ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 22(2), 281-285 (2017) https://doi.org/10.4283/JMAG.2017.22.2.281

Effect of Wall Groove Characteristics on Yield Stress Measurement of Magnetorheological Fluid

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(Received 18 January 2017, Received in final form 24 February 2017, Accepted 24 March 2017)

To suppress the wall slip effect and improve the yield stress measurement precision of magnetorheological fluid, measurement disks with different grooves are first manufactured. Then, the influence of groove characteristics on the yield stress of magnetorheological fluid is investigated by the method of experiments. Finally, the optimization wall grooves of measurement disks are obtained, and the yield stress of a self-prepared magnetorheological fluid is measured. Results indicate that the groove type and groove width have a slight influence on the shear yield stress, whereas the measured yield stress increases with enhanced groove density, and the optimized groove depth is 0.3 mm. The measured shear yield stress of self-prepared MR fluid can be improved by 18 % according to the optimized grooved disks, and the maximum yield stress can reach up to 65 kPa as the magnetic flux density is 0.5 T.

Keywords : yield stress, groove characteristic, magnetorheological fluid, measurement

1. Introduction

Magnetorheological (MR) fluid, which is composed of micro-sized soft magnetic particles, carrier liquid, and stabilizers, is a type of intelligent materials. When the magnetic field is removed, MR fluid behaves as a Newtonian fluid. As an external magnetic field is applied, the viscosity of the MR fluid increases rapidly and shows a visco-plastic solid behavior [1-4]. MR fluid has been a focus of research and widely used in recent years due to its excellent characteristics [5-8].

Yield stress is the most important property parameter of MR fluid and can be measured by different methods. Wollny measured the properties of MR fluid using MRC300 rheology system [9]. Genc developed a cylinder-type rheology instrument [10]. Wang developed a measurement device based on the flow mode of MR fluid [11]. Jong measured a prepared MR fluid by a disc-type yield stress instrument [12]. Although many researchers have developed various devices to measure the yield stress of MR fluid, if the wall surface of the measurement instrument cannot be designed and manufactured appropriately, the wall slip effect of the MR fluid may appear, which will lead to lower testing precision. The wall material and surface groove can influence the friction coefficient and attractive force between soft magnetic particles and wall and further affect the yield stress measurement of MR fluid. Many researchers have investigated the wall surface and anticipated weakening of the wall slip effect of MR fluid. Lemaire and Bossis revealed that using a magnetic wall with a rough surface can reduce the slip [13, 14]. Gorodkin found that the transmission wall with surface grooves can improve the transmission capacity of MR fluid effectively [15]. Hans also revealed that no shear stress increase is obtained for grooves in ferromagnetic transmission disks [16]. At present, optimized wall to improve the yield stress measurement precision is still lacking. In this paper, the measurement disks with different surface grooves are first manufactured. Then, the influence rules of surface groove type, groove density, groove width, and groove depth are investigated, and the optimized disk surface is obtained. Finally, the yield stress of a self-prepared MR fluid is tested using the optimized disk.

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2. Materials and Methods

2.1. Materials

The MR fluid for yield stress measurement is self-prepared, and the preparation method is described in reference 8. The solid phase of MR fluid is carbon iron particles (CIP), which has higher magnetic saturation, and the average diameter is 7.0 μm, as shown in Fig. 1. The carrier fluid is silicone oil, which has higher temperature stability. The additives usually contain the surfactants and thixotropic agent. The surfactants are oleic acid and sodium dodecyl benzene sulfonate, and the thixotropic agent is bentonite.

2.2. Measuring principle and methods

The influence mechanism of wall slip effect on the yield stress measurement of MR fluid can be explained by Fig. 2.

As shown in Fig. 2, the particle chains of MR fluid are formed due to an external magnetic field, and the movable wall can move along the direction, which is vertical to the magnetic field. If the fracture of particle chains happed, the shear yield stress of MR fluid can be measured precisely. If the particles slip on the surface of the wall, an inaccurate test of yield stress will occur. Therefore, to avoid slipping over the wall, the interacting force in particle chains (for example, the interactive force between particles 1 and 2) must be smaller than that in the particles and wall, which can be achieved by improving the magnetic force between the particle and wall as well as increasing the friction coefficient.

