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Wettability and friction coefficient of micro-magnet arrayed surface

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ABSTRACT

Surface coating is an important part of surface engineering and it has been successfully used in many applications to improve the performance of surfaces. In this paper, magnetic arrayed films with different thicknesses were fabricated on the surface of 316 stainless steel disks. Controllable colloid – ferrofluids (FF) was chosen as lubricant, which can be adsorbed on the magnetic surface. The wettability of the micro-magnet arrayed surface was evaluated by measuring the contract angle of FF drops on surface. Tribological experiments were carried out to investigate the effects of magnetic film thickness on frictional properties when lubricated by FF under plane contact condition. It was found that the magnetic arrayed surface with thicker magnetic films presented larger contract angle. The frictional test results showed that samples with thicker magnetic films could reduce friction and wear more efficiently at higher sliding velocity under the lubrication of FF.

1. Introduction

Surface phenomena play a decisive role in the behavior of engineering parts [1]. Failure of most engineering components occurs at the surface, corrosion begins from the surface, fatigue cracks propagate inwards from the surface and wear also occurs on the surface [2]. Surface engineering is a system of engineering to obtain the desired surface properties through surface coating, surface modification or duplex surface treatments on a material surface [3]. Using surface treatments to improve tribological performance of engineering parts is an important application of surface engineering.

Surface coating and surface texture, as typical methods of surface engineer, have been proved to be the effective techniques to improve tribological performance. Coatings in general, are promising candidates for limiting or even replacing environmentally problematic lubricants when deposited onto engineering components which are subjected to sliding contacts [4]. For coating technique, plasma and ion-based vacuum coating techniques have been at the forefront of the coating deposition technologies [5]. A typical example is the diamond and diamond-like hard carbon coatings. In dry sliding condition, the friction can be extremely low and with a coefficient of less than 0.01 [5]. Surface texture, such as arrayed micro-grooves or micro-dimples fabricated on the contact surfaces, is an option of surface engineering leading to improvement in load capacity, wear resistance, etc. The effects of surface texture on the improvement of tribological properties have been widely investigated [6–10]. And the relevant researches showed that textured surfaces exhibit good performances from boundary lubrication to hydrodynamic lubrication. Shallow pores distributed on a frictional surface are expected to generate fluid pressure as well as promoting the effect of oil pockets.

Up to now, most researches about surface modifications to improve tribological performance are focused on one of the means mentioned above and only a few have been combined surface coating and texture together. Nakano et al. [11] produced micro-patterns on Si surface and then deposited NiFe film with the thickness of 150 nm on the patterned surface. The tribological properties of the patterned surface with alloy film were investigated under lubricated conditions. Friction behavior of laser surface texture and chromium coating on piston rings was studied by Etsion et al. [12]. Pettersson et al. [13] studied the friction and wear properties of micro-textured DLC coated surface in boundary lubricated sliding.

In 2009, the authors' group introduced a kind of magnetic surface texture for FF lubrication [14]. Dimple pattern was firstly fabricated on the substrate surface and CoNiMnP permanent magnetic film was electrodeposited into these dimples, so that there were both geometric texture and periodic distribution of magnetic field on the surface. Because of the effects of magnetic force, FF, which can be confined, positioned and controlled at desired places by an external magnetic field, will gather on the surface and produce supporting force to another surface even at a low speed or in a stationary state. The experiment results show that magnetic surface texture can reduce the friction and wear efficiently under a certain conditions when lubricated with FF. According to Ref. [14], the friction reduction may come from two reasons: (a) FF can be

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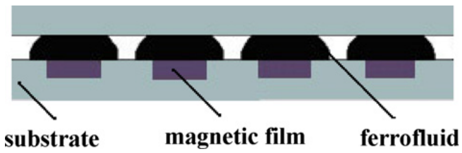

Fig. 1. Design diagram of FF lubrication with magnetic film arrayed surface.

retained at the friction zone due to attraction produced by magnetic film; (b) the micro-dimples of magnetic surface texture have the effect of oil reservoir as geometric texture. However, among the two reasons, which one is the dominant factor? What the friction property will be if there is no geometric texture? In addition, little was mentioned about the effect of magnetic strength of the film on the tribological properties when lubricated with FF.

