Experimental study of lubrication performance of partially/fully textured surface

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Abstract: Series of disc-on-disc experiments are conducted to investigate the lubrication performance of fully/partially textured surface. All tests were conducted on a rotational rheometer under different conditions, which combined with different rotation speeds and different lubricants. Contact angle of three samples has been measured to research the relation between surface wettability and lubrication property.

1. Introduction
Surface texture is an effective means to improve lubricating performance for friction pairs and has been widely investigated since it was introduced in 1960s by Hamilton and his co-workers[1]. It is generally accepted that surface dimples would serve as “lubricant reservoirs” help to maintain a small amount of lubricant in case of poorly lubrication and holders for wear debris[2, 3]. The most dominant effect caused by surface texture is the generation of an additional hydrodynamic force[4, 5]. Plenty of investigations have gained insights into lubrication mechanism of textured surface. The most extensively accepted explanations is the occurrence of local cavitation[6-9], which can produce a negative pressure. The vast majority of research has paid attention to theoretical modeling and experimental research of fully or partially textured surface under sliding operating condition. Yu[10] studied tribological performance of regular arrayed circular dimples in different depth and diameter and compared hydrodynamic pressure of three dimple patterns (circle, ellipse and triangle). He and his co-workers found that shallow and small circular pattern dimples tended to have more obvious friction reduction. Xing[11] experimentally investigated two kinds of regular shaped grooved textures with different spacing and found that textured exhibited higher friction coefficient and excellent wear resistance compared with untextured sample under dry friction conditions. WOS[12] fabricated micro-dimples in the surface of sliding elements and did a series experiments at different temperatures lubricated with five kinds of oils. Finally he observed that the effect of kind of oil on tribological behavior was negligible under those operating conditions. Shen[13] established the numerical model of texture shape based on the sequential quadratic programming (SQP) algorithm and proposed the novel texture shapes which enhanced the
load-carrying capacity for both unidirectional and bidirectional sliding. However, the validity of numerical model was not experimentally proved.

The aforementioned literature has done much work on surface texture, especially focused on fully textured surface, both in theory and by experiment. Geometric parameters of a single texture and arrangement patterns for textures have been gained huge insights. However, among the investigations mentioned above, most of them focus on the fully textured surface of which textures are regular arranged. What’s more, load-carrying capacity between conformal contacting surfaces with fully/partially texture has not been experimentally investigated. The effect of lubricants for fully/partially textured surfaces also need systematic research.

In this article, fully/partially textured surfaces would be adopted to experimentally investigate how the irregular arrangements and lubricants affect the hydrodynamic performance of the mating pairs.

2. Experimental details

2.1 Experimental apparatus, textured samples and lubricants

Experiments were conducted on a rotational rheometer (AR2000ex, TA Instruments.) under lubricated condition with different lubricants.

The scheme of experimental apparatus is shown in Fig.1 (a). The upper one of the co-acting parts was the geometric measurement probe, which is a stainless circular plate with the diameter of 40 mm.

Test sample was fixed on a lubricant reservoir. The micro-dimples were fabricate on the surface of test sample. Two kinds of textured sample were adopted in tests. The untextured sample shown in and Fig.1 (b) was taken as compared one.

One is a partially dimple textured sample, as shown in Fig.1 (c). The texture region is an annular region with the inner radius ($R_1$) of 8.725 mm and the external radius ($R_2$) of 14.65 mm. Micro-dimples radially distributed in the texture region. There were six micro dimples distributed along the radius with the same interval, which is about 400 $\mu$m. And the angle (alphabet $\alpha$ in Fig.1 (b)) of circumferential circular sector texture unit was 5°. That’s to say, there were 72 micro-dimples equally distributed along the peripheral direction.

And another one is a fully dimple textured sample, shown in Fig.1 (c). Texture region was fully covered with micro-dimples in circular shape. The distance between the adjacent micro-dimples was 400 $\mu$m.

![Fig.1 Scheme of experimental apparatus: (a) test configuration; (b) partially textured sample; (c) fully textured sample](image)

All the micro-dimples were in the same geometric size (the diameter is 400 $\mu$m, the depth is 15 $\mu$m). Disc-on-disc tests were performed in unidirectional rotating slide under adequate lubrication. The mating pairs were lubricated by various lubricants. The basic properties of all lubricants used in tests were shown in Table 1.
Table 1 The properties of lubricants

| Lubricant | Density at 20℃, kg/m³ | Kinematic viscosity at 100℃, mm²/s |
|-----------|------------------------|----------------------------------|
| L-1       | 890                    | 10.8                             |
| L-2       | 860                    | 14.4                             |
| L-2       | 940                    | 20.6                             |

The lubricants L-1, L-2 and L-3 were all fully synthetic oils. The SAE viscosities were SAE30, SAE40 and SAE50, respectively.

2.2 Morphology of the test sample

The surface morphology of the micro-dimple textured sample was shown in Fig.2, which was detected by a hyperdepth three-dimensional microscope (OLYMPUS, DSX510). Fig.2 (a) presented 2D optical surface profiler of the fully textured sample at low magnification. It obviously displayed the distance between adjacent micro-dimples was about 400 μm, either horizontally or vertically. Fig.2 (b) and Fig.2 (c) presented 2D optical surface profiler and 3D optical surface profiler of a single micro-dimple. The profiles showed that the diameter of micro-dimple was 400 μm and the depth was 15±0.05 μm.

