# Micro-Magnetic Field Arrayed Surface for Ferrofluids Lubrication

CoNiMnP permanent magnetic films have been electroplated into arrayed round dimples (with diameters from 100 µm to 700 µm) machined on the substrate surface (316 stainless steel). These films could be magnetized and could generate the arrayed micro-magnetic field. Compared with normal surfaces (316 stainless steel flat surfaces without any dimples or coatings), the frictional properties of such magnetic surfaces were investigated under different loads and sliding speeds when lubricated with ferrofluids using a friction test rig. Much attention was paid to the effect of the dimple sizes on the lubrication properties. In addition, the magnetic properties of the dimples arrayed surface were analyzed by finite element analysis software (Ansoft Maxwell 3D). The results show that there exists the optimized geometrical parameter of the arrayed magnetic surface, which displays the best tribological performance when lubricated with ferrofluids. [DOI: 10.1115/1.4005264]

Keywords: CoNiMnP films, magnet arrays, lubrication, ferrofluids

### 1 Introduction

Ferrofluids (FF) are stable colloidal systems with single-domain magnetic nanoparticles suspended in carrier liquids [1]. The magnetic particles, usually Fe<sub>3</sub>O<sub>4</sub> or  $\varepsilon$ -Fe<sub>3</sub>N, are up to 10–20 nm [2]. With many specific and particular physical and chemical properties, FF have been widely used in bearing sealing, lubrication, grinding, separation, ink-jet printing, damper support, and so on [3–5].

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As a lubricant, FF show many special characters and advantages compared with conventional lubricants. The physical properties of the surface, especially the magnetic properties, will strongly affect the behavior of FF. With the external magnetic field, FF can be located on the friction zone and act as a sustaining lubricant to reduce the dosage and the leakage to the environment [6]. The friction behaviors of FF were also affected by the distribution of the magnetic field and the particle concentration of FF [7,8]. Furthermore, the viscosity of FF will be increased with the external magnetic field strength [9], which may affect the lubrication properties. According to theoretical calculation, magnetized FF is capable of supporting loads between parallel plates [10]. Therefore, an optimized design of the surface magnetic fields can, to a great extent, develop the advantages of FF lubrication. Generally, in most sliding bearings lubricated with FF, magnetic fields are provided by block permanent magnets, which require certain spaces to place [11]. To meet the functional requirements, how to reduce the volumes of magnets by as many as possible becomes attractive to researchers.

Among many different magnetic materials, CoNiMnP alloy has been widely used for permanent magnets in micro electro mechanical systems (MEMS) because of its high magnetic energy density, high coercivity ( $H_c$ ), good mechanical properties, low cost, etc. [12–14]. As mentioned in Ref. [12], the electrodeposition technique was chosen to prepare CoNiMnP alloy on the silicon membrane for MEMS devices.

In 2009, our group first fabricated CoNiMnP films into round dimples (with diameters of  $d = 500 \,\mu\text{m}$ ) and studied the lubrica-

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tion effects using FF as lubricant [15]. Shown in Fig. 1 is the construction of the round dimple deposited with CoNiMnP magnetic film. The magnetic film would act as a permanent magnet to provide an external magnetic field to attract FF. It is known that the magnetic nanoparticles in FF can be treated as single domain particles, and each of them is a small permanent magnet in the carrier liquid [16]. In the presence of a magnetic field, the magnetic moment of the particles will try to align in the magnetic field direction, and the chains of particles may be formed in FF. A small protrusion of an FF drop is supposed to appear on the magnetic film surface (see Fig. 1). Preliminary results show that the surface with this kind of CoNiMnP magnetic film arrays exhibits superior tribological properties when lubricated with FF under certain conditions. However, the lubrication properties of this surface would be distinctive as the drawing ability between film arrays and FF would be affected by magnetic parameters (magnetic field strength (H) and gradient  $(\nabla H)$ ), while the array dimensions (dimple's diameter d, height h, etc.) or the area ratio (r) will have an immediate impact on the magnetic properties of the surface. Therefore, the lubrication effects of FF could be improved by optimizing the geometry parameters of CoNiMnP film arrays on the surface.

In this paper, we prepared CoNiMnP films into dimple arrays with different geometrical parameters. The magnetic field distribution regularity of the magnetic film arrays was analyzed using finite element analysis software. The lubrication effects of these film arrayed surfaces were basically studied when lubricated with FF.

