Laser pattern-induced unidirectional lubricant flow for lubrication track replenishment

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Abstract: Effective oil replenishment to the lubrication track of a running bearing is crucial to its sustainable operation. Reliable practical solutions are rare despite numerous theoretical studies were conducted in the last few decades. This paper proposes the use of surface effect, wettability gradient, to achieve the goal. This method is simple and can be nicely implemented using femtosecond laser ablation. A periodic comb-tooth-shaped pattern with anisotropic wetting capability is devised and its effect on the anisotropic spreading behaviour of an oil droplet is studied. Results show that the comb-tooth-shaped pattern enables the rearrangement of oil distribution, thereby escalating oil replenishment to the lubrication track. The effect is due to the unbalanced interfacial force created by the surface pattern. The influence of the shape and the pitch of teeth, which are the two governing factors, on oil transport is also reported. The effects of the newly devised surface pattern on lubrication are experimentally evaluated under the conditions of limited lubricant supply. These results are promising, demonstrating the reduction in bearing friction and the increase in lubricating film thickness.

Keywords: laser surface texture; limited lubricant supply; comb-tooth-shaped pattern; lubricant replenishment; friction coefficient

1 Introduction

Alleviating the loss of lubricant from the lubrication track of running bearings or channeling the depleted oil from the two side-ridges back to the track is of considerable practical need. This is particularly important for bearings running under limited lubricant supply or starved conditions. The former condition is to provide on-demand lubricant and considered to be an inspired strategy to introduce practical benefits, such as less bearing friction and wastage [1–3], whilst the latter is a typical problem for bearings running at high speeds [4]. Using mechanical means to enrich the oil replenishment to the track may lead to the loss of the beauty of typical bearing configurations, that is, simplicity [5]. Thus, a feasible alternative is to use surface effect [6].

Moving liquid droplets in desired directions can be facilitated by the gravitational force [7, 8] and unbalanced interfacial forces attributable to the wettability difference between regions of different surface energies [9]. A large number of studies have been committed to devise wettability gradient surface. These studies are largely accomplished on the basis of micro-texture [10, 11], surface coatings/layers [12, 13] or both [14].

To realize the wettability gradient relies on whether the wettability of surfaces can be manipulated. It is well known in lubricating oil research that surface wettability can be modified by additive-formed boundary films such as zinc dialkyl dithiophosphates (ZDDP) [15], ionic liquids [16], and simple organic compounds [17]. Apart from adsorption films, Ryu et al. [18] developed a method to use cross-linkable

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films of random copolymers to modify the surface energy of solid surfaces. To regulate the liquid spreading and guide its direction, surfaces can be wettability-patterned. Hampson and Wardzinski [19] successfully applied a market-available fluorinated polymeric coating to the two sides of a bearing track as a creep barrier to reduce oil loss. Liao et al. [20] and Ito et al. [21] furnished liquid droplet motion on functional surfaces of wettability gradients developed by using chemical patterns. Recently, our group [6, 22] applied oleophobic coatings on either side of the lubrication track to create wettability steps, which successfully reduced the oil loss to the two sides and enriched the oil replenishment to the bearing contact. As a result, friction and wear are reduced. Even though boundary films and oleophobic coatings function, they may not work well in practice. Fabricated coatings/layers are not long-lasting and particularly susceptible to friction and wear. The thin coating/layer is readily worn out under the shear action of bearings, and the damage cannot be recovered *in situ*.

Surface texturing by laser and/or chemical etching has been utilized to modify the liquid wettability of the surface of different materials [23–25]. Patterned surfaces induced by photolithographic etching and femtosecond laser have been intensively studied recently for improving tribological properties [26, 27]. Anisotropic surface wettability or wettability gradient, which guides the liquid lubricant spreading on solid surfaces, can be created by textured structures [28]. Bliznyuk et al. [29] facilitated anisotropic surface wettability on silicon by fabricating patterned strips with a certain width using femtosecond laser scanning. Ta et al. [30] used a direct nanosecond laser to fabricate textured surface roughness gradients, which led to variations in contact angle on different surface domains. Hans et al. [31] created the anisotropic wetting induced by the parallel capillarity effects and perpendicular contact line pinning effects of copper alloys based on micro-textures fabricated using a nanosecond laser. Rosenkranz et al. [32] investigated the anisotropic spreading behaviour of oil droplets on laser-patterned stainless steel surfaces with line-like topographies and found that the structural parameters, such as periodicity and structural depth, are crucial for oil distortion. Choudhury et al. [33] indicated that surfaces with micro-dimples considerably increased lubricant

film thickness. Hirayama et al. [34] investigated the effect of nano-textured surfaces with parallel grooves at the two sides of the lubrication track on lubrication. They found that the surface textures reduced oil leakage from the bearing contact area, thereby leading to increased lubricating film thickness.

