Chapter

Tribological Characteristics of Smart Materials (Magneto-Rheological Fluids and Elastomers) and Their Applications

Peng Zhang, Chenglong Lian, Kwang-Hee Lee and Chul-Hee Lee

Abstract

Magneto-rheological fluids (MRFs) and magneto-rheological elastomers (MREs), as smart materials, have been widely studied in various engineering fields to address vibration issues because the mechanical properties are controllable under the strength of a magnetic field. Their tribological characteristics are also important to be evaluated, as applications using MRFs and MREs contain various contact interfaces under reciprocating and rotating working conditions. The performance and durability of these materials are related to their tribological characteristics. Therefore, various working conditions and environmental conditions are taken into consideration, and their tribological characteristics are experimentally examined. In addition, applications using MRFs and MREs are introduced, and the tribological performances of these materials are evaluated.

Keywords: tribology, magneto-rheological fluid, magneto-rheological elastomer, smart material, friction control

1. Introduction

Magneto-rheological fluids (MRFs) and magneto-rheological elastomers (MREs) have been extensively studied to solve vibration problems in various engineering fields. They have one or more attributes that can be significantly changed in a controlled way by external stimuli (magnetic fields). It is essential to evaluate the tribological properties as they relate to the performance of smart material-based applications.

MRF consists of base fluid with magnetic particles forming chain shape along the magnetic field direction. Because of its fast response speed, it has the potential to be applied to various industrial sectors such as automotive, aviation, construction, etc., [1]. Although research on MRF-based applications with control method is being conducted, tribological characteristics of MRF remain in early stage.

For example, tribological properties of magnetic particles in MRF are examined by Bullough [2]. It is noted that the parameters such as particle concentration, surface condition, sliding speed, and contact pressure should be considered to understand sliding contact mechanism. Lubrication performance of MRF is evaluated using tribological tester [3].

The performance of MRF is based on the yield stress, which can be changed by the strength of a magnetic field [4]. The applied magnetic field can change the intensity of the particles arranged along the magnetic field direction. The particles can affect the friction and wear at the contact surfaces. Furthermore, the environmental conditions can affect the properties of fluid, and the changed liquid properties can also affect friction and wear. Fridrich studied that the heated surface leads to the high specific wear rate with lower friction coefficient [3]. Most research focuses on the tribological characteristics of MRF without the magnetic field [2, 5].

Since there is a disadvantage that the environmental pollution problem due to leakage can occur, it is essential to apply the technology to prevent leakage of the fluid. Performance degradation due to particle deposition in the fluid is also a major problem. To solve these drawbacks, MRE has been proposed. It consists of base material (generally polymer) and magnetic particles. As with MRF, mechanical properties can be varied depending on the presence or absence of a magnetic field [6]. Studies on the friction and wear characteristics of ordinary rubber have been actively conducted, but the research on MRE is still insufficient [7].

MREs, as smart elastomers, are also investigated for use in various types of equipment [8]. Specifically, MREs are also used in various external environments at different temperatures, relative humidity conditions [9], and vibration conditions [10]. However, there is a paucity of studies examining the friction and wear properties of MREs. The friction coefficient of an MRE can be controlled using external magnetic fields by changing the hardness of the MRE. Therefore, this property can be applied in some hardness-controllable devices.

MRFs and MREs have been widely studied and applied in various mechanical devices. Because of their controllable mechanical properties under the magnetic field, their tribological characteristics are important for evaluation. However, in this chapter, the tribological characteristics of MRFs and MREs will be explained, including friction and wear properties of MRFs and MREs under different environmental conditions such as temperature, humidity, and vibration conditions.

2. Tribological characteristics of magneto-rheological fluids (MRFs) and their applications

2.1 Friction and wear properties of MRF under different applied loads and speeds

The potential applications using MRF are operated under various loads and speed conditions. It is necessary to estimate the performance of applications that take into account friction and wear characteristics. As most contacts are occurred in linear motion, friction and wear characteristics are examined under different working conditions (oscillating frequency, load, and magnetic field). The detailed mechanism of the tester is shown in **Figure 1**. The magnetic field is applied to the MRF, and its direction is perpendicular to the moving direction. Cartridge heaters under the specimen can provide the heat on the contact surface. The oscillating frequency and the applied load are fixed to 0.5/1.0 Hz and 1/5 N, respectively. The results in **Figure 2** show the friction coefficient changes concerning the working cycles. The lower values are observed under higher load condition with no magnetic field. The tendency of the results with different oscillating frequencies is almost the same.

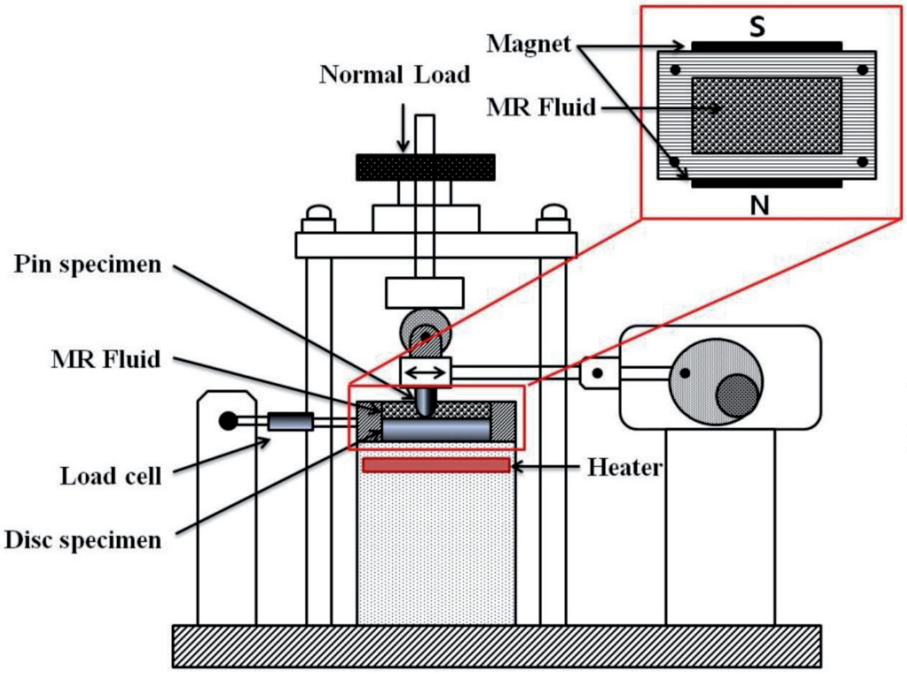

Figure 1.
Schematic of reciprocating friction and wear tester (R&B 108-RF).