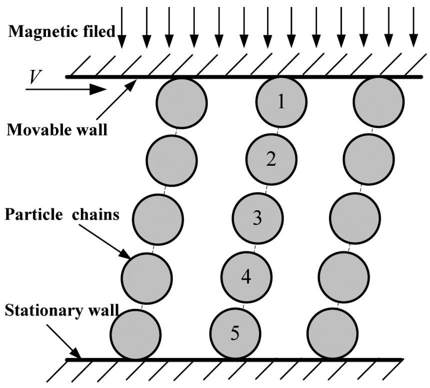


Fig. 2. Relationship between particles and wall.

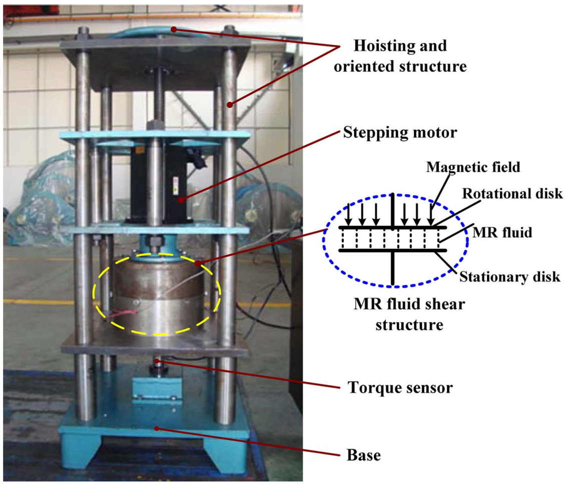
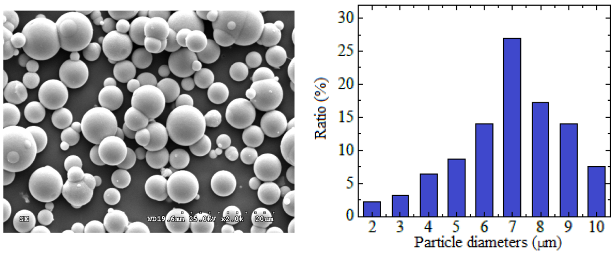
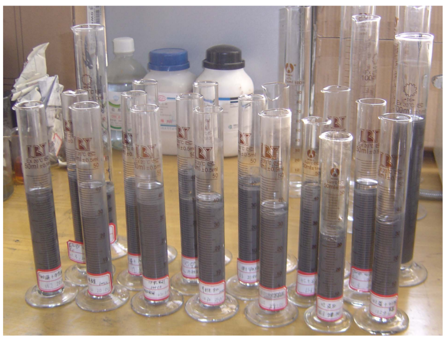


Fig. 3. (Color online) Yield stress measurement device.



(a) SEM photo and diameter distribution of CIP



(b) Prepared MR fluid

Fig. 1. (Color online) Measured material.

A disc-type yield stress measurement system is established to test the yield stress of MR fluid, as shown in Fig. 3. The hoisting and oriented structure can increase the stepping motor and rotational disk and then adjust the working distance between the rotational disk and stationary disk. The transmittable torque (T) of MR fluid under different magnetic fields can be obtained by the torque sensor, and the shear yield stress of prepared MR fluid can be expressed as

$$\tau_0 = \frac{3T}{2\pi R^3}$$

where R is the radius of measurement disk, and τ_0 is the field-dependent yield stress of MR fluid.