The present work aims at enriching oil replenishment to the lubrication track of bearings. The aforementioned studies revealed that gravitational effect, wettability gradient, and the micro-structure of surface patterns would affect the directional motion of oil on a surface, and direct laser micro-patterning is an ideal means to create surface wettability gradients. Thus, this study proposes a surface pattern characterised by anisotropic wettability and topographic features to channel oil to the lubrication track to improve lubrication. The proposed design for actuating oil is based on the following: (i) the unbalanced force created at the boundary between surface domains of different surface energies, (ii) the capillary effect of the micro-pattern, and (iii) the geometrical structure. Consequently, the proposed micro-textured surfaces would prevent oil migration and enrich oil replenishment.

2 Experimental

2.1 Surface pattern design

The proposed surface pattern, as schematically depicted in Fig. 1, comprises two arrays of comb-tooth-shaped grooves located symmetrically on the two sides of a longitudinal central lubrication track. The tips of the triangular grooves point away from the central track. The comb-tooth-shaped pattern was prepared by a femtosecond laser. The cross-section of the grooves is in V-shape, as illustrated in Fig. 1. The slope angle α of the side-wall is a constant, but the depth of the grooves varies linearly from the deepest at the wide end of the wedge to the shallowest at the tip. The high-power laser changes the surface energy during groove formation [23, 35]. Thus, the patterned surface constitutes an array of alternate domains of different surface energies. For a liquid spread across the comb-tooth-shaped patterns, a net interfacial force is created at the boundary between the original surface and the groove due to the difference in surface energy [10, 11],

Fig. 1 Textured surface with V-groove arrays and direction of net interface force (f_{NIF}).

and the direction of the net force is towards the wide end of the groove [36, 37]. Furthermore, the spreading of lubricant along the groove is affected by the triangular shape. The capillary force created by the V-groove (as depicted in Fig. 1) augments the barrier to the oil migration away from the central track. Collectively, the proposed comb-tooth pattern provides a unidirectional effect on the lubricant spreading behaviour.

2.2 Laser surface texturing

Comb-tooth-shaped structures as shown in Fig. 1 were textured on the substrate specimens, using the direct laser writing (DLW) technique. The grooves were generated by the line-by-line unidirectional scanning with different lengths as illustrated in Fig. 1. The patterning process was actualised by a femtosecond-pulsed fiber laser (Spectra-Physics Spirit One) with a wavelength of 1,040 nm, a pulse duration of approximately 400 fs and a repetition rate of 100 kHz. The laser scanning system is schematically illustrated in Fig. 2. The output beam through a focusing lens is scanned at the sample surface with a nominal focal spot size of 12.5 μm . The scanning speed of the laser beam and the laser pulse energy were respectively set as 100 $\mu\text{m/s}$ and 0.046 mW, which were fixed during the femtosecond laser ablation. The width of the wide end was 150 μm , and the length of the groove was 1,000 μm , wherein a sharp apex angle of approximately 8.6° was produced. The pitch of the line-by-line laser beam scanning process was 10 μm , which resulted in a slight overlapping between adjacent scans. The laser scanning process ended up with grooves in wedged

Fig. 2 Setup of femtosecond laser including shutter, mirror, and lens. The output beam of the laser source is 2 mm in diameter and the scan head delivers the laser beam over the sample surface to generate microstructures.

shape. The depth of the grooves varied from 0.2 μm at the tip to 2.5 μm at the wide end and the slope angle α of the side-wall was a constant.

