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A novel surface texture for magnetic fluid lubrication

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ABSTRACT

Magnetic fluid has many advantages when serving as lubricant. With an appropriate magnetic field this lubricant can prevent leakage and increase the load capacity of lubricant film. It can also be fixed at the friction zone by applying an external magnetic field. A novel design of magnetic fluid lubrication with magnetic surface texture was proposed in this paper. A micro-scale dimple pattern was firstly fabricated on the surface of tribo-pair and then a permanent magnet material was electrodeposited into these dimples, so that there are both geometric surface texture and periodic distribution of magnetic field on the surface (magnetic surface texture). In this paper, CoNiMnP permanent magnetic film (about 25 μm thickness) was electrodeposited into micro-dimples (500 μm in diameter) on the surface of 316 stainless steel. The impact of magnetic surface texture on lubrication was investigated using a pin-on-disk test rig. The test results showed that magnetic surface texture was conducive to form effective lubrication at low sliding velocity when lubricated by magnetic fluids.

1. Introduction

Through the process of evolution, functional surfaces of plants and animals have been formed to ensure their survival. For example, the lotus leaf has the ability of self-cleaning and shark skin can reduce drag. Researches show that the self-cleaning ability of lotus leaves results from the tiny, wax-coated protuberances on their surface [1]. The skin scales of some sharks possess tiny ridges that run parallel to the longitudinal body axis. The grooved body surface reduces drag through its influence on the boundary layer [2]. These facts show that some functions of biological surfaces are largely attributed to microstructures of the surfaces. In the realm of engineering, the structured surfaces have been applied in practice. Cross-hatching of a diesel cylinder liner to prevent seizure was introduced in the 1940s. Dimples were introduced to the surfaces of golf balls to alter the aerodynamics to provide extra lift so that the balls can fly further. Since many techniques are available to create surface features with sizes in the micrometer range, surface texturing has emerged in the last decade as an effective method of surface engineering to improve the tribological performance of contacting surfaces [3–8]. The artificially fabricated surface textures can generate additional fluid pressure under hydrodynamic lubrication [9], prevent seizure by providing lubricant under highly loaded contacts [10] and trap wear particles to minimize third body abrasion under non-lubricating conditions [11].Up until now, most surface textures are geometrically designed and only a few have been seen with other functional properties. Zaugg et al. [12] produced micrometer-scale patterns of a defined surface chemistry and structure on ultra-flat Au and gold-coated silicon surfaces by a method combining microcontact printing, wet chemical etching and self-assembled monolayer. Winkelmann et al. [13] fabricated chemical patterns on smooth wafer substrates through vacuum metal deposition and photolithographic techniques aiming at spatial control of cell attachment and organization at surfaces.

Magnetic fluids (MF) are colloidal systems consisting of single-domain magnetic nanoparticles dispersed in a carrier liquid [14]. The particles are usually made from magnetite and have a mean diameter of about 10 to 20 nm. The homogeneous fluids can be magnetized by applying an external magnetic field and still possess flowability of fluid at the same time. These fluids show unusual properties, e.g. they can be confined, positioned, shaped and controlled at desired places by applying an external magnetic field [15]. These lead to important applications in engineering of MF in sealing, lubrication and grinding [16,17]. When serving as lubricant, magnetic fluids have the following advantages: (a) with an appropriate magnetic field the lubricant can be retained at the friction zone, which can enhance lubrication effect and reduce dosage of lubricant [18]; (b) with a designed magnetic field the lubricant is prevented from leaking and polluting the environment [19]; (c) viscosity of the lubricant will increase if a magnetic field is applied and hence the load capacity of lubricant film will be improved [20]; and (d) nanoparticles in magnetic fluids do not worsen but improve the lubricating properties [21].

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Up to date, many investigations of MF lubrication have been carried out by theoretical analysis [15,18,22–25] and only a few by experimental studies. Miyake and Takahashi [26] carried out friction and wear tests on cylindrical specimens constructed of permanent magnets under the lubrication of ferromagnetic fluids to develop a bearing which can be used in clean circumstances. Uhlmann et al. [20] investigated the tribological behavior of MF under boundary conditions using a modified ball-disk model test stand. This research indicated that MF can decrease the wear under boundary conditions and optimized designs of plain bearings and roller bearings with MF need a static magnetic field for the fixation of the MF. Ochonski [27] presented some new design of sliding bearings lubricated with MF and their practical applications. It seems that both analytical and experimental researches of MF lubrication focused on bearing lubrication. Most designs of MF lubrication used a certain amount of magnets to produce magnetic field, which requires sufficient space to arrange magnets and hence limits its application.

