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Controlling lubricant migration using ferrofluids

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ABSTRACT

This article examines the use of ferrofluids (FF) to control lubricant migration and starvation. The effect of magnetic field on the migration behavior of FF driven by temperature gradient was investigated. Friction tests were performed to evaluate the influences of FF migration on lubrication. It shows that the temperature and magnetic fields both govern the FF migration behavior. At the lower energy barrier of magnetic field, FF escaped out of the friction area by temperature gradient and followed by starvation. In contrast, the FF would be controlled by magnetic field and a stable friction could be achieved.

1. Introduction

The control of lubricant migration on the various surfaces is necessary in order to ensure the continued reliability of the lubricated assemblies and to limit the contamination of critical components. Here, the migration refers to the phenomenon that the lubricant freely expands on a contact surface in the absence of external forces [1]. When a drop of liquid is placed on a solid surface, its behavior depends on whether the attractive force of the liquid molecules are stronger for each other than they are for the surface of the solid. Generally, the forces are caused by surface tension [2]. Since the surface tensions of most liquid lubricants are much lower than that of metals, the adhesion work between lubricant molecule and metal surface could be higher than the internal cohesive work of lubricant molecules. Thus, the interaction between liquid and solid can make liquid spread on the solid surface.

Lubricant migration, on one hand, is beneficial since it promotes wetting of the surface. However, as the lubricant migrates away from the friction region excessively, it could lead to oil starvation in the contact zone. The phenomenon should be carefully considered especially in space mechanisms [3], magnetic recording media [4], the flip-chip and hard disk industries [5]. Therefore, controlling the interface behaviors of the lubricant is a key step to ensure effective lubrication.

Ferrofluids (FF) is a functional colloid suspension of single domain ferromagnetic particles dispersed in a carrier liquid [6]. Brownian motion keeps suspending the 10 nm size particles under gravity, and a surfactant is placed around each particle to provide a short range steric repulsion between particles and to prevent particle agglomeration in the presence of non-uniform magnetic field [7]. Owing to its unique physical and chemical properties, this kind of functional colloid has attracted wide interests since its inception in the late 1960s. The most usual engineering applications of FF are in sealing, grinding, separation, ink-jet printing, damper, among others [8–10].

Lubrication could be another important application for FF [11–17]. The obvious advantage of FF in lubricated contacts is to increase the load capacity and to control decrease of cavitation in some cases [12]. Another advantage of FF as lubricant, over the conventional lubricant, is that the former can be retained at the desired location by an external magnetic field [18]. Could this mechanism be applied to restrain the lubricant migration and avoid oil starvation in the contact position using external forces? During the migration procedure, what is the relationship between the FF migration and surface magnetic field intensity? And how is about the influence of migration on the friction behavior in a real operating mode? There is little knowledge. So in this paper, the feasibility of the FF anti-migration and the corresponding lubricating property that followed controlled by external magnetic field were discussed.

The previous experiments show that no distinct migration was observed when FF was exposed to a weak magnetic field. Commonly, small temperature gradients cause the rapid and complete migration of oil films toward the regions of lower temperature [19]. In this study, to observe the obvious fluid migration process, a

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temperature related accelerating migration of FF droplet was adopted on a substrate surface, in which the liquid can spread along the direction of temperature gradient. The effect of external magnetic field on FF migration was investigated and attention was also paid on the relationship between fluid migration and surface lubrication behaviors.

2. Experimental section

In this paper, liquid migration induced by a temperature gradient is adopted and Fig. 1a shows a schematic diagram of the apparatus. A substrate of 304 non-magnetic stainless steel was used with the dimensions of 100 mm × 30 mm × 3 mm and average surface roughness Ra of 0.02 μm. The magnetic field was generated by a cuboid SmCo permanent magnet, which was placed under the substrate with a variable gap. Once the FF drop falls on the substrate, it will be trapped by the magnetic field. Two temperature-controlled blocks were fixed at the ends of the substrate. One block was a ceramic plate heater and the other was a thermoelectric cooler. Using the blocks, a temperature gradient was generated along the length of the substrate. Fig. 1b shows a typical temperature gradient map obtained by a thermal imaging acquisition device (Fluke, USA). As can be seen, the temperature gradient is nearly linear along the length of the substrate. The migration behavior of the FF drop was recorded by a digital video camera.