The microscopic images of the specimen before and after the tests are compared as shown in **Figure 3**. The machining marks are only observed on the surface before the tests, but some wear marks such as ridges are shown on the surface after the tests. The distance between wear marks is very close, and a smoother surface is observed when a magnetic field is applied. The particles in MRF form a chain shape along the direction of a magnetic field. The formed structure works as resistance resulting in small motion at contact interfaces. However, the main reason for surface wear is free-moving particles.

2.2 Friction and wear properties of different types of MRFs

Since the mechanical properties of MRF are controllable, various types of MRF (122EG, 132DG, 140CG) are studied to improve the MR effects. The weight percentage of particles in the fluid is one of the key factors. The particles in the fluid affect friction and wear properties at contact interfaces. Therefore, various MRF types are taken into consideration to estimate the tribological characteristics under different working conditions such as the strength of the magnetic field, load, and oscillating frequency. The magnetic field strength is changed to 9 mT from 3 mT with a 3 mT step. Moreover, oscillating frequency and the applied load are fixed to 1 Hz and 10 N, respectively.

The results of the friction coefficient change with different magnetic field strengths are shown in **Figure 4**. The friction coefficient tends to increase as the magnetic field strength increases. The particles are constrained in the chain shape along the direction of the applied magnetic field. Some may have an abrasive effect on the surface during the friction process. Most of them show the resistance on the surface due to the gathered particle under the presence of a magnetic field. The particles are turned into the additional tribological pair and increase the friction coefficient. Moreover, the interactions among the particles under the magnetic field continuously occur during the movement, and it causes energy consumption, resulting in friction coefficient increase. Such an interaction force tends to increase under higher magnetic field strength.

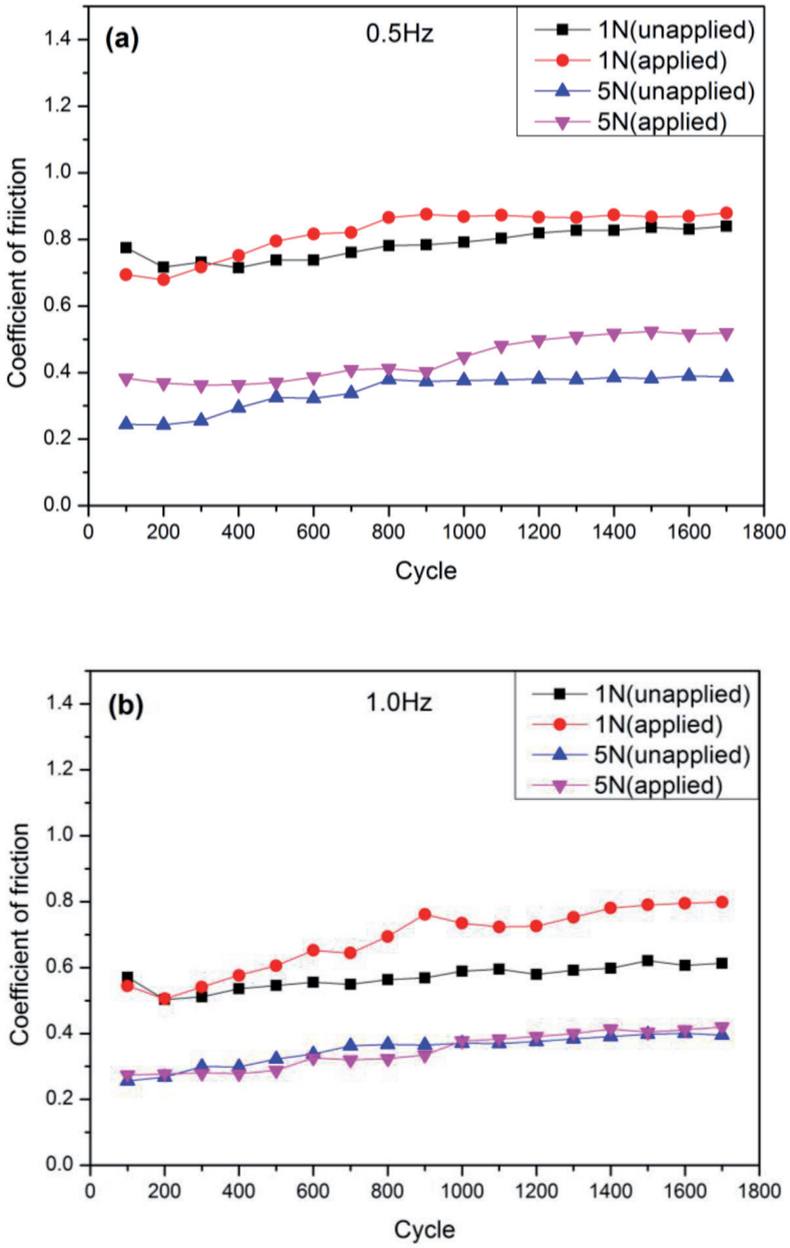

Figure 2.
Friction coefficient change of MRF under different loads and speed conditions (aluminum). (a) 0.5 Hz/unapplied and applied magnetic field and (b) 1.0 Hz/unapplied and applied magnetic field.

2.3 Friction and wear properties of MRF with the coatings

Since the types of MR fluid have influence on the tribological properties, the demand for the improved friction and wear performance in contact interfaces is increasing. The surface coating is the solution that can enhance the friction and wear performance while maintaining the controllable properties of MR fluid in various industrial applications. Various coating materials are taken into consideration to evaluate the friction and wear properties of MRF. Most common coating materials widely used in industrial area are PTFE and DLC. Therefore, two different coating materials and pairs are considered with the fixed working conditions. The oscillating frequency, applied load, the strength of a magnetic field, and temperature are 1 Hz, 5 N, 5 mT, and 25°C, respectively.