In this paper, a novel design of magnetic surface texture was proposed for MF lubrication. Magnetic surface textures were created on the surface of nonmagnetic stainless steel using micro-electrochemical machining and electrodepositing. Friction and wear tests were conducted with a pin-on-disk test rig. The effects of magnetic surface textures on tribological behavior under the lubrication of MF were investigated by comparing untextured surfaces lubricated by carrier liquid and MF and normal textured surface lubricated by MF.

2. Design of magnetic surface texture

Combining advantages of surface texture and magnetic fluids in improving tribological performance, the design of magnetic surface texture lubricated with MF is proposed. Surface patterns such as micro-dimples are firstly fabricated on a surface and then a permanent magnetic film is deposited into each pattern to form magnetic surface textures on the surface. Because of the effects of magnetic force, magnetic fluids will gather on the surface and produce supporting force to another surface even at low speed or stationary state, which is likely to enhance lubrication effect in the condition of boundary and mixed lubrication. Design diagram of MF lubrication with magnetic surface textures is shown in Fig. 1.

For nonconductive MF, the unit volume value of the induced magnetic force under the effect of magnetic field can be written as [25]:

$$F_\mathrm{m} = \mu_0 M_\mathrm{g} \nabla H \tag{1}$$

where μ_0 is magnetic permeability of free space, M_g is the magnetization of MF and ∇H represents the gradient of magnetic field. According to this formula, magnetic fluids gather at the place where there is the highest gradient of magnetic field, such as edges of permanent magnet, for they have the strongest magnetic force there. Therefore a magnetic film array in this design is supposed to be more helpful to maintain MF at friction zone than a whole magnetic film because MF will gather at edges of the whole magnetic film and cannot reach the entire friction zone while magnetic film array can fix MF on the whole surface though MF just gather at edges of each magnetic film. In addition, the permanent magnetic film is deposited into patterns, which can prevent the film from being worn down.

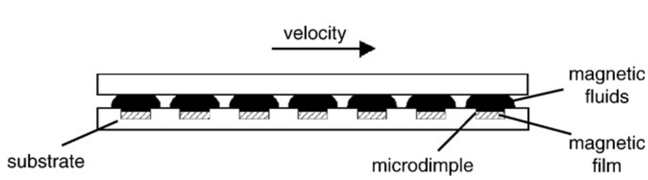

Fig. 1. Design diagram of MF lubrication with magnetic surface textures.

This micrometer-scale magnetic surface texture saves space for arrangement of magnets which is necessary in previous designs of MF lubrication and thus makes it possible to apply MF lubrication in micro machines. Through optimization of parameters of magnetic surface texture, such as size, shape and depth, it is also possible to improve its effects.

3. Experimental details

3.1. Fabrication of magnetic surface textures

Fig. 2 schematically describes the fabrication process of magnetic surface textures. A photolithographic technique was used to fabricate a photoresist mask on the disk surface with a specific surface feature; the uncovered surface was then electrolytically etched in NaCl solution (5 wt.%) with a current density of 85 A/cm^2 at room temperature to create micro-dimples. After that, CoNiMnP permanent magnetic film, which has a high magnetic vertical coercivity of 1100 Oe and retentivity of 1900 Gs [28], was electrodeposited into these dimples. Electrodepositing was performed at the current density of 10 mA/cm^2 and used Co foil as an anode. The composition of CoNiMnP bath can be seen in Ref. [28]. The depth of the depression and thickness of the permanent magnetic film were both controlled by the time. After completing the electroplating, the photoresist was stripped and then deposited magnetic film was magnetized using permanent magnets.

