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Tribological properties of magnetic surface lubricated by ferrofluids

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Abstract. In this study, arrayed magnetic films were fabricated on the surface of 45# steel (magnetic). The magnetic field distribution of the micro-magnet arrayed surface was studied. Magnetically controlled suspension – ferrofluids was used as lubricant, which can be adsorbed by magnet. The tribological performance of the arrayed surface affected by the factors of micro-magnet, i.e., area ratio (r), thickness of each magnetic film (t) and magnetized or not, was evaluated using a pin-on-disk test rig. The results suggest that the specimen with 5% area ratio of arrayed magnet is the best of tried ones for low friction at the load-speed conditions. Compared with unmagnetized one, the arrayed surface after magnetizing mainly presents obvious anti-friction properties. The higher magnetic intensity of the surface is, the better anti-friction performance it shows at higher sliding speed condition (0.062–0.188 m/s).

1 Introduction

The understanding of the surface phenomena, particularly at micro- and nanometer scales, has played a fundamental role in the development of many advanced fields, such as electronics, information technology, energy, etc. [1]. Friction is a kind of typical surface phenomenon and about 30% of the world energy consumption is used to overcome friction [2]. To improve the tribological performance, many surface modification techniques appeared since the availability of technologies that permit the manufacture and control of micro-/nano-surface features.

Recently, surface texture, such as patterned micro-dimples or grooves, has received much attention as a viable means to enhance tribological performances of sliding surfaces. Kovalchenko et al. studied the friction properties of laser texturing fabricated on steel surfaces and the results showed that textured surface could benefit tribological pairs from boundary to hydrodynamic conditions [3]. The relation between surface texture and tribological properties in dry and boundary lubricated sliding was investigated by Pettersson and Jacobson [4]. Yuan et al. introduced the effect of grooved textures on the frictional performance and the results indicated that the orientation of grooves has a strong effect on the friction properties [5]. In short, surface textures mentioned above are only geometrically designed without any functional properties.

In 2009, the authors' group introduced a kind of magnetic surface texture for ferrofluid (FF) lubrication [6] as shown in Figure 1. Dimple pattern was firstly fabricated on a substrate surface and CoNiMnP permanent magnetic film was electrodeposited into these dimples, so that there were both geometric texture and periodic distribution of magnetic films on the surface. After magnetizing process, the final surface with magnetic texture could generate the arrayed micro-magnetic field.

Ferrofluid is a stable colloidal suspension composed of single-domain magnetic nanoparticles dispersed in a carrier liquid [7]. Brownian motion keeps the magnetic particles from settling under gravity and the surfactant is placed around each particle to provide short-range steric repulsion between particles to prevent particle agglomeration. In the presence of an external magnetic field, the single-domain colloidal magnetite particles suspended in the carrier liquid of a FF become magnetized.

The advantage of FF as lubricant, over the conventional oils, is that the former can be retained at the desired location for the effects of magnetic force [8]. This kind of attractive magnetic force shows itself as a body force on the liquid [9]. For nonconductive FF, the unit volume value of the induced magnetic force (F_m) under the effect of magnetic field can be written as [10,11]:

$$F_m = \mu_0 X_m H_m \nabla H, \qquad (1)$$

where μ_0 is magnetic permeability of free space, X_m is susceptibility of FF, H_m is magnetic field intensity and ∇H represents the gradient of magnetic field.

According to equation (1), the induced magnetic force acted on FF is proportional to the magnetic field intensity (H_m) of magnet. The arrayed micro-magnet with higher

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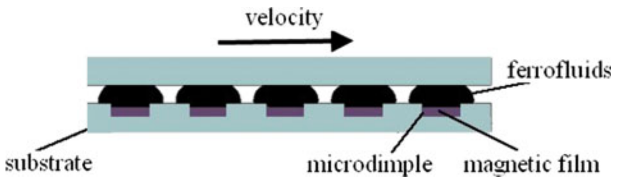


Fig. 1. (Color online) Design diagram of FF lubrication with magnetic surface textures. [6]

intensity can generate stronger coupling force between FF and the rubbing surface, which can maintain more FF on the surface and produce higher supporting force to the opposite. The friction tests show that magnetic surface texture can reduce the friction and wear efficiently under certain conditions when lubricated with FF [6]. In addition, different wettability of FF on the magnetic surface was achieved by controlling the properties of the micro-magnets [12].

According to references [6,12], it could be found that the micro-magnets were all fabricated on a substrate material of nonmagnetic (316 austenitic stainless steels) and the surface contained both geometric dimples and periodic distribution of magnetic field. What will the surface property be if the substrate is ferromagnetic material? Can excellent friction performance also be obtained if the arrayed dimples are completely filled with CoNiMnP films (without geometric dimples) when lubricated with FF? There is still no available knowledge about this.

