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Reciprocating friction characteristics of magneto-rheological fluid for aluminum under magnetic field

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Abstract: Reciprocating friction characteristics of magneto-rheological (MR) fluid for aluminum under a magnetic field at different loads and oscillation frequencies were studied when MR fluids were worked in reciprocating motions such as in dampers for automobiles, and surface polishing and other finishing. Thus, experiments were carried out to evaluate the reciprocating friction characteristic of MR fluid for aluminum. The obtained data from the tests are sorted in groups depending on various loads and oscillation frequencies, to analyze the relationship between test condition and travel cycle. Surfaces of specimens were compared by measuring the surface roughness and observing the surface images. The performance of reciprocating friction characteristics of MR fluid for aluminum is evaluated through analyzing the experiment results.

Key words: magneto-rheological fluid; reciprocating friction; aluminum; magnetic field; smart material

1 Introduction

Magneto-rheological (MR) fluid is a material whose rheological properties change rapidly under a magnetic field [1]. Typical MR fluids have the scattered magnetic particles in a liquid with a low magnetic permeability and are colloid suspensions. The liquid is so fluent that it can easily change its form according to the different shapes of vessel [2]. The viscosity increases rapidly (more than two orders of magnitude) under a magnetic field, so its shear stress becomes similar to the one in solid. In other words, a fluent MR liquid changes into semi-solid. The viscosity change is continuous and reversible, which means that it can change its form between liquid and semi- solid according to the activation of a magnetic field. MR fluid has a quick response as one of advantages thus it can be potentially applied to various industrial areas such as automotive, construction, machinery, aviation, and health care. MR fluid is considered one of the most promising intelligent materials [3]. Research on developing applications and controlling methods using the characteristics of MR fluid has been carried out so far. Research on tribological characteristics of MR fluid, however, is still remaining on progress. For example, BULLOUGH et al [4,5] investigated friction and wear properties between MR fluid particles and the block. They showed that sliding contact mechanism with an MR fluid is so complicated that condition parameters such as concentration, surface conditions, speed and pressure must be considered in the measuring process. The types of material and surface modifications are the main factors for evaluating tribological characteristics of MR fluids. LIU et al [6−8] examined lubrication performance of MR fluid using the four-ball machine method. The efficiency of MR fluid is firstly judged through its yield stress, which is the strength of the structure formed by the particles under a magnetic field [9]. Surface finishing process using MR fluid shows better surface characteristics with a low material removal rate [10,11]. Recently, SEOK et al [12] investigated the fabrication method for curved surfaces on micro structures using MR fluid and examined the tribological properties of MR fluid in a finishing process.

In most applications, the surface of devices is in contact with fluid as it is working in a relative motion (such as linear stroking motion of a shock absorber). The surface wears much faster in such devices due to the abrasive nature of the iron particles within MR fluid. Thus, a proper choice of surface material is important for wear resistance and acceptable durability [13−15]. Therefore, MR fluids have received interests for practical

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applications as considering friction and wear characteristics under a magnetic field [16,17]. Most studies have been focused on tribological characteristics of MR fluids under the presence of magnetic field in rotating situations. However, as most applications are working in relatively linear motions or reciprocating motions such as in damper used in automobiles, reciprocating friction characteristics of MR fluid is evaluated in the study.

2 Experimental

The goal of this study was to investigate the reciprocating friction characteristics of MR fluid under a magnetic field as considering working conditions of experiments. The reciprocating friction wear tester (R&B 108-RF) was used to carry out the experiments, which is shown in Fig. 1 consists of a motor, a crankshaft device, upper and lower holders, an electromagnet and a loading system. The tester used in this study was capable of applying magnetic field during experiments. The upper and lower holders were used to locate specimen of pin and disk, respectively. The various loads can be applied for the tests using upper holder. A motor moved the crankshaft to let the pin have reciprocating motions on the disk. The specimens of pin and disk used for experiments were made of aluminum (Al6061) which is widely used in engineering applications. The diameter and heights of a pin are 10 mm and 20 mm, and the diameter and the thicknesses of the disk are 60 mm and 15 mm, respectively.