Friction tests were performed using a reciprocating sliding tribometer (Sinto Scientific, JAP) (see Fig. 1c). It consisted of a stationary holder where a 304 non-magnetic stainless steel ball with a diameter of 8 mm was placed and a reciprocating table where the substrate with heating and cooling blocks was mounted. The reciprocating motion, right above the SmCo magnet, was perpendicular to the direction of temperature gradient and a stroke of 20 mm with a sliding velocity of 16.6 mm/s was used. The test time was 6500 s and the normal load was 2 N, corresponding to the Hertzian contact pressure of 650 MPa.

Before each test, the specimens were ultrasonically cleaned in ethanol and blow-dried with nitrogen. As a desired temperature gradient was generated, a certain volume of FF was dropped on the substrate right above the magnet and the migration behavior of FF was recorded and the migration velocity could be calculated by a subsequent image processing. The surface magnetic intensity (H) on the substrate was controlled by the space (d) between substrate and magnet. The special test conditions of lubricant migration were shown in table 1. Over a fixed initial migrating time, the friction tests were performed at the original position where FF dropped.

3. Results and discussion

Fig. 2 shows the surface magnetic field generated by the SmCo permanent magnet with different spaces of 3, 6 and 9 mm, simulated using Ansoft Maxwell 10.0 software. The coercivity of magnet was calculated as 9.5×10^3 Oe and the relative magnetic permeability was fixed at 1.06. It can be seen that the simulated results of the surface magnetic field intensity right above the magnet were close to the measured values (56, 125 and 500 Gs) and the simulated results decreased gradually along the direction of temperature gradient. However, the magnetic field gradient for each condition increased to the maximum and then decreased with increasing distances, though the amplitude of $d = 9$ mm was much lower than the other two conditions.

Fig. 3 shows typical FF migration processes under different surface magnetic intensities at the migrating time of 0, 20, 60, 120 and 300 s, respectively. It can be seen that when the FF was poured on the surface, thermally driven migration took place along the direction of the temperature gradient for the H of 0, 56 and 125 Gs. While the FF droplet remained stationary at the highest H of 500 Gs and no migration was observed. According to the images, it is sure that the spreading process of FF is closely related to the magnetic intensity and the trace under the low H of 56 Gs was similar to that of non-magnetic surface. Obvious differences appeared when the H increased to 125 Gs and the migration distance dropped considerably compared with the lower H of 0 and 56 Gs within the same time interval.

Table 1
Test conditions.

Experiment temperature (°C)	20
Temperature gradient (°C/mm)	3.67
Space of substrate and magnet d (mm)	3, 6 and 9
Surface magnetic intensity (Gs)	0, 56, 125 and 500 (measured)
Experimental liquid*	FF
Volume of oil (μL)	4
Initial migrating time (s)	0–300

* Properties of the FF: density, 1.05×10^3 kg/m^3; viscosity, 67 mPa.s; saturation magnetization, 100 Gs; particle volume fraction, 4.8 vol%.