In this paper, 45# steel was chosen as magnetic-inductive substrate material and the arrayed micro-magnet was fabricated on its surface. To eliminate the oil reservoir effect of the magnetic surface texture, the patterned dimples were fully filled with magnetic films. The magnetic field intensity of the arrayed surfaces, which can indirectly reflect the induce magnetic force, was calculated using Ansoft Maxwell version 10.0 software (ANSYS Canonsburg, PA). Friction tests of the magnetic surface were conducted with a pin-on-disk test rig. The purpose of this work is to investigate the tribological performance of the arrayed magnets when fabricated on magnetic-inductive substrate surface. More attention was paid to the different friction properties of the micro-magnet arrayed surface before and after magnetizing. In addition, the effect of the magnetic strength of the arrayed surface on the friction property was also studied.

2 Experimental procedures

2.1 Specimens' preparation and surface magnetic field intensity

45# steel is chosen as substrate material and the magnetic depositing material is CoNiMnP alloy. The preparation process mainly consists of four steps: photolithographic, electrolytical machining, electrodeposition and polishing. The specific fabrication process can be found in reference [6]. As mentioned above, the patterned round dimples (diameter: d) were filled with micro-magnet and the thickness of the depositing film (t) equals the depth of the dimple. Figures 2a and 2b show 3D images of a single micro-dimple before and after electrodeposition, respectively. As can be seen in Figure 2b, the surfaces of magnetic film and substrate are approximately located in the same plane after grinding. The final specimen coated with arrayed micro-magnet is given in Figure 2c and the roughness Ra is about 0.1 μm. Figure 2d presents the disk specimen with magnet arrays covered with FF. It can be seen that FF produces the spontaneous generation of an ordered pattern of surface protuberances due to magnetic interaction between magnetic films and FF.

The geometrical parameters of the film arrays on each specimen surface are given in Table 1. In addition, the normal surface specimen (No. 8) was also made of 45# steel without any dimples or films on the surface.

As mentioned above, the induced magnetic force and magnetic intensity are directly linked. The relation between surface magnetic field intensity distribution and the area ratio (r) of micro-magnet was studied. Figure 3a illustrates the computing model of the sample with four arrayed micro-magnets on the surface.

Figures 3b–3e give the surface magnetic flux density distribution of the four samples (Nos. 1, 2, 3 and 4) with different r. It can be seen that the magnetic flux is concentrated on the boundary of the magnetic films. With the increase of r, the magnetic flux lines begin to overlap (see Figs. 3d and 3e), which indicates the existence of interactions between nearby magnets. In the four calculation models, the maximum magnetic density in each magnet's boundary is almost the same (4.5×10^4 A/m).

The effect of film thickness (t) on the surface magnetic flux density distribution was also investigated. Figure 4 presents the magnetic flux density distribution in the transverse section of a single micro-magnet (Nos. 5, 6 and 7). As shown in Figure 4, the maximum magnetic flux density of the three samples is located at the boundary of the magnet, respectively. The average magnetic flux density on the surface of the film increases with the increase of t. The magnetic film in the micro-dimple can be approximately considered as a small cylindrical magnet. Based on the theory of magnetic charge, for cylindrical magnet, the demagnetizing factors decrease with the increase of axial thickness of the magnet [13]. For the same diameter of cylindrical film magnet, the thicker of the magnetic film in the pore is, the higher the surface magnetic intensity is.

2.2 Tribological test procedures

The friction tests were performed between the end faces of the two disks under FF lubrication at room temperature. Figure 5 shows the principle of the apparatus used in this experiment. The upper disk is 10 mm round flat made of 316 stainless steel. The surfaces were polished with abrasive paper and the final roughness Ra is the same as lower specimens. After being cleaned in alcohol, the upper specimen was fixed on the upper ball-joint holder to realize automatically face-to-face contact with the lower specimen.