In this paper, arrayed magnetic films were filled in the micro-dimples. The surfaces of magnetic films and substrate are approximately located in the same plane (see Fig. 1), which will eliminate the oil reservoir effect compared with micro-dimples. The wettability of FF on the arrayed magnetic surfaces was measured. Friction and wear tests of the magnetic surface were conducted with a pin-on-disk test rig. The purpose of this work is to investigate the effect of film thickness on the tribological performance of magnetic surface when lubricated with FF.

2. Experimental procedures

2.1. Specimens preparation and surface magnetic field intensity

In this paper, three specimens with magnet arrays were fabricated on disk surfaces by using electrolytic machining and electrodeposition technique as mentioned in Ref. [14]. The concept of arrayed magnets will greatly help to reduce geometrical anisotropy energy in vertical direction and also to decrease residual stress of the plated magnet film [15]. The pattern of magnet arrays was prepared on the 316 stainless steel (nonmagnetic) substrate surface. Fig. 2a shows the micro-dimple pattern after electrolytic machining and fresh metal can be seen in the bottom of the dimples. The micro-dimples, each with a diameter of 300 μm, area density of 10%, are arranged as a square array on the three sample surfaces. The depths of the dimples on the three specimens are about 20 μm, 60 μm and 80 μm, respectively. 3D image of a single micro-dimple with 60 μm depth was shown in Fig. 2b.

After electrolytic machining, CoNiMnP permanent magnetic allay was electrodeposited in these dimples until the corresponding dimples is full. The specimen surface after electrodeposition is given in Fig. 2c and the 3D image of a single micro-magnet in dimple is shown in Fig. 2d. Then the magnets arrayed surface of specimens was polished to an average roughness of 0.07 μm Ra by using abrasive paper. All the samples with magnetic films were magnetized in the axial direction. Fig. 3 presents the disk specimen with magnet arrays covered with FF. It can be seen that FF gathered around the micro-magnet surfaces and small protrusion arrays of FF appears due to the influence of the magnetic interaction between magnetic films on FF.

Fig. 4a illustrates the computing model of the three samples with magnetic film. The local surface magnetic field intensity of the samples was calculated by Ansoft Maxwell 10.0 software. The theoretical basis of the calculation is Maxwell equations. As can be seen in Fig. 4b–d, the maximal surface magnetic field intensity appears at the fringe of the dimples. And the maximal magnetic intensity values of the three magnetic surfaces are H_{20} = 0.15 T, H_{60} = 0.19 T, and H_{80} = 0.21 T, respectively. It is discovered that the surface magnetic field intensity increases with the increase of the film thickness. Each magnetic film in the dimple can be regarded 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 [16]. 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.