#### 2 Magnetic Filed Analysis of CoNiMnP Film Arrays

For nonconductive FF, the unit volume value of the induced magnetic force  $(F_m)$  is given as follows [17]:

$$F_m = \mu_0 \chi_m H \cdot \nabla H \tag{1}$$

where  $\mu_0$  is the permeability of free space or air,  $\chi_m$  is the susceptibility of ferrofluid, *H* is the magnetic field intensity, and  $\nabla H$  is the gradient of magnetic field. It shows that the higher *H* and the  $\nabla H$  will lead to the stronger  $F_m$  between the film and FF.

To analyze H distribution on this new surface construction, Ansoft Maxwell 11 software was used. Each CoNiMnP film in the

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Fig. 1 Diagram of CoNiMnP film in dimple covered with FF



Fig. 2 Calculation model of the magnet arrayed surface

dimple can be regarded as a small cylindrical magnet. The setting model for calculation is illustrated in Fig. 2, where the thickness of dimples and CoNiMnP films are  $45 \,\mu\text{m}$  and  $25 \,\mu\text{m}$ , respectively. Meanwhile, the substrate material is nonmagnetic 316 stainless steel.

The geometrical parameters of round dimples include diameter d as well as the area ratio r of dimples on the surface, etc. Diameters of the round dimples in the analytical models range from 100  $\mu$ m to 1000  $\mu$ m with r = 5%. The schematic of r is also shown in Fig. 2, and r can be calculated as follows:



Fig. 4 Average H on dimple boundary of model with different d

$$r = \frac{S_P}{S} = \frac{\pi d^2}{4l^2} \tag{2}$$

where *r* is the area ratio,  $S_p$  is the total area of surface dimples, *S* is the whole area of surface, *d* is the diameter of dimple, and *l* is the distance between every two dimple centers.

Figure 3 gives the result of the surface magnetic field *H* distribution ( $d = 500 \ \mu m$ , r = 5%). It can be seen that the magnetic flux were mainly concentrated on the boundary of the dimples, which implies that the film's boundary owned the highest *H*. The analytical result shows that the value of *H* on the dimple's boundary reaches about 11,000 *A/m*, but in the center, it drops to merely 300 *A/m*. In Si unit, *A/m* is the unit of magnetic field intensity. Where *A* represents ampere and *m* represents a metric unit of length.

Dimples with different diameters own various magnetic properties. Figure 4 shows the relationship between the average value of Hin the dimple's boundary and d. In order to improve computational accuracy, four dimples (as shown in Fig. 2) in every model were calculated. It can be seen that the average H increases with the increasing of d. When d is between 400–800  $\mu$ m, the value of H tends to be constant (10,500 A/m). However, it sharply decreases to 8700 A/mwhen d exceeds 900  $\mu$ m. According to Eq. (1), if  $\nabla H$  is ignored,  $F_m$ is proportional to H. It shows that when d is around 400–800  $\mu$ m, the maximum value of the average H on the dimple's boundary was obtained, which implies their superiority in attracting the FF.

The effects of the CoNiMnP films' density (the area ratio: r) were also analyzed. Figure 5 shows the surface magnetic flux density distribution of the four models with different r (5%, 10%, 15%, and 20%) and the same d (500  $\mu$ m). When r is 5% and 10%,



Fig. 3 H evolution on model surface ( $d = 500 \,\mu\text{m}, r = 5\%$ )

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Fig. 5 *H* distribution on surface of different area ratio ((*a*) r = 5%, (*b*) r = 10%, (*c*) r = 15%, and (*d*) r = 20%)

Table 1 Geometrical parameter of dimples on each specimen

No.	$d$ ( $\mu$ m)	$l(\mu m)$	r (%)	No.	$d$ ( $\mu$ m)	$l(\mu m)$	r (%)
1	100	400	5	13	400	1600	5
2	100	275	10	14	400	1100	10
3	100	225	15	15	400	900	15
4	100	200	20	16	400	800	20
5	200	800	5	17	500	2000	5
6	200	550	10	18	500	1375	10
7	200	450	15	19	500	1125	15
8	200	400	20	20	500	1000	20
9	300	1200	5	21	700	2800	5
10	300	825	10	22	700	1925	10
11	300	675	15	23	700	1575	15
12	300	600	20	24	700	1400	20
				25	0	0	0

the magnetic flux lines are far more concentrated on the dimple's boundary than they are for the models with higher r. When r reaches 20%, the magnetic flux lines begin to overlap with each other, which indicates that the H of the dimples have already cross-influenced with each other. In the four models, the average H in each dimple's boundary is almost the same value (10,500 A/m).

