textured stainless steel under starved oil lubrication

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ABSTRACT

Surface textures with dimples were fabricated on stainless steel surface by a Nd:YAG pulsed laser. Friction and wear behaviors were investigated by rubbing against PTFE under starved oil lubrication and the effect of dimple density from 2.0% to 20.9% was examined. The result shows that friction coefficient of stainless steel is reduced from 0.08 to 0.05 due to texturing, and the longevity of oil film is prolonged by 50%. The dimple density of 7.9–8.8% appears the optimal tribological performance with the friction coefficient of 0.055 and wear rate of 5.2×10^{-7} mm^3/N m. The beneficial effect of dimples is to act as oil reservoirs and the sink for capturing wear debris under starved lubrication.

1. Introduction

Lubrication of sliding surfaces is very important for the success of operation and longevity of various machines and engines both automotive and aerospace applications. Reduction of friction and wear is considered to be a necessary requirement for saving energy, prolonging durability and improving efficiency [1–3]. Several methods like super-finishing processes are being attempted to improve the machining accuracy and reduce the surface roughness, to enhance the galling and abrasion resistance of the machine elements that have to work under relative motion. However, these finishing processes increase the costs of manufacturing greatly. Also, the improvement of surface roughness is limited by manufacturing accuracy and natural properties of materials.

As a means for enhancing tribological performance of contact components, laser surface texturing (LST) is now well known for many years [4–6]. It involves creation of an artificially distributed array of micro-dimples or channels on components surface by a material ablation process with a pulsating laser beam [7–9]. The formation of patterned micro-dimples may affect hydrodynamic lubrication and load carrying capacity of the textured surface [10,11]. The dimples are expected to act as reservoirs of the fluid enhance hydrodynamic action that helps in reduction friction and at the same time they may trap wear particles also which is expected to reduce wear [8–10].

The technology of surface texturing has fruitfully been utilized in enhancing the performance of mechanical seals, sliding bearings of hydraulic machines, piston ring of diesel engine, cylinder liner, and thrust bearings [12–15]. In recent years, great steps have been made in the development of various smart surface texturing technology, providing lower friction and wear under hydrodynamic and mixed-boundary lubricated sliding conditions [16–19]. According to the aforementioned researches, the micro-hydrodynamic bearing effect of surface texture under fluid lubrication is well understood by theoretical and experimental researches, while more work is needed for the case of starved oil lubrication [2,20,21].

In this paper, ring-on-disc friction tests were carried out on textured surface of stainless steel to investigate the effect of surface texture on tribological properties. A drop of oil was added into the sliding interface without subsequent supplement to keep the starved oil lubrication condition. Different area densities were textured by systematical combination of tangential distance and diameter of dimples, and its effect on tribological properties was discussed in detail.

2. Experimental details

2.1. Laser surface texturing

The surface of stainless steel discs (1Cr18Ni9Ti) with diameter of 48 mm and roughness (R_a) of about 0.1 μm was textured to

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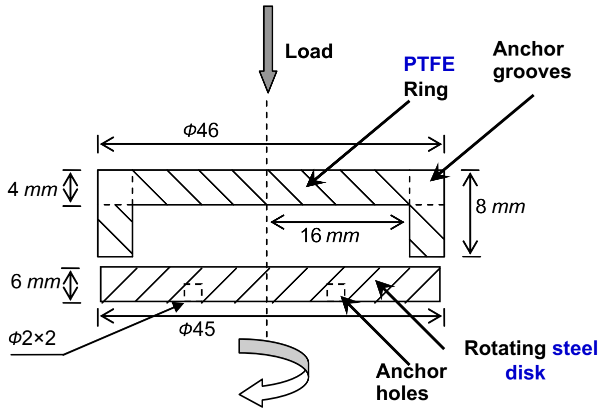

Fig. 1. Schematic representation of ring-on-disc arrangement.

induce arrays of micro-dimples with the help of a pulsed Nd:YAG laser having a wavelength of 1064 nm and a pulse width of 450 ns. The dimple arrays are textured in a cyclic distribution on the steel disc with the inner and external diameters of 32 mm and 46 mm, respectively. All the discs were polished by 1200# SiC emery paper to completely remove the raised rims [16] and the roughness of polished discs is about 0.04 μm. The structure and morphology of dimples were observed using an optical microscope and a white-light interferometer surface mapping microscope. PTFE ring (Φ46 mm × 8 mm), which was polished to a roughness (R_a) less than 0.05 μm, was used as the counterface.