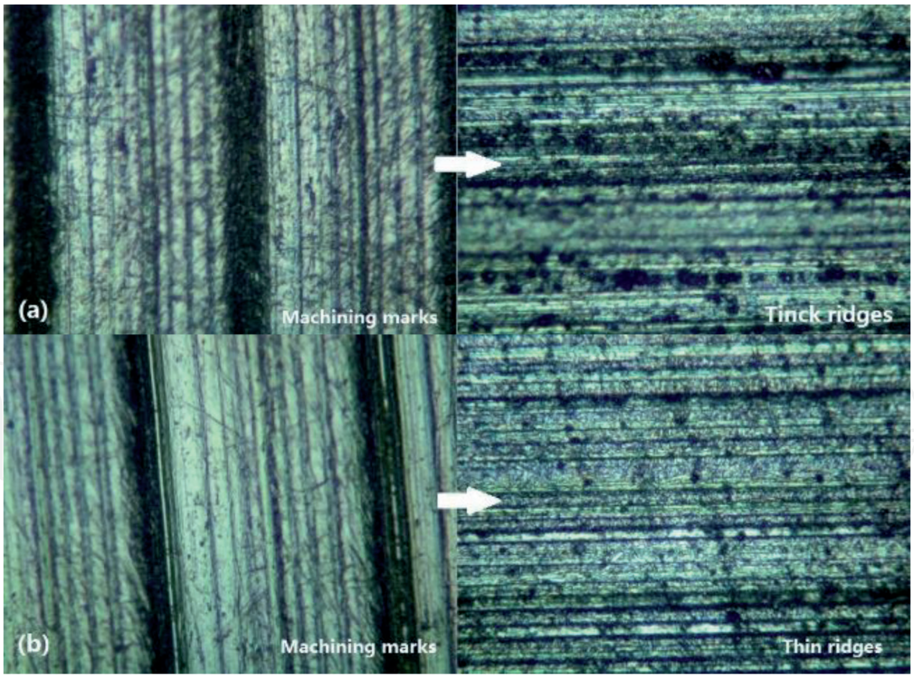

Figure 3.
Microscopic surface images before and after wear (5 N/1 Hz). (a) magnetic field on and (b) magnetic field off.

Figure 5 shows the friction coefficient changes with different coating materials and pairs. The material of the specimen is aluminum (pin and plate), and they are coated with DLC and PTFE. The friction coefficient tends to increase with no coatings. However, it shows the lower values with coatings. The stable results are shown for the coating surface. PTFE-coated surfaces show improved friction performance compared to DLC and no coating. The best friction performance is observed for PTFE coating pairs.

DLC coating is widely used for industrial applications due to the better mechanical properties than PTFE. Thus, it is suggested that the DLC coatings are more appropriate to most of the applications. The temperature is another factor that affects friction performance as the properties of fluid change at higher temperature conditions. The specimen with DLC coating under different temperature conditions is tested. The results of the friction coefficient change with temperature up to 130°C are shown in **Figure 6**, and it tends to decrease as the cycles increase. The degraded viscosity of MRF due to the temperature increase gives more freedom to the particles in the fluid resulting in the improved friction performance [9].

2.4 Friction and wear behavior of MRF applied to pin-bushing system

Bushings are widely used in many mechanical applications working as bearings. Therefore, it is important to either maintain or enhance the tribological properties of bushings. MRF can be applied as a lubricant to bushings to enhance the load-carrying capacity. The friction performance of bushing is evaluated using specially designed tester shown in **Figure 7**. This tester can adjust the oscillating frequency, angle, and load. Friction performance of MRF is tested with a step load up to 5kN from 1kN with and without a magnetic field. The results are compared to the one with conventional grease. In **Figure 8**, the friction coefficient tends to decrease when the load is 3kN and becomes stable. The highest friction coefficient is shown when a magnetic field is activated during the test. It is assumed that the particles in the fluid work as a solid lubricant in the shape of the chain in the direction of a magnetic field. The force among the particles leads to resistance during the operation. The friction performance at the contact interface can be controlled with a magnetic field. The load-carrying capacity also can be changed with MRF.