2.3 Surface characteristics

The surface topography of the samples was characterised by profilometers (Form Talysurf PGI and White Light Interferometry Veeco) before and after the DLW. The statistical surface parameters, such as R_a of the original and patterned surfaces, as well as the absolute dimensions of the pattern, such as the depth, the width, and the periodicity, were measured. The wettability of the specimen surfaces was characterised on the basis of the contact angle measurement using a small droplet of poly-alpha-olefins oil (PAO4, 0.2 μL) with a goniometer (JC2000, Powereach).

One patterned surface was purposely produced with particularly long grooves (3,500 μm in length) for capturing the motion of a liquid droplet to illustrate the wettability gradient of the devised surface pattern. The motion of the droplet was recorded by a digital microscope (VHX-1000, Keyence Digital Microscope) at 20 $\times$ magnification for 60 s. The three-phase line position of the droplet was captured at different time intervals. At the end, the direction of the spreading was identified, and the spreading total distance and velocity were calculated.

2.4 Tribological performance

The effect of the comb-tooth-shaped patterns on oil

replenishment was evaluated under limited lubricant supply conditions on the basis of the lubricating film thickness and friction tests by two apparatuses, namely, an optical ball-on-disc tribometer and a UMT machine, respectively. The film thickness measurements were conducted with the optical tribometer as shown in Fig. 3, where the contact runs in a pure rolling reciprocating mode. The micro-patterns were fabricated on the surface of a glass disc originally coated with Cr+SiO₂ thin layers. The UMT sliding friction tests were conducted with a stationary steel ball loaded on a linearly reciprocating comb-tooth patterned steel plate.

2.5 Specimen samples

In the UMT friction tests, the commercially available bearing steel disc samples (AISI51000, Ø20 mm × 5 mm) with mirror-like surface finish ($R_a = 0.015 \mu\text{m}$) were used for the fabrication of comb-tooth-shaped textures. In the interferometry film thickness measurement, a BK7 glass disc (Ø150 mm × 15 mm) was adopted. The working surface of the glass disc was coated with a thin Cr layer (20 nm) to facilitate interferometry and further coated with a SiO₂ layer (200 nm) for protection. The comb-tooth-shaped patterns were fabricated on the working surface of the disc. The grooves were effectively formed on the glass disc through the two thin surface coatings as their depths varying from 2.5 to 0.2 μm . Thus, the surface of the grooves was largely glass. Before the experiments, the samples were cleaned in an ultrasonic bath with acetone, alcohol, and deionised water for 5 min to remove contaminations. The contact angles of a tiny oil droplet on different locations of the surface were measured

Fig. 3 An optical ball-on-disc tribometer with reciprocating motions. The black dot in the 0.5 mm wide lubrication track represents the contact that is typically 0.2–0.3 mm in diameter. It reciprocates largely linearly ($\pm 5 \text{ mm}$) on the lubrication track. The contact is 60 mm away from the center of the disc.

to determine the localised wettability of the patterned surfaces. Table 1 gives the properties of the lubricant PAO4 used in the experiments. Poly- α -olefins (PAOs) are type IV synthetic base oils and commonly used in lubrication research. In practice, they are widely utilised in rolling element bearings. PAO4 is adopted in the study because of its low viscosity and good fluidity.

Table 1 Properties of the lubricant.

Lubricant	Viscosity (mPa·s, 22 °C)	Density (kg/m ³ , 22 °C)
PAO4	28.5	870

3 Results and discussion

3.1 Micro-morphology of the patterns

Parallel grooves of equal width were initially produced on a steel specimen to evaluate the lasered surface. Figure 4 shows the scanning electron microscope (SEM) image of the grooves. As shown in the image, the width d of the groove on the steel surface is 12.5 μm (as the diameter of the laser beam), and the pitch D is 20 μm . The SEM images show that the upper portion of the groove surface comprises irregular ripples, indicating laser-induced periodic surface structures, which are parallel to the direction of the laser beam polarization (as shown in the inset of Fig. 4). The comb-tooth-shaped grooves were generated by the line-by-line scanning process with different lengths, as illustrated in Fig. 1. The laser-scanned grooves and their surface structure provide a multiscale artificial dual structure. In applications of the laser patterned surface, the fluid transportation could be controlled by the wettability gradient induced by the laser patterned grooves [37] and the spreading of the lubricant in V-shape grooves could be clarified by Washburn approach due to the capillary effect [38].