Optical microscope images and profiles of a single micro-dimple in the fabrication process are shown in Fig. 3. Comparing the image and profile of micro-dimple before and after electrodepositing, it is apparent that the magnetic film has been successfully deposited into the micro-dimple. The geometries of the textured surface were measured using a phase-shift white light interferometer. The micro-

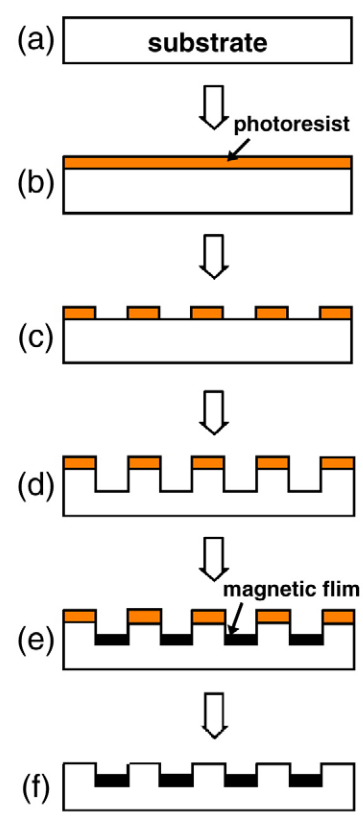

Fig. 2. Schematic diagram of the fabrication process of magnetic surface textures. (a) Polished substrate, (b) spin coat photoresist, (c) photolithography, (d) electrolytic etching, (e) electrodepositing, and (f) photoresist stripping and magnetizing.

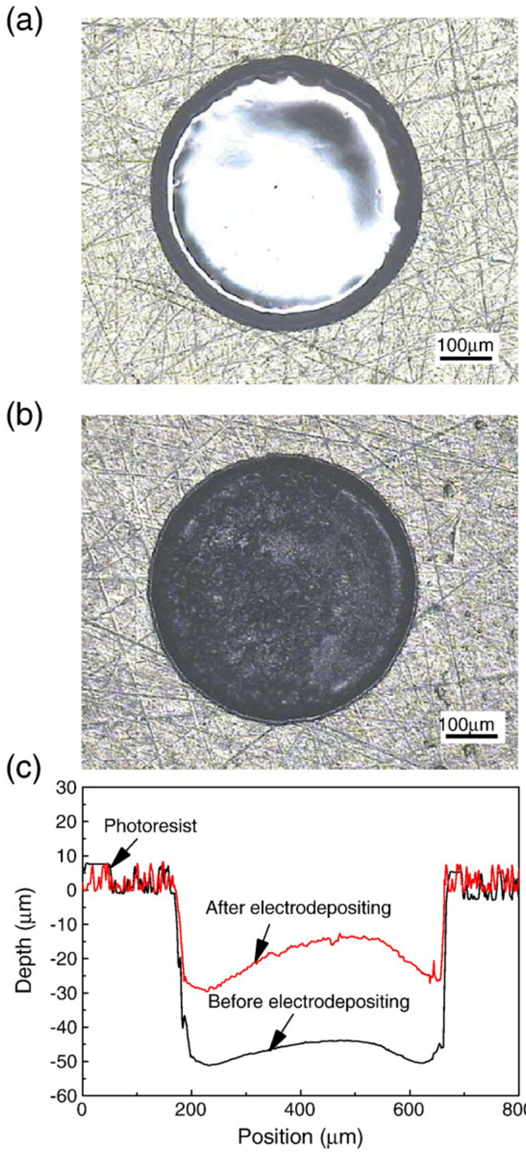

Fig. 3. Optical microscope images and profiles of a single micro-dimple in the fabrication process. (a) Micro-dimple created by electrolytic etching, (b) micro-dimple after electroplating, and (c) profiles of the micro-dimple before and after electro-depositing (measured using a phase-shift white light interferometer).

dimples are arranged as a square array and have average diameter of 500 μm, depth of 45 μm and area density of 5%. The thickness of magnetic film deposited is about 25 μm. Fig. 4a displays the disk with magnetic surface textures and the disk covered with MF is also shown in Fig. 4b. It can be seen that small protrusions of MF appear on the surface due to the effects of magnetic surface textures.

3.2. Tester and specimens

A pin-on-disk test rig was modified slightly to enable a flat-on-flat test, as shown in Fig. 5. An upper disk (10 mm in diameter) was attached to a ball-joint holder so that its surface automatically aligns with the surface of a lower disk (40 mm in diameter). Both disks were made of 316 stainless steel (nonmagnetic) and polished to an average roughness of 0.067 μm Ra using abrasive paper. Both magnetic surface textures and normal surface textures (only geometric textures) were fabricated on the lower disk. The normal surface textures were created by micro-electrochemical machining and have the same

