lubricants

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Communication

Facilitating the Study of the Texturing Effect on Hydrodynamic Lubrication

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Abstract: To facilitate fundamental study of the surface texturing effect on hydrodynamic lubrication, analytical and experimental tools are required. While there is an extensive amount of theoretical and analytical analyses in the literature, relevant experimental studies are much rarer. A detailed study requires techniques by which one can (a) produce micron-sized textures on a millimeter-scale area on a specimen surface and (b) accurately measure the lubricating film thickness and load-carrying capacity of a bearing. The paper introduces the use of an efficient laser technique (direct laser interference patterning) and a custom-designed fixed-incline slider tester to address these points. A steel slider was textured with the laser technique to produce a surface pattern in the inlet region of the bearing contact. The characterization of the load-carrying capacity for different convergence ratios K is presented.

Keywords: textured surfaces; laser interference; hydrodynamic lubrication

1. Introduction

There has been considerable interest in the study of surface texturing effects on the tribological performances of lubricated sliding surfaces. It is, in fact, well known that reducing friction and increasing load-carrying capacity and film thickness in various sliding bearing applications can be facilitated by appropriately texturing the bearing surfaces [1,2]. The texturing effect is most prominent under full thin film lubrication, where the film thickness and texture are in the same order of magnitude. Furthermore, surface texturing provides a possible load-carrying capacity for parallel or even slightly diverging bearings, where the geometric wedge does not exist.

Hamilton et al. [3] performed experiments with parallel sliding between an optically flat transparent rotor and a stator with artificial micro-asperities in the 1960s. The lubrication film was directly observed through the transparent rotor. Effective lubrication with films characterized by long and narrow cavitation trails was reported. This phenomenon was attributed to the hydrodynamic effect generated by the wedge of the micro-asperities, which act as micro-hydrodynamic bearings. About a half-century later, more studies on the effect of various surface micro-textures were done owing to the development of powerful lasers. Etsion [4,5] and Gachot et al. described in a recent article [2] the potential of laser surface texturing techniques in enhancing the tribological performance. Friction can be significantly reduced with laser-textured components compared to the non-textured. Substantial improvement in load-carrying capacity, lubrication, and friction can be obtained using micro-dimple surface textures.

Tonder [6,7] proposed texturing the front part of a slider (inlet region) instead of texturing the whole surface, which was expected to further benefit to the enhancement of tribological performance.

Inlet texturing is particularly prominent for parallel bearings. The artificial roughness (formed by transverse or longitudinal grooves) in the inlet of the bearings generates pressure due to the effective (or virtual) wedge formed by the micro-textures. The surfaces with inlet texturing show significant improvement in load-carrying capacity of sliding bearings. Micro-textures in the inlet ensure less resistance to flow and hence generate higher pressure, load, stiffness, and damping as well as lower leakage. Fowell et al. [8] analyzed slider bearings with pockets close to the bearing inlet. A new lubrication mechanism, referred to as "inlet suction" was identified. Their analytical results showed that the inlet texture enhanced lubricating film formation and reduced friction. Similar conclusions were also found in the numerical study of Dobrica et al. [9]. The load-carrying capacity with inlet textures is substantially larger than that of completely textured surfaces. This is due to the ratio of texture/non-texture portions of the surface resembling a step bearing. Etsion and his co-workers [10,11] experimentally investigated performance enhancements by laser-surface-textured parallel-thrust bearings. They compared the lubrication effects of partial and full laser surface texturing on one of the mating surfaces of a thrust bearing in terms of load-carrying capacity. Their results showed that the surface with partial texturing generates a substantially larger load-carrying capacity than the surface with full texturing. It was attributed to "collective" effects, such as the texture or "virtual" wedge, which was generated by the textured/untextured portions of the surface [10]. Their results validated the inlet texture concept of Tonder. Nevertheless, running tests with thrust bearings are susceptible to the thermal effect, which may also contribute to the film formation via the "thermal viscosity wedge" mechanism as described by Cameron in the 1950s [12].