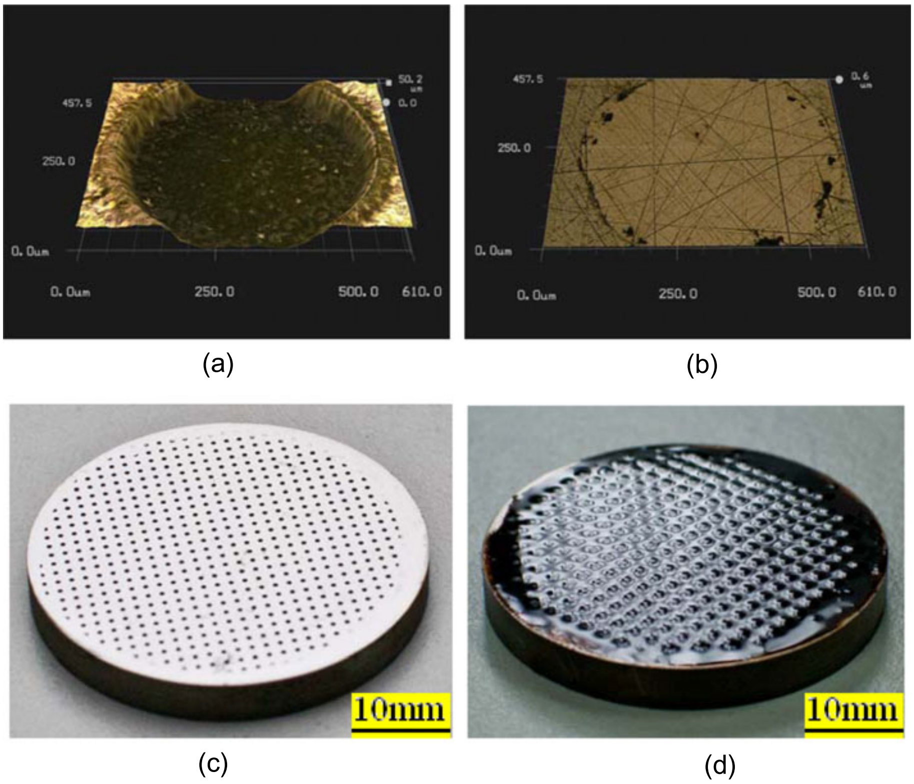


Fig. 2. (Color online) Specimen in the fabrication process. (a) 3D image of a single micro-dimple created by electrolytic etching, (b) 3D image of a single micro-magnet after electrodeposition, (c) image of the final specimen and (d) image of the final specimen covered with FF.

Table 1. Geometrical parameter of arrayed micro-magnet on each specimen.

No.	$d\,(\mu\text{m})$	r (%)	$t\,(\mu\text{m})$
1	500	5	20
2	500	10	20
3	500	15	20
4	500	20	20
5	500	5	10
6	500	5	30
7	500	5	50
8	0	0	0

While the lower specimens with CoNiMnP magnetic films were fastened on the rotating cup. The test conditions are listed in Table 2.

Lubricant was home-made Fe_3O_4-based FF prepared by the coprecipitation technique. The magnetic particle coated with succinamide was dispersed in diester by ultrasonic. The mass fraction of the particles in FF is about 7.8%. The properties of FF used are presented in Table 2. In each test, the dosage of FF used was strictly controlled at 1 mL.

The process of testing is shown in Figure 6. A large number of preliminary tests show that the friction coefficient of almost all specimens tends to be stable after running for 4 min. In order to obtain the friction coefficient in a steady state, we chose the first 4 min as the process of running-in and the following 1 min as the process of testing. The friction coefficients acquired within this 1 min were averaged and used as an index to evaluate the effect of the arrayed micro-magnet surface. To ensure the accuracy and reliability of experimental data, each test was repeated three times and the final coefficient was the mean value of the three times.

To investigate the tribological behavior of the arrayed magnets on the substrate of magnetic material (45# steel), experiments were carried out in two groups: (1) the arrayed micro-magnet surface with different area rates; (2) the arrayed micro-magnet surface before and after magnetization.

3 Results and discussion

Figure 7 presents the frictional properties of the magnet arrayed surfaces with different area rates when lubricated with FF. The four specimens (Nos. 1, 2, 3 and 4) with micro-magnet were magnetized in the vertical direction of the rubbing surface. Specific test conditions are shown in Table 2.

At the sliding speed of 0.006 m/s, the friction coefficient of the surface without arrayed magnet (No. 8) always decrease with the increase of normal load. While the friction coefficients of the magnetic surface show a decrease to a certain extent and then stabilize gradually at the loads of 10N and 20N. When the sliding speed increases to

