Tribol Lett (2011) 41:145–151
DOI 10.1007/s11249-010-9693-2

ORIGINAL PAPER

# Study on the Ferrofluid Lubrication with an External Magnetic Field

**Wei Huang · Cong Shen · Sijie Liao · Xiaolei Wang**

Received: 16 August 2009 / Accepted: 6 September 2010 / Published online: 22 September 2010


**Abstract** Ferrofluids (FFs) are stable colloidal systems consisting of single-domain magnetic particles with a diameter of approximately 10 nm coated with surfactants and dispersed in a carrier liquid. By applying an external magnetic field, these fluids can be confined, positioned, shaped and, controlled at desired places. The load capacity of a lubricant film of FF can also be increased with an appropriate magnetic field. In this paper, $Fe_3O_4$-based FFs with different saturation magnetizations ($M_s$) were prepared by the co-precipitation technique. The tribological experiments of FFs under different magnets distributions were conducted on a ring-on-cylinder tribometer. The results show that the magnetic field intensity distributions on the rubbing surface have a significant influence on the tribological properties of FFs. The experimental results also indicate that FFs have a good friction-reduction performance in the presence of an external magnetic field compared with the carrier liquid and that its lifetime of friction can be greatly improved.

**Keywords** Ferrofluids · Friction · Wear · Magnetic field distribution · Lifetime

## 1 Introduction

Ferrofluid (FF), also known as magnetic fluid, is a colloidal suspension of single-domain magnetic particles, with typical dimensions of about 10 nm, dispersed in a carrier liquid [1]. In order to prevent agglomeration due to attractive Van der Waals interactions, the nanoparticle surface is covered with chemically adsorbed surfactant [2]. Owing to their unique physical and chemical properties, these ferromagnetic liquids have attracted wide interests since their inception in the late 1960s. The most usual engineering applications of ferrofluids are in sealing, grinding, separation, ink-jet printing, damper, among others [3–5].

Lubrication is another important application of FFs. The main advantage of FF as a lubricant, over the conventional oil, is that the former can be retained at the desired location by an external magnetic field and still possess flowability of fluid at the same time. Further advantages are the small amount of the necessary lubricant and the avoidance of leakages [6] because the lubricant is prevented from leaving the contact zone. Moreover, when subjected to an external magnetic field, the viscosity of the lubricant will increase and, hence, its load capacity will be improved. These have led to important applications of such fluids in the area of lubrication engineering, especially in journal bearing, thrust bearing, short bearings, etc. [7–9]. As theoretically calculated by Rajesh Shah [10, 11], the parallel plate slider bearing can support a load with FF lubricant, and the use of FF can increase the load capacity in step bearing. Chao and Huang [12] found that the usage of the FF provides the capability to alter and improve the general dynamic characteristics of a hydrodynamic grooved journal bearing. Prajapati [13] observed that in the presence of an externally magnetic field, the bearing with FF can support a load even when there is no flow. However, to date, most reports on FF lubrication have focused on theoretical analysis, and only a few experimental studies have been published.

W. Huang (✉) · C. Shen · S. Liao · X. Wang
College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, Jiangsu, People's Republic of China
e-mail: 5543837@sina.com

Our previous studies revealed that FF has good friction-reduction behavior in the presence of the field distribution from eight magnets [14]. However, the relationship between tribological properties of FF lubrication and the external magnet distribution is still unknown. In this paper, the tribological properties of FF under different magnetic distributions were examined using a ring-on-cylinder tribometer. The lubrication properties of the carrier liquid and FFs were carried out at the operating conditions. The aim of this study was to optimize the surface magnetic field distribution of FF lubrication and reduce friction. As the choice of FF is also an important factor that affects tribological performance, we compared the lubrication effects of FFs at different magnetization. The finial objective of this research is to improve the FF lubrication effect by optimizing the surface magnetic field distributions and choosing the proper FF.

## 2 Experimental Details

In this paper, $Fe_3O_4$-based FFs at different concentrations were prepared by the co-precipitation technique. Details on the synthetic procedures can be found elsewhere [15]. The transmission electron microphotographs of the nanoparticles were obtained using a 2000fx transmission electron microscope (TEM) operated at 200 keV. Samples were prepared by air-drying drops of diluted solutions of the preparations on carbon films supported by copper grids. The TEM images (Fig. 1) show that $Fe_3O_4$ nanoparticles are nearly spherical, with an average size of 14 ± 3 nm. The saturation magnetization of the FF samples was examined by a LDJ9600 vibrating sample magnetometer (VSM). The properties of the carrier liquid and FFs are given in Table 1.

