ASME Journal of Tribology
Online journal at:
https://asmedigitalcollection.asme.org/tribology

Juntuo Wen
College of Mechanical & Electrical Engineering,
Nanjing University of Aeronautics & Astronautics,
Nanjing 210016, China
e-mail: maple2821@163.com

Zeeshan Anjum
College of Mechanical & Electrical Engineering,
Nanjing University of Aeronautics & Astronautics,
Nanjing 210016, China
e-mail: zeeshan.anjum@nuaa.edu.cn

Qingwen Dai
College of Mechanical & Electrical Engineering,
Nanjing University of Aeronautics & Astronautics,
Nanjing 210016, China
e-mail: daiqingwen@nuaa.edu.cn

Wei Huang[1]
College of Mechanical & Electrical Engineering,
Nanjing University of Aeronautics & Astronautics,
Nanjing 210016, China
e-mail: huangwei@nuaa.edu.cn

Xiaolei Wang
College of Mechanical & Electrical Engineering,
Nanjing University of Aeronautics & Astronautics,
Nanjing 210016, China
e-mail: wxl@nuaa.edu.cn

Controlling Starvation of Thrust Ball Bearing Using Magnetic Fluids

Magnetic fluids (MFs) are a kind of magnetically manipulated colloid, which may serve as an active lubricant. These fluids can be retained at the desired locations, by the application of an appropriately designed external magnetic field. In this research work, initially, centrifugal experiments were conducted to estimate the antispreading behavior of the MFs, in the presence of an external magnetic field. Later, the starvation behavior of a thrust ball bearing was investigated after lubricating it with an MF, under different magnetic field distributions and operating temperatures. The preliminary results presented that the application of an external magnetic field can maintain more residual MFs in the raceway at higher rotational speeds. Tribological tests showed that proper magnetic field distribution on the raceway may effectively inhibit the lubricant loss and prolong operation before the starvation of the bearing. In addition, an increased operating temperature of the bearing accelerated the occurrence of a starved state of lubrication. [DOI: 10.1115/1.4068222]

Keywords: ball bearings, magnetic fluids, starvation, tribological tests, bearing design and technology, bearings

1 Introduction

Bearings are the key components used to support the rotating parts of the machinery in many applications, like ultra-high-speed machine tools and the transmission system of the aviation industry. Their operational stability is of great significance for the safety and reliability of the entire mechanical system. Lubrication plays a vital role in ensuring a smooth operating condition for the bearings. A suitable availability of the lubricant in the raceway may avoid asperity contact, overheating, and the ultimate bearing seizure condition [1,2]. The lubricant film thickness controls the frictional losses, temperature, and speed limit in high-speed lubricated bearings, while a drastic reduction in lubrication may lead to undesired starvation conditions. Centrifugal force is a major cause of lubricant loss experienced by the rolling bearings, especially for those operating under high-speed conditions [3]. It causes the lubricant to spread and escape from the raceway of the bearing. In addition, the increased temperature can cause surface tension gradient and oxidation, which may also lead to undesired starvation conditions [4,5]. Bearing failures, caused by lubricant loss or starvation, can result in a catastrophic failure of the mechanical systems.

Grease is a commonly applied lubricant in rolling bearings due to its ease of application, low friction, corrosion protection, and inherent sealing ability, but it has a limited service life. Its structure deteriorates under mechanical work and an increase in temperature causes oxidation. Additionally, evaporation, side flow due to the contact pressures, cage scraping, and ball vibrations may also lead to lubricant loss [6,7]. Periodic re-lubrication with fresh grease is often needed for the smooth operations of the bearings [4]. Therefore, to avoid the lubricant loss or the unwanted starvation condition, it is crucial to maintain the lubricant in the frictional area.

Magnetic fluids (MFs) are the colloidal suspensions of nano-sized ferromagnetic particles in a suitable carrier liquid like conventional oil, water, and organic solvents [8]. Brownian motion keeps these particles suspended under gravity, and to overcome the van der Waals forces and magnetic dipole interactions, these particles are coated with a layer of a suitable organic surfactant.

One of the attractive properties of MFs is that they possess the behavior of a conventional lubricant as well as the magnetic property [9]. The application of an external magnetic field can confine and position them at the desired location, and the migration behavior of the fluid can be controlled. Therefore, an improved lubrication behavior can be achieved by maintaining MFs between the tribo-pairs, under the action of an external magnetic field. Uhlmann et al. [10] explored the boundary lubrication behavior of MFs and observed that the lubricant could be prevented from leaving the contact zone by the application of an external magnetic

[1]Corresponding author.

Contributed by the Tribology Division of ASME for publication in the Journal of Tribology. Manuscript received December 23, 2024; final manuscript received March 7, 2025; published online April 3, 2025. Assoc. Editor: Wenyang Zhang.

field. Wang et al. [11] investigated the lubrication behavior of MFs under an external magnetic field and observed that the load-carrying capacity of the lubricant increases with an increase in magnetic induction. The thin-film rheological performance of MFs in a hydrodynamic regime was studied by Efrén et al. [12]. It was observed that MFs, in conjunction with a suitable magnetic field, can be used to promote replenishment and control lubricant starvation conditions. In our previous work [13], it was observed that MFs can be maintained at the contact interface of the tribo-pair by the application of an external magnetic field, but their tribological performance depends on the surface distribution of the magnetic field.