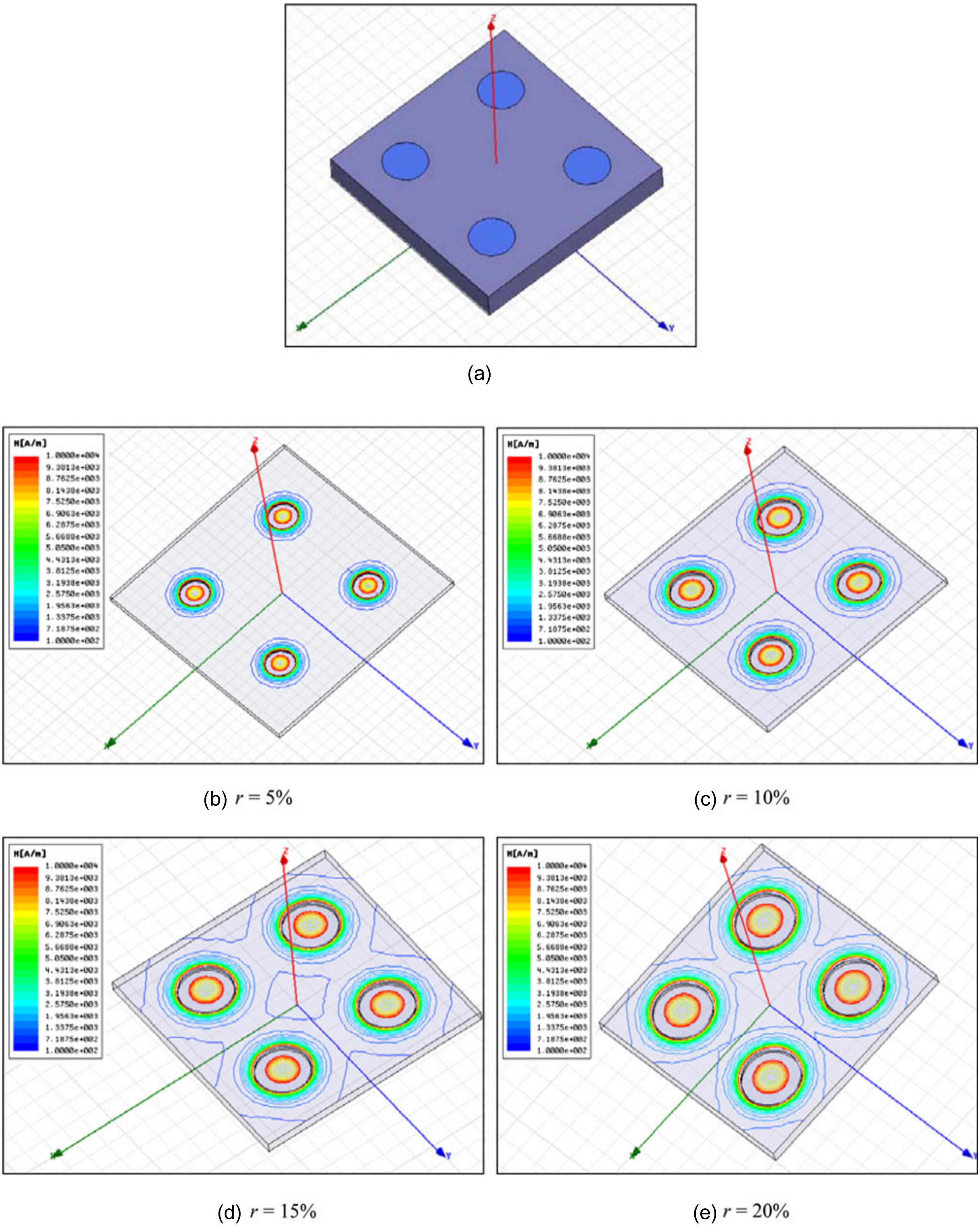


Fig. 3. (Color online) The calculated magnetic flux density distribution of the arrayed surfaces. (a) Calculation model of the arrayed surface, (b) with r of 5%, (c) with r of 10%, (d) with r of 15% and (e) with r of 20%.

