The friction and Wear behavior of Silicon oil-based Magnetorheological fluid with Solid lubricant

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Abstract: Due to its lower energy consumption, higher mechanical properties and easier to control, magnetorheological(MR) fluid has been widely used in the engineering field. However, the friction and wear behavior of it, which may hinder its applicability, needs to be modified. The tribological behavior of silicon oil-based MR fluid with different types and contents of solid lubricant was investigated on a four-ball machine. The worn surfaces of the steel balls were observed by using a scanning electron microscope (SEM). The results showed that the friction and wear property of silicon oil-based MR fluid could be improved by some solid lubricants. Both of molybdenum disulfide and graphite can decrease friction coefficient of silicon oil-based MR fluid significantly, but graphite has the better wear resistance than molybdenum disulfide. Adding polytetrafluoroethylene (PTFE) can enhance the wear resistance of MR fluid obviously, but the friction coefficient is larger than the first two. The friction and wear property of MR fluid hardly changes by adding boron nitride. Increasing the content of graphite can improve the friction and wear resistance of MR fluid, and the wear resistance of MR fluid has an optimal point when the weight percent of graphite is 2%.

1. Introduction
Magnetorheological(MR) fluid is a classical smart material that consists of base fluid, such as mineral oil, silicon oil and water, etc. suspended with magnetic particles, which are typically micro-sized iron particles[1,2]. Apparent viscosity and other rheological characteristics of it can quickly be controlled by applying an external magnetic field. Due to its quick, continuous and reversible change in rheological characteristics, MR fluid has gained a great interest in developing a new generation of brakes, clutches, shock absorbers and other devices[3,4]. However, as working in devices at high speed, the particles in it have more contact with the wall of devices because the particles randomly dispersed in the base oil can move freely. Therefore, the friction and wear problems between the particles and the wall of container are unavoidable. So the tribological properties of MR fluid have to be considered seriously.

Several researches refer to tribological property of MR fluids have been published in recent years. Song, et al. [5-7] carried out the tribological experiment of brass, steel and aluminum to investigate the effect of a commercial MR fluid on the interfacial surface with and without a magnetic field, the experimental results showed that the MR fluid in the presence of magnetic field displays better tribological behavior compared to the case in the absence of magnetic field with steel and aluminum. But the wear rate of brass with the magnetic field is higher than that without the magnetic field. Bombard, et al. [8,9]examined the effect of particles size and base oil viscosity on the tribology of MR fluid. It was concluded that the friction coefficient strongly depend on the viscosity of the base oil, and silica-coated iron microparticles can improve tribological properties of MR fluid. In our previous
researches [10,11], the influence of base oil, thixotropic agents and the magnetic field on the tribological properties of MR fluid was evaluated. The result showed the tribological property can be altered by applying a magnetic field or changing an appropriate component.

As we know, the silicon oil is usual the first choice as the base oil of MR fluid due to its availability, low viscosity and high temperature stability [12]. However, there are few studies on improving the tribological properties of silicon oil-based MR fluid, even though the silicon oil appears very poor tribological properties compared to other lubricant oils[13,14]. Therefore, the technical skills needed to improve their tribological performance must be developed. Considering that some solid lubricants such as polytetrafluoroethylene (PTFE), molybdenum disulfide (MoS2), graphite and boron nitride are considered as effective additives on improving the friction and anti-wear abilities, this study is mainly focused on revealing the tribological performance of silicon oil-based MR fluid with these solid lubricants. Experiments are performed to examine the friction and wear behaviors of silicon oil-based MR fluid using a four-ball tribological tester. The microscopic changes on the surface of the steel balls are observed by scanning electron microscope (SEM) in order to understand the wear mechanism.