Gropper et al. [1] recently published a review paper on the hydrodynamic lubrication of textured surfaces. They conducted a survey on the number and type of studies conducted in the field of surface texturing in the last 50 years and remarked that the vast majority of research in the field was based on theoretical modeling. The purpose of this communication is to address two key issues that have to be resolved in order to promote experimental studies of surface texturing effects on hydrodynamic lubrication. One is the production of micron-sized textures on a millimeter-scale area on a steel bearing surface, and the other is an effective experimental technique to measure thin lubricated films under stable and isothermal conditions. The paper presents a piece of collaborative work where one partner prepared the textured slider specimen and the other measured the lubricating film thickness of the textured slider using a self-developed fixed-incline optical slider test rig.

2. Results and Discussion

2.1. Patterned Specimen Preparation

With the recent development of powerful lasers, such as femtosecond lasers, laser surface texturing (LST) is now widely used to enhance the tribological performance of bearings. However, the process using conventional LST techniques is in general very time-consuming, and it is difficult to produce complex surface textures covering a relatively large bearing area. Mücklich et al. [13] developed an efficient surface texturing technique based on the interference of powerful laser beams. The technique, termed direct laser interference patterning (DLIP), produces interference fields that form micron/submicron surface topography on a fairly large area of interest.

A specimen steel block with a sliding surface of 4 mm (in the sliding direction) and 6 mm (in the lateral direction) in size was used in the experiment. The sample surface was highly polished and its roughness, R_a, was about 6 nm. A pulsed Nd:YAG laser (Spectra Physics, Quanta Ray PRO 290, Darmstadt, Germany) with a pulse duration of 10 ns and a repetition rate of 10 Hz was used for the laser patterning process. The out-coming laser beam with a wavelength of 355 nm was divided into two laser beams, which were finally superimposed with each other, thus leading to a line-like interference pattern (see Figure 1a). Half of the slider surface was patterned with two rows of laser spot alignments parallel to the inlet zone (Figure 1b,c). The intensity of each beam can be precisely adjusted by applying suitable beam splitters. The laser energy density (fluence) was set to be 400 mJ/cm^2 for all treated steel substrates. The structural wavelength (line spacing) was fixed at about 9 µm. All sample surfaces were laser-textured under standard atmospheric conditions in air using a single laser pulse. More details of the experimental setup can be found in [14]. The topography of the resulting laser surface texture was measured by optical interferometry (Zygo New View 100 white light interferometer (WLI), AMETEK, Weiterstadt, Germany). The patterns are homogeneous with a pattern periodicity of around 9 µm and a structural depth of approximately 1 µm, as shown in Figure 2. At positions of maximum laser intensity, the material is molten, whereas the positions of minimum laser intensity are nearly unaffected. The sinusoidal intensity distribution of the laser interference process leads to a temperature and thus a surface tension gradient. Thus, the material flows from locations of maximum to minimum laser intensity and re-solidifies. Because of this, positions of maximum laser intensity correspond to topographic minima and vice versa. The square-shaped single laser spots (Figure 1b) are then stitched together (Figure 1c) by a motorized *x*–*y* stage. The interference patterns also continue in the overlapping spot areas but with a slightly larger structural depth as the material is molten twice there.