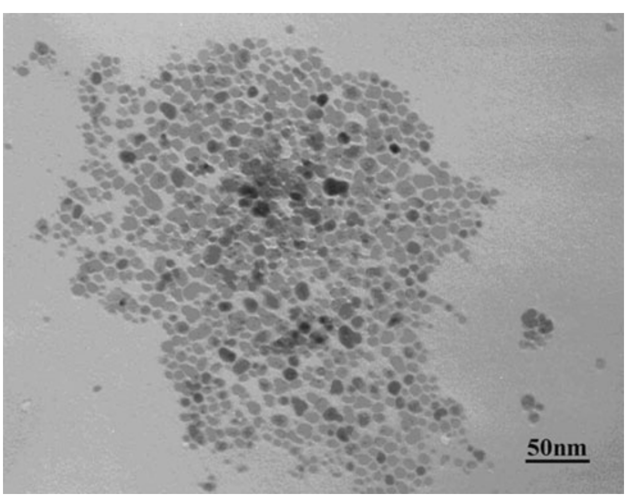


**Fig. 1** Transmission electron microscopy (TEM) image of $Fe_3O_4$ particles

In order to study the effect of magnetic field on FF lubrication, we designed four cylinders with different magnet distributions. Bores with different diameter sizes were fabricated on the surface of each cylinder, and columniform NdFeB magnets (magnetic property: 35MGOe) with corresponding diameters were situated in each bore. The area ratio of the magnets on each cylinder surface is about 14%, and the thickness of the four kinds of columniform magnets is 4 mm. Thus, the total volume of permanent magnets in each cylinder is the same. All of the magnets in each cylinder are along the same magnetic pole direction. The distance between the two end surfaces (cylinder and NdFeB magnet) is 0.20 mm. Both cylinder and ring are made of aluminium (nonmagnetic metal), and the roughness of the end faces is about 0.20 μm. Figure 2 shows the ring and the cylinder with eight magnets. Figure 3 shows the four cylinders covered with FF; it can be seen that small protrusions appear on the surface of the cylinder. The absolute values of magnetic field intensity ($H$) on the cylinder surfaces were calculated using Ansoft Maxwell ver. 10.0 software (ANSYS, Canonsburg, PA). Figure 4 shows the distribution of the surface magnetic field intensity of the four cylinders. The theoretical basis of the calculation is Maxwell equations. As can be seen in Fig. 4, the maximum intensity of the surface magnetic field appears at the fringe of the columniform magnets. The maximum value at the surface of the four cylinders was $H_a = 0.52$ T, $H_b = 0.49$ T, $H_c = 0.47$ T, and $H_d = 0.42$ T, respectively.

The friction and wear tests lubricated with carrier liquid and FFs were conducted on a ring-on-cylinder tribometer. Figure 5 shows the principle of the apparatus used in this experiment. The ring is fixed on the rolling shaft driven by a motor with an adjustable rotational speed. The cylinder is supported by a hemispherical tip so that its friction surface is automatically aligned to match the surface of the ring. The load was applied on the cylinder by a serve motor and spring mechanism, which has a closed-loop control with a load cell for load measurement. Friction torque was measured by the torque sensor. The test conditions are listed in Table 2. The dosage of FFs and carrier liquid used in each test was strictly controlled at 1 ml.

In order to investigate the tribological behavior of FF lubrication, experiments were carried out in two groups: (1) four cylinders with different magnet distributions lubricated by the same FF sample; (2) optimized cylinder lubricated with four kinds of FFs and carrier liquid.

## 3 Results and Discussion

Figure 6 shows the original friction coefficient curves of the four cylinders at a rotational speed of 50, 100, 200, and

**Table 1** Properties of carrier liquid and ferrofluids (FFs) at 20°C

| Lubrication | Density (kg/m$^3$) | Viscosity (mPa s) | $M_s$ (kA/m) | Volume fraction of particles (vol%) |
|---|---|---|---|---|
| Carrier liquid | $0.84 \times 10^3$ | 50 | 0 | 0 |
| FF-1 | $0.96 \times 10^3$ | 59 | 7.9 | 2.61 |
| FF-2 | $1.05 \times 10^3$ | 67 | 15.9 | 4.83 |
| FF-3 | $1.12 \times 10^3$ | 78 | 23.9 | 6.32 |
| FF-4 | $1.21 \times 10^3$ | 95 | 31.8 | 8.52 |