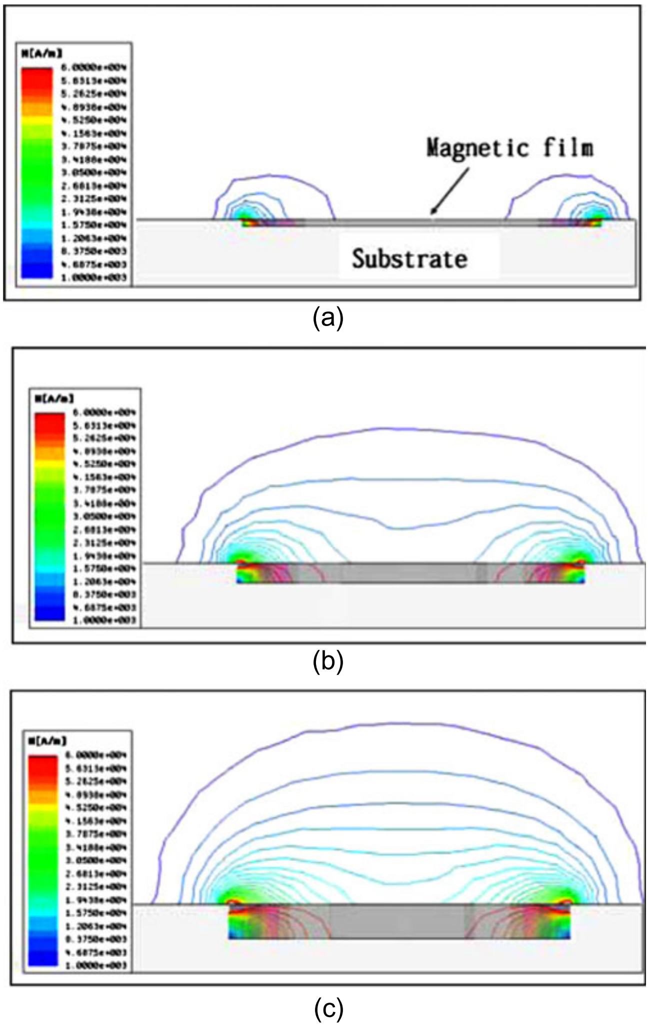


Fig. 4. (Color online) The magnetic flux density distribution in the transverse section of a single micro-magnet with different film thicknesses. (a) With 10 μm thickness film, (b) with 30 μm thickness film and (c) with 50 μm thickness film.

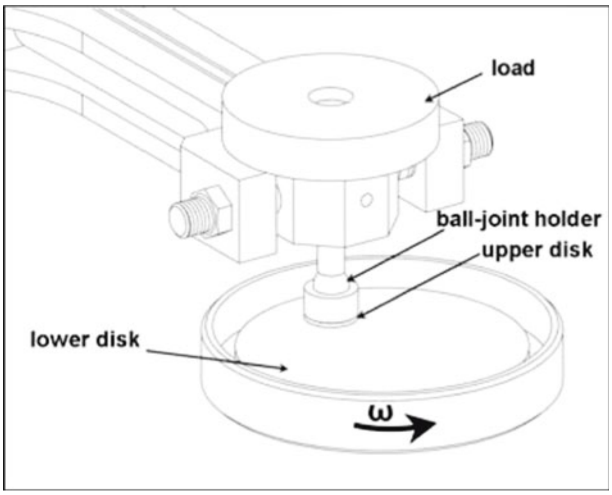


Fig. 5. Schematic diagram of pin-on-disk test rig.

Table 2. Test conditions.

Normal loads	2 N~20 N
Sliding speed	0.006~0.188 m/s
Lubricant[a]	Fe_3O_4 based FF

[a] Properties of the lubricant: density: 1.05 × 103 kg/m^3, viscosity: 67 mPaos, saturation magnetization: 15.9 kA/m.

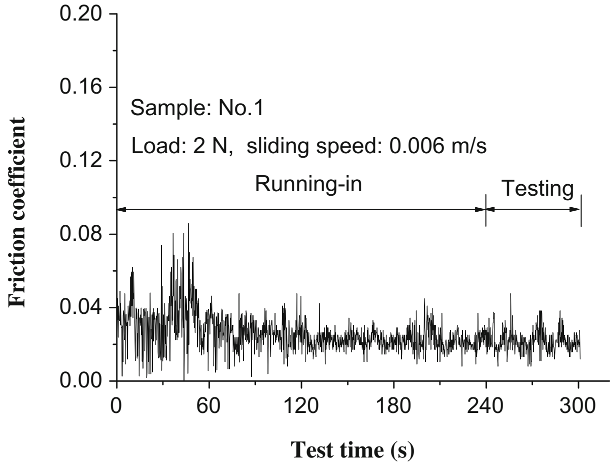


Fig. 6. The process of running-in and testing.

0.188 m/s, each friction coefficient increased by ten times at corresponding load compared with that of low speed (0.006 m/s). And all the coefficients show the decreasing trend with the increase of load.

According to Figure 7, it can be seen that the specimen of $r = 5\%$ (No. 1) shows better friction reduction than others, especially at the higher sliding speed condition. As mentioned above, the magnetic flux is concentrated on the boundary of the single micro-magnet. And for the four specimens with different r, the maximum magnetic flux at each micro-magnet's boundary is similar. With the increase of r, the magnetic flux lines begin to overlap (see Figs. 3d and 3e), which may weaken the strength and gradient of magnetic field at the corresponding area. As a result, induced magnetic force (F_m) acted on FF will be reduced according to equation (1). Therefore, it could be deduced that arrays of the micro-magnet on the rubbing surface could not be too dense.