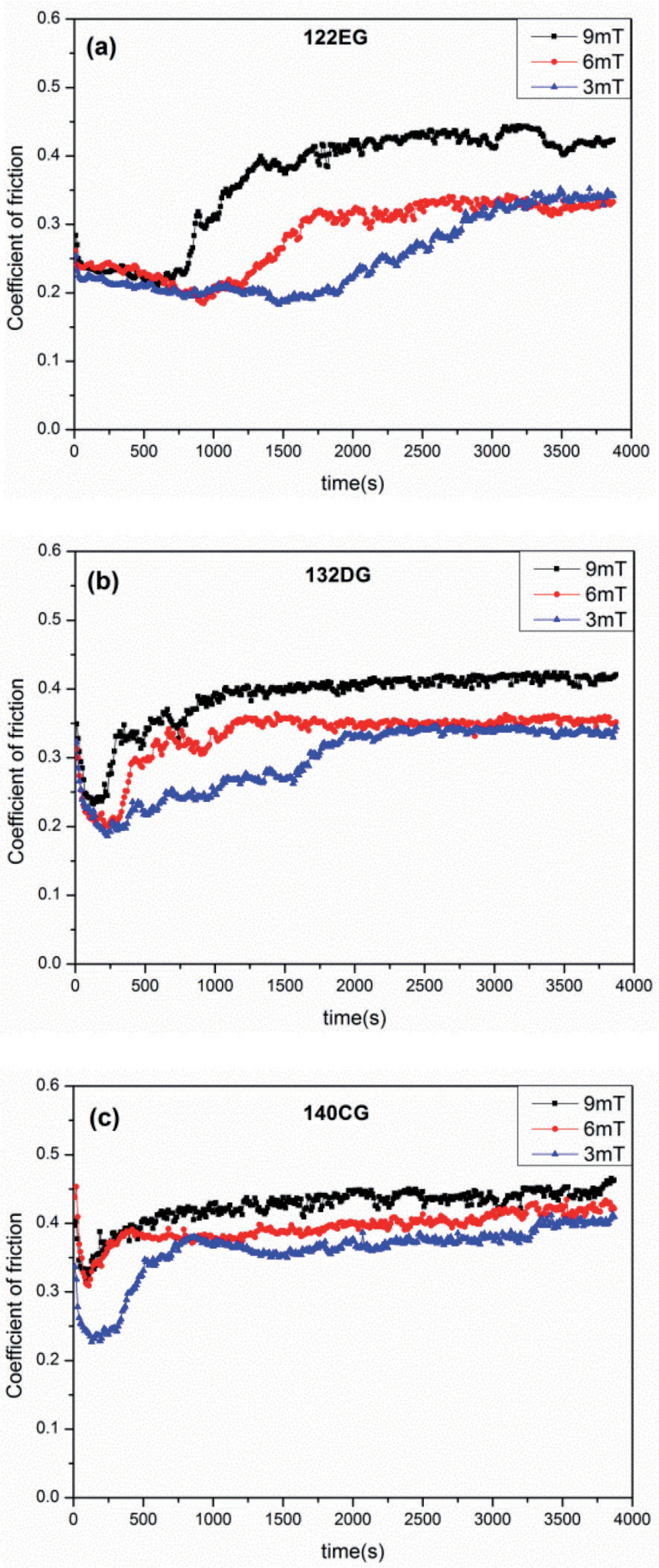

Figure 4.
Friction coefficient changes with respect to types of MRF and strength of magnetic field. (a) MRF, 122 EG; (b) MRF, 132 DG; and (c) MRF, 140 CG.

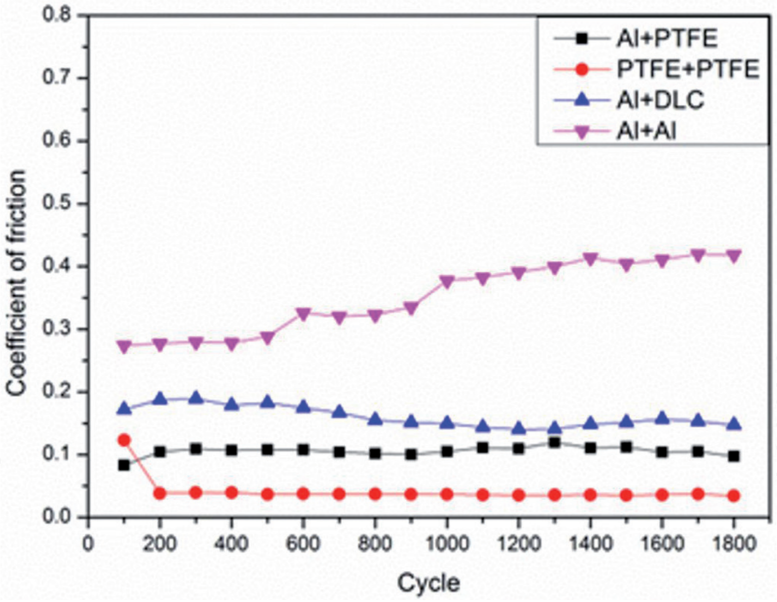

Figure 5.
Friction coefficient changes of MRF with various coating surfaces (5 N/1 Hz).

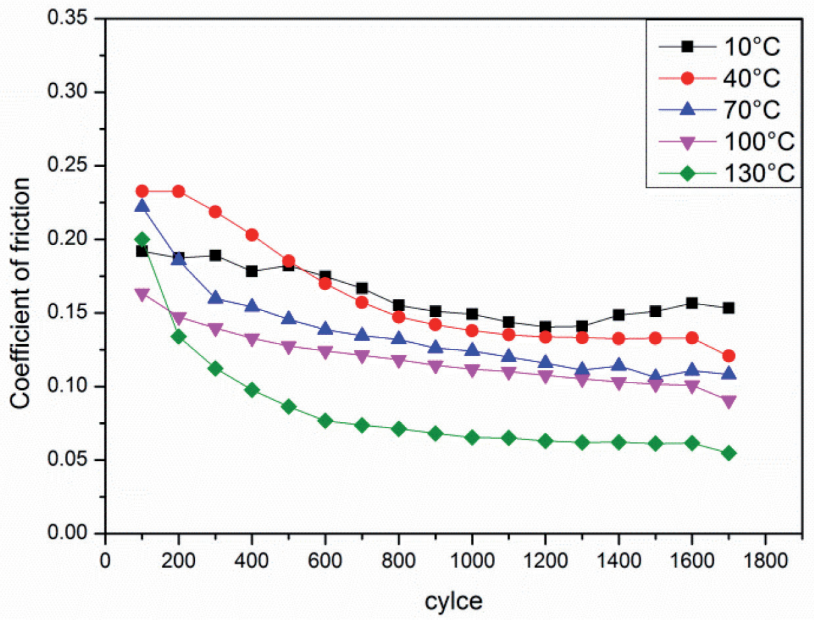

Figure 6.
Friction coefficient changes of MRF with various temperature conditions on DLC-coated surface (5 N/1 Hz).

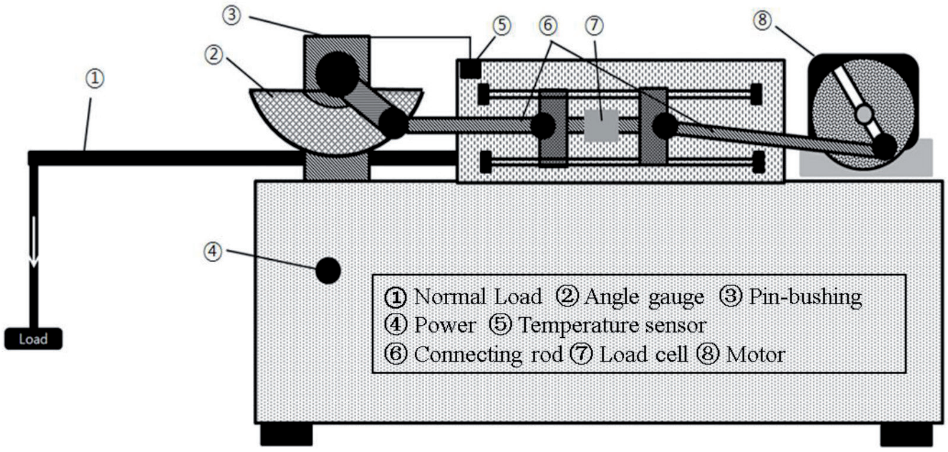

Figure 7.
Schematic diagram of pin-bushing friction and wear tester.