$M_s$, Saturation magnetizations

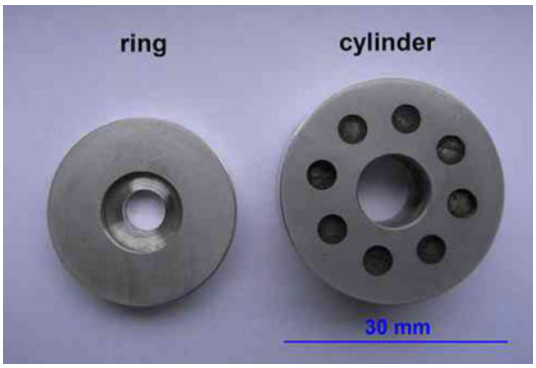


**Fig. 2** Picture of the ring and the cylinder with 8 magnets

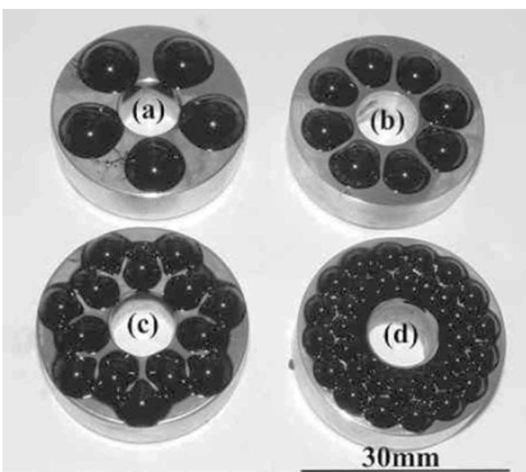


**Fig. 3** Cylinders covered with ferrofluid: **a** 5 magnets ($\varphi$ 5.0 × 4.0 mm), **b** 8 magnets ($\varphi$ 4.0 × 4.0 mm), **c** 14 magnets ($\varphi$ 3.0 × 4.0 mm), **d** 32 magnets ($\varphi$ 2.0 × 4.0 mm)

400 rpm, respectively. The normal load is fixed at 150 N and the lubricant is FF-2 (Table 1). It can be seen that for the four cylinders, the friction trend shows a clear transition from a high-friction coefficient of about 0.09 at the lowest speed to lower values as the speed increases, which is consistent with the Stribeck curve [16]. The fluid retained at the frictional surface reduces the direct contact between the sliding surface. The friction decreases in a step-wise manner as the speed increases, and the friction curve becomes relatively smooth at a high speed. The friction coefficients are in the range of 0.01–0.1, which is usually the friction coefficient of a mixed lubrication regime according to a typical Stribeck curve [16].

The arithmetic average of the original data at every speed during the test time was calculated for all cylinders; the results are shown in Fig. 7. As can be seen in Fig. 4, the outer edge of a magnet has a maximal surface magnetic intensity, indicating that the fringe magnetic field has a large effect on FF lubrication. Thus, the abscissa axis in Fig. 7 represents the sum length of the magnets' circumference in every cylinder. The variation in the trend of friction first decreased with increasing sum length of the magnet's circumference and then increased. The friction coefficient of the cylinder with 14 magnets is the lowest of the four cylinders at any speed. As the outer border of the columniform magnet surface has the highest magnetic field, the sum length of the 14 magnets' circumference is larger than that of either the five or eight magnets' circumference. The longer circumference is conducive to retaining FF on the friction region, which led to this lower friction coefficient.

Although the cylinder with 32 magnets has the largest sum length of magnets' circumference, its surface magnetic field ($H_d = 0.42$ T) is the lowest. Under this condition, the FF cannot be attracted effectively to the surface relative to the other three cylinders, which causes higher friction. All of the friction coefficients tend to be close together much lower at the high rotation speed of 400 rpm.

The effect of surface magnetic field distribution on FF lubrication was also evaluated by frictional service time. Tests were performed at a moderate rotation speed of 200 rpm, and the lubricant was FF-2. The tribological test was automatically stopped when the friction coefficient reached a limit value $\mu_{\text{lim}} = 0.2$. Figure 8 depicts the evolution of the friction coefficient during the test. The lifetime of a sample was defined as the distance at which friction starts to increase rapidly and reaches the limit value.