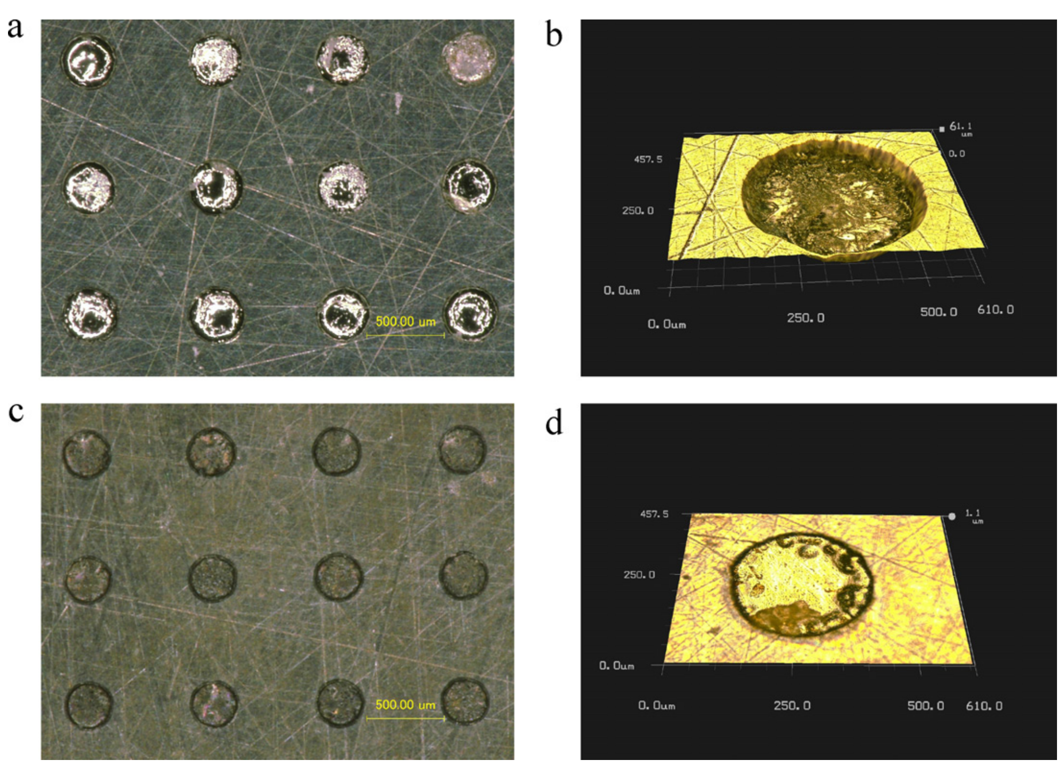

Fig. 2. Surface machining process (a) micro-dimple pattern after electrolytic machining; (b) 3D image of a single micro-dimple; (c) specimen surface after electrodeposition CoNiMnP magnet film; (d) 3D image of a single micro-magnet.

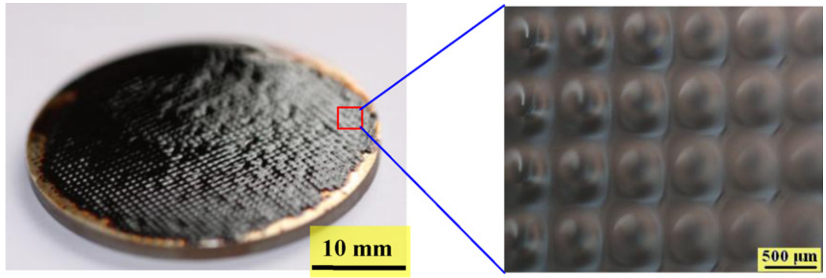

Fig. 3. Photos of magnetic film arrays covered with ferrofluids.