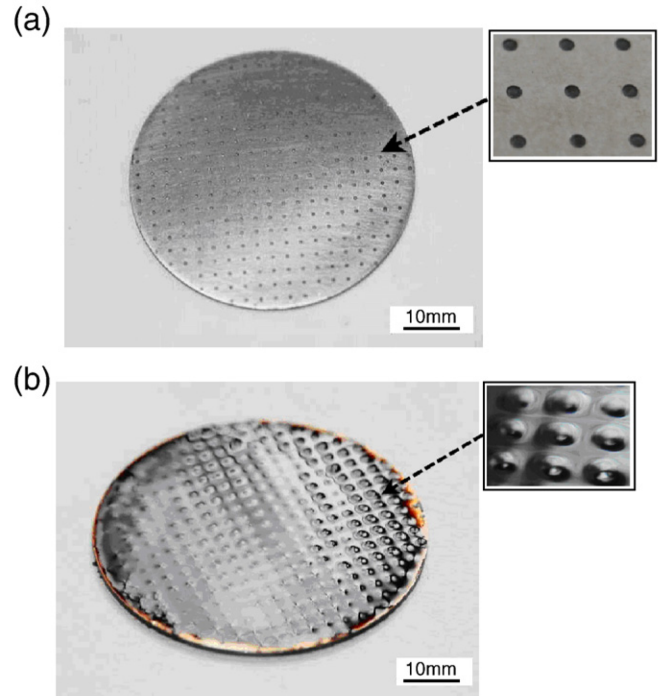

Fig. 4. Photos of disk with magnetic textures. (a) Disk with magnetic surface textures, (b) disk with magnetic surface textures covered by MF.

geometric parameters (diameter, depth and area density) with those of magnetic surface textures.

3.3. Test procedures

In order to investigate the effects of magnetic surface textures on tribological behavior under the lubrication of MF, experiments were carried out in four groups: (1) untextured lower disk lubricated with carrier liquid; (2) untextured lower disk lubricated with MF; (3) lower disk with magnetic textures lubricated with MF; and (4) lower disk with normal textures lubricated with MF. In each group, tests were conducted at normal loads of 2, 5, 10, and 20 N, corresponding to contact pressures of 0.025, 0.064, 0.130, and 0.250 MPa. The radius of the contact track on the disk was 12 mm. Tests were performed at rotation speeds of 5, 10, 15, 25, 50, 75, 100, 125 and 150 rpm, corresponding to sliding speeds of 0.006, 0.013, 0.019, 0.031, 0.063, 0.094, 0.126, 0.157 and 0.188 m/s. At each load-speed condition, tests were conducted for 5 min and stable friction coefficient data of the last minute was averaged as the result of this test. Fe_3O_4 based MF

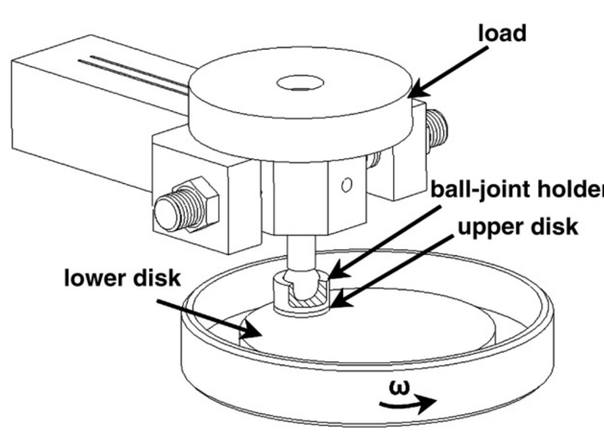

Fig. 5. Schematic diagram of pin-on-disk test rig.

with a volume fraction of particles of 4.83% and its carrier liquid (diester) were used as lubricant;their properties are presented in Table 1. Fig. 6 shows the transmission electron micrograph of Fe_3O_4 particles of MF used in this experiment. It can be seen that the particles have an average diameter of about 15 nm. The dosage of MF and carrier liquid used in each test was 1 ml.