2.3. Experimental disks

Different grooved disks are manufactured to obtain the optimization surface, as shown in Fig. 4. Figure 4(a)

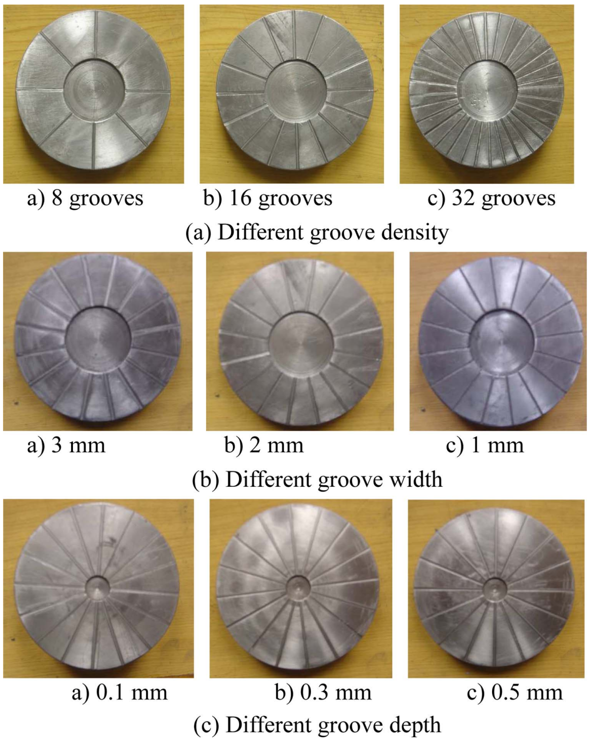


Fig. 4. (Color online) Measurement disks with different wall grooves.

shows the measurement disks with different groove densities, and the groove numbers in the disk surface are 8, 16, and 32. Figure 4(b) shows the measurement disks with different groove widths, namely, 1.0, 2.0, and 3.0 mm. Figure 4(c) shows the measurement disks with different groove depths of 0.1, 0.2, 0.3, 0.4, and 0.5 mm, and the groove number and groove width are 16 and 2.0 mm, respectively. Furthermore, the disks with different groove types, including triangle groove, rectangle groove, and trapezoid groove, are also manufactured.

3. Results and Discussions

3.1. Groove type

In this experiment, the influence rule of groove types, including triangle groove, rectangle groove, and trapezoid groove, on the yield stress of MR fluid are investigated. Results are shown in Fig. 5. Moreover, the groove number, groove width, and depth are 32, 2.0 and 0.3 mm, respectively. The y-axis is the shear yield stress of MR fluid, and the x-axis is the magnetic flux density applied on MR fluid.

The groove type has a slight influence on the shear yield stress measurement, and the triangle groove is much higher than the rectangle groove and trapezoid groove. The phenomenon can be explained by the magnetic field

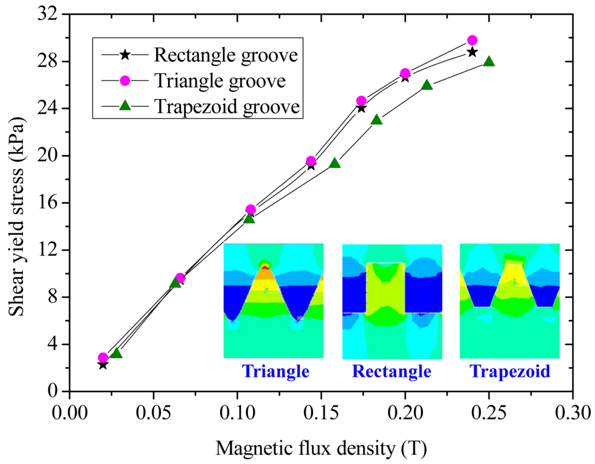


Fig. 5. (Color online) Shear yield stress of MR fluids with different groove types.

nephogram obtained by ANASYS, as shown in Fig. 5. The triangle groove could cause the accumulation of surface magnetic field that enhances the force between particles and wall and further increases the measured yield stress, whereas the trapezoid groove causes the reduction of effective shear area and results in the decrease in shear yield stress. According to the manufacturing characteristic of each groove type, the rectangle groove will be adopted in the next experiments due to its easy machining.