Nevertheless, the difference of r shows little effect on the H of the dimple's boundary.

## **3** Fabrication and Characterization of CoNiMnP Film Arrays

316 stainless steel was chosen as substrate material. The geometrical parameters of the film arrays on each specimen surface are given in Table 1. Furthermore, the normal surface specimen (No. 25) was also made of 316 stainless steel without any dimples or coatings on the surface.

The preparation process mainly consists of three steps as shown in Fig. 6, photolithographic (Fig. 6(a), 6(b), and 6(c)), electrolytical machining (Fig. 6(d)), and electrodeposition (Fig. 6(e)). The specific fabrication process can be found in Ref. [15]. The surface roughness Ra of the final specimen is about 70 nm. The depth of the dimples after electrolytical machining is about 45  $\mu$ m, and the thickness of CoNiMnP film is 25  $\mu$ m. So the finial depth between the film and substrate surface is about 20  $\mu$ m.

The SEM photo of the CoNiMnP film as well as its composite is shown in Fig. 7, which illustrates that the film is compact and smooth. There are some cracks in the film, which may partly come from the inner stress in the film. In the energy spectrum, Fig. 7(*b*), the elements of Co, Ni, Mn, and P could be found in the film. The *B*-*H* hysteresis loop of the film is shown in Fig. 8 using



Fig. 6 Fabrication process: (a) polished substrate, (b) spin coat photoresist, (c) photolithography, (d) electrolytic etching, (e) electrodepositing, and (f) photoresist stripping and magnetizing

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Fig. 7 SEM photos and EDS of CoNiMnP films ((*a*) SEM image of CoNiMnP films and (*b*) the EDS spectrum of the films)



Fig. 8 *B-H* hysteresis loops of CoNiMnP films in the parallel and perpendicular direction

the vibrating sample magnetometer (VSM) while the maximum of  $H_{c\perp}$  and  $H_{c//}$  are 959 *Oe* and 554 *Oe* respectively, which is close to the value reported in Ref. [18].

After electrodepositing the CoNiMnP films in dimples, the films were magnetized with permanent magnets. Figure 9 demonstrates the photos of specimens (r = 15%,  $d: 100 \mu$ m, 200  $\mu$ m, 300  $\mu$ m, 400  $\mu$ m, 500  $\mu$ m, and 700  $\mu$ m) before and after being covered with FF. Micro-bumps of FF could be found under the effect of magnetic film arrays (see Fig. 9(*b*)).

#### 4 Friction Testing

The friction tests were carried out using a pin-on-disk test rig, shown in Fig. 10(a). The upper specimen is the 10 mm round flat made of 316 stainless steel. Its surfaces were polished with abrasive paper and the final roughness Ra is the same as the lower specimens. After being cleaned in alcohol, the upper specimen was fixed on the upper ball-joint holder to realize automatic faceto-face contact with the lower specimen. The lower specimens (with CoNiMnP magnetic films) were fastened on the lower disk. The upper and lower specimens can be seen in Fig. 10(b). The tester rotation speed comes at 5, 10, 15, 25, 50, 75, 100, 125, and 150 rpm and the corresponding linear sliding speed (v) was 0.006, 0.013, 0.019, 0.031, 0.063, 0.094, 0.126, 0.157, and 0.188 m/s. In each testing group, the normal load was selected from 2, 5, 10 and 20 N. Each test lasted 5 min and the friction coefficient data resulted from the average data of the last 1 min. The physical properties of FF were displayed in Table 2. At each test the dosage of FF was controlled at 1 ml.

#### 5 Results and Discussion

The lubrication properties of the magnetic surface specimen (No.13:  $d = 400 \,\mu\text{m}$ , r = 5%) and normal surface specimen (No.

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Fig. 10 The scheme of the experimental apparatus and specimens, (a) pin-on-disk test rig and (b) lower and upper specimens

Table 2 Physical parameters of FF

Lubricant	Density	Viscosity	Saturation magnetization
	(kg/m <sup>3</sup> )	(mPa·s)	(kA/m)
FF	$1.09 \times 10^3$	80	15.9

25) lubricated with FF are shown in Fig. 11. At lower v (0.006-0.019 m/s), the friction coefficient of the magnetic surface specimens at four loads is approximately 0.1, while the normal surface specimen is much lower at about 0.02. With v increasing, the friction coefficients of specimen No. 13 decreased to a mere 0.02 and then increased a bit to roughly 0.04 except under the load of 2 N. Conversely, the friction coefficient of a normal surface specimen increases with the increase of v all of the time. The original friction curves of the magnetic surface and normal surface at the load of 20 N can be seen in Fig. 12. At a low v(0.006 m/s) condition, the friction curve of a normal surface is smoother than that of a magnetic surface, and the average friction coefficients are 0.02 and 0.1, respectively. At higher v (0.188 m/ s), compared with normal surface, the friction curve of the magnetic surface always keeps smooth with a lower value, showing superior lubrication.