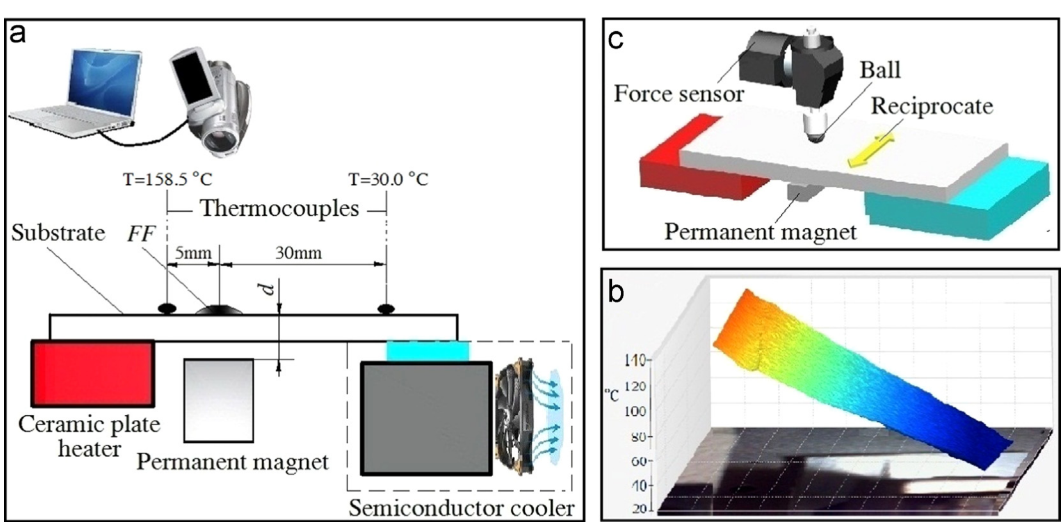

Fig. 1. (a) Schematic diagram of the migration apparatus, (b) distribution of temperature gradient on the substrate surface, and (c) sketch map of friction tester.

When there is no external magnetic field, the properties of FF are similar to those of conventional lubricants. As mentioned previous, the driving force for the FF flow is mainly dominated by the surface tension gradient ($d\gamma/dx$), which arises from the variation of the surface tension with temperature ($d\gamma/dT$) and from the imposed temperature gradient (dT/dx). The shearing stress generated in the FF film surface can be written as follow [20]:

$$\tau = d\gamma/dx = d\gamma/dT \cdot dT/dx \quad (1)$$

where γ is the surface tension of FF, T is the temperature and τ is the shearing stress. The stress causes the FF to spread toward the region with higher surface tension, which means the FF subjected to a temperature gradient will be pulled to the colder region. The most distinct migration trend appeared on the free surface without external magnetic field (see Fig. 3).

As the surface magnetic intensity increased, the creep trend slowed down. The behavior of the liquid during the spreading process is controlled by the motion of the contact lines where the liquid, solid and the bounding gas meet [21] or in short, surface tension. To find out the relation between the surface tension of FF and external magnetic field, the contact angles of FF at different H were measured as shown in Fig. 4. The dosage of the FF used was 2 μL and the picture was taken within several seconds after the droplet came to an equilibrium state. It can be seen clearly that the contact angle increases gradually with the increased H. As mentioned in Ref. [22], the equilibrium contact angle reflects the relative strength of the liquid, solid, and vapor molecular interaction. It indicates that the existence of an external magnetic field has contributed to enhance the FF cohesion work. While for the substrate in which no magnetic field is applied, the FF droplet spreads freely on surface, showing complete wetting.

When a liquid droplet is placed on a smooth isothermal solid surface, it will spread or contract to an equilibrium shape in which the capillary and hydrostatic pressure fields are balanced inside the droplet. While for FF, one more field of magnetic should be considered. In general, the interface shape of FF under external field could be governed by using ferrohydrodynamic Bernoulli equation [23], which is related to several boundary conditions such as magnetic normal traction and the volumetric magnetic overpressure. Both play an important role in the appearance of FF.