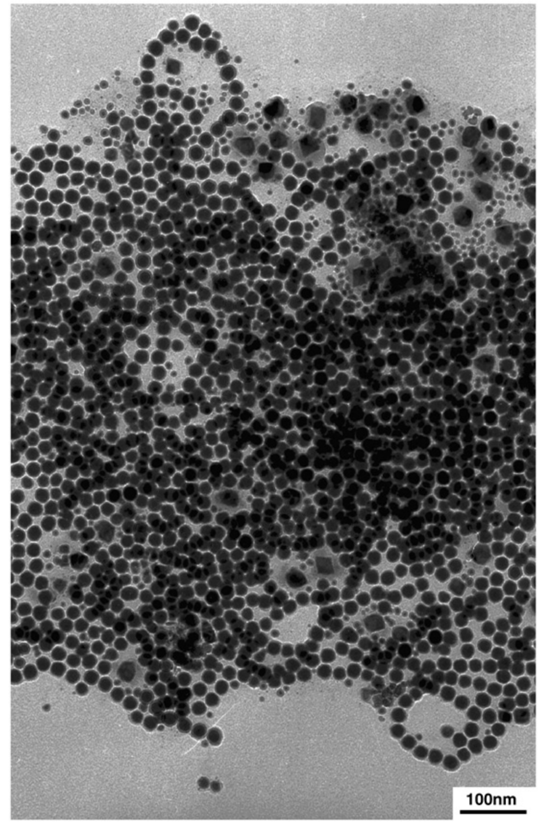

Fig. 6. TEM image of Fe_3O_4 particles.

4. Results and discussion

Fig. 7 shows magnetic texture's effects on friction coefficients at loads of 2 N, 5 N, 10 N, 20 N, respectively. When lubricated with carrier liquid, all the friction coefficients of untextured specimen at each load decrease as the sliding speed increases and show a clear transition from a high value of more than 0.11 to a lower value of less than 0.01. This is consistent with the transition from boundary to mixed and finally to hydrodynamic lubrication of the Stribeck curve. A similar trend was observed with untextured specimen lubricated by MF, but the friction coefficients are lower at low sliding velocity and slightly higher at high sliding speed. For specimen with magnetic surface textures lubricated by MF, the friction coefficients are clearly reduced under low sliding velocity (0.006–0.019 m/s) at all loads in the experiments compared with untextured specimen. On the other hand, under higher sliding velocity (0.063–0.188 m/s) the specimen with magnetic textures lubricated by MF has higher friction coefficient than untextured specimen, but the increment of friction coefficient decreases as the load increases. The difference value between friction coefficient of specimen with magnetic surface texture f_m and friction coefficient of untextured specimen f_0 when both lubricated with MF is shown in Fig. 8. When compared with normal textured specimen, specimen with magnetic surface textures showed the same trend. It has lower friction coefficient under low sliding speed (0.006 m/s) and higher friction coefficient under high sliding speed (0.031–0.188 m/s) than normal textured specimen. And the increment of friction coefficient also decreases as the load increases. Overall, the specimen with magnetic textures lubricated by MF has the lowest friction coefficient at low speed condition and shows good frictional behavior in the case of high load and low sliding velocity.

The untextured specimens have the same surface roughness. Therefore, differences between the friction coefficients of untextured specimen lubricated by carrier liquid and that lubricated by MF are due to dissimilarities of the two lubricants' properties. As shown in Table 1, MF has a higher viscosity than carrier liquid. According to the Stribeck curve, lubricant with a higher viscosity can reduce friction coefficient in the boundary or mixed lubrication region and raise friction coefficient in the hydrodynamic lubrication region, which is consistent with the experiment results that untextured specimen lubricated with MF has lower friction at low sliding velocity (boundary or mixed lubrication) and slightly higher friction at high sliding speed (hydrodynamic lubrication). Besides, Fe_3O_4 nanoparticles as an additive to carrier liquid can improve the tribological performance of MF [21].

Because the surface roughness besides dimples of specimen with magnetic surface textures is the same as that of the untextured one and they are both lubricated by MF, the differences between their friction trends can be attributed to the effects of magnetic surface texture. At low sliding speed it is difficult to form lubrication film and some mechanical contacts occur between sliding surfaces, which results in high friction coefficients of untextured specimen. However, with magnetic surface texture, MF can be retained at the friction zone due to attraction produced by magnetic film. And the magnetic surface texture also has the effect of oil reservoir as geometric texture. Hence, effective lubrication can be formed even at low sliding velocity for specimen with magnetic surface textures lubricated by MF. On the other hand, as the rotation speed increases the centrifugal force dispels the MF attracted on the surface, which weakens the lubrication effect. In addition, as mentioned in Ref. [20], an applied magnetic field leads to an increase of viscosity and a change of the flow behavior of MF, which may be the reason of higher friction coefficients of specimen with magnetic textures lubricated by MF at higher sliding speed. The effects of deposited permanent magnetic film can be seen from the differences between friction behavior of normal surface textures and magnetic surface textures, because they have identical geometric parameters. Due to magnetic force produced by permanent magnetic film, MF was attracted on the surface of specimen (as shown in Fig. 4b) and hence magnetic surface textures have lower friction coefficients than normal surface textures under low sliding velocity (0.006 m/s) for more sufficient lubrication. At high sliding speed when full lubrication film is formed, magnetic field produced by permanent magnetic film increased MF viscosity and affected the flow behavior of MF, which leads to higher friction coefficient of magnetic surface textures than normal surface textures. It can also be deduced from the experiment results that the antifriction effect of magnetic surface textures at low sliding speed results from joint action of surface textures and permanent magnetic film, while the friction-increasing effect of magnetic surface textures at high sliding speed is mainly due to the effects of permanent magnetic film.