Taking account of the controllability of MFs, can the pattern of MF lubrication, cooperated with the magnetic field, be introduced to inhibit the lubricant loss under the effect of centrifugation? What is the effect of different magnetic field distributions on the tribological performance? What is the effect of different operating temperatures on the MFs' lubrication behavior? There is little knowledge about it.

The objective of this study is to investigate the lubrication performance of MFs in high-speed thrust ball bearings, at different magnetic field distributions and operating temperatures. Initially, centrifugal tests were conducted to investigate the effect of different magnetic field distributions, on the antispreading behavior of MFs in the bearing raceway. Later, tribological tests were conducted to investigate the lubrication performance of MFs for the bearings under different magnetic field distributions and operating temperatures.

2 Experimental Details

Commercially available Fe_3O_4-based MF, having a saturation magnetization of 35.8 kA/m, was used during this research work. The magnetic particles had an average size of 10–15 nm and a particle fraction of about 9% by volume and were dispersed in a diester (the carrier liquid). It had a viscosity of about 56 mPa s, a little higher than the carrier liquid (50 mPa s).

Stainless steel thrust ball bearings (SS51104) were used during this research. The flat rings of the bearing were installed between two specially designed fixtures made of aluminum alloy, as shown in Fig. 1. Eight holes, equally spaced and having a size of φ5 mm × 5 mm, were machined in the lower fixture. To generate a magnetic field on the raceway of the bearing, cylindrical permanent magnets (NdFeB) with the magnetic parameter of 35 MGOe were chosen. The size of each magnet was φ5 mm × 3 mm. These magnets were embedded in the holes with the same pole orientation and rubber gaskets were applied at the bottom of the holes, to make the surface of the magnets and the fixture at the same level.

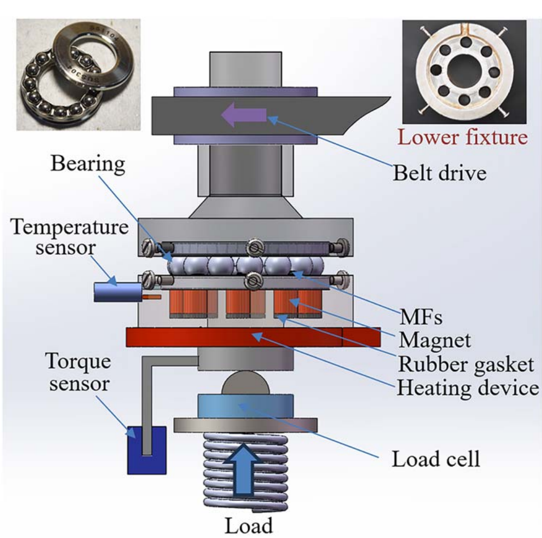

Fig. 1 Schematic diagram for the tribological test

ANSYS MAXWELL 16.0 software package was used to predict the distribution of magnetic field strength at the raceway as shown in Fig. 2, while MATLAB was used for the analysis of data. Magnetic field intensity at the raceway depends upon the magnet and it had a maximum value of $H = 120$ mT. The magnetic field distribution around the lower raceway was varied by altering the number of magnets embedded in the holes of the lower fixture, i.e., 4, 6, and 8 (represented as H_4, H_6, and H_8, respectively).

Centrifugal tests were conducted to analyze the antispreading behavior of the MFs at different speeds (0–2000 rpm), without any magnet and by varying the number of magnets. The volume of the MFs applied at the raceway was controlled at 0.04 mL and tests were conducted for 2 min. The centrifugal force caused some of the lubricant volume to spread out of the raceway and this lubricant loss was measured by weighing the samples after each test.

A modified MMW-1 tribo-tester was utilized to investigate the MFs lubrication behavior for the bearing under varying distribution of the magnetic field intensity, as shown in Fig. 1. The flat rings of the thrust bearing were mounted between two specially designed fixtures made of aluminum alloy, as mentioned above. Before testing, bearing parts were ultrasonically cleaned for five minutes in acetone and dried in the oven at 50 °C. The lower fixture remained stationary while a belt drive was used to rotate the upper fixture at different speeds. A certain volume of MF was deposited at the raceway of the lower ring as a lubricant. An axial load of 800 N was applied to the lower fixture while the rotational speed was kept constant at 1600 rpm. These conditions were selected to simulate the severe working environment and to achieve the starvation condition earlier. The torque sensor and thermocouple were used to measure the friction and temperature at the raceway, respectively. A heating device was also attached below the lower fixture to investigate the effect of temperature on the lubrication behavior. To quantitatively assess the starved state of lubrication, the service life of each bearing was defined as the time at which the friction torque of the bearing exhibited a sudden increment. Each test was repeated thrice to ensure the reliability. An optical microscope (Keyence Corp., Japan) and surface profilometer (Bruker Corp., USA) were used to analyze the raceway surfaces after each test.

3 Results and Discussion

Four groups of centrifugal experiments were conducted: MFs without any magnet, MFs with four magnets (H_4), MFs with six magnets (H_6), and MFs with eight magnets (H_8). At the start of each test, one drop of MFs having a volume of 0.04 mL was deposited in the raceway. In the presence of magnets, as soon as the fluid drop was deposited in the raceway, it was strongly attracted by the magnetic field, forming magnetically triggered MF droplet division on the ring surface.