2. Materials and methods

2.1. Materials

Up to five MR fluid samples were prepared by a series of processes such as ultrasonic dispersion, high-speed dispersion and mechanical milling. Firstly, the modified carbonyl iron particles and additives were mixed with silicon oil in a zirconia container by hand for several minutes. Then the mixture was handled by ultrasonic dispersion for 20 minutes. Afterwards, the mill balls were added in the container according to a certain ball percentage. Finally, the MR fluid sample was got after a 12 hours mechanical milling process for the mixture. The chemical composition of the materials is shown in Table 1.

| No. | Suspended phase | Base oil     | Thixotropy | Lubricate additives |
|-----|----------------|--------------|------------|---------------------|
| MR1 | Cl* methyl silicon oil | SiO2 | —— | —— |
| MR2 | Cl methyl silicon oil | SiO2 | —— | Boron nitride |
| MR3 | Cl methyl silicon oil | SiO2 | —— | PTFE |
| MR4 | Cl methyl silicon oil | SiO2 | —— | Graphite |
| MR5 | Cl methyl silicon oil | SiO2 | —— | MoS2 |

*Cl represents the modified carbonyl iron particles.

2.2. Measurement and analysis method

All friction and wear tests were carried out on a MMW-1P model four-ball tribological tester made in Shandong Province of China as reported in the previous study [10]. The steel ball, which was made of GCr15, was specially used for the tester. The hardness and the diameter of it were 58—62 HRC and 12.7mm, respectively. The MR fluid was poured continuously in the oil box until the below steel balls were immerged. All experiments in this paper were performed at the following conditions, namely 1200 rpm, 98 N, 10 minutes and room temperature. The mean friction coefficient value of the ten minutes was called as average friction coefficient, the average value of scar width and length on the three steel balls measured by a special light microscope after each test was recorded as wear scar diameter, which is typically examined as an index to evaluate the anti-wear properties of lubricant.

The surface morphology analysis of steel balls was observed at 15 kV with a JSM-6490LV model scanning electron microscope (JEOL, Japan). Before the morphology analysis, all steel balls were carefully cleaned with acetone for several times until the steel balls were completely cleaned up. Then, the sample was dried at room temperature. The micrographs were made at 1200 power magnification.
3. Results and discussion

3.1. Coefficient of friction with different solid lubricant

Fig. 1 displays the change of the friction coefficient in test duration time for MR fluid with different solid lubricant. The friction coefficient without solid lubricant varied in a large range from 0.232 to 0.337, and the values are fluctuated up and down with the average friction coefficient value 0.278 (see Fig.1 (a)). As observed in Fig.1, when the solid lubricant was introduced into MR fluid, the friction coefficient curves exhibited a descending trend during the experimental process, although the curves still showed the marked fluctuations which may be attributed to the poor tribological property of the silicon oil.

![Friction coefficient vs. test time curve for silicon oil-based MR fluids with different lubricants.](a) No lubricant, (b) Boron Nitride, (c) PTFE, (d) Graphite and (e) MoS2

It can be seen that MoS2 has the lowest average friction coefficient 0.211. It provides the best friction-reduction behavior, which is improved by 24.1% as compared to the MR fluid without solid lubricant in terms of the average friction coefficient. The friction-reduction behavior of graphite is just second to MoS2, which has the lower average friction coefficient 0.214. That may be owing to the easy shearing along the basal plane of their hexagonal crystalline structures. On the other hand, although boron nitride has a lamellar crystalline structure similar to graphite and MoS2, it gives the largest average friction coefficient 0.277, which is almost the same to MR fluid without solid lubricant.
It is likely to be because boron nitride only plays a role in friction reduction at high temperature [15]. In addition, it can be concluded that the sequence of friction-reduction behavior for different solid lubricant is MoS2 > graphite > PTFE > boron nitride.

Fig.2 shows the wear scar diameter for different solid lubricant based MR fluids. Similar results can be clearly observed, the wear scar diameter of boron nitride (1.90mm) is equal to the MR fluid without solid lubricant. However, what is interesting is that the sequence of anti-wear behavior for other solid lubricants is exact opposite with the result of friction-reduction. The PTFE has the lowest wear scar diameter 1.53mm. As compared to the MR fluid without solid lubricant, the wear property is moderated by 19.5% associated with the wear scar diameter. And graphite is also the second one in the anti-wear property of MR fluid, the wear scar diameter of which is reduced by 17.9% as compared to the blank sample.