As the experiment results show that the specimen with magnetic textures lubricated by MF has clear advantage of low friction in the case of high load and low sliding velocity, wear tests were carried out to investigate magnetic texture's effect on wear characteristics under such condition. The tests were conducted at the load of 20 N and

Table 1
Physical properties of lubricants used for testing.

Lubrication	Density (kg/m^3)	Viscosity (mPa•s)	Saturation magnetization (kA/m)	Volume fraction of particles (vol.%)
Carrier liquid (diester)	0.84×10^3	50	0	0
MF	1.05×10^3	67	15.9	4.83%

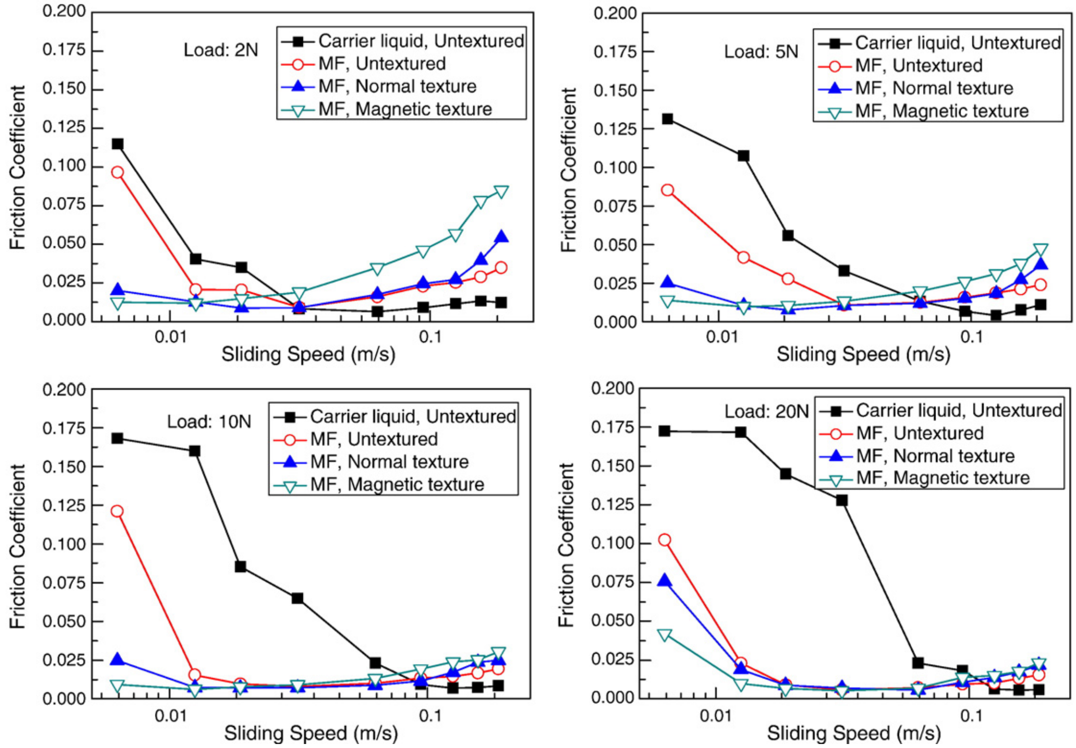

Fig. 7. Friction coefficients versus sliding speed of untextured specimen, normal textured specimen and specimens with magnetic texture at different loads.

sliding speed of 0.013 m/s. The sliding time was fixed at 30 min. Fig. 9 shows the time histories of friction coefficients for each specimen during the wear tests. The untextured specimen lubricated by carrier liquid has a high average friction coefficient of approximately 0.17, which is in the boundary lubrication regime, while the specimen with magnetic textures lubricated by MF has the lowest average friction coefficient of about 0.01.