For different dimensions (d and r) of the dimple, the friction performance with FF would be diverse. The lubrication effects of specimens with different d are shown in Fig. 13. At the four loads, the friction coefficients of most magnetic surface specimens firstly decrease as v increases and then increase gradually at higher v. But the friction coefficient of normal surface specimens always



Fig. 12 Original friction curves of specimens No. 13 and No. 25

increases with the increasing of v. At the speed of 0.188 m/s, all of the friction coefficients of magnetic surface specimens are lower than that of the normal surface specimen.

In Fig. 13(*a*), most friction coefficients of magnetic surface specimens are greater than that of normal surface specimen at low *v*. When *v* increases, the friction coefficients of magnetic surface specimens first decrease and then increase with the increasing of *v*. This is especially true for specimen No. 13 ( $d = 400 \mu m$ ), where the lowest friction coefficient is 0.02 and increases to 0.06 at 0.188 m/s, much lower than that of a normal surface specimen,



Fig. 11 Friction coefficient versus v of magnetic surface specimen and normal surface specimen, (a) specimen No. 13 ( $d = 400 \ \mu m$ , r = 5%) and (b) normal surface specimen No. 25

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Fig. 13 Friction coefficient versus *v* of specimens with different *d* and normal surfaces under different loads



Fig. 14 Friction coefficient versus r under different experimental conditions

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which is 0.27. The same characters could be found in Figs. 13(b), 13(c), and 13(d). In Fig. 13(d), the friction coefficient of the magnetic surface specimens No. 1, No. 5, and No. 21 ( $d = 100 \,\mu\text{m}$ , 200  $\mu$ m, and 700  $\mu$ m) are much larger than that of normal surface specimens when v is lower than 0.126 m/s, while the friction coefficient of magnetic surface specimens No. 9, No. 13, and No. 17  $(d = 300 \,\mu\text{m}, 400 \,\mu\text{m}, \text{and } 500 \,\mu\text{m})$  are lower than that of normal surface specimen at higher speeds (v > 0.031 m/s). Thus, compared with a normal surface, the film arrayed specimens with dimple sizes of 400–500  $\mu$ m appear to have a apparent low friction at high speeds.

As mentioned above, geometrical parameter r has little influence on surface H distribution, but there still existed the influences on the lubrication properties (see Fig. 14). For the five specimens (No. 13, 14, 15, 16, and 25), it can be seen that the specimens of r = 5% - 10% show lower friction coefficients than others at the experimental conditions. It could be deduced that arrays of the film could not be too dense.

It is believed that the existence of CoNiMnP film arrays on the surface have distinct influences on tribological performance when lubricated with FF. With the external magnetic field, the viscosity of FF would increase in low shearing rate [9]. As shown in Fig. 11 and Fig. 13, at lower v, the surface with CoNiMnP films did not show advantages compared with the normal surface, which is probably due to the increasing viscosity of FF. At higher v, since normal surface has no magnetic attraction ability, FF could not be located in the friction zone and much of FF escaped out of the friction surface because of the centrifugal effect, which leads to the increase of high friction. According to the friction coefficients, it may be in the state of boundary lubrication. For the magnetic specimen, the increased viscosity of FF under a magnetic field shows a characteristic shear thinning at a high shearing rate [9], and the friction coefficients decrease gradually with the increase of speed. When the sliding speed increased continuously, the full film lubrication could be formed and it was in the hydrodynamic state, which is in some degree consistent with the Stribeck curve [19].

The optimal r is between 5–10%, as can be seen in Fig. 14. According to software analysis, r of the dimple has little effect on the average H of the dimple's boundary. But a higher r may lead to an overlap of magnetic flux lines (see Fig. 5), which may also indicate that r should not be too dense.

#### Conclusion 6

In this study, CoNiMnP films have been fabricated into arrayed micro dimples with different dimensions on the surface of 316 stainless steel (nonmagnetic). The tribological performance of the magnetic film arrayed surface and a normal surface were studied when lubricated with FF. The main results are as follows:

- (1) The magnetic arrayed surface shows the improvement in friction reduction especially in the higher v conditions.
- (2) The highest average value of H of the dimple's boundary appears at the diameter of 400-800  $\mu$ m. The preferable

diameter to achieve the best friction performance is approximate at 400-500 µm.