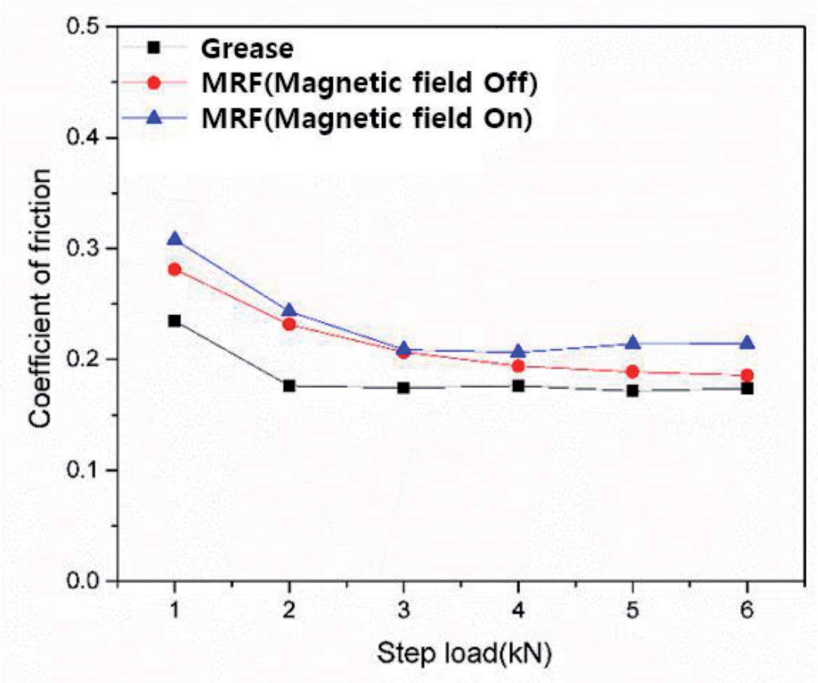

Figure 8.
Friction coefficient chance under step-load condition.

3. Tribological characteristics of magneto-rheological elastomer (MRE) and its applications

3.1 Friction and wear properties of MREs under different temperature conditions

MREs are new types of a smart material that can change mechanical properties under a magnetic field. Like other smart materials, MREs should maintain its durability under severe environmental conditions. As MRF shows different friction characteristics under different temperature conditions, MRE should be tested under the same conditions. The friction and wear performance of MRE surfaces are evaluated on the temperature up to 100°C from room temperature. **Figure 9** shows the results of the friction coefficient and wear depth changes concerning the temperature increases. Friction coefficient tends to increase as the temperature increases, and higher values are observed with no magnetic field. The presence of a magnetic field increases the hardness. The difference in wear depth is larger than the friction coefficient. The friction and wear performance of MRE is affected by the temperature condition. It seems that lower resistance is observed at high-temperature conditions. In the case of fixed load and velocity conditions, the temperature is the major factor of wear at contact interfaces.

3.2 Friction and wear properties of MRE under different humidity conditions

It is mentioned that temperature is the major factor related to the friction and wear characteristics of MRE. It is considered that humidity is another factor. The same tests are conducted with different humidity conditions to estimate friction and wear performance. The test conditions were implemented by adjusting the relative humidity through the humidifier. The humidity conditions are 40, 60, and 80%. The result in **Figure 10** shows the friction coefficient and wear depth change according to the humidity variation. Additionally, the results are compared with or without a magnetic field. Higher values of friction coefficient appear when a magnetic field is applied, and they tend to decrease as the

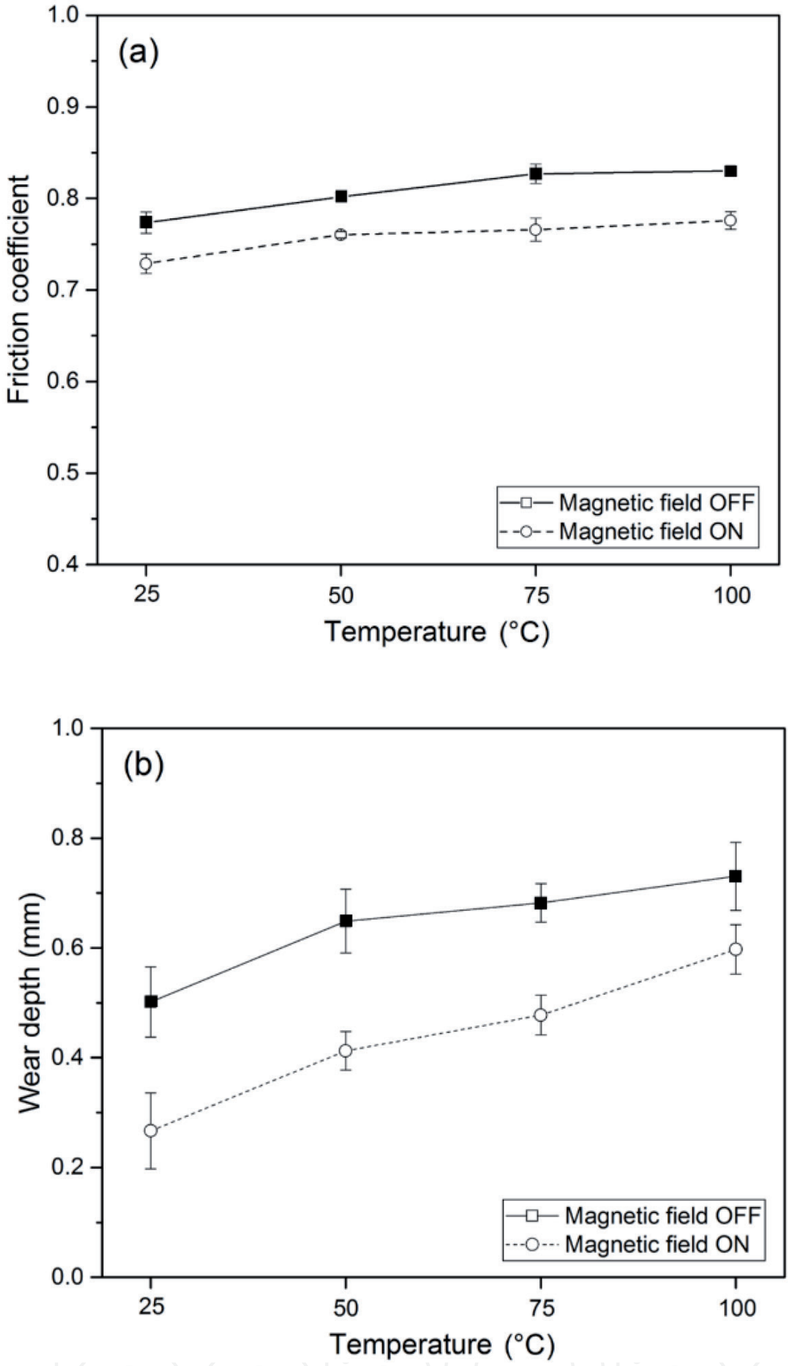

Figure 9.
Results of (a) average friction coefficient and (b) wear depth for MRE under different temperature conditions.