The magnetization of the fluid interacts with the external magnetic field to produce attractive forces on each particle. The unit volume value of the induced magnetic force for nonconductive FF is

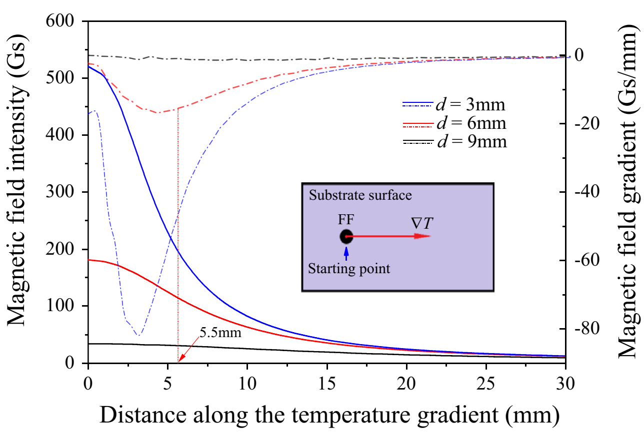

Fig. 2. Calculated values of surface magnetic field intensity and gradient along the temperature gradient. The starting point (0 mm) is right from the position of magnet. (Solid is magnetic field intensity and dash dot is magnetic field gradient; d is the space between substrate and magnet).

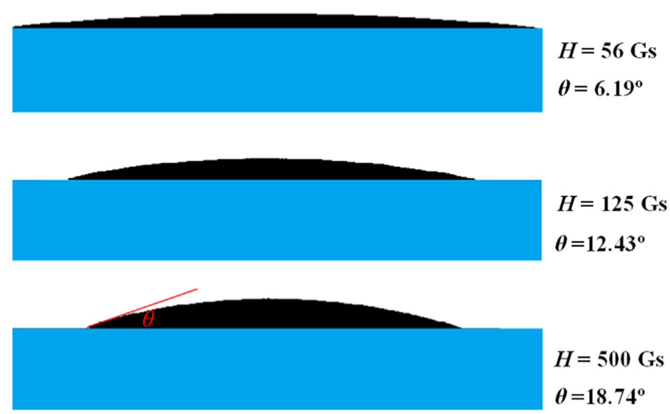

Fig. 4. Equilibrium contact angle of FF under different surface magnetic field intensities.

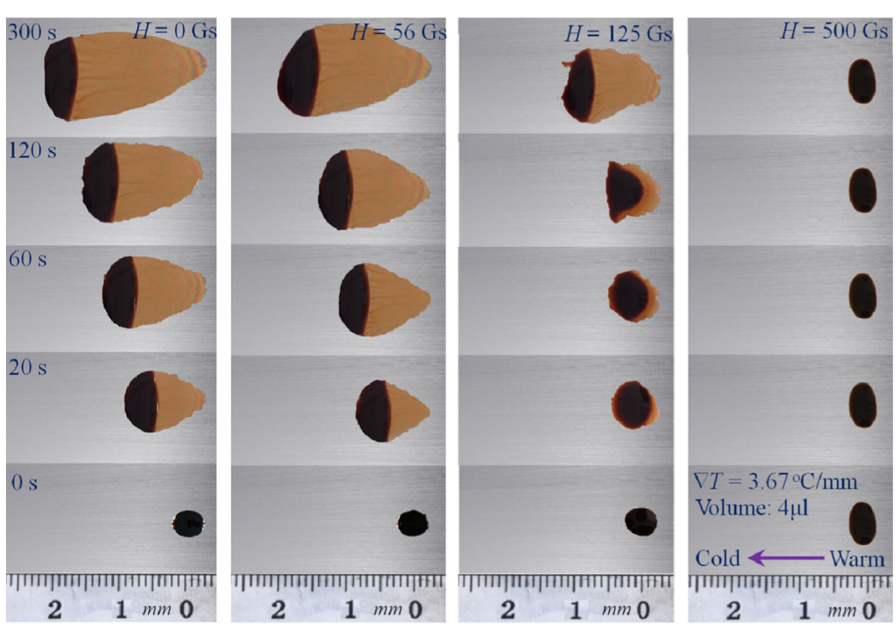

Fig. 3. Images of FF migration traces at different moment on substrates with different surface magnetic intensities (H).