To make clear the effect of magnetic field of the arrayed surface on the friction properties, experiments were carried out using specimen (No. 6) before and after magnetizing. Figure 8a shows the friction variation observed of specimen (No. 6) before magnetizing. In this condition, the effect of FF is the same as conventional oils since there is no magnetic force between friction surface and FF. It can be seen that, when lubricated with FF, all the friction coefficients of unmagnetized specimen at each load increase as the sliding speed increases. According to the friction coefficients, it may be in the state of hydrodynamic lubrication for the high load conditions. The high viscosity of FF may lead to higher friction coefficients for the lower loads. However, at each sliding speed, the coefficients decreases with the increase of normal load and the

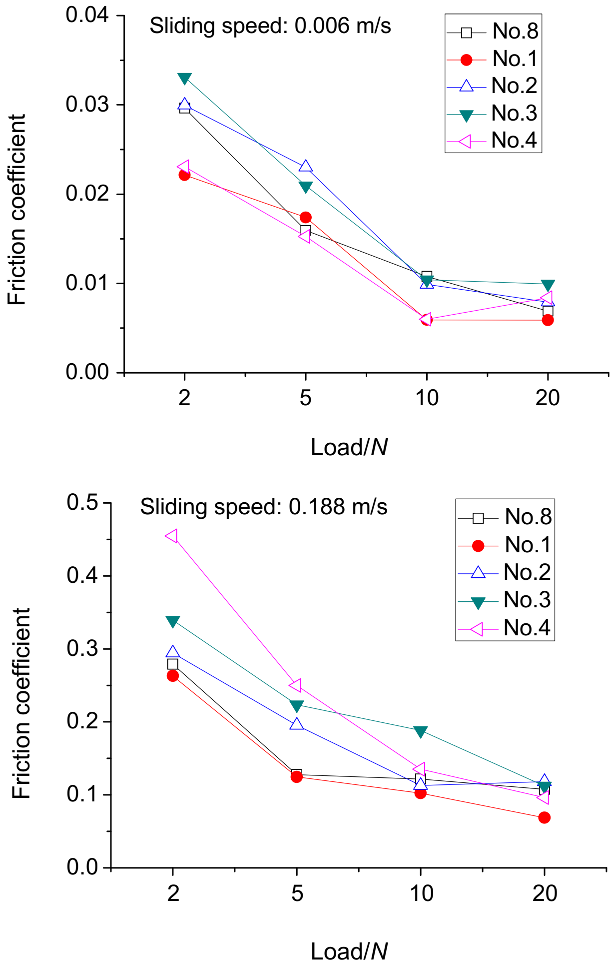


Fig. 7. (Color online) Friction coefficients versus r under different experimental conditions.

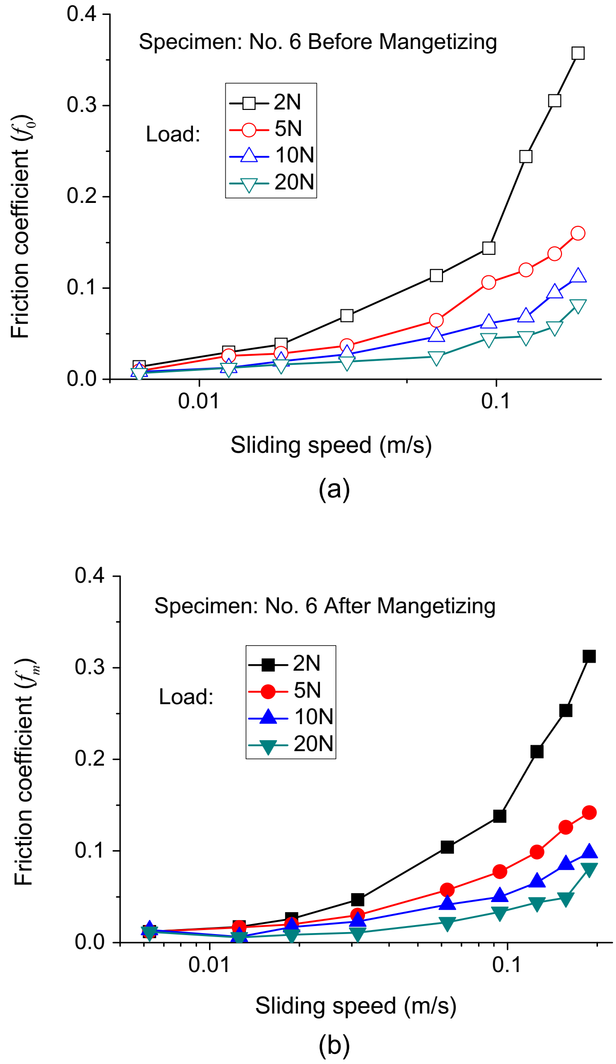


Fig. 8. (Color online) Friction coefficients versus sliding speed of specimen No. 6 when lubricated with FF. (a) Specimen before magnetizing and (b) specimen after magnetizing.

variation trend is pronounced especially at higher speed conditions.