The optical microscope images of upper disks' worn surfaces are shown in Fig. 10. Fig. 10a shows the untested state of the upper disk. It can be seen that the worn surface of upper disk whose opposite specimen is untextured and lubricated by carrier liquid is rough with many thick and deep furrows while the rubbing surface lubricated by MF has less furrows. The normal surface texture reduced the amount of furrows effectively under the lubrication of MF. The worn surface of upper disk whose opposite specimen is with magnetic texture and lubricated by MF has the least furrows and the furrows are thin and shallow. The differences in surface roughness (Ra) before and after test of the upper disks are shown in Fig. 11. The smaller ΔRa indicates less wear during the tests. As can be seen in Fig. 10, the ΔRa of upper disk whose opposite specimen is untextured and lubricated by carrier liquid is the highest, the one lubricated by MF takes the second place and upper disk whose opposite specimen is with magnetic textures and lubricated by MF has the least ΔRa. This result is in accordance with the friction performance of each specimen as shown in Fig. 9. The wear experiments show that MF has better friction-reduction performance and anti-wear ability than its carrier liquid under the present test conditions. And normal surface textures reduced the wear evidently. When lubricated by MF magnetic surface texture is clearly conducive to form effective lubrication under the condition of high load and low sliding speed, which can reduce the friction and wear.

5. Conclusions

A new concept of magnetic surface texture was introduced, which may provide ideas for designing surface texture with other functional properties. Magnetic surface textures were successfully fabricated on

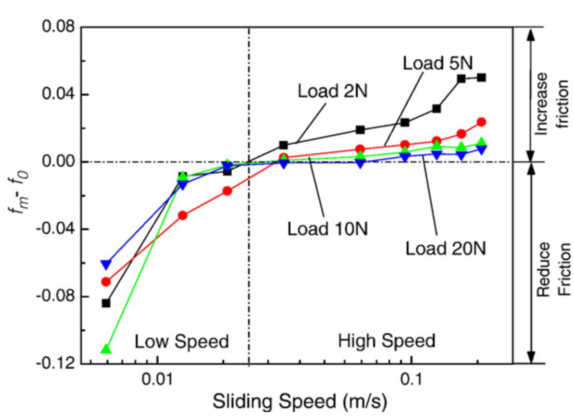

Fig. 8. Difference value between f_m (friction coefficient of specimen with magnetic surface texture) and f_0 (friction coefficient of untextured specimen) when both lubricated with MF.

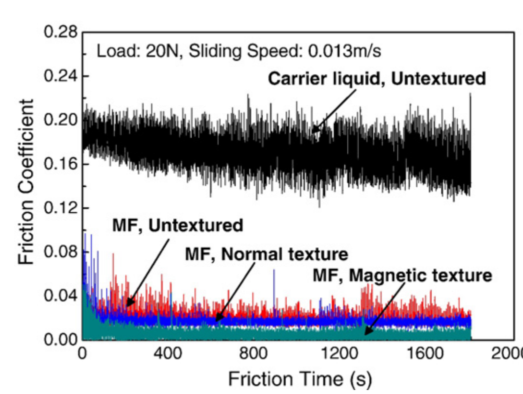

Fig. 9. Variation of friction coefficients during the wear tests.