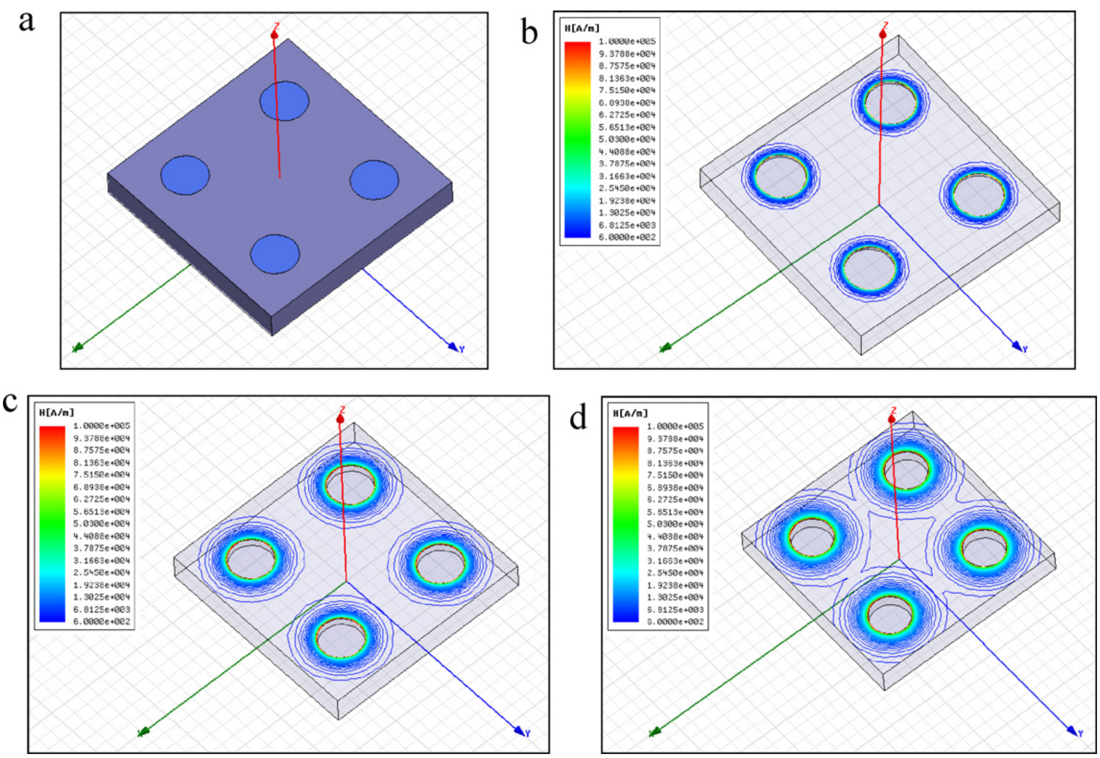

Fig. 4. The calculated magnetic flux density distribution of the arrayed surfaces. (a) Calculation model of the arrayed surface; (b) with 20 μm thickness film; (c) with 60 μm thickness film; (d) with 80 μm thickness film.

2.2. Contact angles of ferrofluid droplets

Contact angles are characteristic constants of liquid/solid systems. They provide valuable information on the surface free energy of solids that is important in understanding the wetting and adhesion properties of the material. The tendency of the lubricants to spread on a metal surface can also be rated on the basis of the contact angle. Compared with traditional lubricants, FF can be collected and held firmly in the regions with magnetic field. In order to investigate the FF contact angles on different magnetic surfaces, an SL-200 contact angle meter was introduced. Drops of FF were applied to the sample surfaces and the dosage of FF used in each experiment was strictly controlled at 5 μl for measurements. The FF droplets were imaged by a CCD camera before the included software calculated their shape and respective contact angles. The instrumental measuring error was controlled in the range of ±1°.

2.3. Tribological test procedures

In order to figure out the effects of magnetic field strength on tribological performance under the lubrication of FF, experiments were carried out on a pin-on-disk test rig, which was modified slightly to enable a flat-on-flat test, as shown in Fig. 5. The upper disk (10 mm in diameter) was attached to a ball-joint holder so that its surface automatically aligns with the surface of the lower disk specimen (40 mm in diameter). Both disks were made of 316 stainless steel (nonmagnetic) and polished to an average roughness of 0.07 μm Ra by using abrasive paper. Arrayed magnetic films were

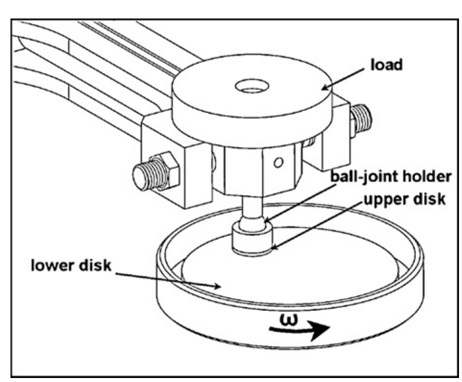

Fig. 5. Schematic diagram of pin-on-disk test rig.