When the arrayed surface was magnetized, similar results have been attained at the loads of 2N and 5N, respectively (see Fig. 8b). When the load increased to 10N and 20N, it can be seen that the friction coefficients show a slight decrease at low sliding speed (0.006–0.012 m/s) and then increase gradually, which are consistent with the transition from mixed to hydrodynamic lubrication of the Stribeck curve [14]. It indicates that the lubrication status can be changed by the effects of surface magnetic field for the same specimen.

Different substrate materials change the frictional performance. When using 316 stainless steel as substrate material, the transition of lubrication region from mixed to hydrodynamic is distinct and usually appears at high speed (0.1 m/s) [12]. While the hydrodynamic pressure lubrication region shifts to the slower sliding speed especially at lower load conditions when the micro-magnet was fabricated on magnetic substrate (45# steel). The results implied that the hydrodynamic lubrication region could be expanded to the lower sliding speed when using 45# steel as substrate.

The difference value between friction coefficient of specimen (No. 6) before and after magnetizing when both lubricated with FF is shown in Figure 9. It can be seen that, the specimen after magnetizing exhibits an increasing friction property at low speed (0.006 m/s), except under the load of 2N. With the increasing speed, the magnetic surfaces gradually show anti-friction effects under four load conditions.

After the specimen was magnetized, the arrayed micro-magnets can generate periodic gradient magnetic field as shown in Figure 3. For the effect of magnetic force, much of the fluid is gathered on the surface of arrayed magnetic films and the increase of friction seems to be due to the removal of FF from the sliding surface under low sliding speed [15]. A supporting load generated by FF may be the reason for friction reduction at the lower load of 2N. Meanwhile, with the applied magnetic field, the viscosity of FF will increase significantly [16], which will lead to the addition of shear stress. While at higher sliding speed,

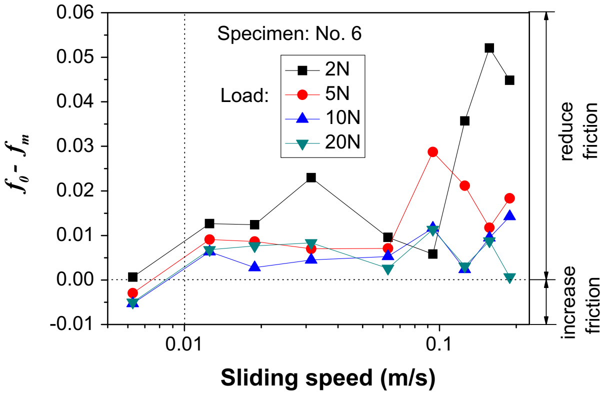
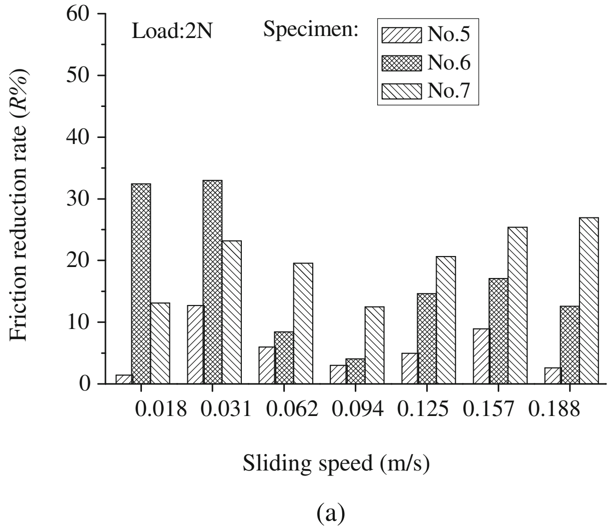


Fig. 9. (Color online) Difference value between f_0 (friction coefficient of specimen No. 6 before magnetizing) and f_m (friction coefficient of specimen No. 6 after magnetizing) when both were lubricated with FF.