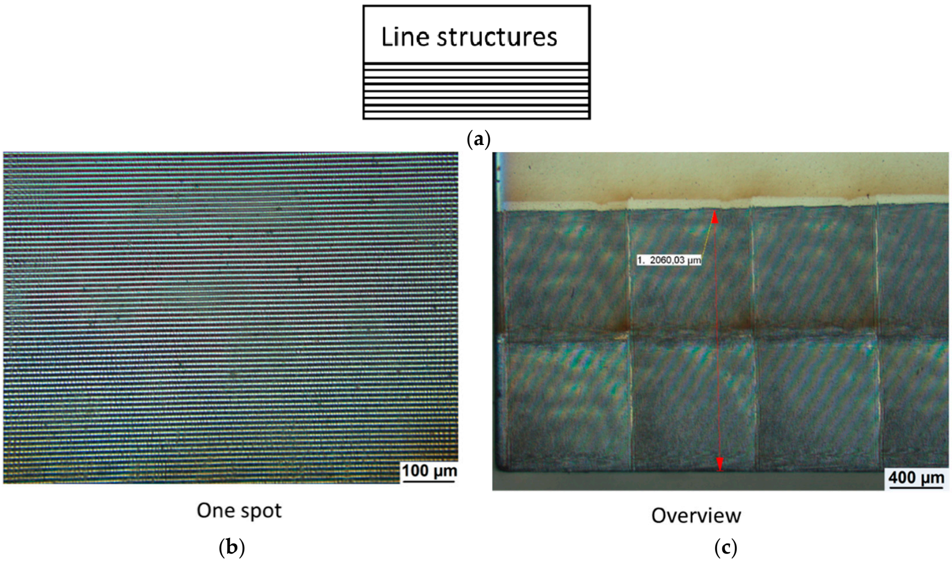


Figure 1. (**a**) Schematic drawing of transverse grooves formed on half of the slider surface by direct laser interference patterning (DLIP); (**b**) Laser interference pattern on one spot; (**c**) Transverse grooves formed on half surface.

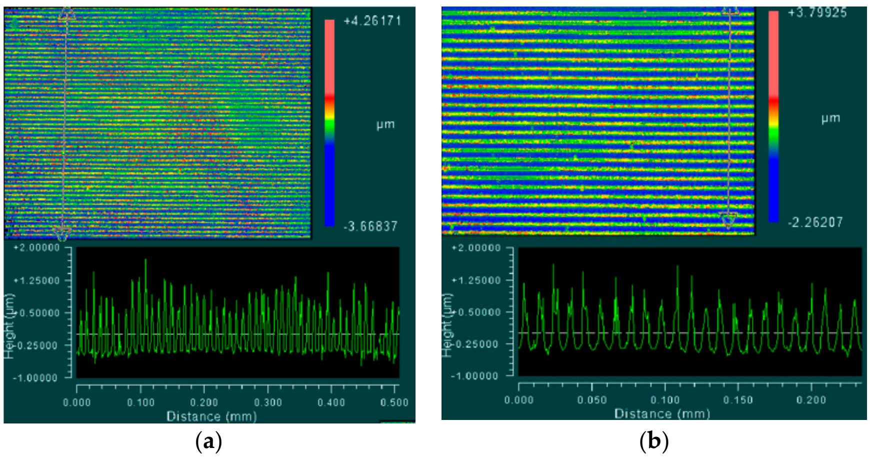
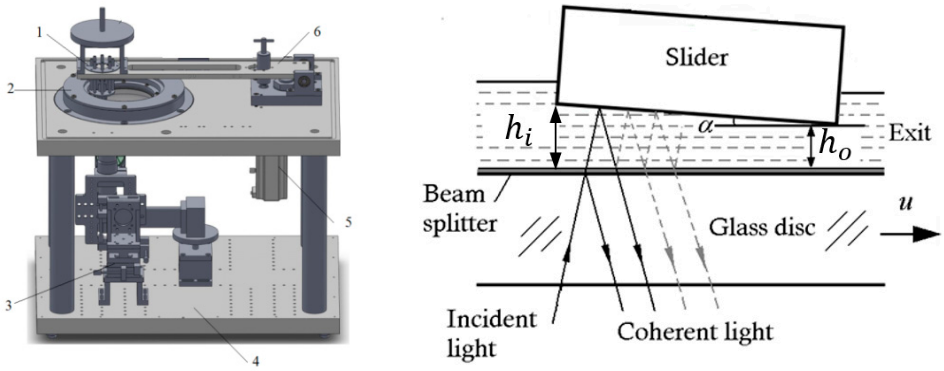


Figure 2. Topography of prepared pattern recorded by white light interferometer (WLI). (**a**) Magnification 10×; (**b**) Magnification 20×.