The fabricated texture results in more surface area than the original non-textured flat surface. The depth of a tooth varies from the tip to the end by around 2.5 μm , as shown in Scan A in Fig. 5. The cross-sectional area of a tooth continuously reduces from the tooth end to the tip. A large cavity is formed at the end of the teeth, i.e., the boundary of the lubrication track, as shown in Fig. 5. By controlling the overlapping

Fig. 4 SEM images of femtosecond-laser-induced line-patterned surface ($D = 20 \mu\text{m}$ and $d = 12.5 \mu\text{m}$). The inset is the corresponding magnified SEM image of the side region of the line-pattern.

Fig. 5 Profile of one tooth from the tooth tip to the end.

region of the laser scanning lines, the ultrafast laser heating effect created the variation of the groove depth. The micro-nano structure of the patterned area by laser overlapping ablation was similar in form of cones. A structure variation in the groove from the tooth end to the tip was also fabricated.

3.2 Anisotropic wetting behaviour

The effects of the comb-tooth patterns on wettability were evaluated through the spreading of a PAO4 droplet ($0.2 \mu\text{L}$) on the surface. The PAO4 droplet naturally acquired a circular shape on plain steel surface without texture, as shown in Fig. 6(a). This circular

shape reveals no preferential spreading direction on an untextured surface. Figure 6(b) shows a PAO4 droplet on the designed comb-tooth-patterned surface. The tiny PAO4 droplet was placed at the central axis of the 0.5 mm wide lubrication track. The total width of the pattern was 2.5 mm . The spreading of the oil towards the two sides was restricted by the two arrays of comb-tooth-shaped grooves. The contact angles of the PAO4 droplet (Fig. 6(b)) were measured from the lateral ($\theta_{\perp}$) direction and the longitudinal direction ($\theta_{\parallel}$). These angles were plotted together with the contact angle of a similar droplet on a plain steel surface, as shown in Fig. 7. The proposed pattern enabled the lubricant droplet readily spreading along the lubrication track (the longitudinal direction) but not in the lateral direction (Fig. 6(b)). Thus, the droplet was elongated in the longitudinal direction such that the contact angle viewed from the lateral direction $\theta_{\perp}$ was smaller than the one viewed from the longitudinal direction $\theta_{\parallel}$ (Fig. 7), and the both angles were larger than the contact angle of the droplet on the plain surface.

The two arrays of comb-tooth-shaped grooves were reversely fabricated to illustrate their unidirectional flow effect, i.e., the tips of the comb-tooth-shaped

Fig. 6 Shapes of a PAO4 droplet on (a) plain steel surface; (b) surface with proposed pattern; and (c) surface with reversed pattern (dark triangles: comb-tooth-shaped grooves).

Fig. 7 Contact angles of PAO4 droplets on the central track of the comb-tooth-patterned surface and on the original surface (θ).

grooves pointed towards the track as shown in Fig. 6(c). The oil spreading to the two sides was augmented by the reversed patterns. Thus, the oil droplet was laterally elongated. This result proved that the tooth direction to the track has a unidirectional effect on spreading.

Figure 8 shows the spreading of a PAO4 oil droplet on the left comb-tooth array. The droplet was deposited on the middle of the patterned area, and the motion of the droplet profile was recorded. Figure 8 reveals that the spread of the oil droplet to the two sides are different and moving to the wide end of the groove is significant, demonstrating unbalanced resultant force applied to the oil. It took around 60 s for the three-phase line of the oil droplet towards the wide end to arrive at the central lubrication track, as shown in Fig. 8(a). The temporal displacements of the three-

phase lines towards the wide end and the tip are plotted in Fig. 8(b). The movement of the three-phase line of oil droplet towards the tip end stopped at the instant of 5 s.