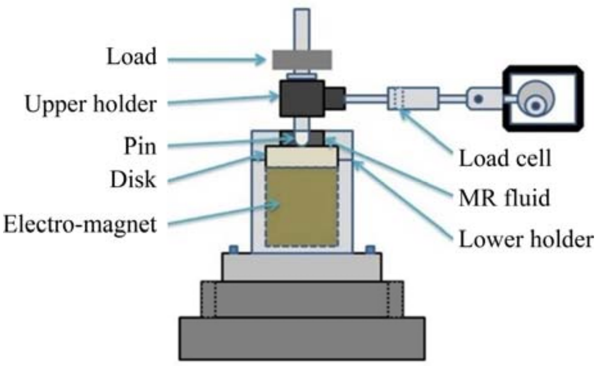

Fig. 1 Schematic diagram of reciprocating friction wear tester

When a magnetic field is applied, the MR particles are polarized and aligned along the direction of the magnetic field (Fig. 2). In order to investigate the nature of MR fluid under a magnetic field during experiments, the appropriate magnetic field was adopted at 10 mT. MR fluid can be in semi-solid under a stronger magnetic field. Magnetic induction produced by an electromagnet was measured using a Tesla meter (TM−701).

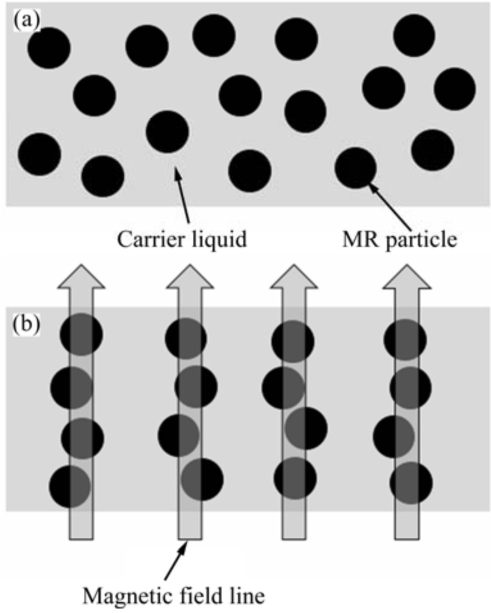

Fig. 2 Schematic diagram of chain of ferromagnetic particles: (a) Without magnetic field; (b) With magnetic field

The friction with or without a magnetic field was also measured under the proposed test conditions, which are listed in Table 1. The friction characteristics of MR fluid at different loads and oscillation frequencies under a magnetic field were investigated. A commercial MR fluid supplied by the LORD Corporation, MRF−132DG, was chosen as a sample. The properties of MR fluid used in this study are shown in Table 2. The obtained data were used to analyze the relationship between travel cycle (one period of reciprocating oscillation) and friction coefficient with activation of the magnetic field, loads and oscillation frequencies. Also the surfaces of specimen were examined by measuring surface roughness.

Table 1 Reciprocating friction test conditions

Magnetic field strength/mT	Load/ N	Oscillation frequency/Hz	Temperature/ °C	Cycle
0, 10	1, 5	0.5, 1.0	25	1800

Additional experiment was carried out for different materials (brass) under the load of 5 N and oscillation frequency of 1.0 Hz. The friction characteristics of different materials can be compared by this experiment. Microscopic images of disk surface were investigated to study the effects of magnetic field on friction and wear characteristics before and after tests.

3 Results and discussion

Figure 3 shows that the friction coefficient changes

Table 2 Properties of MRF-132DG

Appearance	Viscosity (at 40 °C)/(Pa·s)	Operating temperature/°C	Phase change time/ms	Density/ $(g \cdot cm^{-3})$	Particle size/ μm
Dark gray liquid	0.0920 ± 0.015	−40 to 150	1−2	2.98−3.18	1–4