![Figure 2: Wear scar diameter of silicon oil-based MR fluids with different solid lubricants](image)

To better understand the wear mechanism of the MR fluid based on different solid lubricant, the surface morphology of the wear scar on the steel ball was carefully observed under a scanning electron microscope. Fig.3 shows the SEM morphologies of the worn surface lubricated with the MR fluids based on different solid lubricant. It is seen that the evident grooves and powder debris present on the worn surface, which indicates the wear mechanism is abrasive wear. This is because that the iron particles dispersed freely into silicon oil can easily get into the contact zone and participate in the friction and wear of the contact point, causing three body abrasions. While the solid lubricants except boron nitride smear on the worn surface, their lubricating effect decrease the influence of carbonyl iron on the abrasive wear, so the grooves become slight and the size of wear scar diameter is reduced. With regard to the best anti-wear property of PTFE in the silicon oil-based MR fluid, it may be associated with its self-lubricating mechanism. A thin transfer film of PTFE can be formed onto the surfaces of steel ball [16, 17], the wear behavior happened directly between iron particles and the contact zone of steel ball is weakened to a large extent, so the wear scar diameter is reduced.
Fig. 3. SEM images of worn steel surfaces for silicon oil-based MR fluids with different lubricants. (a) No lubricant, (b) Boron Nitride, (c) PTFE, (d) Graphite and (e) MoS2

The variation of average friction coefficient and wear scar diameter of silicon oil-based MR fluid with different graphite contents is shown in Fig.4. It can be seen that the average friction coefficient and wear scar diameter is reduced by the graphite as compared to the MR fluid without graphite. It is suggested that graphite improves the tribological properties of MR fluid. Taking it by and large, the average friction coefficient trends down with the increase of graphite content, and the change is obvious while the content is more than 1.5%. In addition, the wear scar diameter decreases significantly with the increases of graphite content, and gets the minimum value at the content of 2%, then enhances slightly. It is revealed that the wear resistance of MR fluid has an optimal point.
Fig. 4. Average friction coefficient and wear scar diameter vs. content of graphite for silicon oil-based MR fluids

This phenomenon can be attributed to that, as the friction and wear begins, graphite lubricant enters into the contact zone and gradually spreads out along the grooves, forming a layer of lubricating film [18]. This improves lubricating property and enhances the anti-wear ability of MR fluid. With increasing of graphite content, the lubricating film is more continuous, so the friction coefficient becomes lower. And in the meanwhile, the scuff and abrasive wear between carbonyl iron and the steel ball is attenuated, which explains the descent of wear scar diameter with increasing of graphite content. However, with the content of graphite further increases, the lubricating film becomes thicker and more iron particles will be squeezed out the contact zone. These particles will accumulate around the wear zone and indent the edge of the wear scar formed at the beginning and enlarge the diameter of the scar.

4. Conclusion
The effect of different types and contents of solid lubricant on the friction and wear behavior of silicon oil-based MR fluid was investigated using the four-ball geometry and stainless steel-steel point contacts. The friction coefficient curve and wear scar diameter histogram indicate that the friction and wear property of silicon oil-based MR fluid can be controlled by selecting appropriate solid lubricant. The worn surfaces of the steel balls reveal that the wear occurs mainly by three-body abrasion. The friction property of silicon oil-based MR fluid can be improved significantly by molybdenum disulfide and graphite, but graphite has the better anti-wear property than molybdenum disulfide. PTFE can enhance the wear resistance of MR fluid obviously, but the friction coefficient is larger than the first two. In addition, the friction and wear property of MR fluid can hardly changes by boron nitride. The tribological properties of MR fluid can be modified by increasing graphite content, but the wear resistance of MR fluid has an optimal point when the weight percent of graphite is 2%.

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