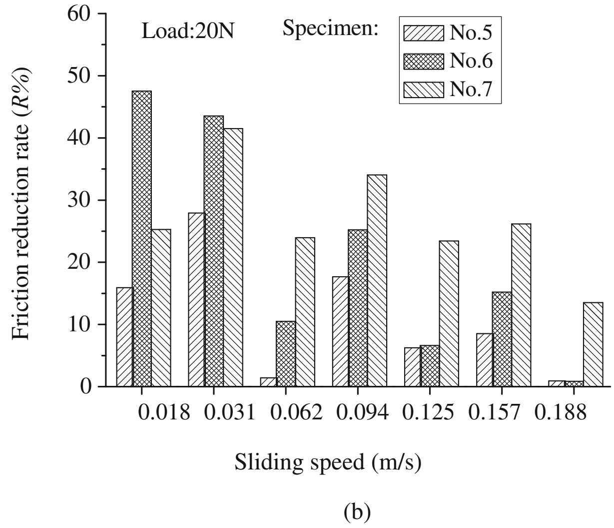


Fig. 10. The effect of magnetic field intensity on the friction reduction rate. (a) Low load condition and (b) high load condition.

obvious anti-friction properties appeared. Since the magnetized specimen (No. 6) has magnetic attraction ability, FF prefers to stay on the surface of micro-magnets and there exists a concentration gradient between the surface of substrate and micro-magnet. During the frictional process, an induced resistance for FF to flow through the edge of micro-magnet appears, forming a "magnetic wedge", which could generate additional hydrodynamic fluid pressure in the areas. The carrying capacity of the lubrication film was enhanced by the hydrodynamic edge pressure, which will reduce the direct contact between the frictional pairs. Meanwhile, magnetic surface can maintain more lubricant on the rubbing surface for the induced magnetic force especially at higher sliding speed. In addition, the viscosity of FF also shows a characteristic shear thinning at high shear rate [17] and it decreases at higher speed. Hence, more effective lubrication films may be formed at high sliding speed after the surface was magnetized. While for unmagnetized surface, centrifugal force may dispel the FF attracted on the surface at high speed, which may weaken the lubrication effect.

To further explore the effects of magnetic field on the tribological performance, three specimens with different film thicknesses were fabricated (Nos. 5, 6 and 7). The friction tests using the specimens before and after magnetization were carried out. Figure 10 summarizes the effects of magnetic field intensity and the friction reduction rate ($R\%$) was used to evaluate the effectiveness of magnetic field.

Figure 10 shows the effect of magnetic field on the friction reduction rate of specimen before and after magnetizing. Under the present test conditions, the existence of periodic gradient magnetic field on the surface had the obvious effect of decreasing friction compared with unmagnetized samples. At lower sliding speed (0.018–0.031 m/s), there was no explicit relation between friction reduction rate and magnetic film thickness, which may result from the indeterminate lubrication state. While the friction reduction rate increases with the increase of magnetic film thickness at each sliding speed condition (0.062–0.188 m/s). According to equation (1), the interaction between the micro-magnets and FF increases with the increase of magnetic intensity. As indicated in Figure 4, the average surface magnetic flux density increases with the increase of film thickness. Namely, the surface with thicker film has the larger induced magnetic force on FF. Thus, more FF can be reserved on the disk's surface to form lubrication film at a high speed even though it possesses centrifugal force. The load capacity of FF squeeze film increases as the strength of the applied magnetic field increases [18]. Hence, the magnetic field strength of the arrayed surface has significant impact on the tribological performance, and the higher magnetic intensity is more conducive to achieve better anti-friction properties at high sliding speed.

4 Conclusions

In this paper, we have investigated the influence of magnetic field on the tribological performance of micro-magnet arrayed surface. The photolithographic, electrolytical machining and electroplating processes were used for arrayed micro-magnet fabrication on the surface of 45# steel disk. The magnetic flux distributions on the specimens' surface were calculated. The friction tests of the magnet arrayed disks with different geometrical parameters were carried out using FF as lubricant. The conclusions are as follows:

(1) The area ratio (r) of the micro-magnet on the surface influences the lubrication. The specimen with the area ratio of 5% shows the best of the tried ones for low friction at the load-speed condition.
(2) The specimen after magnetizing exhibits a superior anti-friction effect at higher sliding speed under four kinds of load conditions.
(3) Compared with nonmagnetic substrate, the range of speeds to generate hydrodynamic lubrication could be expanded to the lower region when fabricating the micro-magnet on the magnetic-inductive substrate.
(4) Tribological performance of the arrayed surface was affected by the magnetic field strength, and the higher magnetic intensity is more conducive to achieve better anti-friction properties at high sliding speeds.

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