2.2. Friction testing

Friction tests were conducted on a ring-on-disc MG-2000 tribological tester at room temperature in air, as used in the previous research [22]. As shown in Fig. 1, the upper PTFE ring fixed on the upper spindle by anchor-groove structure (commercial Teflon, external and inner diameter of 46 mm and 32 mm, $E_1=300$ MPa and $\upsilon_1=0.46$) was kept stationary and in contact against a rotating lower specimen i.e., the laser-textured stainless steel disc (1Cr18Ni9Ti, φ48 mm × 8 mm, $E_2=210$ GPa and $\upsilon_2=0.3$). The lower disc was fixed on the support-stage by two anchors and a steel ball was fixed in an anchor-groove between sample and support-stage to keep the dynamic alignment of the mating surface. Tests were performed under a normal load of 100 N and a speed of 500 rpm (1 m/s). The average diameter of the frictional track was about 40 mm. Before tests, all the samples were cleaned by acetone. A drop of commercial oil (kinetic viscosity of 0.0136 Pa s) was added to the sliding orbit of PTFE ring on steel disc using a transfer pipette before starting the test, and the lubricated oil with the volume of about 0.05 mL would never be supplemented during the test process. Another friction test was conducted with a constant load of 100 N and a starting velocity of 0.4 m/s, and the velocity was increased in steps of 0.1 m/s after sliding every 1000 cycles. The wear rate was calculated in terms of the mass loss measured by an analytical balance having a resolution of 0.0001 g.

3. Results and discussion

3.1. Morphology of surface texture

The dimple parameters are listed in Table 1. The tangential distances (l_1) are 300, 500 and 800, respectively, corresponding to a constant radial interval (l_2) of 500 μm. The dimple area ratio (s) is calculated on the basis of Eq. (1) given below, and a series of values from 2.0% to 20.9% are given by the systematical combination of diameter (d) and tangential distance of surface dimples

$$s=(\pi \cdot d^2)/4l_1l_2 \tag{1}$$

Table 1
Parameters of surface micro-dimple array.

Number	Diameter (m)	Tangential distance (m)	Area density (%)
1	100	300	5.2
2	150	300	11.8
3	200	300	20.9
4	100	500	3.14
5	150	500	8.8
6	200	500	12.6
7	100	800	2.0
8	150	800	4.4
9	200	800	7.9

The optical micrographs of three representative samples textured with a diameter of 100 μm and different tangential distances (800, 500 and 300 μm) are shown in Fig. 2(a)–(c), respectively. It is observed that the dimples are distributed in the form of an annular array and the density increases from 2.0% to 5.2%. High magnification morphology and 3D image of the polished dimple are presented in Fig. 3(a) and (b), and the dimensions of the same are shown in Fig. 3(c). It could be seen from Fig. 3(a) that an orbicular area called "heat-affected zone" is created due to the laser–metal interaction which have led to melting and vaporization of the steel surface during ablation. The raised rims are almost completely removed, and the diameter of single polished dimple is about 100 μm whereas the depth is 40 μm, as could be seen in Fig. 3(b) and (c).

During the laser-texturing process, metal absorbs the energy supplied by laser and ejects out of the surface as a result melting and plastic deformation. The rapid ejection of material from the specimen during laser–material interaction leads to the formation of a shock wave in the surrounding dimple. During the laser interaction the molten metal spatters and the ejected particulates from the work piece surface get solidified on the substrate after the interaction is over. The solidified particles could easily be observed in Fig. 4 which represents SEM micrograph of a severely polished dimple.

3.2. Effect of laser surface texturing on tribological behavior

Fig. 5 shows the variation of coefficient of friction with sliding distance for both smooth (untextured) and textured specimens. The friction coefficient of textured sample is observed to be lower than that of smooth sample as evident from Fig. 5(a). The stable friction coefficient of textured surface is about 0.05, while that of smooth one is about 0.08. The textured specimen is able to sustain a low friction coefficient up to about 47,000 m, while the smooth surface could sustain it only up to 32,000 m. This indicates the effect of surface texturing in reducing the coefficient of friction and prolonging regime of low friction up to larger sliding distance. Fig. 5(b) shows the wear rates for both smooth and textured specimens as well as the counterface ring. It is clear from the bar diagram given in Fig. 5(b) that the wear rates of both the stainless steel and the counterface PTFE get reduced by surface texturing. The wear rate of the counterface ring sliding against the textured steel is even one order of magnitude lower than un-textured sample.

Fig. 6 shows the worn surface morphology of smooth as well as textured surface after the test. The worn surfaces show the characteristics indicative of abrasive wear as observed earlier also by other researchers [23,24]. However, it could be seen that the laser textured surface was worn mildly with fewer shallow wear

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