As can be seen from Fig. 8, the friction curves of the four samples start at a value of 0.1, which is in the regime of mixed lubrication. After the running-in process has continued for a period of time, the local area becomes

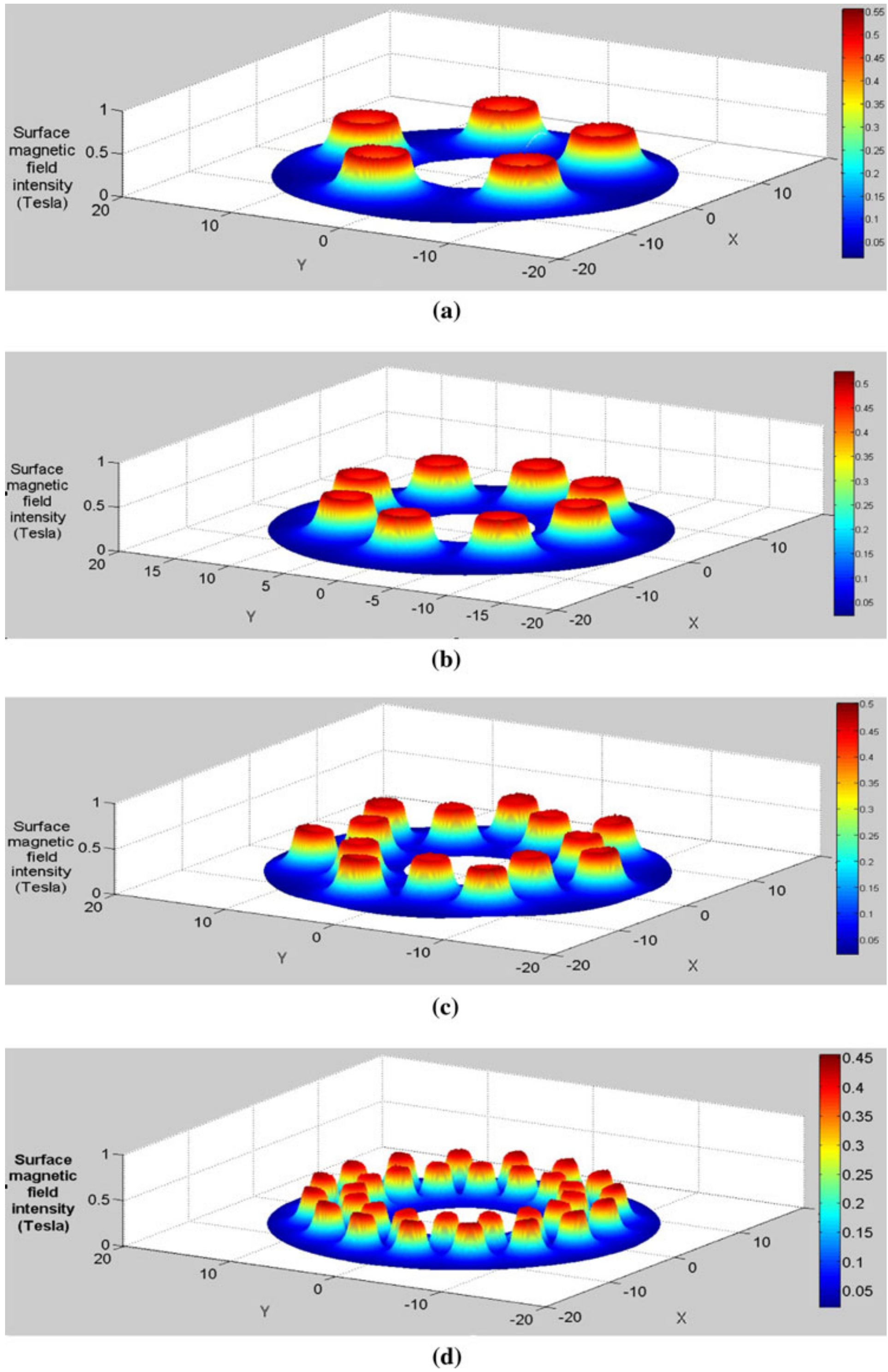


**Fig. 4** The surface magnetic field intensity distribution of the four cylinders

smooth. As the sliding distance increases, smooth and flat surfaces are formed on the ring and cylinder, leading to a stable friction curve.