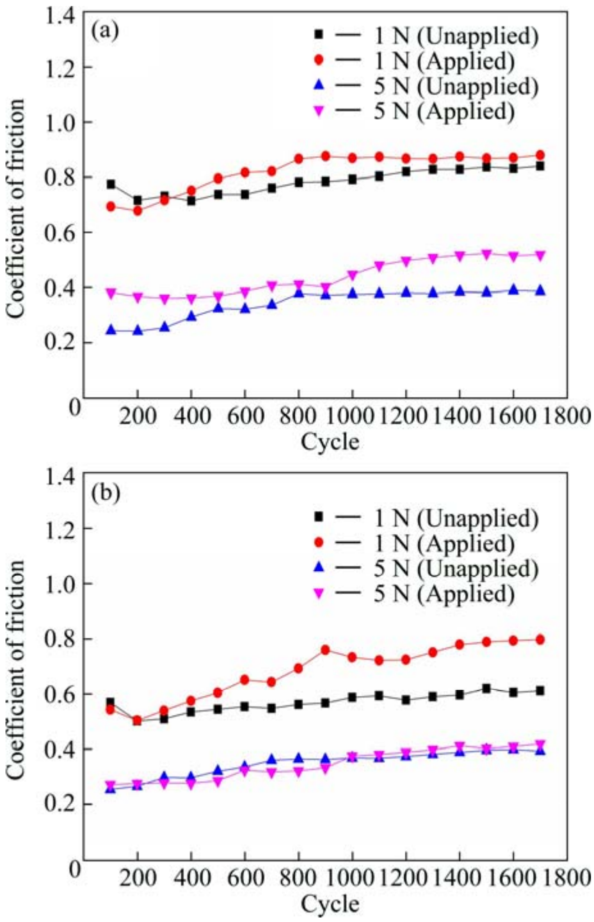

Fig. 3 Coefficient of friction in terms of travel cycle (aluminum): (a) 0.5 Hz with unapplied or applied magnetic field: (b) 1.0 Hz with unapplied or applied magnetic field

under different loads and oscillation frequencies with respect to travel cycle. Higher friction coefficients are observed when the applied loads are low under different oscillation frequencies (0.5 and 1.0 Hz). In each oscillation frequency, the friction coefficient is generally high when a magnetic field is applied. The coefficient of friction decreases with increasing load. In addition, the coefficient of friction presents an increasing trend due to the influence of the applied magnetic field during the whole experiment. The obvious friction characteristics of MR fluid with loads and frequency under the magnetic field are listed in Table 3 that shows the average coefficient of friction. It is clear that the increasing load leads to lower friction coefficients and the increasing oscillation frequency shows the same results in regardless of the magnetic field. The coefficient of friction generally becomes lower as the oscillation

Table 3 Friction coefficient of aluminum

Oscillation frequency/Hz	Unapplied magnetic field		Applied magnetic field	
	1 N	5 N	1 N	5 N
0.5	0.783	0.343	0.822	0.439
1.0	0.570	0.330	0.686	0.357

frequencies increase at a fixed applied load of 1 N or 5 N, respectively. When the magnetic field is not applied (Table 3), the coefficient of friction generally becomes lower at a fixed applied load under oscillating frequencies of 0.5 Hz and 1.0 Hz, respectively. From Table 3, it is similar that the variation trend of coefficient of friction is clearly observed when the magnetic field is applied. The results show that the fast or slow oscillation frequency and the applied load affect the stability of the coefficient of friction. Also the coefficients of friction were compared under the magnetic field, which are shown in Table 3. Carbonyl iron particles are constrained in a chain shape under the magnetic field. A few particles have an abrasive influence on the friction process. Most of the magnetic particles are gathered on the surface of the pin and disk and they have considerable resistance in the presence of magnetic field. Magnetic particles are turned into other friction pairs with the pin and disk, and direct friction occurs between the particles and sample, resulting in an increase in the overall coefficient of friction. The results show that the friction coefficient is related to the presence of magnetic field, load, and oscillation frequency. When a magnetic field is applied, the friction coefficient increases in regardless of applied load and oscillation frequency. However, the obvious change of friction coefficient is not observed under low oscillation frequency and loads or high oscillation frequency and loads.

Additional experiment was carried out for brass samples (C2800) under the same experiment conditions (Load: 5 N, oscillation frequency: 1.0 Hz). Figure 4 indicates that the coefficient of friction remains almost steady state as the travel cycle increases. And higher coefficients of friction are observed when the magnetic field is applied. The observed trend of the friction coefficient of brass is similar to that of aluminum.

