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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%.

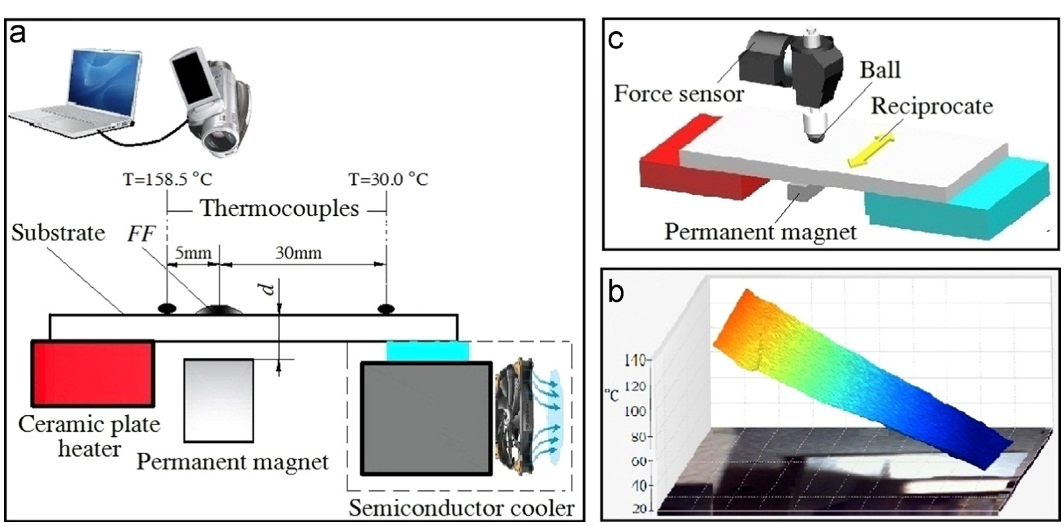

Fig. 1. (a) Schematic diagram of the migration apparatus, (b) distribution of temperature gradient on the substrate surface, and (c) sketch map of friction tester.