For those cylinders with five and 32 magnets, the limit friction coefficient of 0.2 is reached after sliding for about 1,000 m. However, the curve of the cylinder with 14 magnets decreases with siding distance in a smooth trend. At the end of the lifetime, the curve rises abruptly to the set threshold of 0.2. Although the cylinder with five magnets has the highest surface magnetic field intensity ($H_a = 0.52$

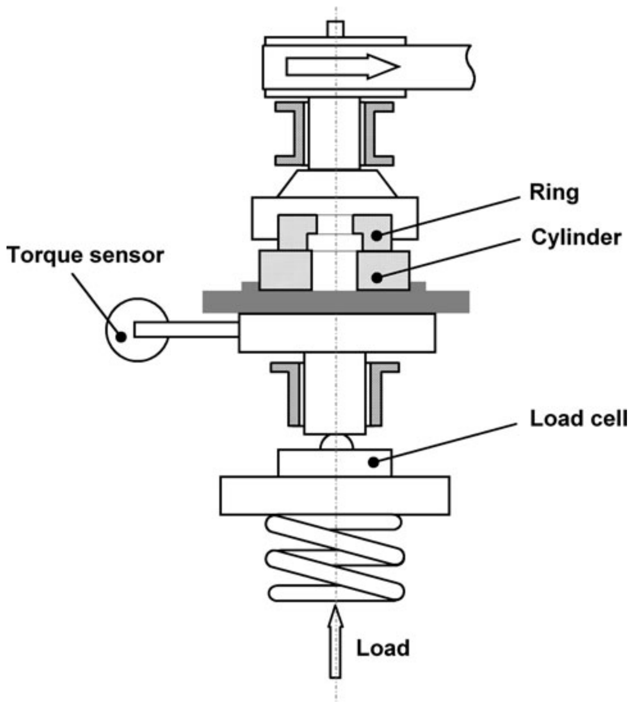


**Fig. 5** Schematic diagram of the tribotester

T), the effective magnetic covering area is less due to the decreased length of the magnet's circumference. The cylinder with 32 magnets has the least magnetic field on the rubbing surface. Both of these conditions may cause the loss of lubricant. Therefore, the proper magnet distribution on the surface of cylinder can result in an extension of the lifetime by a factor 2 compared with those cylinders with five and 32 magnets. This result is in accordance with the better friction-reduction performance of cylinders with 14 and eight magnets (Fig. 7).

After the friction characteristics of the cylinders with different magnets distribution had been compared, we tested the effects of lubricants on friction using the cylinder with 14 magnets for its best friction performance. Figure 9 shows the evolution of the friction coefficients during the tribological tests when lubricated with carrier liquid and different magnetization FFs. The three-dimensional (3D) profiles and optical microscope (OM) images of the fixed rings' surfaces before and after the test are shown in Fig. 10.

**Table 2** Experimental conditions

| Parameter | Experimental condition |
|---|---|
| Normal loads | 150–800 N |
| Sliding velocities | 50–400 rpm |
| Lubricants | Carrier liquid and ferrofluids (see Table 1) |

The friction curve lubricated with only carrier liquid started at a value of 0.3. After a short period, it rose quite rapidly to the friction coefficient of 0.47 and the rotating shaft seized. It is evident that the magnets cannot effectively attract the non-magnetic carrier liquid on the contact surface and that, in contrast to FFs, it is scattered by the centrifugal force. As a result, there was direct contact between the sliding surfaces, which in turn led to the short lifetime. A smoother friction curve could be detected following lubrication with either of the four FFs with different saturation magnetization. The lower friction of FFs may be ascribed to: (1) the FF can be effectively absorbed under the applied magnetic field; (2) the viscosity of the FF is higher than that of the carrier liquid (see Table 1), and it will increase significantly under the external magnetic field, leading to an increase in its load carrying capacity; (3) the nanoparticles in the carrier liquid can produce the ball effects between frictional couples [17].

The friction coefficient lubricated with FF-1 is much higher than those of the other three FFs. According to [7], the lower the magnetization of FF, the less attractive the FF force. Compared with the other three higher magnetization FFs, FF-1 may not be well retained within the contract cavity at the lower attractive force, possibly leading to the appearance of the higher friction coefficient. High saturation magnetization keeps the fluid well within the contract surface under shear stress and under centrifugal, shock, and vibration forces. According to [11], the load carrying capacity of the lubrication film arises from the higher magnetization of FF. The higher load carrying capacity and attractive magnetic force result in the lower coefficients of friction. We also found that the friction coefficient lubricated with FF-4 was higher than that of FF-2 and FF-3 in the duration test. This situation may be caused by FF-4 having the highest viscosity (Table 1).