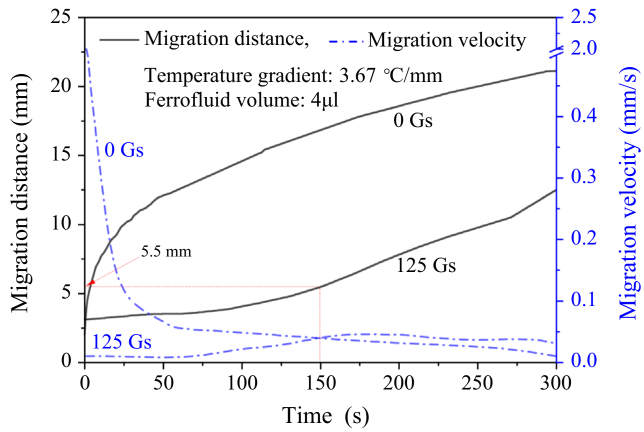

Fig. 5. Migration distances and the corresponding velocities with the test time measured from the recorded migration process.

given by [24]:

$$F_m = \mu_0 \chi H \nabla H \quad (2)$$

where F_m is induced magnetic force, μ_0 is magnetic permeability of free space, χ is susceptibility of FF, H is magnetic field intensity and ∇Hrepresents the gradient of magnetic field.

According to Eq. (2), the interaction between the magnetic field and FF increases with the increasing of magnetic intensity and gradient. The higher magnetic intensity and gradient can gather more FF 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 larger contact angle. In other words, the surface tension of the FF under external magnet increased, which might effectively suppress the FF spread.

It can be found that during the process of FF droplet migration, the temperature and magnetic fields both play critical roles. The effects, temperature and magnetic fields imposed on FF, seem to be in a dynamic balance. When the H is low, the temperature gradient governs the spreading behavior. Otherwise, the magnetic field becomes the dominated factor.

Fig. 5 sums up the relations of migration distance and the corresponding velocity measured according to the videos recorded under the H of 0 and 125 Gs, respectively. It shows that the migration distances under the two conditions both increase with the time. While for the velocity curves, it can be found that the initial migration velocity under the condition of no magnetic field is much higher than that of under the magnetic field condition. It decreases dramatically with the test time and then remains flat. However, the experiment result reveals that the migration velocity under the H of 125 Gs increases gradually to a steady value of about 0.03 mm/s.

As pointed by Young et al., in the case of negligible convective transport of momentum and energy, the theoretical prediction for the velocity of liquid drop is inversely proportion to the viscosity [25]. For the no magnetic field condition, the olefin based FF with 4.8 vol% is pulled in the direction of temperature gradient. The temperature on substrate surface reduced gradually and the viscosity of FF increased, similar as the property of the carrier liquid, which leads to the decrease of migration velocity. In theory, when a magnetic field is applied to the FF, the magnetic moment of the particles will align with the field direction, which may lead to the increase of FF viscosity [26]. Experimental studies have shown that increasing the H yields a rise of the FF viscosity [27]. On the magnetic surface, the H decreases along the direction of the temperature gradient, as shown in Fig. 2, and the viscosity of FF decreased gradually, which could cause to the increment of migration velocity.

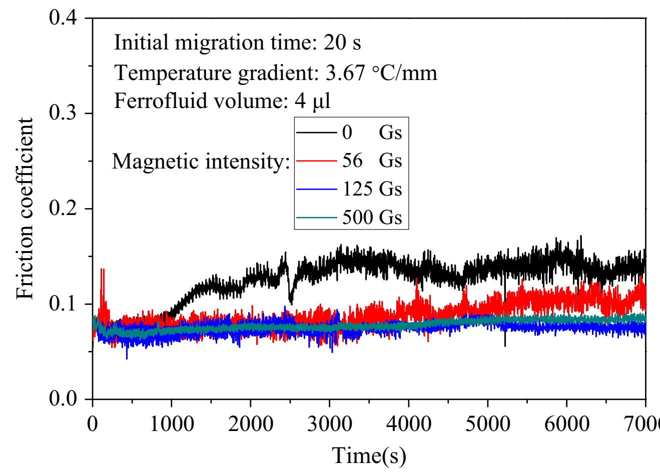

Fig. 6. Evolution of friction curves under different surface magnetic intensities at initial migration time of 20 s.