Figure 3 presents the images of the original and the remaining lubricant in the raceway after conducting centrifugal tests for two minutes at different speeds. The dark region indicates the presence of MF. The tests conducted without any magnet revealed that at a low-speed of 200 rpm, the total volume of the MF was maintained in the raceway. With an increase in the rotational speed up to 800 rpm, more volume of the MF escaped out due to the centrifugal force and resulted in a significant decrease in film thickness in the raceway. After a further increase in speed up to 1000 rpm, merely a thin film of the fluid was left in the raceway.

The antispreading behavior of the MFs was improved by the application of magnets. These magnets produced a magnetic field distribution on the raceway and the MF was attracted toward the locations with the strongest magnetic field (i.e., right above the magnets) and it retained there spontaneously in the form of drops, as shown in Fig. 3. In the presence of four magnets (H_4), no obvious spread out of MF was observed during centrifugal tests conducted at speeds varying from 400 to 1000 rpm. The magnetic

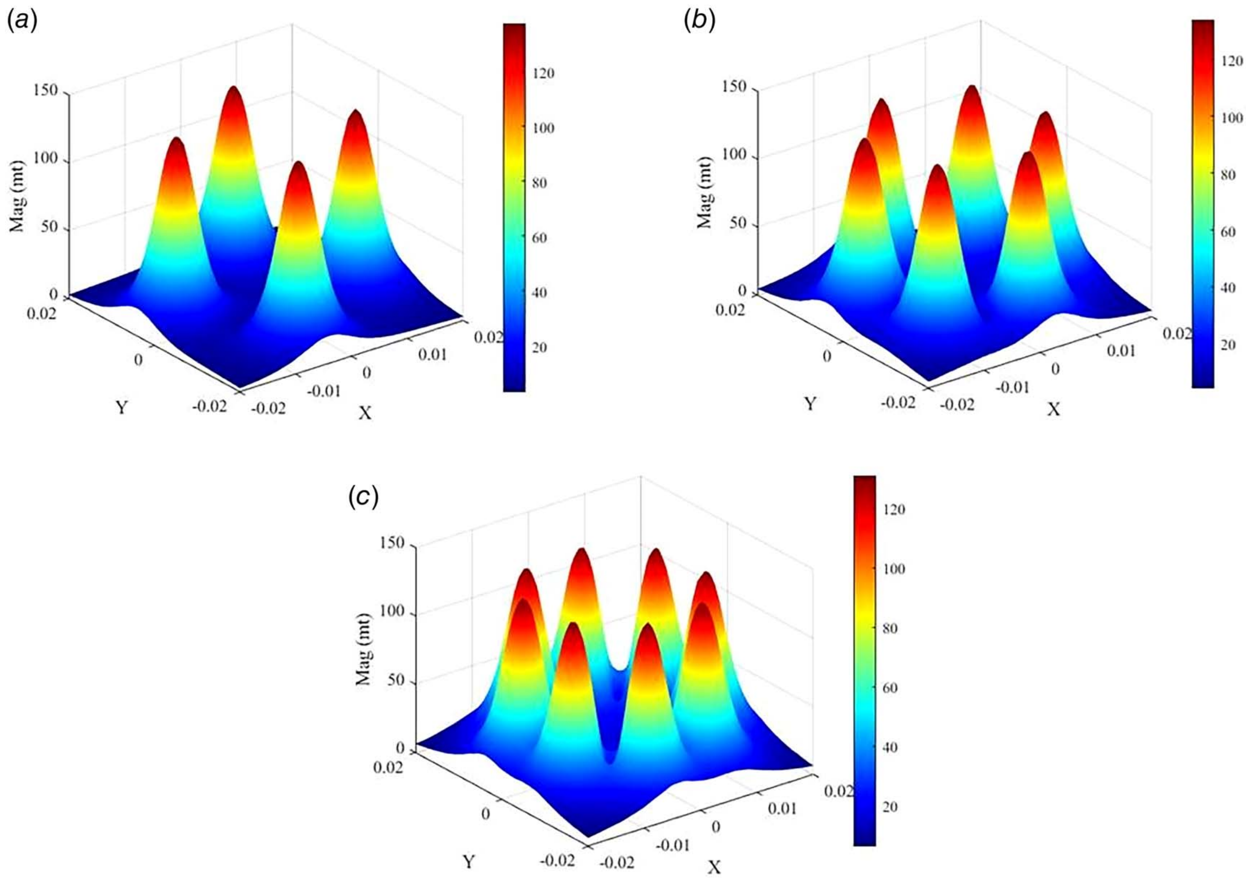

Fig. 2 Distribution of magnetic field intensity produced at the raceway at (*a*) H_4, (*b*) H_6, and (*c*) H_8

force dominated the centrifugal force and it remained restricted at the four locations with the strongest magnetic field, which is a clear contrast to the nonmagnetic condition. With an increase in rotational speed from 1200 to 1800 rpm, the centrifugal force started dominating the magnetic force, causing the MF to spread out of the raceway and a corresponding decrease in volume. In the presence of six and eight magnets (H_6 and H_8), an improved antispread behavior was observed due to the stronger magnetic