The anisotropic movement of the three-phase line of the oil droplet is attributed to the net force towards the wide end, which is created at the boundary between areas of different oleophobicity: the original surface and the patterned grooves [36]. Also, the unbalanced capillary force from the oil in the groove can also account for the movement of the oil droplet, which is caused by the variation in the cross-section across the groove. The capillary force applied to the liquid in the open V-groove (Fig. 1) could be delineated by a model of Washburn [38],

$$S^2 = f(\alpha, \theta) \frac{\gamma h}{\mu} t \quad (1)$$

where S is the spreading distance, and large S indicates high driving force; $f(\alpha, \theta)$ is the geometrical factor of the V-groove; α is the slope angle of the side-wall and θ is the contact angle; γ is the surface tension coefficient; μ is the viscosity of the lubricant; h is the groove depth; and t is time. $f(\alpha, \theta)$ was approximately fixed along the axis in the currently designed pattern. The viscosity and surface tension of the lubricant PAO4 were constant. Thus, the spreading distance was governed by the groove depth. A deep groove results in long spreading distance, indicating more driving

Fig. 8 Oil droplet transportation on the comb-tooth patterned surface. (a) Oil droplet transportation at different time; (b) displacement of the droplet edge towards the end and tip of the groove; and (c) displacement and transportation velocity for different groove numbers.

force towards the wide end of the comb-tooth groove.

Different numbers of grooves were employed on the steel substrates of the same area to characterise the influence of the groove density (or pitch) on oil transportation. More grooves on a fixed area indicate a large density and a small tooth pitch. Figure 8(c) gives the displacement D and the velocity V of the droplet edge towards the wide end and the tip of the grooves on the patterned surface with different numbers of comb-tooth grooves. D_A and D_B are the distances from the original centre of the droplet to the three-phase lines (or the edge) near the wide end and the tip, respectively, as indicated in Fig. 8(a). In the experiments, the transportation of the droplet was recorded until its edge reached the lubrication track. It can be seen clearly that the increase in the groove density could enhance the transportation velocity of the droplet edge towards the lubrication track or the wide end. This enhancement is attributed to the increase in the number of boundaries between the original and the patterned surface domains. Unbalanced interfacial forces towards the wide end of the grooves are generated and related to the difference in contact angles of the two adjacent domains [7, 8, 36]. Thus the replenishment of the lubrication track can be improved by the comb-tooth texture. The spreading of the oil droplets on the patterns away from the lubrication track would be mitigated by the wettability gradient. With the increase in the density (or decrease in the pitch) of the comb tooth, the distance D_B would decrease slightly first, and then increase.

3.3 Tribological behaviours

Tribological effects of the comb-tooth-shaped patterns were evaluated using UMT friction tests with the reciprocating-sliding contact of a steel ball and a steel disc. The width of the lubrication track was 0.5 mm, whilst the loaded ball-on-disc contact was of 0.068 mm in diameter (estimated as Hertzian contact with parameters: Young's modulus, 210 GPa; Poisson's ratio, 0.3; ball diameter, 6 mm; and load, 1 N). Thus, the reciprocating contact was within the lubrication track, and the ball had no direct contact with the two arrays of micro-patterns. A control test was conducted with a plain steel surface without any surface texture. All the tests were lubricated with a single oil droplet

of PAO4 (0.5 μL), i.e., under limited lubricant supply conditions. Figure 9(a) shows typical temporal variations of the coefficient of friction (COF) during the tests. Each friction test lasted for one hour and was repeated three times. The COF value of each test was the average of the data measured in the last 10 min when the steady state prevailed (as depicted in Fig. 9(a)). The final average COFs and error bar values, as shown in Fig. 9(b), were from those data obtained in the three tests. Figure 9(b) gives a comparison of average COF versus the speed of surfaces with and without patterns. The one with the comb-tooth-shaped pattern demonstrated steadily low values of COF, whilst that with

Fig. 9 COF and wear profile of the patterned and the original surfaces (PAO4). (a) Ball-on-disc COF vs. time (0.5 μL , 4 Hz, 1 N, $d = 6$ mm); (b) ball-on-disc average COF vs. velocity (0.5 μL , 1 N, $d = 6$ mm); and (c) wear profile at the intermediate position of a stroke (0.5 μL , 4 Hz, 1 N, $d = 6$ mm).

no texture maintained consistently high COFs. The patterned surface acquires much lower friction coefficient. Figure 9(c) shows the wear scar profiles measured across the lubrication track at the mid-stroke location. The one with no surface pattern (original surface) suffered serious damage but not the one with the pattern-bounded track. The better lubrication performance with the patterned surface is attributed to the enhancement of oil replenishment to the track.