Interestingly, the finial velocities with and without surface magnetic field reach to almost the same magnitude after the migration time of 150 s (see Fig. 5) and the corresponding migration distance is about 5.5 mm for the magnetic surface. As can be seen in Fig. 2, when the migration distance is over 5 mm, the surface magnetic field intensity and gradient both decrease along the direction of temperature gradient. Since the magnetic field gradient is a derivative of magnetic field intensity with respect to distance, the value is negative. The induced magnetic force (F_m) for FF drops rapidly and magnetoviscous effect fades away. And the temperature gradient becomes the only dominate factor pulling the FF. That may be the reason why the migrating velocities with and without magnetic field tend to be close.

To further explore the effects of FF migration on tribological performance and identify the roles of external magnetic field, friction tests were carried out after the FF completing different initial migrating time of 20 and 120 s, respectively. Fig. 6 presents the typical evolution of friction coefficients of tribopairs under different H and the tests all started after an initial migrating time of 20 s. For the four conditions, the starting friction coefficients are all in a steady-state value of about 0.08. After running-in for 1000 s, the coefficients of the no magnetic field case first showed a gradual increase with the time prolonged. And it always remained at a high level of 0.14 during the rest time. When the external field increased to 56 Gs, a similar phenomenon appears at the test moment of 4000 s or so, but the difference is that the growth rate of the coefficient is smooth and the final coefficients reach about 0.1. The friction curves for the higher H of 125 and 500 Gs tend to be stable during the whole test time.

As mentioned in Ref. [20], the driving force for the lubricant flow is mainly of the surface tension gradient, which helps to draw more FF to move out of the friction region. As can be found in Fig. 3, most of the FF on the lower H (0 and 56 Gs) has spread from the original place at an initial migrating time of 20 s and the friction process falls quickly into the poor lubricated condition. When a higher magnetic field was introduced into the surface, the surface tension of the FF increased much according to the result of contact angle (see Fig. 4), which can maintain more FF on the friction area, forming a long-lasting lubrication.

Fig. 7 gives the evolution of friction curves under different H at an initial migration time of 120 s. It can be seen that the coefficients also started at the value of 0.08, which was in the regime of mixed lubrication. For the surfaces with H of 0 and 56 Gs, the friction coefficients continued to increase at the very beginning of the tests. While the H was 125 Gs, after a short duration of stable

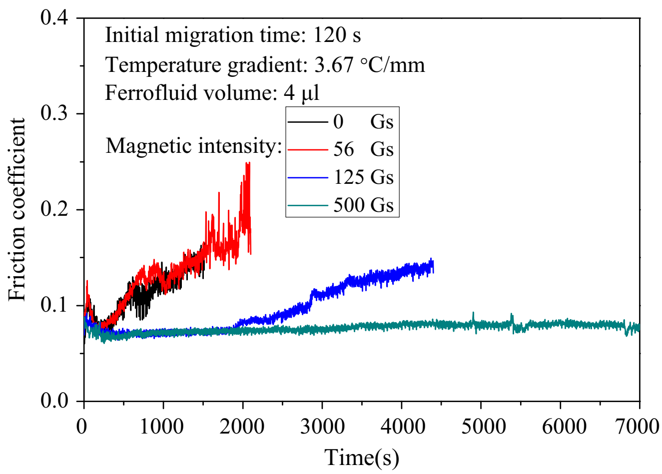

Fig. 7. Evolution of friction curves under different surface magnetic intensities at initial migration time of 120 s.