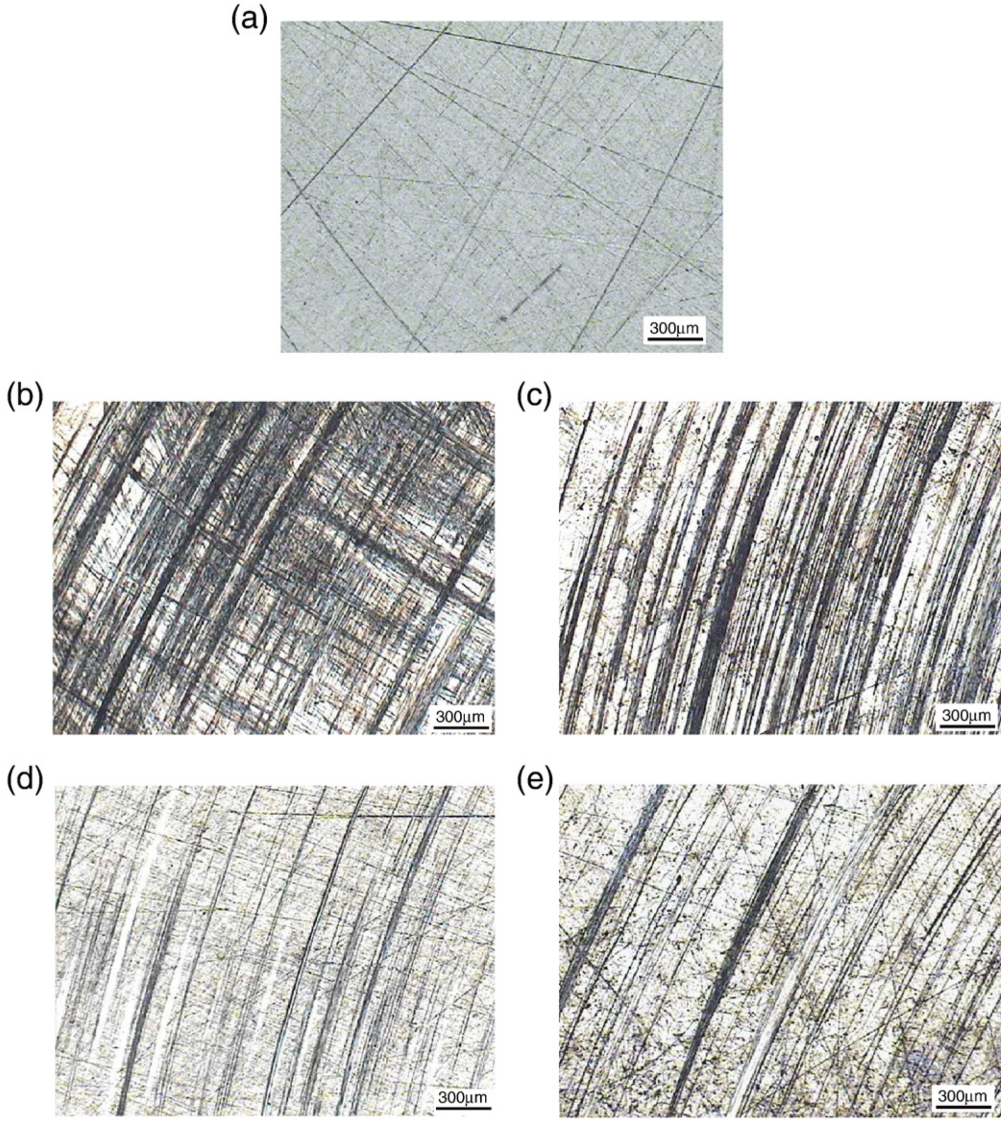

Fig. 10. Optical microscope images of the upper disks' worn surfaces. (a) Untested, (b) untextured opposite specimen lubricated by carrier liquid, (c) untextured opposite specimen lubricated by MF, (d) opposite specimen with normal textures lubricated by MF, and (e) opposite specimen with magnetic textures lubricated by MF.

316 stainless steel surfaces using micro-electrochemical machining and electroplating. In order to investigate the effects of magnetic surface texture on MF lubrication, friction and wear tests were conducted with a pin-on-disk test rig. The results show that MF can reduce the friction coefficients at low sliding velocity compared with its carrier liquid. MF also shows better anti-wear ability than its carrier liquid in the condition of high load and low sliding velocity. When lubricated with MF, magnetic surface texture was observed to be conducive to form effective lubrication at low sliding velocity, which can reduce the friction and wear efficiently. On the other hand, magnetic surface texture increases the friction coefficient at high sliding velocity when lubricated by MF under the present test conditions.

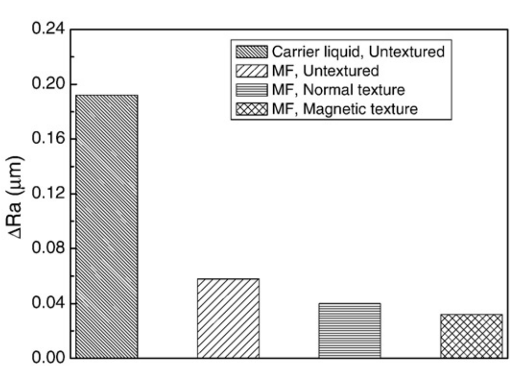

Fig. 11. Differences in surface roughness (Ra) before and after wear test of the upper disks.

Acknowledgements

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