Figure 10a shows the ring surface before the test. The worn surface lubricated by carrier liquid shown in Fig. 10b is evidently rough with many thick and deep furrows, while the rubbing surface lubricated by FF is rather smoother and the furrows are rather shallower (Fig. 10c, d, e). This comparison shows that FF has a good friction-reduction behavior under an external magnetic field. As can be seen in Fig. 10c, the worn surface shows severe wear compared to that shown in Fig. 10d, e, which consistent with the friction curves shown in Fig. 9.

## 4 Conclusions

The friction properties of ferrofluid lubrication under different magnet field distributions were investigated using a

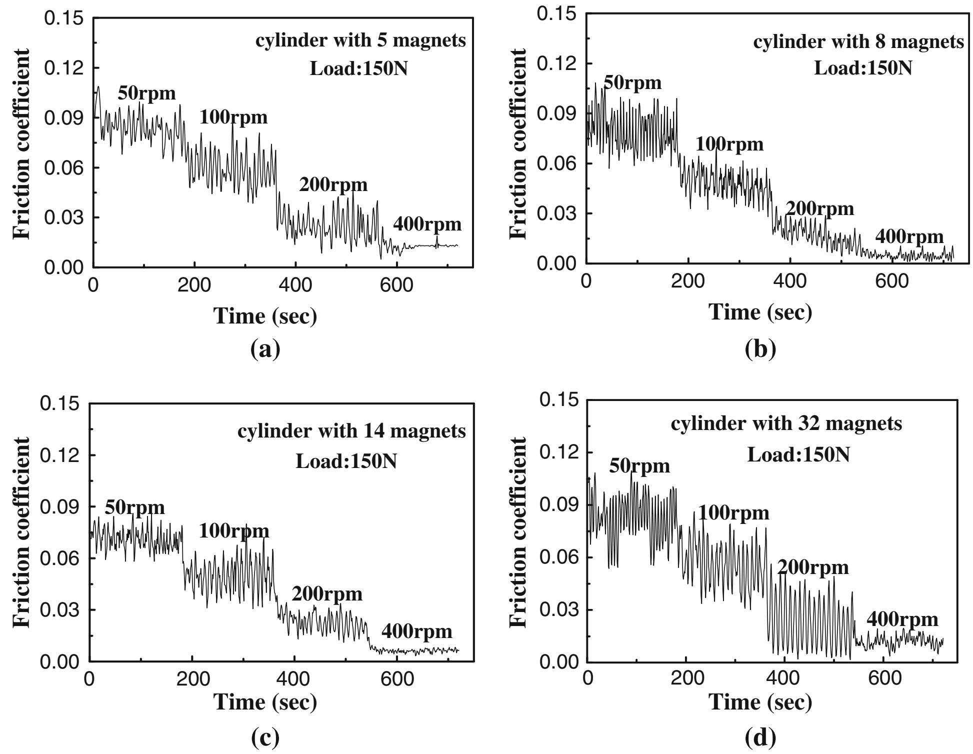


**Fig. 6** Variations in the friction coefficient at a sliding speed for various cylinders lubricated with FF-2. **a** Cylinder with 5 magnets, **b** cylinder with 8 magnets, **c** cylinder with 14 magnets, **d** cylinder with 32 magnets

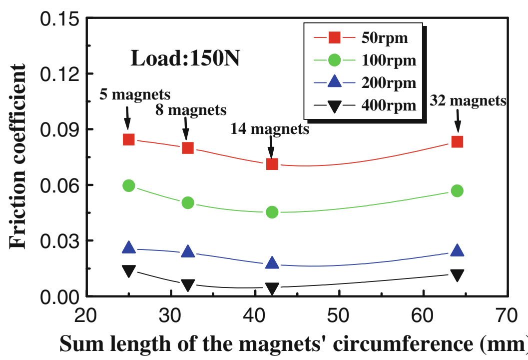


**Fig. 7** Variation in the friction coefficient according to sum length of the magnets' circumference

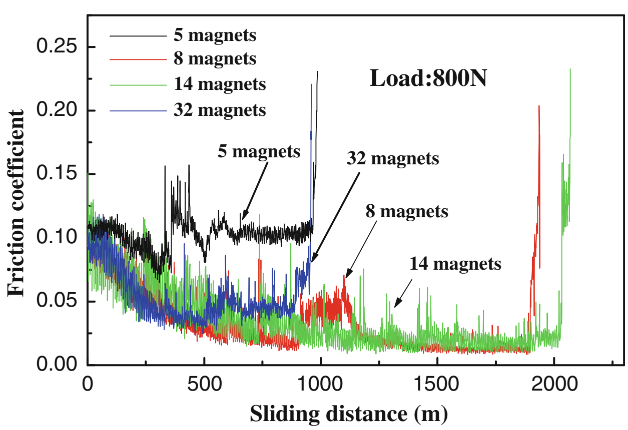


**Fig. 8** Evolution of the friction coefficient on the four cylinders lubricated with FF-2 (the time scale is expressed in sliding distance)