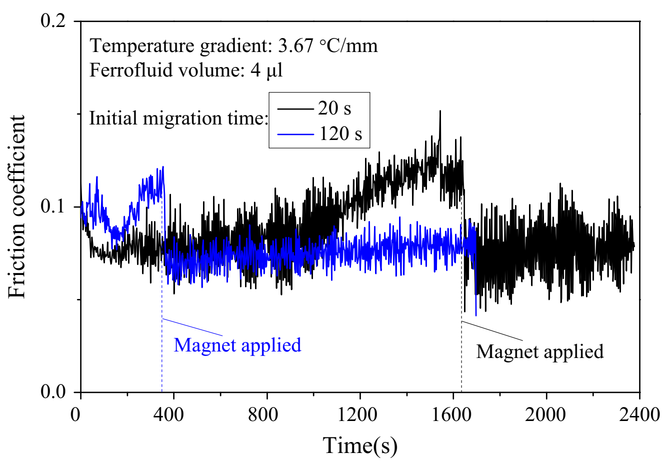

Fig. 8. Evolution of friction curves with and without external magnetic field.

friction, a sudden friction increment was accompanied and it grew continuously till the value of about 0.16. The only one maintained unchanged was the surface with the highest *H* of 500 Gs and the friction curve kept stable, which means the lubricant is still valid.

As the result shown in Fig. 3, the migration distance increased with the time and more FF escaped to the low temperature regions except for the highest magnetic field. The result of FF migration may be closely related to the film thickness. For the no or lower external magnetic field conditions, the FF was vanishing at the very beginning of the migration process. Then the friction test began, the film thickness was thin and oil starvation appeared first. With the increase of *H*, it could be thicker after the 120 s migration process. As time passed by, the lubricant film became thinner gradually and it fractured at the last for the magnetic intensity of 125 Gs condition and the contact was operating in the starved regime. When the *H* increased to 500 Gs, no migration occurred, lubrication film kept constant and the starvation was prevented.

Since the FF migration leads to the increment of friction, the question is that can the migrated FF be drawn back to improve the replenishment of lubricant to the contact. Fig. 8 presents the evolution of friction coefficients of tribopairs under different initial migrating time of 20 and 120 s, and the magnet, which can generate 500 Gs surface magnetic intensity was used at the moment a significant improvement of coefficient appeared. For the initial migration time of 20 s, when no magnet was used, the coefficient increased gradually and it plummeted to stable value when an external magnetic field was applied. It means that a contact operated in a fully flooded regime at the very beginning turned to a starved regime as migration continued and it went back to the flooded when the external field was applied. Similar phenomenon was found for the initial migration time of 120 s. The final coefficients are approximately in the same level. The results show that using the external magnetic field, which is independent of the other conventional lubrication parameters, can control and draw back the escaped lubricant to the contact area when a natural replenishment mechanism is restricted. Similar result was also found in Ref. [28].

4. Conclusions

In this paper, an effective method of using FF to prevent lubricant migration was proposed. The influence of surface magnetic field on thermally driven migration of FF droplet was investigated. Besides, the relationship between fluid migration and lubrication behavior was also discussed. The results showed that, as a kind of lubricant, FF expresses anti-migration performance under the external magnetic field. When the surface magnetic field is low, the temperature gradient governs the migration behavior. Otherwise the magnetic field becomes the dominated factor. Meanwhile, lubricant migration has an important effect on the lubrication performance. When the energy barrier of magnetic field is low, excess FF runs out of the friction area and starvation follows. On the contrary, the FF lubricant will be retained on the rubbing surface and the low and stable friction can be achieved. In addition, the initial migrating time also shows an effect on the lubrication properties and starvation first takes place for the longer initial migrating time. Finally, using an external magnetic field can draw back the escaped lubricant to the contact, which is an effective way of lubricant replenishment.

Acknowledgments

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