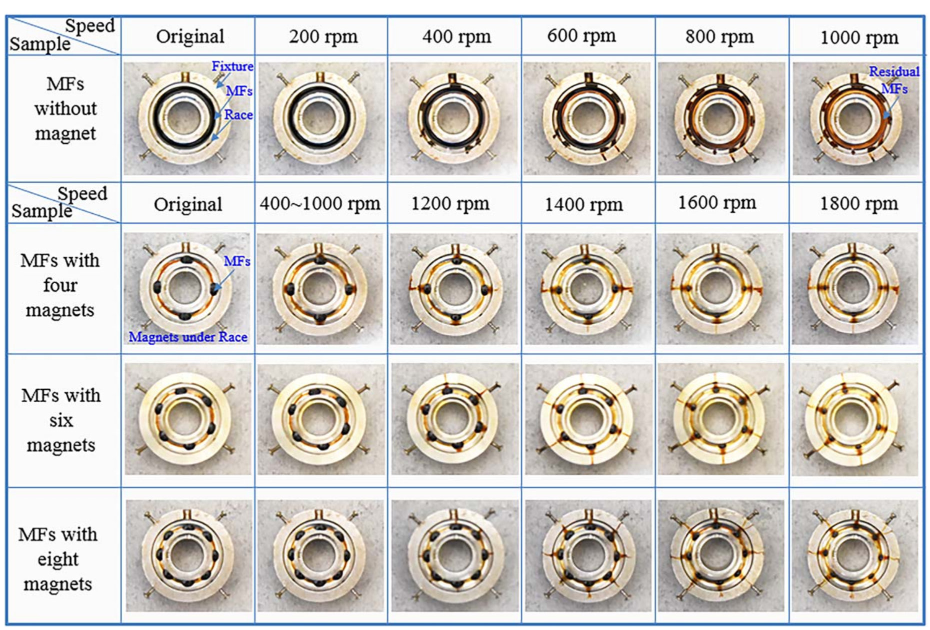

Fig. 3 Images of MFs on the raceway of the bearing before and after 2-min centrifugal experiments. (The ring was held in the aluminum fixture, where eight holes were uniformly machined and different numbers of cylindrical magnets (0, 4, 6, and 8) were embedded into the holes.)

field distributions on the raceway. Hence, the critical speed of lubricant spreading out increased with an increase in the magnetic field strength (number of magnets), and the loss in lubricant volume was reduced accordingly.

Figure 4 presents the relationship between the remaining mass of the lubricant in the raceway and rotational speed, during centrifugal experiments. Without an external magnetic field, it started decreasing earlier at the rotational speed of 300 rpm and reached a minimum value at 1200 rpm. However, in the case of H_4, the presence of a magnetic field increased the critical speed up to 900 rpm. The critical speed values were increased to 1100 rpm and 1200 rpm for H_6 and H_8, respectively. Hence, the strongest magnetic field distribution resulted in the least loss in the volume of MFs.

It is known that each of the nanoparticles, dispersed in a carrier liquid, can be treated as a thermally agitated permanent magnet. These are magnetized by an external magnetic field and the magnetic moment of each particle is along the direction of the applied field [14]. This magnetization generates attractive forces between them. By virtue of the stable suspension of the particles in the carrier liquid, this attractive magnetic force manifests itself as a controllable body force in the fluid [15]. A magnetic field induces a magnetic body force in the MFs, which enhances its cohesive energy and restricts the spreading behavior. Since the same volume of MF (0.04 mL) was deposited at the ring during this work, it is divided into smaller droplets with an increased number of magnets due to the strong magnetic forces produced by these magnets. Due to a linear relationship between the magnetic body force and external magnetic field, the stronger adsorption is imposed on the smaller droplets. Therefore, an improved anti-spreading ability was observed at the raceway surface, with an increase in the number of magnets. Additionally, an external magnetic field causes an increase in the viscosity of MFs [16], which may also contribute to inhibit the spread of the fluid in the raceway during the centrifugal tests. With an increase in rotational speed, the centrifugal force starts dominating the magnetic forces and the MFs can start spreading out of the raceway.

Figure 5 presents the variations observed in frictional torque and temperature (at the raceway surface) of the MFs lubricated bearings, at the rotational speed of 1600 rpm and normal load of 800 N. These tests were conducted at room temperature without an external magnetic field. To investigate the effect of volume, three different volumes of 0.01, 0.02, and 0.04 mL were applied.

Initially, a frictional torque of about 0 N mm was observed for each of the three-volume conditions. As reported in Refs. [17,18], the shape of the magnetic particles is approximately sphere in nature, and they behave like micro balls at the frictional interface of the bearing ball and raceway and partially reduce the direct contact between them. Thus, the mode of friction for the ball bearing changes from the macroscopic rolling to a mixed mode of the macroscopic and microscopic rolling frictions. This resulted in a low value of frictional torque at the very beginning of the tests. For the volume of 0.01 mL, a sharp rise in frictional torque was observed after 500 s of test time, accompanied by a sudden rise in temperature. A similar behavior was observed at a volume of 0.02 mL, and the starved state of lubrication appeared after about 900 s of test time. However, for an increased volume of 0.04 mL, the low frictional torque of 0 N mm was exhibited throughout the experiment with a stable rise in temperature. It was observed that at a volume of 0.04 mL, a sufficient quantity of MFs remained in the raceway and the bearing operated in the fully flooded regime, avoiding the lubrication starvation condition.