humidity increases. The friction coefficient difference remains almost constant under magnetic field conditions. The applied magnetic field changes the hardness. The reason for the lower friction coefficient under high humidity condition is that the contact surface is affected by the local hydrodynamic effect resulting in a lubricating effect. Also, the water is absorbed in MRE, and its shear strength seems to be decreased.

The wear depth is also reduced as the humidity increases. It is assumed that the shear strength of the contact surface can be reduced by the hydrodynamic effect. This leads to lower energy consumption during frictional movement. The results of wear depth show that severe wear does not appear when the humidity reaches to 80% regardless of a magnetic field. Furthermore, it does not show the significant change of wear depth when the humidity is 60%, which is assumed to be a saturation point.

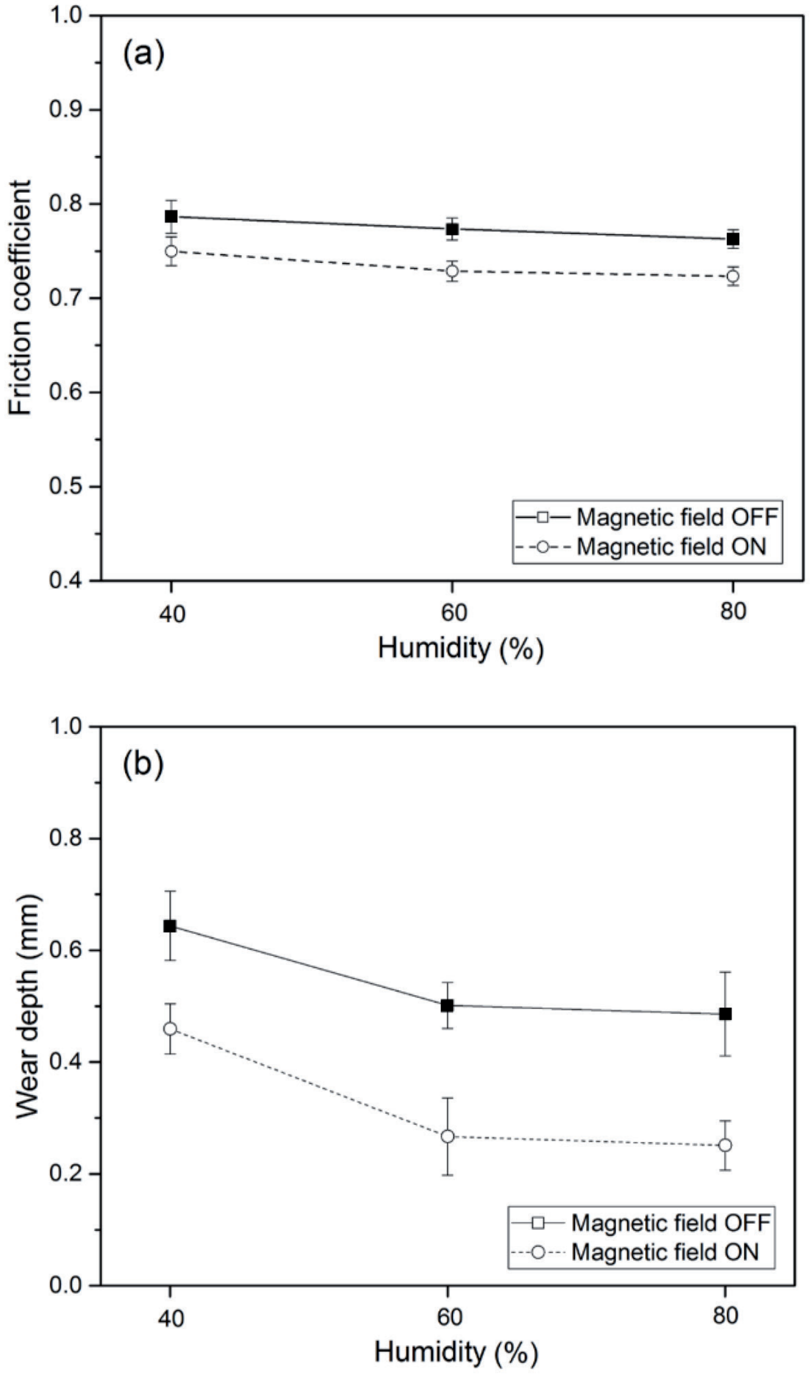

Figure 10.
Results for average friction coefficient (a) and wear depth (b) of MRE at different relative humidity conditions.

3.3 Friction and wear properties of MRE under different vibration conditions

Most industrial applications have vibration issues during the operation. Such vibration is correlated to friction and wear. Previously, friction and wear properties are affected by various environmental conditions. Additionally, it is necessary to estimate the tribological performance of MRE under vibration condition. The tests are conducted under various frequencies and amplitude conditions. The results are shown in **Figure 11**. The average friction coefficients are obtained, which are compared each other, to analyze how the vibration frequency and amplitude affect.