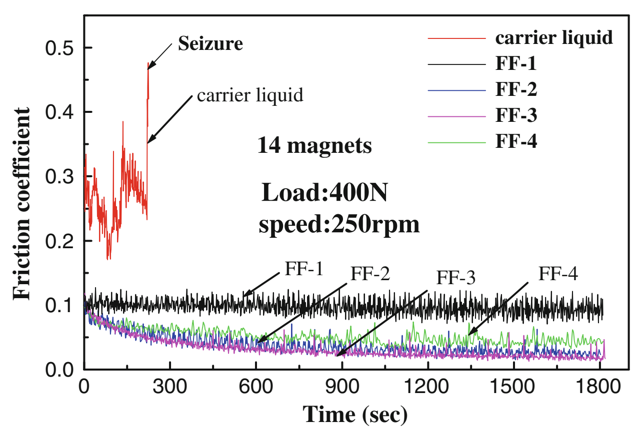


**Fig. 9** Variation in the friction coefficient during the test carried out with different lubricants (cylinder with 14 magnets was used)

ring-on-cylinder tribometer. The results show that the friction behavior was mainly affected by the distribution of the surface magnetic field intensity and choice of FF. The proper magnet distribution seemed to be suitable for the fixation of the lubricant in the contact zone of the friction pairs. The frictional characteristic was also affected by the $M_s$ of the FF. The FF with the appropriate $M_s$ was able to effectively decrease the friction coefficient. These experimental results also indicate that, compared with carrier liquid, the friction lifetime can be greatly improved with lubrication with FFs.