The magnitude of friction at the linear reciprocating-sliding friction test is related to the lubrication regime, which could be roughly assessed by the lambda ratio (λ), as given by Eq. (2). The λ at the mid-stroke point was 1.6 at 8 Hz (the highest speed in the test), which means the contact is probably in mixed or boundary lubrication.

$$\lambda = h_{\min} / R_{a\Sigma} \quad (2)$$

where $h_{\min}$ is minimum film thickness of point contact calculated by Hamrock–Dowson formula [39]; $R_{a\Sigma}$ is composite RMS surface roughness of the two contact bodies.

The effect of the comb-tooth-patterned surface on the lubricating film formation was evaluated with the optical ball-on-disc tribometer with a steel ball of 25.4 mm in diameter under a pure rolling reciprocating motion. Figure 10(a) presents the lubricating film thickness in a complete reciprocating stroke of 10 mm at a speed of 4 Hz under a fixed load of 30 N. The lubrication without the textured surface was poor for the substantially thin film thickness formed due to the limited lubricant supply (0.1 μ L). The situation was the worse at the two stroke ends, wherein the lubricating film was hardly established. However, the film thickness was increased by more than double with the implementation of the surface pattern despite the same volume of oil supply. Figure 10(b) shows the images of the lubricated contacts at the mid-stroke and the end-stroke of the tests with the two different surfaces (with and without pattern). The width of the central track of the patterned surface is also marked on the images for reference. The reciprocating motion follows, in fact, a circular arc path as the glass disc spins about its centre. Thus, the bearing contact would slightly exceed the border of the central track at the stroke end, as shown in Fig. 10(b). The interferograms

in Fig. 10(b) depict that a much larger oil pool was generated with the patterned surface than the one with no pattern. Most importantly, a large oil pool at stroke ends helps to reduce friction and wear. Figure 10(c) presented the measured central film thickness at mid-stroke, which are the average of three tests. The film thickness increases with the velocity, indicating that the lubricated pure rolling contacts were largely under elastohydrodynamic lubrication regime. The patterned surface provided thicker lubricating film than the one without pattern for the entire specified speed range.

Fig. 10 Film thickness and interferograms of the patterned and the original surfaces (PAO4). (a) Optical ball-on-disc reciprocating test (0.1 μ L, 4 Hz, 30 N); (b) interferograms from optical reciprocating tests (0.1 μ L, 4 Hz, 30 N); and (c) intermediate point film thickness vs. velocity (0.1 μ L, 30 N).

The merit of the patterned surface is proven by the thick lubricating film thickness maintained over the entire stroke of the reciprocating motion (Fig. 10(a)) and for the whole specified velocity range (Fig. 10(c)). The results signify a large oil supply to the lubrication track due to effective oil replenishment. The arrays of comb-tooth patterns on the two sides of the lubrication track induce wettability gradient and provide interfacial force to drag the lubricant back to the track, i.e., oil replenishment is enhanced. Furthermore, the large cavity at the root of the wedged grooves assists in creating a large oil reservoir at the border of the lubrication track, which is beneficial to the lubricating film build-up. The lubrication track bounded by the comb-tooth-shaped patterns demonstrated good lubrication with no oil starvation under limited oil supply (Fig. 10(b)) via the enhancement of oil replenishment.

4 Conclusions

The present study shows that the proposed surface pattern, i.e., two symmetrical arrays of comb-tooth-shaped grooves, is highly effective in oil replenishment for lubrication in non-conformal ball-on-disc contact. The devised pattern is for the synergistic effects of the geometrical structure and surface energy gradient, and the unidirectional oil flow for replenishment can be readily facilitated. The oil transportation is governed by the orientation of the comb-tooth shaped grooves. The speed of oil transportation on the patterned surface is a function of the groove density. Dense groove patterns lead to rapid oil transportation. Therefore, proper design of the groove length, micro surface roughness, and groove density would optimize the replenishment via the lubricant spreading behaviour. The newly devised comb-tooth-shaped pattern in enhancing lubrication is demonstrated by its substantial lubrication film formation and friction reduction.

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