Table 1
Test conditions.

Normal loads	1 N and 10 N
Sliding velocities	0.012–0.251 m/s
Lubricant[a]	Fe_3O_4 based ferrofluids

[a] Properties of the lubricant: density: 1.05×10^3 kg/m^3; viscosity: 67 mPa s; saturation magnetization: 15.9 kA/m.

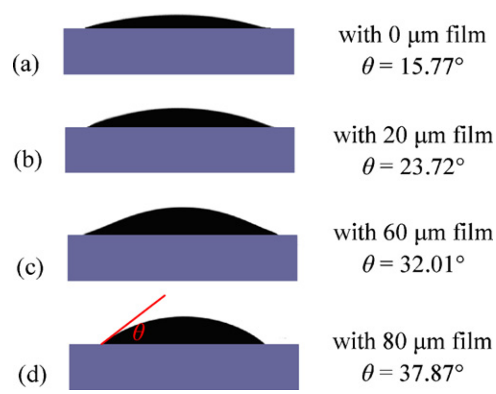

Fig. 6. The droplet shapes of FF on normal and magnet arrayed surface.

all fabricated on the lower disk. The test conditions are listed in Table 1. The dosage of FF used in each test was strictly controlled at 1 ml.

3. Results and discussions

Fig. 6 shows the droplet shapes of FF on horizontal sample surfaces. The surface of Fig. 6a is normal surface (316 stainless steel surface without any magnetic films) and the other three (Fig. 6b–d) are all deposited with magnetic arrayed films. The pictures were taken within several seconds after the droplet came to an equilibrium state.

Wetting refers to the contact between a solid surface and liquid and depends on intermolecular interactions [1]. The degree of surface wetting is evaluated in terms of the contact angle. The wetting of the normal surface is the best, which has the minimum contact angle, and it means that FF spreads easily on normal surface. For the magnetic surface specimen, it can be seen that the contact angles increase with the increasing thickness of magnetic films. The protrusions of FF on the surface indicate that there exists a certain interaction between the magnetic film and the FF drop besides intermolecular interactions. Force balance governs the equilibrium of a sessile FF drop on specimen surface surrounded by air. The interplay among gravity, capillary and magnetostatic forces causes the interfacial instabilities.

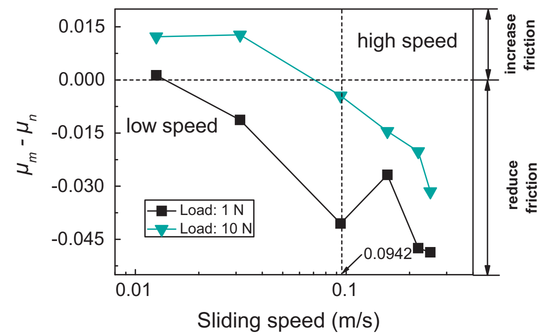

Fig. 8. Difference value between μ_m (friction coefficient of specimen with 80 μm films) and μ_n (friction coefficient of normal surface) when both lubricated with FF.

As is known the magnetic particles in the fluid, with a diameter of about 10 nm, can be treated as single domain particles, i.e. each of them is a small permanent magnet. In the presence of a magnetic field induced by the magnetic film, the magnetic moment of nanoparticles will be attracted partially to the external magnetic field [17]. For the patterned surface with 80 μm film has the strongest magnetic field, it can gather more magnetic nanoparticles on its surface, which may generate higher magnetic pressure in fluid per unit of volume. The increasing energy of the liquid system may make the contact angle get larger. The higher contact angle indicates that the magnetic interaction between the magnetic field and FF can prevent them from spreading away from the surface, which would affect the rheological behavior of FF at the same time. The surface wettability decreases with the increasing of contact angle. Among the four specimens, sample with normal surface has the optimal wettability for FF lubrication.