The inset diagram provides a comparison of the worn surfaces of the bearing raceway before and after friction tests. It can be observed that the width of worn tracks on the raceway was wider for the volume of 0.01 mL than 0.02 mL, while for the volume of 0.04 mL, the width of the wear track was the lowest since the bearing remained fully lubricated throughout the test. From Fig. 5, it was concluded that the starvation condition could be achieved earlier for the lower volume of the lubricant. Therefore, severe operating conditions of a low volume of MF (0.01 mL), a

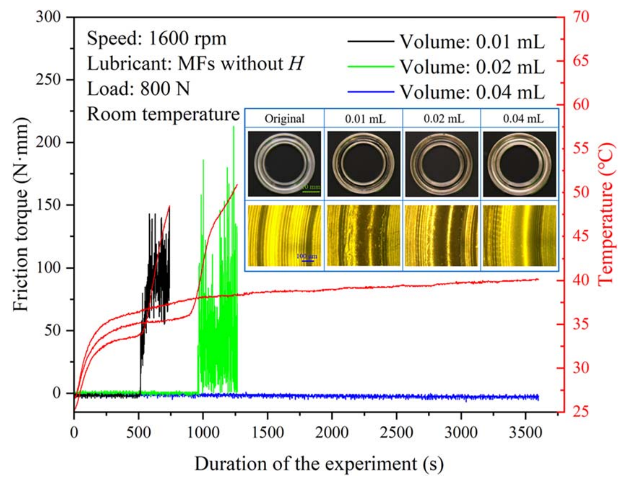

Fig. 5 Comparison of the frictional torque and temperature curves of the bearing lubricated with different volumes of MFs

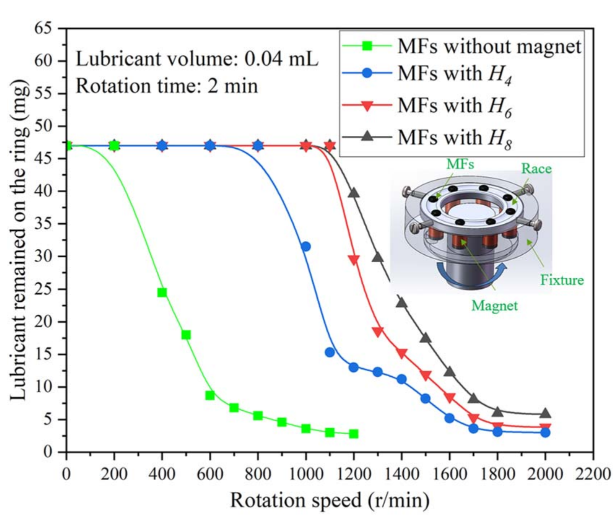

Fig. 4 The relationship between the rotational speed and the residual mass of the MFs without and with magnets

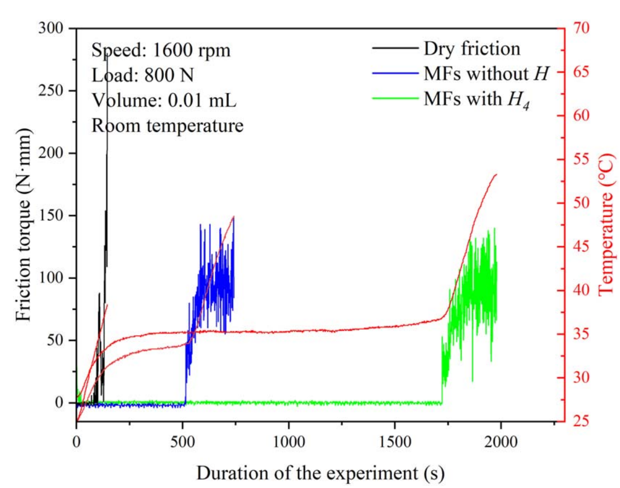

Fig. 6 Comparison of the frictional torque and temperature observed at dry friction, MFs without *H* and MFs with H_4