However, the coefficient of friction generally presents a decreasing trend in terms of travel cycle when the magnetic field is unapplied and a decreasing trend in

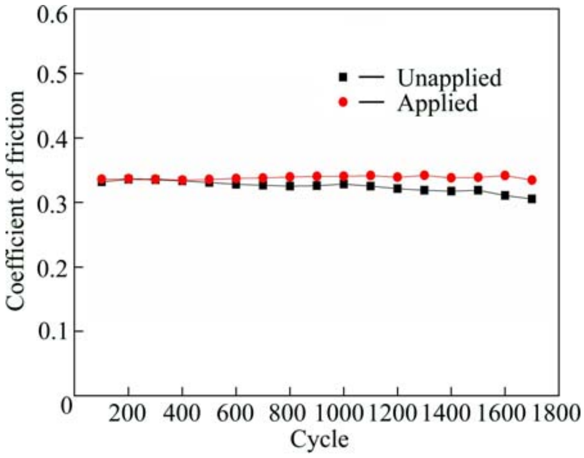

Fig. 4 Friction coefficient of brass under load of 5 N, oscillating frequency of 1 Hz and magnetic field of 10 mT or no magnetic field

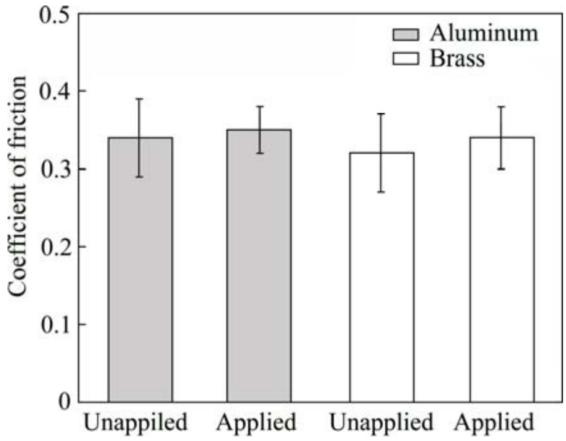

Fig. 5 Friction coefficient of aluminum and brass in the presence of magnetic field (5 N, 1.0 Hz)

terms of travel cycle when a magnetic field is applied. This is due to the material properties of aluminum sample. The lower hardness of aluminum accelerates the change of the coefficient of friction and wear during experiments.

The overall coefficients of friction from Fig. 5 for both aluminum and brass are compared to investigate the relationship between the coefficient of friction and material type. Aluminum sample shows a higher coefficient of friction compared with brass. Also brass sample shows the similar coefficient of friction with or without an applied magnetic field like aluminum. For both materials, higher coefficients of friction are observed when a magnetic field is applied.

As shown in Fig. 6, the surface images of disk are observed through optical microscope. The MR fluids are tested under a normal load of 5 N and oscillation frequency of 1.0 Hz with an activation of magnetic field. It shows that machining marks on the original surface of disks, many thin grooves and ridges are observed on the worn surface after tests, respectively. The results show that the surface under magnetic field is much smoother than the one without magnetic field. In addition, to