2.2. Thin Film Lubrication Experiment

Optical interferometry is widely used in lubrication research for its high accuracy in measuring lubricating film thickness. The technique was first introduced for the measurement of the thickness of oil films in non-conformal elastohydrodynamic lubrication by Gohar and Cameron [14] in the 1960s. While optical interferometry is readily implemented to measure the film profile of a lubricated point contact, it is not easy to facilitate steady measurements of conformal contacts such as slider bearings. An optical slider-bearing test rig was successfully developed by Guo et al. [15]. The steady conformal sliding contact was achieved via a universal joint with backing bolts (Component 1 in Figure 3a), which fastens the slider rigidly on the load arm. The slider set up is schematically shown in Figure 3a. Figure 3b illustrates the details of the sliding contact, which is constructed with a rotating glass disc and a stationary slider. Eight bolts are used to fix and adjust the inclination angle of the slider. To facilitate interferometry, the surface of the glass disc is coated with chromium and the reflectivity of the Cr-layer is about 20%. Figure 4 shows an optical interferogram formed between the inlet-textured slider and the glass disc. The slider is separated from the disc by the hydrodynamic effect of the lubricant once the disc starts rotating. By recording the change in optical interference formed between the slider and glass disc, the lubricant film thickness can be obtained directly with the developed algorithm [16].



(**a**) (**b**)

Figure 3. (**a**) Schematic illustration of fixed-incline slider test rig. 1—slider holder and adjustment; 2—rotation disc part; 3—interference optics; 4—base frame; 5—motor; 6—load arm; (**b**) Schematic of the testing geometry and film measurement principle.

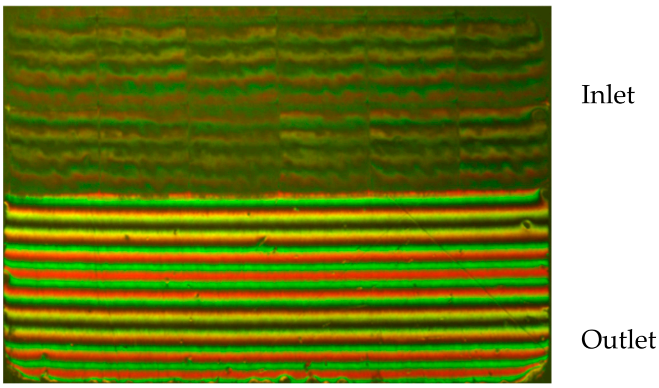


Figure 4. A typical optical interferogram formed between the inlet-textured steel slider and the Cr-coated glass disc.

In this lubrication study, a synthetically based PAO oil without any additives was selected. The properties of the applied oil are listed in Table 1. A plain slider and a slider having transverse grooves on the front half of its sliding surface were applied. The size of these sliders is 4 mm (breadth, in the entrainment direction) × 6 mm (length, perpendicular to the entrainment direction). During the experiment, the change of lubricant film thickness versus speed was measured for sliders with different inclinations. A set of typical results of film thickness under a constant load of 6 N and with three different inclinations is shown in Figure 5. The corresponding isothermal–theoretical curves are also plotted. The film thickness data of the plain slider (non-textured) for these three inclinations are well correlated by the theoretical curves in the whole speed range, which verifies the accuracy of the developed slider test rig. It also implies that there is no noticeable thermal effect generated in the experiment. Therefore, the thermal effect is ignored in the current study on hydrodynamic lubrication of inlet-textured surfaces. The measured film thickness data with a small inclination (Figure 5a) are almost equal to those of the plain slider, except the first one under a low speed. The departure of experimental values of film thickness of the inlet-textured slider from theoretical values at low speeds becomes more pronounced as the inclination increased (Figure 5b). For high inclination, the inlet-textured slider generated significantly higher film thickness than the plain slider in the whole speed range of the study (Figure 5c). The inclination is, indeed, a key parameter which determines the texture effect on hydrodynamic lubrication.