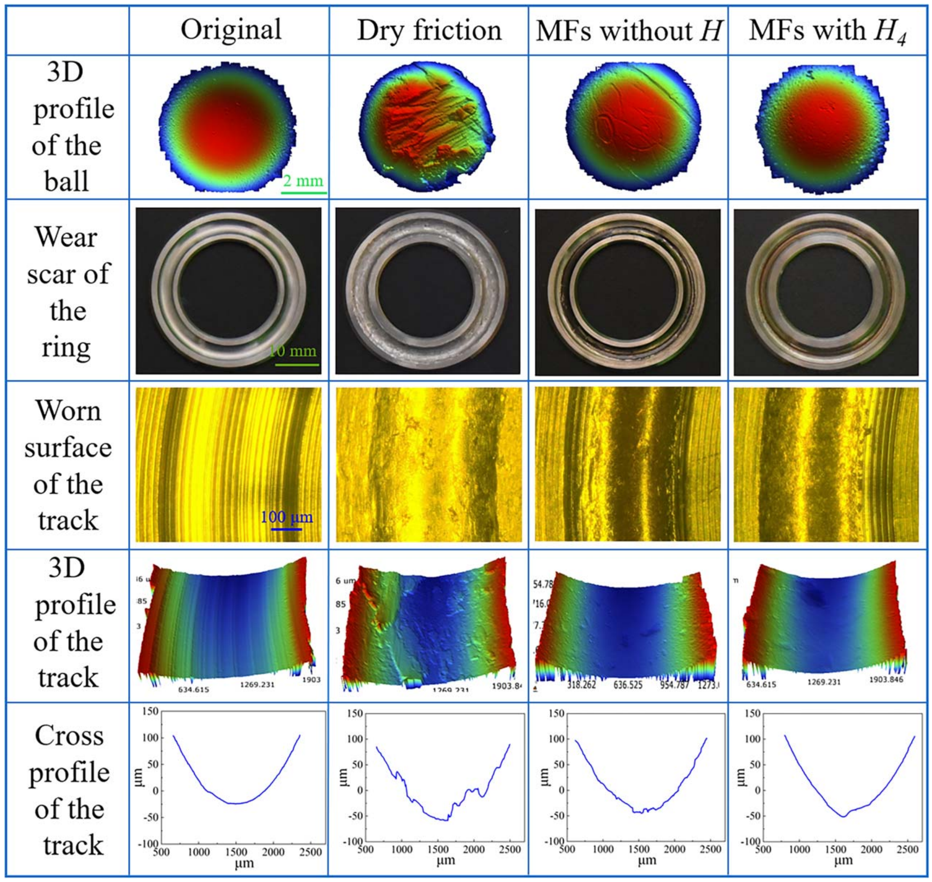

Fig. 7 Images of the worn bearing ball and raceways before and after friction tests

high axial load (800 N), and a high rotational speed (1600 rpm) were selected for further experiments.

Figure 6 presents the variations in frictional torque and temperature (at the raceway surface) conducted at the following conditions: dry friction, MF lubrication without H (no magnet), and MF lubrication with H_4 (four magnets). Initially, frictional torques were stable at their least value for each of the three conditions. Under dry friction conditions, a sharp increase was observed after about 100 s and it reached a peak value of about 280 N mm. The absence of a lubricant resulted in more wear and friction, which was also evident from the corresponding rise in the temperature. Application of MFs delayed the lubrication starvation time up to 500 s. A better lubrication behavior was exhibited by the MF in the presence of four magnets since a magnetic field attracted the MF and more volume could be restricted in the raceway. This prolonged the lifetime of the bearing to about 1700 s, which is 3.4 times higher than the nonmagnetic field condition. The temperature rise was also stable during the low friction process, which is beneficial for the chemical stability of the lubricant.

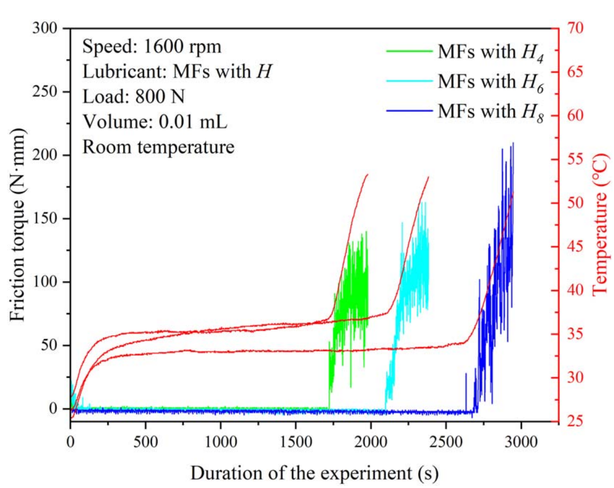

Fig. 8 Frictional torque observed at varying magnetic field distributions

As expected, the presence of MFs depicted a better lubrication behavior than in dry conditions. It was observed during the centrifugal tests (Figs. 3 and 4) that at speeds above 800 rpm, only a small volume of MF was left in the raceway under the nonmagnetic field condition, while most of it was spread out due to the centrifugal effect. Therefore, at a higher speed of 1600 rpm, a starved state of lubrication was prone to occur. The application of four external magnets helped to improve the lubrication performance of MFs and delayed the starvation condition of lubrication.

The starved state of lubrication was also evident from the 3D profiles of the bearing ball and the worn raceways, as shown in Fig. 7. Due to a high Hertzian contact pressure, both the ball and the raceway exhibited severe wear, plastic deformation, and wide wear scars after 100 s of the dry friction test. The application of an MF partially eliminated the direct contact between the ball and the raceway. This reduced the severity of the abrasion and plastic deformation, which was evident from their respective 3D profiles. The starvation state of lubrication leads the contact pair into a severe situation where asperity contacts take place and scuffing increases. Although lubricant starvation condition was experienced at about 1700 s of test time for H_4, a reduction in wear and plastic deformation was observed due to the external magnetic field produced at the surface of the raceway. Hence, it is evident that the antispreading ability of the fluid was enhanced by the adsorption