Fig. 7 presents the frictional properties of the normal and magnet arrayed surfaces at the loads of 1 N and 10 N, individually, corresponding to contact pressures of 0.013 MPa and 0.130 MPa. Specific test conditions were shown in Table 1.

At the load of 1 N, all the friction coefficients increase with the rising of sliding speed. When the sliding velocity is higher than 0.0314 m/s, the friction coefficients of magnetic surfaces are lower than that of normal surface. The specimens with thicker magnetic films seem to have better tribological performance when lubricated with FF. It indicates that magnetic arrayed surfaces can prevent FF from spreading away the rubbing surface and effective FF lubrication film is formed at a higher speed.

When the normal load increases to 10 N, most friction coefficients show a decrease for a certain extent and then increase gradually, which are consistent with the Stribeck curve [18]. The samples with thicker films also show significantly anti-friction at higher speeds compared with that of normal surface sample. The results suggest that thicker film or higher surface magnetic strength may be more helpful at higher speed lubricating environment.

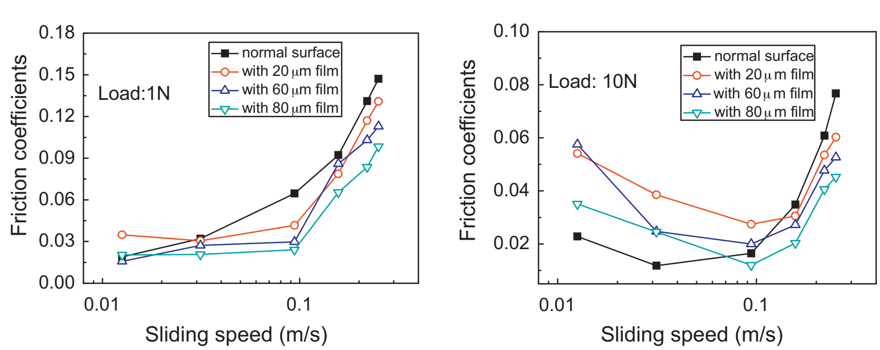

Fig. 7. Friction coefficients versus sliding speed of normal surface specimen and specimens with magnetic surface.

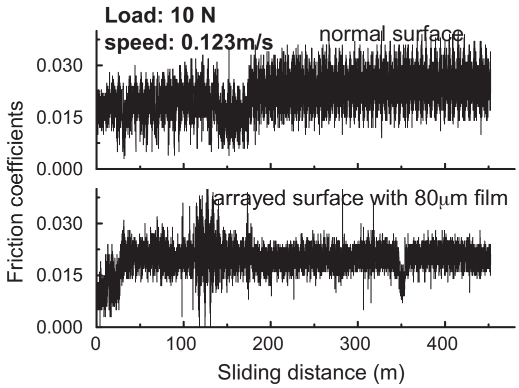

Fig. 9. Variation of friction coefficients during the wear tests.

It can be observed from Fig. 7 that most magnetic film arrayed surfaces show friction-increasing compared with normal surface at a lower velocity (0.0125 m/s). As mentioned before, compared with normal surface, magnetic surfaces have larger contact angles, which mean that magnetic surface has a poor average wettability for FF. Much of the fluid is gathered on the surface of magnetic films and effective lubrication film cannot be formed at a low sliding velocity. Meanwhile, with the effect of magnetic field, the viscosity of FF will increase significantly [19], which will lead to the addition of shear stress. Nevertheless, at higher speeds (0.157–0.251 m/s), obvious anti-frictional properties appeared compared with normal surface. For magnetic surface, FF can be retained at the friction zone due to magnetic attraction produced by arrayed films. Similar to traditional lubricants, the viscosity of FF, under the external magnetic field, also shows a characteristic shear thinning at high shear rate [20] and it decreases at high speed. Hence, effective lubrication films may be formed at a high sliding velocity for the surface with magnet arrays lubricated by FF. While for normal surface, centrifugal force may dispels the FF attracted on the surface at high speed, which weakens the lubrication effect.