The friction coefficient tends to increase as the frequency increases except at the resonant frequency. Elastomers show different tribological properties,

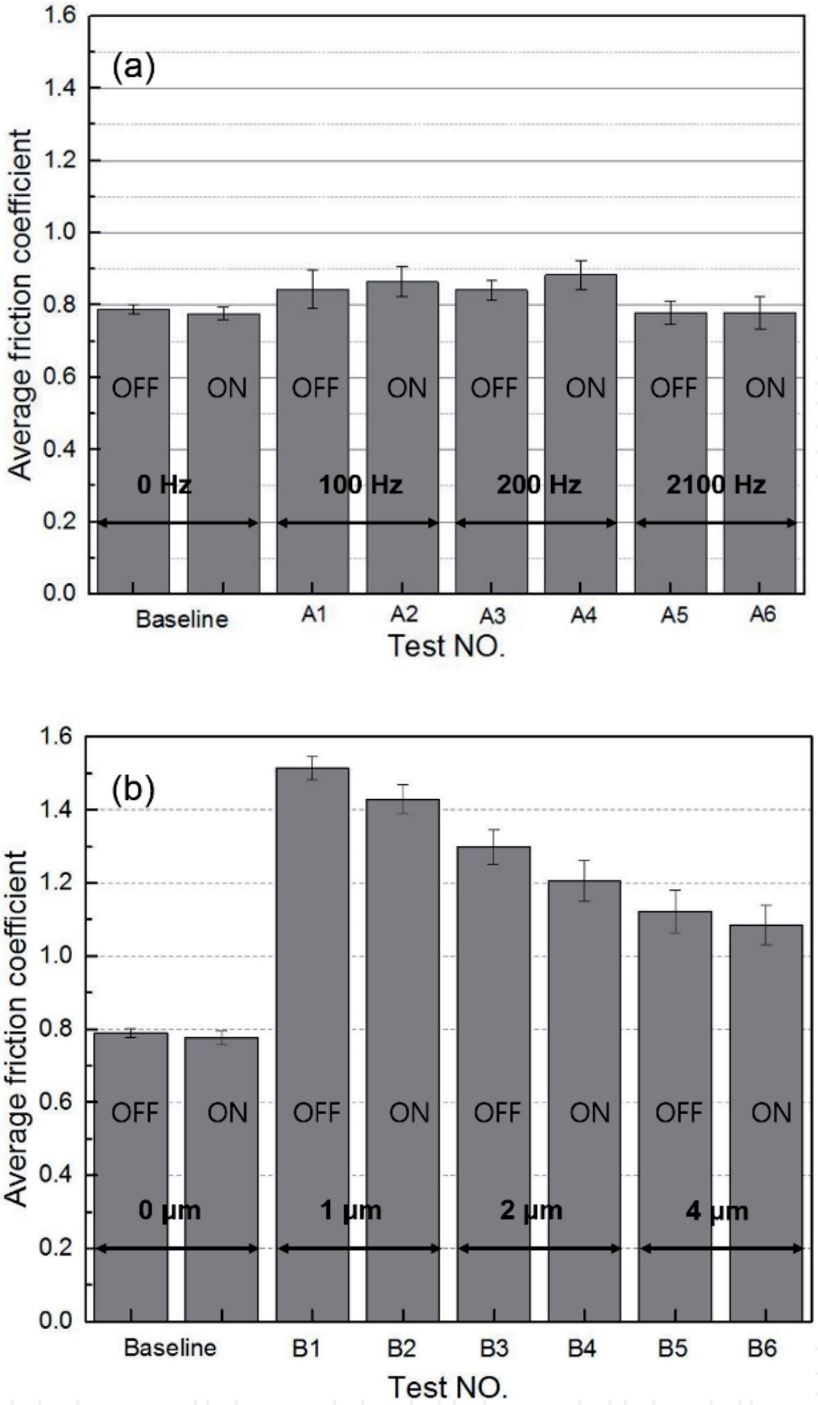

Figure 11.
Average friction coefficient results of MRE under (a) different vibration frequencies and (b) vibration amplitudes. A1, A3, and A5: 100, 200, and 2100 Hz without a magnetic field. A2, A4, and A6: 100, 200, and 2100 Hz with a magnetic field. B1, B3, B5: 1, 2, 4 μm without a magnetic field. B2, B4, and B6: 1, 2, and 4 μm with a magnetic field.

unlike metal material in which friction coefficient reduces under vibration conditions [10]. The surfaces of elastomer have less resistance as temperature increases, reducing the friction coefficient. When high-frequency oscillations occur, vibration energy is converted into heat energy. The temperature of MRE is increased by 2°C when a vibration is applied. It is assumed that the generated heat on the surface leaded higher friction coefficient under vibration conditions. Also, the increased contact time under high frequency causes a higher friction coefficient. The lower values are observed at the conditions of 100 and 200 Hz. After 200 Hz, the vertical load at the contact surface is reduced by the resonance. The lower friction coefficient can be obtained due to the reduced load. The vibration amplitude is taken into consideration to evaluate the tribological properties of MRE. The previous results show that the friction coefficient clearly decreases when a magnetic field is applied, which is related to the hardness change. The small deformation on the contact surface appeared when a magnetic field is applied, resulting in small deformation; when a vibration amplitude increases, the friction coefficient decreases. It is assumed that the separation of the contact pair appears when the amplitude is high.

3.4 Rolling friction characteristics of MRE

Previously, the friction coefficient under reciprocating motion can be controlled by the strength of a magnetic field. Rolling friction is another factor to be considered in engineering applications. As the motion is different, tribological characteristics of MRE under rolling motion should be taken into consideration. The tests are carried out under a fixed velocity and load conditions.

The micro slip at the contact interfaces, adhesion, and plastic deformation are the key factors of rolling friction of elastomer. The schematic of the rolling friction of elastomer is shown in **Figure 12**. In the analytical model [11], the rolling friction coefficient can be obtained as follows:

$$\mu_R = \frac{M_R}{WR} = \alpha\frac{2a}{3\pi R} = \frac{4\alpha}{3\pi}\left\{\frac{W}{\pi R E^*}\right\}^{\frac{1}{2}} \tag{1}$$

According to Eq. (1), the rolling friction coefficient can be reduced by increasing the modulus. It can be increased under a magnetic field. Thus, the theoretical values of rolling friction coefficient can be obtained. The theoretical and experimental values are compared in **Figure 13**. The results show that the values tend to decrease as the magnetic field strength increases. The tendency of experimental results is similar to the one in theory. The difference between experiment and theory is caused by micro slip and adhesion at contact interfaces.