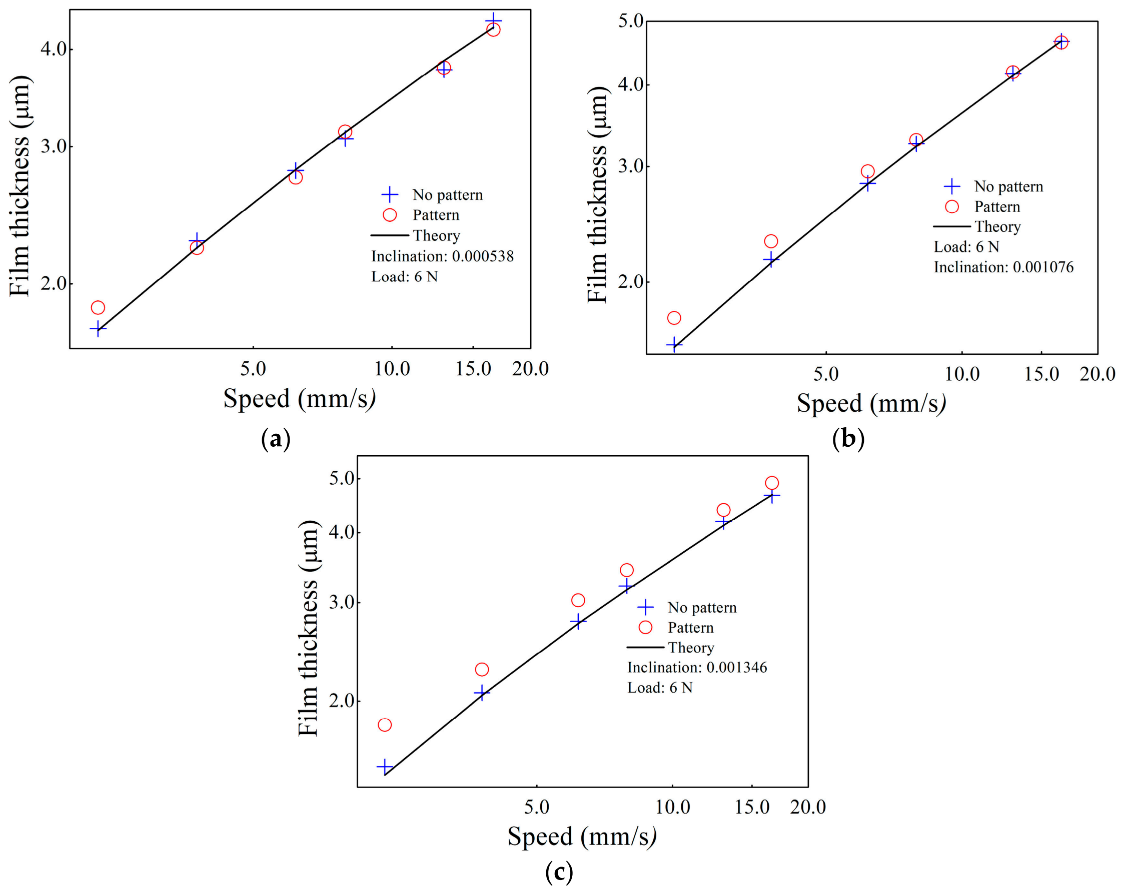


Figure 5. Change of film thickness with speed for different inclination of slider (**a**) 0.00538; (**b**) 0.001076; (**c**) 0.001346.

The load carried by a tilted slider, which is the integral of the pressure over the slider plane, is expressed as [17]

$$W = \frac{6U\eta B^2 L}{(h_i - h_o)^2}\left[\log_e \frac{h_i}{h_o} - \frac{2(h_i - h_o)}{(h_i + h_o)}\right] \tag{1}$$

where

W: applied load (N);
h_i, h_o: film thickness at the inlet and outlet edges of slider, respectively (m);
U: sliding speed (m/s);
η: viscosity (Pa s);
B, L: breadth and length of the slider (m), respectively.

A non-dimensional parameter that includes inclination and film thickness is defined as the convergence ratio:

$$K = \frac{(h_i - h_o)}{h_o}. \tag{2}$$

As illustrated in Figure 5, the effects of inlet texturing are functions of inclination and film thickness. To give a comprehensive view, Equation (2) is substituted into Equation (1) to produce

$$W^* = \frac{h_o^2}{6U\eta B^2 L} W = \frac{1}{K^2}\left[\log_e(K+1) - \frac{2K}{(K+2)}\right]. \tag{3}$$

Equation (3) is the analytical relation of the two non-dimensional terms, W^* and K. The non-dimensional load-carrying capacity, W^*, can also be experimentally obtained from the measured film thickness for a given applied load. The inclination of the slider can be obtained from the number of fringes on the interferogram of the slider. Thus, the film thickness at the inlet, h_1, can be calculated once h_o is detected.