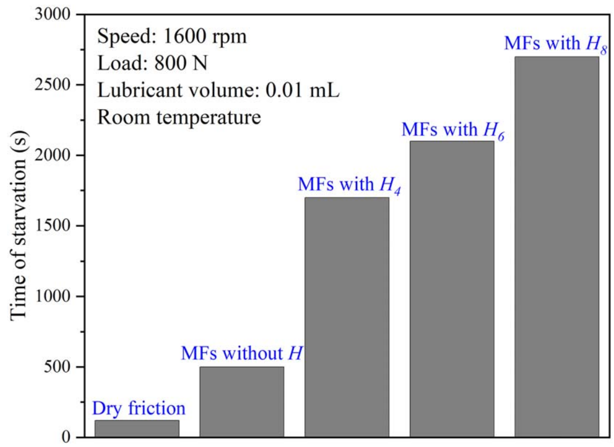

Fig. 9 Comparison of the starvation time observed under severe test conditions

of an external magnetic field and more residual lubricant was retained in the raceway to extend the steady lubrication time.

To evaluate the optimum magnetic field distribution, tribological tests were conducted under severe operating conditions and applying H_4, H_6, and H_8. Frictional torque was observed to remain stable at its minimum value from the beginning of the tests, as shown in Fig. 8. Lubricant starvation condition, represented by a sharp rise in frictional torque, was obtained after about 1700 s of test time for H_4, after 2100 s for H_6, and after 2700 s for H_8. A stronger magnetic field distribution (by increasing the number of magnets) imposed stronger adsorption on each of the droplets with a more evenly dispersed lubricant in the raceway. Therefore, the frequency of the balls rolling over the droplets enhanced during each cycle. The time to achieve the starved lubrication condition was increased by about 5.4 times for the MF with H_8 when compared with the MF without H (Fig. 6), with a corresponding reduction in temperature.

Figure 9 presents a comparison of the time to achieve a starved condition of lubrication, observed under different lubrication and severe operating conditions (also discussed in Figs. 6 and 8). MF without H exhibited about five (5) times improvement in the starvation time when compared with the dry condition. The introduction of an external magnetic field with H_4 prolonged the starvation time

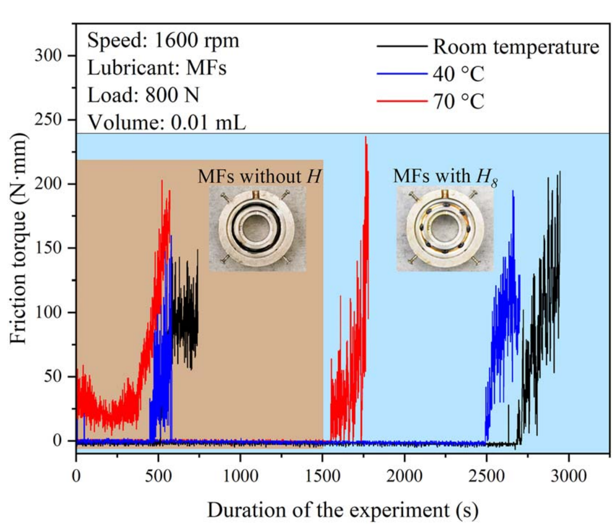

Fig. 10 Effect of temperature on the frictional torque observed under severe conditions, for MFs lubrication without H and with H_8

to about 3.4 times than MFs without H. An increase in the number of magnets resulted in a further improvement in the starvation time.

Figure 10 presents a comparison of the tribological results observed at room temperature, 40 °C and 70 °C, for the lubrication conditions of MF without H and MF with H_8. For MF without H, frictional torque remained stable in the beginning at about 0 N mm for both the room temperature and 40 °C, while lubricant starvation was observed at about 520 s and 450 s, respectively. At the higher temperature of 70 °C, the frictional torque started from the higher value of 25 N · mm and remained stable till about 360 s, after which it started to increase gradually and reached a peak value of 240 N mm. For MF with H_8, the value of about 0 N mm was observed in the beginning for each of the three temperature conditions. At room temperature, a sharp rise in frictional torque occurred at about 2700 s, while this time was reduced to 2500 s and 1520 s for 40 °C and 70 °C, respectively. MF with H_8 prolonged the lubricant starvation time to about 4.2 times than MFs without H, at 70 °C.

Hence, the starved state of lubrication seems more prone to occur at higher temperatures due to the decreased viscosity of MFs. It is known that the viscosity of the lubricant reduces with an increase in the operating temperature. A low viscosity may lead to a reduction in the load-bearing capability of the lubricant film. Additionally, low viscosity contributes to lubricant spreading. With an appropriately designed external magnetic field, more volume of MFs can be prevented from escaping the contact area and a less volume can meet the lubrication requirements. Interaction between the nanoparticles and the designed external magnetic field causes an increase in the viscosity [10], which is also conducive to improve the load-bearing capability and the service life of the bearings.