For the three magnetic specimens, the friction coefficient of the sample with 20 μm film is higher than those two at higher speed (0.219–0.251 m/s). As mentioned above, specimens with thicker magnetic film has a higher surface magnetic intensity. For non-conductive FF, the unit volume value of the induced magnetic force

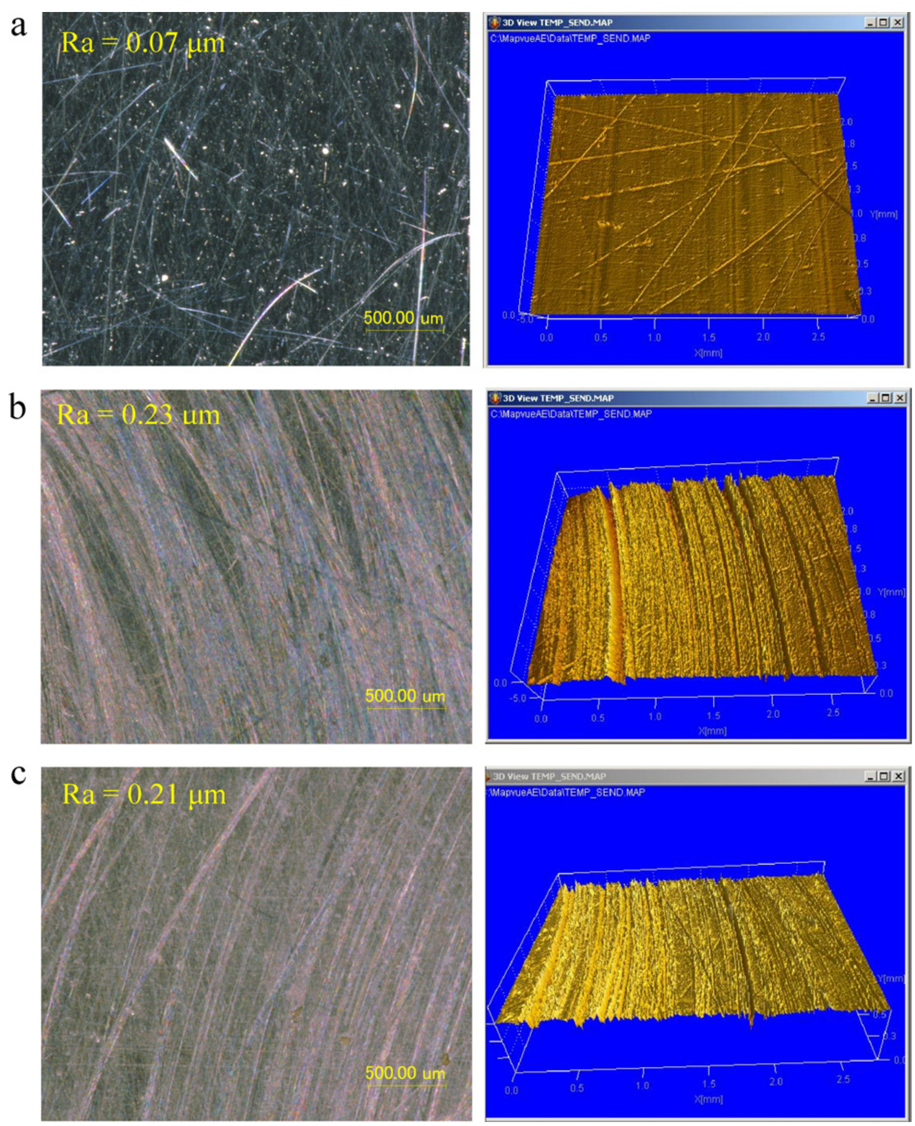

Fig. 10. Optical microscope images and 3D profiles of the upper disks' surfaces (a) before test; (b) opposite specimen with normal surface; (c) opposite specimen with 80 μm magnetic films.