![Fig.2](image)

Fig.2 Surface morphology of the fully textured sample: (a) 2D optical surface profiler at low magnification; (b) 3D optical surface profiler of a single micro-dimple;

2.3 Contact angle measurement

The wettability of the textured surfaces, having an influence on the tribological performance, is also related to the surface morphologies of samples. The wettability was usually evaluated by the contact angle. The static water contact angles of samples in this study were measured by using a DropMeter Experience A-300 (MAIST vision Instrument, China). The 3 L distilled water droplets was deposited on the tested sample. Before measurements all the samples have been cleaned by alcohol in ultrasonic bath.

2.4 Lubricated experimental procedure

Test was conducted with a constant gap each time and two kinds of gap (10 μm) were performed. Test duration was 15 min. Rotating speeds of 30, 60 and 90 rev/min increased in a stepwise after running for 5 min. That’s to say, each rotating speed operated for 5 min.

All the tests were evaluated in air atmosphere with a constant room temperature of 25° and a constant relative humidity of 45%. Each test was repeated 3 times.
3. Results and discussion

3.1 Contact angle
The images of samples were shown in the Fig.3. The fully textured sample exhibits the optimum hydrophobic performance enhancement with the maximum contact angle of 107.3° ($3 \mu$L). The initial contact angle of the untextured sample are 83.9° (Fig.3(c)).

![Fig.3 Contact angles on sample surfaces: (a) partially textured sample, (b) fully textured sample, (c) un-textured sample](image)

As contact angles of textured samples are reduced, it shows that the hydrophobic performance of surfaces could be enhanced by texture processing. As the 90° was the divider between contact angles of hydrophilic and hydrophobic surfaces, textured samples obviously had hydrophobic surfaces while surface of un-textured sample was hydrophilic. Furthermore, fully textured sample is slightly superior to partially textured sample. It was because the fully textured surface increased the contact area of solid-liquid two phases to a greater extent.

3.2 Lubrication performance analysis
Fig.4 presented the steady-state load-carrying capacities of different samples lubricated with different lubricants as the rotating speed was 60 rad/s, which were mean values of the steady state portion in measurements. The standard deviation error from the average of three unidirectional rotating tests was shown as error bars in the Fig.4. It could be seen that surface texturing make for an increase in the load-carrying capacity for all tested textured samples, regardless of which lubricant used in the test. In these cases the minimum load-carrying capacity was between 0.05 N and 0.12 N, while the maximum was between 0.25 N and 3.5 N. What’s more, the minimum of these three case arose when lubricated by the L-1 lubricant.

Fully textured sample exhibited the greatest load-carrying capacity of 0.12 N, 1.32 N and 3.50 N lubricated with L-1, L-2 and L-3, respectively. By comparing with untextured sample, the increment (3.25 N) occurred for mating surfaces lubricated by L-3 lubricant was comparatively higher than the case of L-1 lubricant (0.08 N). It could be interpreted that, for fully textured sample, the higher viscosity of lubricant was more likely to generate a superior lubrication effect. The similar trend was found in tests of untextured sample, the higher the viscosity of lubricant was, greater the load-carrying capacity was.

However, in the case of partially textured sample, the maximum (0.42 N) occurred in the test lubricated by L-2 lubricant. The value (0.38 N) measured for L-3 lubricant was slightly smaller than it. These two values were 8.4 times and 7.6 times the smallest value (0.05 N), which was tested when lubricated by L-1 lubricant.
Fig. 4 Load-carrying capacity of samples lubricated with different lubricants.

Fig. 5 presented load-carrying capacity varied with testing time at different rotating speeds for textured samples when lubricated by L-2. The same trends, the higher rotating speed would be conducive to enhance the load-carrying capacity, were found in those two cases. The micro-dimple number of fully textured sample is about 1052, which is about 14.6 times as many as which of partially textured sample. However, the load-carrying capacity is

Fig. 5 Load-carrying capacity at different rotating speeds for textured samples: (a) Partially textured sample; (b) Fully textured sample.
4. Conclusion
Series of disc-on-disc experiments are conducted to study the hydrodynamic performance of fully/partially textured surface. And three types of lubricants have been used in the experiments to investigate the hydrodynamic effects caused by viscosity under rotating condition.

Compared with the untextured surface, two texture arrangement patterns and three kinds of lubricants were adopted to investigate how the factors above affect the load-carrying capacity in the abundantly lubricated circumstances. It was found that:

• Surface texture has an obvious advantage in enhancing hydrodynamic lift force, both fully textured surface and partially textured surface.

• The measurement results of contact angle are in good agreement with the lubrication performance.

• For each sample, there is a positive correlation between load-carrying capacity and rotation speed. Higher rotation speed is more beneficial to generate a great and steady load-carrying capacity.

• In general, for fully textured surface and untextured one, high viscosity would promote the formation of great oil film support force. However, the load-carrying capacity doesn’t always enhance with increasement of lubricant viscosity.

Acknowledgment
The project was supported in part by the National Natural Science Foundation of China under Grants 5197051112 and the Graduate Innovation and Entrepreneurship Fund of Wuhan University of Science and Technology.

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