4 Conclusions

This article presents the results of the experimental investigations conducted for controlling starved states of lubrication in ball bearings, using MFs as a lubricant. Centrifugal experiments were conducted to analyze the influence of an external magnetic field distribution on the antispreading ability of the MFs, while tribological tests were performed to estimate the service life of the bearings under different external magnetic field distributions. The preliminary results exhibited that with an appropriately designed external magnetic field, MFs could be restricted in the raceway and prolong the time to achieve a starvation state of lubrication. The main conclusions are as follows:

(1) During centrifugal tests without an external magnetic field, the MF started spreading out of the raceway earlier at a low-speed. A stronger external magnetic field retained more volume of MF in the raceway at higher rotational speeds. Hence, the residual volume of MFs in the raceway increases with the increase in external magnetic field distribution.
(2) Under the fully flooded state (at the volume of 0.04 mL), the frictional torque of the bearing remained steady and no starvation state of lubrication occurred after operating for 3600 s.
(3) Under insufficient lubrication conditions (at the volume: 0.01 mL), lubricant starvation is unavoidable. However, the service life can be extended due to the antispreading ability of MFs with the introduction of an external magnetic field. The time to achieve the starved state of lubrication was increased to about 5.4 times by the application of eight magnets (H_8) when compared with MFs without H (no external magnetic field).
(4) The increased operating temperature accelerates the appearance of a starved state of lubrication. Application of MFs with a suitably designed external magnetic field can prolong the lubricant starvation time and increase the service life of the bearings.

Funding Data

- The National Natural Science Foundation of China (No. 52275195).

Conflict of Interest

There is no conflict of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

References

[1] Wang, Z., Yu, Q., Shen, X., and Chen, X., 2018, "A Simple Model for Scuffing Risk Evaluation of Point Contact Under Mixed Lubrication," ASME J. Tribol., **140**(3), p. 031502.
[2] Wen, C., Meng, X., Gu, J., Xiao, L., Jiang, S., and Bi, H., 2023, "Starved Lubrication Analysis of Angular Contact Ball Bearing Based on a Multi-Degree-of-Freedom Tribo-Dynamic Model," Friction, **11**(8), pp. 1395–1418.
[3] Olaru, D. N., and Gafiţanu, M. D., 1997, "Lubrication Safety in High-Speed Ball-Bearings," Lubr. Sci., **9**(4), pp. 365–389.
[4] Lugt, P. M., 2009, "A Review on Grease Lubrication in Rolling Bearings," Tribol. Trans., **52**(4), pp. 470–480.
[5] Ke, H., Huang, W., and Wang, X., 2016, "Insights Into the Effect of Thermocapillary Migration of Droplet on Lubrication," Proc. Inst. Mech. Eng., Part J: J. Eng. Tribol., **230**(5), pp. 583–590.
[6] Damiens, B., Lubrecht, A. A., and Cann, P. M., 2004, "Influence of Cage Clearance on Bearing Lubrication©," Tribol. Trans., **47**(1), pp. 2–6.
[7] Van Zoelen, M. T., Venner, C. H., and Lugt, P. M., 2010, "The Prediction of Contact Pressure–Induced Film Thickness Decay in Starved Lubricated Rolling Bearings," Tribol. Trans., **53**(6), pp. 831–841.
[8] Scherer, C., and Neto, A. M. F., 2005, "Ferrofluids: Properties and Applications," Braz. J. Phys., **35**(3a), pp. 718–727.
[9] Fannin, P. C., 2004, "Characterisation of Magnetic Fluids," J. Alloys Compd., **369**(1–2), pp. 43–51.
[10] 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.
[11] Li-jun, W., Chu-wen, G., Ryuichiro, Y., and Yue, W., 2009, "Tribological Properties of Mn–Zn–Fe Magnetic Fluids Under Magnetic Field," Tribol. Int., **42**(6), pp. 792–797.
[12] Andablo-Reyes, E., de Vicente, J., Hidalgo-Álvarez, R., Myant, C., Reddyhoff, T., and Spikes, H. A., 2010, "Soft Elasto-Hydrodynamic Lubrication," Tribol. Lett., **39**(1), pp. 109–114.
[13] Huang, W., Shen, C., Liao, S., and Wang, X., 2011, "Study on the Ferrofluid Lubrication With an External Magnetic Field," Tribol. Lett., **41**(1), pp. 145–151.
[14] Odenbach, S., 2003, "Magnetic Fluids—Suspensions of Magnetic Dipoles and Their Magnetic Control," J. Phys.: Condens. Matter, **15**(15), pp. S1497–S1508.
[15] Oldenburg, C. M., Borglin, S. E., and Moridis, G. J., 2000, "Numerical Simulation of Ferrofluid Flow for Subsurface Environmental Engineering Applications," Transp. Porous Media, **38**(3), pp. 319–344.
[16] Afifah, A. N., Syahrullail, S., and Sidik, N. A. C., 2016, "Magnetoviscous Effect and Thermomagnetic Convection of Magnetic Fluid: A Review," Renew. Sustain. Energy Rev., **55**, pp. 1030–1040.
[17] Li-jun, W., Chu-wen, G., and Yamane, R., 2008, "Experimental Research on Tribological Properties of $Mn0.78Zn0.22Fe_2O_4$ Magnetic Fluids," ASME J. Tribol., **130**(3), p. 031801.
[18] Huang, W., Wang, X., Ma, G., and Shen, C., 2009, "Study on the Synthesis and Tribological Property of Fe_3O_4 Based Magnetic Fluids," Tribol. Lett., **33**(3), pp. 187–192.