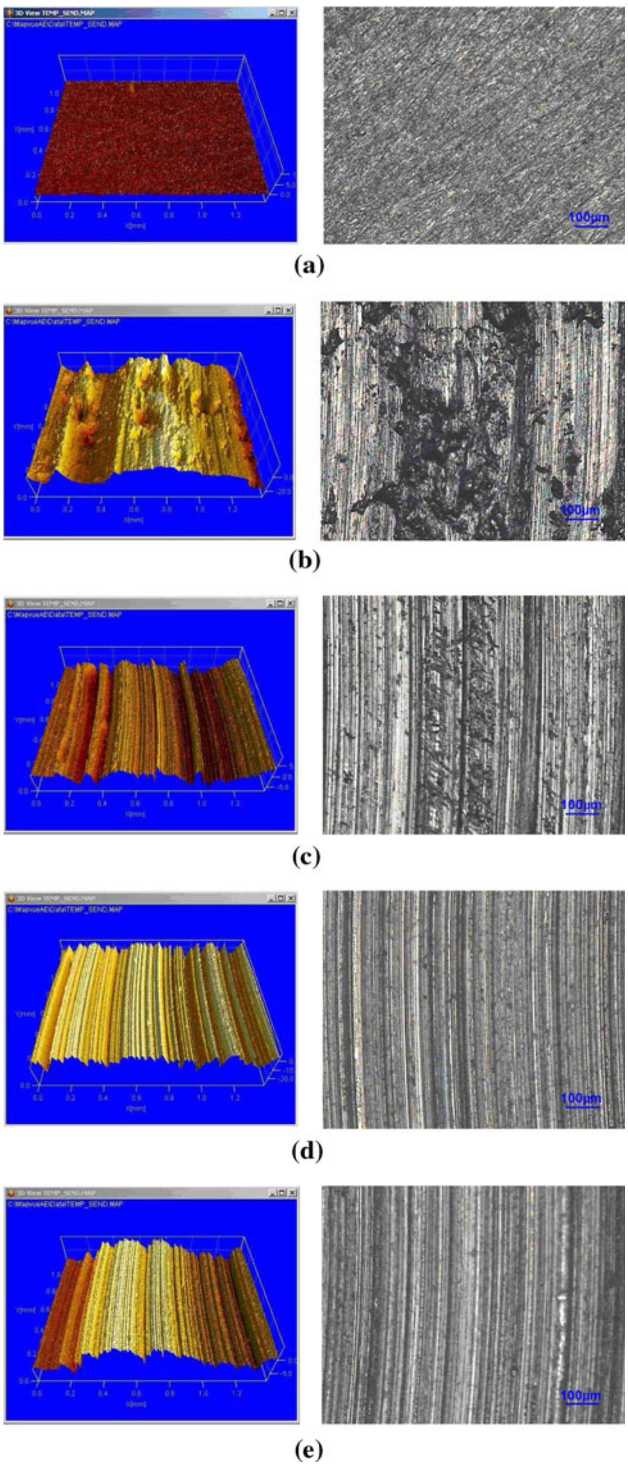


**Fig. 10** Three-dimensional profile and optical microscope images of a worn scar lubricated with carrier liquid and FFs. **a** Before test, **b** lubricated with carrier liquid, **c** lubricated with 7.9 kA/m FF-1, **d** lubricated with 23.9 kA/m FF-2, **e** lubricated with 31.8 kA/m FF-4

**Acknowledgment** This work was supported by National Natural Science Foundation of China (no: 50875125), China Postdoctoral Science Foundation funded project (no: 200904501094) and NUAA Research Funding (no: NS2010125).

## References

1. Scherer, C., Figueiredo Neto, A.M.: Ferrofluids: properties and applications. Braz. J. Phys. **35**, 718–727 (2005)
2. Socoliuc, V., Bica, D., Vékás, L.: Estimation of magnetic particle clustering in magnetic fluids from static magnetization experiments. J. Colloid Interface Sci. **264**, 141–147 (2003)
3. Kanno, T., Kouda, Y., Takeishi, Y., Minagawa, T., Yamamoto, Y.: Preparation of magnetic fluid having active-gas resistance and ultra-low vapor pressure for magnetic fluid vacuum seals. Tribol. Int. **30**, 701–705 (1997)
4. Umehara, N., Komanduri, R.: Magnetic fluid grinding of HIP-$Si_3N_4$ rollers. Wear **192**, 85–93 (1996)
5. Nakatsuka, K.: Trends of magnetic fluid applications in Japan. J. Magn. Magn. Mater. **122**, 387–394 (1993)
6. Uhlmann, E., Spur, G., Bayat, N., Patzwald, R.: Application of magnetic fluids in tribotechnical systems. J. Magn. Magn. Mater. **252**, 336–340 (2002)
7. Nada, G.S., Osman, T.A.: Static performance of finite hydrodynamic journal bearings lubricated by magnetic fluids with couple stresses. Tribol. Lett. **27**, 261–268 (2007)
8. Nagaya, K., Takeda, S., Sato, A., Ikai, S., Sekiguchi, H., Saito, N.: Thrust bearing using a magnetic fluid lubricant under magnetic fields. Tribol. Int. **26**, 11–15 (1993)
9. Tipei, N.: Theory of lubrication with ferrofluids: application to short bearings. ASME J. Lubr. Technol. **104**, 510–515 (1982)
10. Shah, R.C.: Ferrofluid lubrication in step bearing with two steps. Ind. Lubr. Tribol. **55**, 265–267 (2003)
11. Shah, R.C., Bhat, M.V.: Lubrication of porous parallel plate slider bearing with slip velocity, material parameter and magnetic fluid. Ind. Lubr. Tribol. **57**, 103–106 (2005)
12. Chao, P.C.P., Huang, J.S.: Calculating rotor dynamic coefficients of a ferrofluid-lubricated and herringbone-grooved journal bearing via finite difference analysis. Tribol. Lett. **19**, 99–109 (2008)
13. Prajapati, B.L.: Magentic-fluid-based porous squeeze films. J. Magn. Magn. Mater. **149**, 97–100 (1995)
14. Huang, W., Shen, C., Wang, X.L.: Study on static supporting capacity and tribological performance of ferrofluids. Tribol. Trans. **52**, 717–723 (2009)
15. Huang, W., Wang, X.L., Ma, G.L., Shen, C.: Study on the synthesis and tribological property of $Fe_3O_4$ based magnetic fluids. Tribol. Lett. **33**, 187–192 (2009)
16. Wen, S., Huang, P.: The Principle of Tribology, 2nd edn. Tsinghua Press, Beijing, China (2002)
17. Huang, H.D., Tu, J.P., Gan, L.P., Li, C.Z.: An investigation on tribological properties of graphite nanosheets an oil additive. Wear **261**, 140–144 (2006)