(3) The area ratio (r) also influences the lubrication effect. The area ratio between the 5%-10% performed the best friction reduction during the tests.

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#### References

- [1] Fannin, P. C., Marin, C. N., Malaescu, I., and Stefu, N., 2007, "An Investigation of the Microscopic and Macroscopic Properties of Magnetic Fluids," Physica B, 388, pp. 87-92.
- [2] Huang, W., and Wang, X. L., 2008, "Preparation and Properties of &-Fe<sub>3</sub>N-Based Magnetic Fluid," Nanoscale Res. Lett., 3, pp. 260-264.
- [3] Kanno, T., Kouda, Y., Takeishi, Y., Minagawa, T., and Yamamoto, Y., 1997, "Preparation of Magnetic Fluid Having Active-Gas Resistance and Ultra-Low Vapor Pressure for Magnetic Fluid Vacuum Seals," Tribol. Int., 30, pp. 701-705
- [4] Umehara, N., and Komanduri, R., 1996, "Magnetic Fluid Grinding of HIP-Si<sub>3</sub>N<sub>4</sub> Rollers," Wear, 192, pp. 85-93.
- [5] Nakatsuka, K., 1993, "Trends of Magnetic Fluid Applications in Japan," J. Magn. Magn. Mater., 122, pp. 387–394
- [6] Berkovsky, B. M., Medvedev, V. F., and Krakov, M. S., 1993, "Magnetic Fluids in Chemical Engineering," Magnetic Fluids Engineering Application, Chap. 4, Oxford University Press, Oxford, UK.
- [7] Huang, W., Shen, C., Liao, S. J., and Wang, X. L., 2011, "Study on the Ferrofluid Lubrication With an External Magnetic Field," Tribol. Lett., 41, pp. 45-151.
- [8] Huang, W., Shen, C., and Wang, X. L., 2009, "Study on Static Supporting Capacity and Tribological Performance of Ferrofluids," Tribol. Trans., 52, pp. 717-723
- [9] Uhlmann, E., Spur, G., Bayat, N., and Patzwald, R., 2002, "Application of Magnetic Fluids in Tribotechnical Systems," J. Magn. Magn. Mater., 252, pp. 336-340.
- [10] Shah, R. C., 2003, "Ferrofluid Lubrication in Step Bearing With Two Steps," [10] Johan X. C., 2003. For our labor lab
- Lubr. Tribol., 59, pp. 252–265.
- [12] Guan, S., and Nelson, B. J., 2005, "Electrodeposition of Low Residual Stress CoNiMnP Hard Magnetic Thin Films for Magnetic MEMS Actuators, J. Magn, Magn. Mater., 292, pp. 49-58.
- [13] Liakopoulos, T. M., Zhang, W., and Ahn, C. H., 1996, "Electroplated Thick CoNiMnP Permanent Magnet Array for Micromachined Magnetic Device Applications," MEMS, IEEE, San Diego, CA, pp. 79-84.
- [14] Liakopoulos, T. M., Zhang, W. J., and Ahn, C. H., 1996, "Micromachined Thick Permanent Magnet Arrays on Silicon Wafers," IEEE Trans. Magn., 32, pp. 5154-5156.
- [15] Shen, C., Huang, W., Ma, G. L., and Wang, X. L., 2009, "A Novel Surface Texture for Magnetic Fluid Lubrication," Surf. Coat. Technol., 204, pp. 433-439
- [16] Odenbach, S., 2003, "Ferrofluids-Magnetically Controlled Suspensions," Colloids Surf., A., 217, pp. 171-178.
- [17] Osman, T. A., Nada, G. S., and Safar, Z. S., 2001, "Effect of Using Current-Carrying-Wire Models in the Design of Hydrodynamic Journal Bearings Lubricated With Ferrofluid," Tribol. Lett., 11, pp. 61-70.
- [18] Cho, H. J., Bhansali, S., and Ahn, C. H., 2000, "Electroplated Thick Permanent Magnet Arrays With Controlled Direction of Magnetization for MEMS Application," J. Appl. Phys., 87, pp. 6340–6342.
- [19] Lu, X. B., and Khonsari, M. M., 2006, "The Stribeck Curve: Experimental Results and Theoretical Prediction," ASME J. Tribol., 128, pp. 789-794.