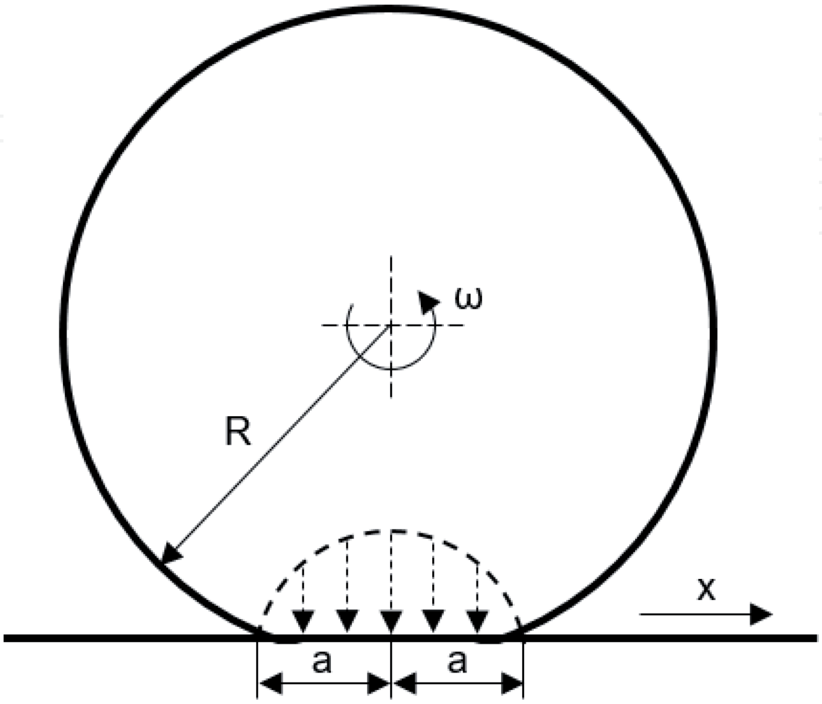

Figure 12.
Analytical model of rolling friction of an elastomer.

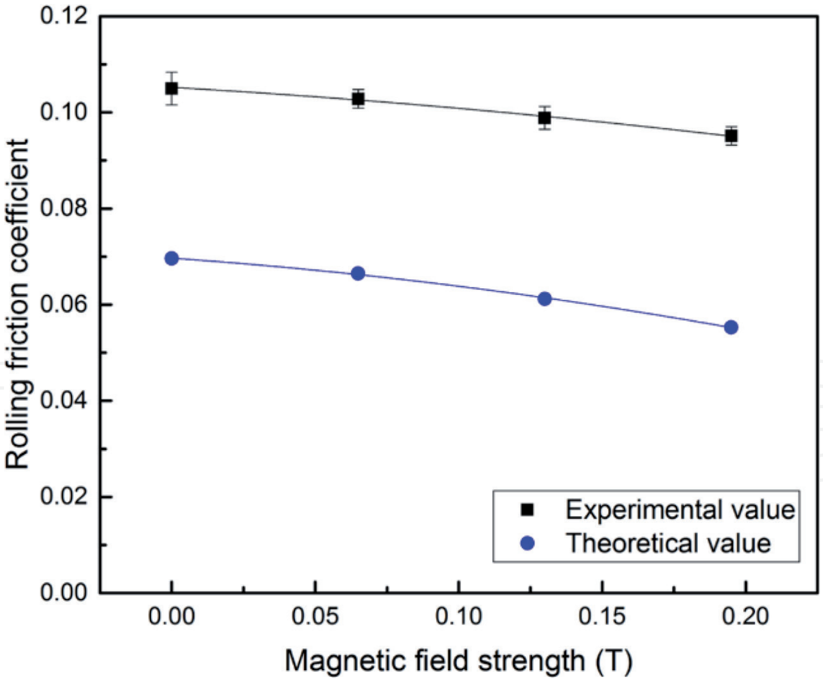

Figure 13.
Comparison of rolling friction coefficient of MRE with respect to magnetic field strength from experiment and theoretical analysis.

Author details

Peng Zhang[1], Chenglong Lian[2], Kwang-Hee Lee[3] and Chul-Hee Lee[3]*

1 Nanjing Research Institute for Agricultural Mechanization Ministry of Agriculture, Nanjing, PR China

2 College of Forestry, Shandong Agricultural University, Taian, PR China

3 Department of Mechanical Engineering, Inha University, Incheon, South Korea

*Address all correspondence to: chulhee@inha.ac.kr

References

[1] Bullough W, Wong P, Fen C, Leung W. Fundamental boundary tribology: ESF. Journal of Intelligent Material Systems and Structures. 2003;**14**:71-78. DOI: 10.1177/104538903030330

[2] Wong P, Bullough W, Feng C, Lingard S. Tribological performance of a magneto-rheological suspension. Wear. 2001;**247**:33-40. DOI: 10.1016/S0043-1648(00)00507-X

[3] Song W, Cai Q, Choi S, Lee C. A study of finishing process of magneto-rheological fluid on steel surface. Civil Engineering and Building Materials. 2011;**1**:17-24

[4] Zhang P, Lee K, Lee C. Reciprocating friction characteristics of magneto-rheological fluid for aluminium under magnetic field. Transactions of Nonferrous Metals Society of China. 2014;**24**:171-176. DOI: 10.1016/S1003-6326(14)63044-2

[5] Zhang P, Lee K, Lee C. Friction behavior of magnetorheological fluids with different material types and magnetic field strength. Chinese Journal of Mechanical Engineering. 2016;**29**:84-90. DOI: 10.3901/CJME.2015.1126.139

[6] Carlson J, Jolly M. MR fluid, foam and elastomer devices. Mechatronics. 2000;**10**:555-569. DOI: 10.1016/S0957-4158(99)00064-1

[7] Lancaster J. A review of the influence of environmental humidity and water on friction. lubrication and wear. Tribology International. 1990;**23**:371-389. DOI: 10.1016/0301-679X(90)90053-R

[8] Persson B. Rubber friction and tire dynamics. Journal of Physics: Condensed Matter. 2010;**23**:015003. DOI: 10.1088/0953-8984/23/1/015003

[9] Odfalk M, Vingsbo O. Influence of normal force and frequency in fretting. Tribology Transactions. 1990;**33**:604-610. DOI: 10.1080/10402009008981995

[10] Wen S, Huang P. Principles of Tribology. Beijing: John Wiley & Sons; 2012. DOI: 10.1002/9781118062913

[11] Williams J. Engineering Tribology. Oxford city: Cambridge University Press; 2005. DOI: 10.1017/CBO9780511805905