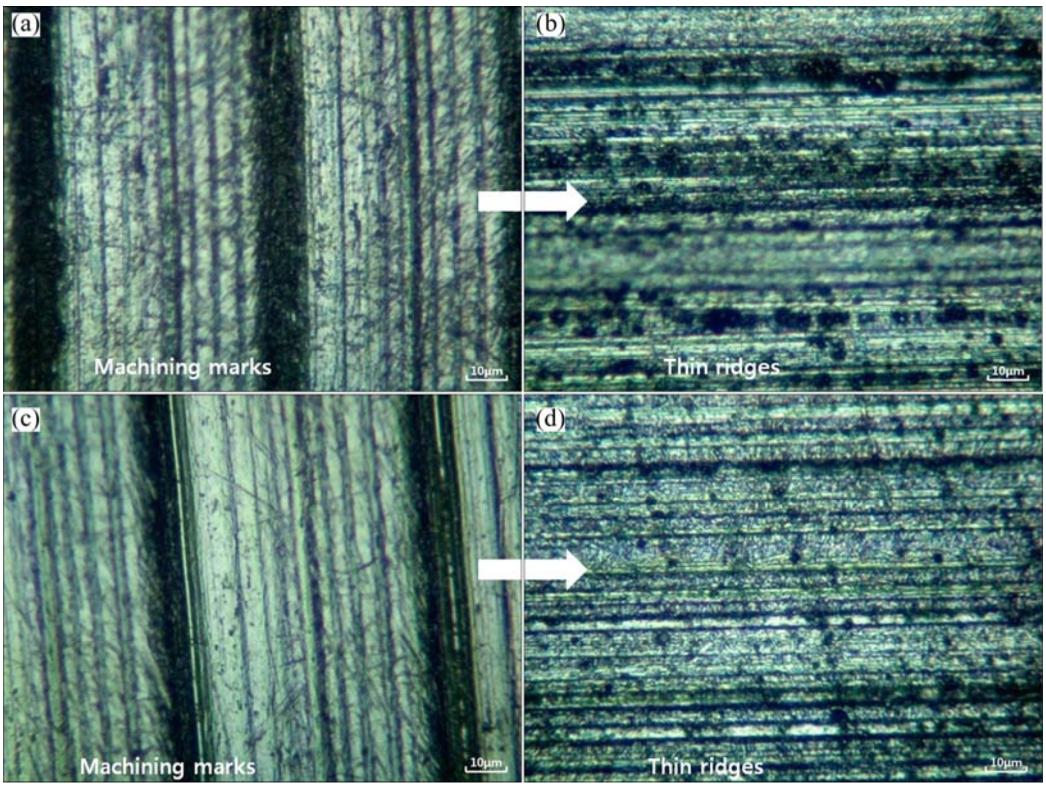

Fig. 6 Optical images of surface without (a, b) or with (c, d) magnetic field

compare the surface roughness of the disk with or without magnetic field, a surface profilometer (Mitsutoyo SurfTest SV−3100) was used to measure the arithmetical mean roughness (R_a) on the surface of disk. The roughness values were obtained at oscillation frequencies of 0.5 Hz and 1.0 Hz, loads of 1 N and 5 N, and compared with R_a with or without magnetic field, which are shown in Table 4. From Table 4, it shows that R_a decreases with increasing load and oscillation frequency. Also, the surface roughness of the disks without magnetic field is clearly greater than that under an applied magnetic field. It is assumed that the particles in MR fluid can be transformed into an assembled structure of individual chains under the applied magnetic field [18]. The particles are arranged in chain shape under the influence of the external magnetic field. It is assumed that the particles do not make relatively huge motions when a magnetic field is applied. However, particles can move freely within fluid and cause damages to the surface of specimens during contact between pin and disk.

Table 4 Surface roughness of aluminum disk at 0.5 Hz and 1 Hz

Oscillation frequency/Hz	Roughness			
	Unapplied magnetic field		Applied magnetic field	
	1 N	5 N	1 N	5 N
0.5	0.56023	0.43407	0.3381	0.26943
1.0	0.81637	0.73033	0.66793	0.4444

4 Conclusions

MR fluid is one of the smart materials and can change its rheological property under a magnetic field. It consists of magnetizable particles in base oils such as mineral oil. When a magnetic field is applied to MR fluid, particles form a chain following the direction of magnetic field. For most applications using MR fluids, linear motions occur. Thus, reciprocating friction characteristics of MR fluid at different loads and oscillation frequencies with or without a magnetic field were investigated with a reciprocating friction tester. The experiments were carried out under the different test conditions of load and oscillation frequency with activation of magnetic field. The results show that the coefficient of friction generally decreases as the applied load increases and oscillation frequency increases when a magnetic field is applied. The average coefficient of friction under magnetic field is lower than that without magnetic field regardless of loads and oscillation frequencies. The surface of disk under a magnetic field is much smoother than that without magnetic field because moving particles without magnetic field cause damages to the surface during contact between pin and disk. The obtained results can be used in the process of design applications to improve friction performance.

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磁流变液在磁场作用下基于铝的往复式摩擦特性

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摘 要：磁流变液被广泛地应用在汽车减震器、表面抛光和其他精加工处理中。讨论基于铝的磁流变液在磁场、不同的负载和振荡频率条件下的摩擦特性。在有、无磁场下对磁流变液基于铝的往返式摩擦特性进行评估。在不同荷载和振荡条件下分析实验条件与运动周期的关系。通过测量表面粗糙度和观察表面图像比较样品表面，并评估了磁流变液基于铝的往复摩擦特性。

关键词：磁流变液；往复摩擦；铝；磁场；智能材料

(Edited by Xiang-qun LI)