Table 1. Properties of applied lubricant.

Lubricant	Viscosity	Refractive Index
PAO 40	0.88 Pas (@22 °C)	1.47

Different sets of experiments were conducted with the inlet-textured slider under various operating conditions. Similar tests were also conducted with the plain slider for comparison. All film thickness measurements were converted to W^* using Equation (1) and are plotted against K in Figure 6. Theoretical W^*–K curves of finite (L/B = 1.5) and infinite ($L/B = \infty$) length are also plotted in the figure. The load-carrying capacity of the finite-length slider is smaller than that of an infinite-length slider owing to the side leakage in the finite-length slider, as would be expected. The experimental results of the plain slider show very good agreement with the analytical solutions (L/B = 1.5) for a wide range of K, which eliminates any thermal effect in the current study. For the textured slider, the results can be separated into two parts. When K is less than 1.5, there is almost no difference in measured load-carrying capacity with or without texture, which means the texture plays almost no role in affecting the load-carrying capacity when the film thickness is high enough. However, the textured slider yields a higher load-carrying capacity than that of the non-textured slider when K is greater than 1.5. The effect of the inlet texture as proposed by Tonder [6,7] is demonstrated. As illustrated in Equation (2), a smaller h_0 yields a greater K. Thus, the effect is particularly significant when the film thickness is small.

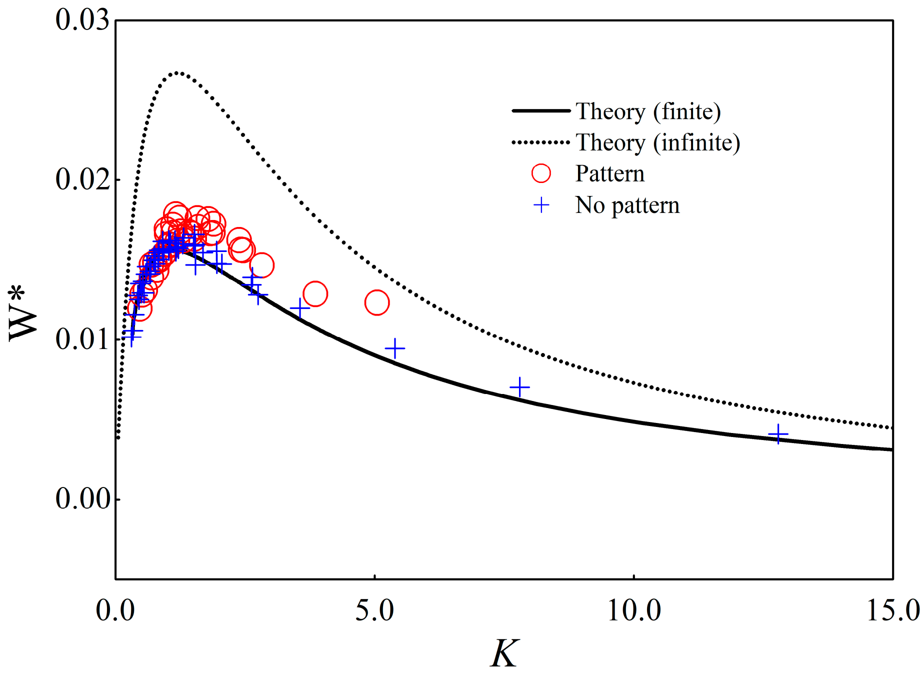


Figure 6. Change of load capacity with *K*.

3. Conclusions

DLIP is an effective technique to form micron-scale surface textures on a macroscopic area of a bearing. The fixed-incline optical slider tester yields accurate measurements of the thickness of lubricating film. The present work demonstrated that pairing up these two techniques could form a good platform for studying the surface texturing effect on hydrodynamic lubrication. The thin film lubrication tests conducted show the positive effects of inlet texture on the load-carrying capacity of a slider bearing. The experimental results illustrate that the transverse grooves on the inlet of the slider bearing can enhance the load-carrying capacity, which are consistent with previous studies [6,7,9]. The effect is substantially prominent for *K* values larger than about 1.5.

Conflicts of Interest: The authors declare no conflict of interest.

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