for FF under the effect of external magnetic field can be written as [21]:

$$F_m = \mu_0 X_m H \cdot \nabla H \quad (1)$$

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

According to the Eq. (1), the interaction between the magnetic films and FF increases with the increase of magnetic intensity. As shown in Fig. 4, the surface magnetic field intensity of the sample went higher with the film thickness increased. Namely, the surface with thicker films has the larger induced magnetic force on FF. As a result, more FF can be reserved on the disk's surface to form lubrication film at a high speed even though there exists centrifugal force. According to ref. [22], the load capacity of squeeze film increases as the strength of the applied magnetic field rises. For the surface with 80 μm film, the friction coefficient decreased by 25.3% compared with the sample of 20 μm film at the speed of 0.251 m/s with the load of 10 N.

Fig. 8 shows the difference value between friction coefficients of specimen with magnetic surface (magnetic film of 80 μm thickness) μ_m and friction coefficients of normal specimen μ_n when both lubricated with FF. It can be seen that, the magnetic surface exhibits an increasing friction property compared with normal surface at low speed (0.0125 m/s). With the increasing speed, the magnetic surfaces gradually show good anti-frictional effects both at high and low load conditions.

Overall, compared to the normal surface, the specimen with magnetic film lubricated by FF shows good frictional performances at higher sliding velocity in the four loads conditions. The magnetic samples with thicker film may show a better anti-frictional property.

As the experimental results shown, the specimens with magnetic surface lubricated by FF have a good frictional behavior at high speeds. Compared studies were carried out to evaluate the wear characteristics between normal and magnetic surface samples. The load is 10 N and the sliding speed is fixed at 0.123 m/s. Fig. 9 displays the evolution of the coefficient of friction as recorded during the tribological test when lubricated with FF. The optical microscope (OM) and 3D images of the upper disks' surfaces before and after test are shown in Fig. 10. The surface roughnesses (R_a) of the upper disks were measured and also given in Fig. 10.

As can be observed in Fig. 9, the friction curves of the two specimens are stable. Compared to magnetic sample, the specimen with normal surface lubricated by FF has a higher average friction coefficient of approximately 0.022. While the specimen with the 80 μm magnetic film shows the lower average friction coefficient of about 0.018 and the fluctuation of the curve is much lower compared with normal surface. Fig. 10a shows the optical microscope images of the upper disk's surface before test. It can be found that the disk's surface (Fig. 10b) whose opposite specimen is normal surface, is evidently rough with many thick and deep furrows. However, the worn surface of upper disk whose opposite specimen is magnetic surface (80 μm) has the less furrows and the grinding cracks are thin and shallow (see Fig. 10c). And the R_a of the upper disk is also a little lower than that of the disk whose opposite specimen is normal surface. The result shows that the magnetic arrayed films on the surface can also help to improve the anti-wear property at high sliding speed.

4. Conclusions

In order to investigate the effects of magnetic intensity on the tribological performance of magnetic surface when lubricated with FF, magnetic surface with arrayed magnetic film were introduced on the disks' surface by electrolytical machining and electrodeposition technique. The geometric parameters of the square array arranged pores have average diameter of 300 μm and area density of 10%. The thicknesses of the CoNiMnP film in the dimples are 20 μm, 60 μm and 100 μm, respectively. The findings are concluded as follows:

(1) According to calculation, the surface magnetic intensity of the films on the magnetic arrayed surfaces increases with the increase of the film thickness.
(2) The maximum contract angles of FF on magnetic surface are more than doubled compared with that on normal surface. And the angles also increase with the increasing film thickness.
(3) Compared with normal surface, specimens with magnetic arrayed films have lower friction coefficients at high sliding speeds. Samples with thicker magnetic films could be conducive to forming effective lubrication at a high sliding velocity, which can reduce the friction and wear efficiently.

Acknowledgments

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