3.2. Groove density

The groove density can be expressed by groove number on the surface of disks. The disks with 32, 16, and 8 grooves are manufactured and tested in the yield stress instrument. Moreover, the groove width is 2.0 mm, and the depth is 0.3 mm temporarily; the shear yield stress of

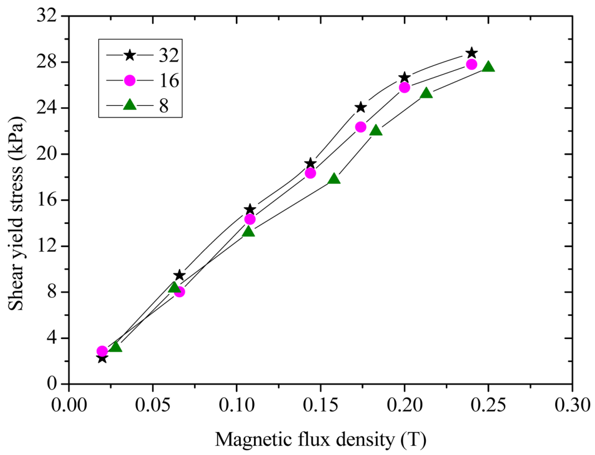


Fig. 6. (Color online) Shear yield stress of MR fluids with different groove densities.

prepared MR fluid with different grooved disks can be obtained, as shown in Fig. 6.

The groove density has a certain influence on the shear yield stress of MR fluid, that is, the shear yield stress enhances with increasing groove number. In detail, when the magnetic flux density is 0.2 T, compared with that by 8 grooved disk, the yield stress of MR fluid measured by 32 grooved disks increases by 12 %. The higher groove number can suppress the wall slip of particles, and the measured yield stress could be enhanced appropriately. That is, one rectangle groove can generate two magnetic field accumulations, and these accumulations are key barriers that suppress the wall slip of particles. A large number of barriers can effectively improve the measured yield stress.

When the magnetic flux density is smaller than 0.05 T, the yield stresses measured by different grooved disks are nearly similar, and the wall slip effect disappears. The reason is that the particle chains are easy to detach due to the lower external magnetic field.

3.3. Groove width

The disks with 3.0, 2.0, and 1.0 mm surface groove widths are manufactured and tested in the yield stress instrument. Moreover, the groove number is 16, and the groove depth is 0.3 mm. The shear yield stress of prepared MR fluid with different grooved disks can be obtained, as shown in Fig. 7.

The surface groove width has a slight effect on the shear yield stress of MR fluid; the key barriers that suppress the wall slip effect are the boundary between the groove area and smooth area, and one groove has two barriers. Therefore, the barrier quantity is 32 for the disk with 16 grooves, and the three grooved disks have similar barriers, which lead to the same wall slip effect. However, in this experiment, the groove widths are 1.0, 2.0, and 3.0 mm, and the width difference is small. If the groove widths are 1.0 and 10 mm, the measured results may be different because of the change in the effective working area of the measurement disks.

Combining the influence rule of groove density and width, the groove width should be reduced to improve the groove density.

3.4. Groove depth

The disks with 0.1, 0.3, and 0.5 mm surface groove widths are manufactured and tested in the yield stress instrument. Moreover, the groove number is 16, and the groove width is 2.0 mm. The shear yield stress of prepared MR fluid with different grooved disks can be obtained, as shown in Fig. 8.

According to Fig. 8, the groove depth has an attractive influence on the shear yield stress test of MR fluid. The yield stress obtained by 0.3 mm groove depth disk is larger than that of 0.1 and 0.5 mm groove depth disks and has a better barrier effect. That is, the 0.1 mm depth groove is flat and will lead to a smaller integrated magnetic field, which encounters difficulty in forming the effective barrier. The 0.5 mm groove depth is much larger and brings on the reduction of the magnetic field in the groove area and further decreases the shear area of MR fluid.

According to the experimental results, the optimized disk surface manufacturing process for the yield stress measurement of MR fluid is as follows: the groove number is 32, the groove depth is 0.3 mm, and the groove width is 2 mm.

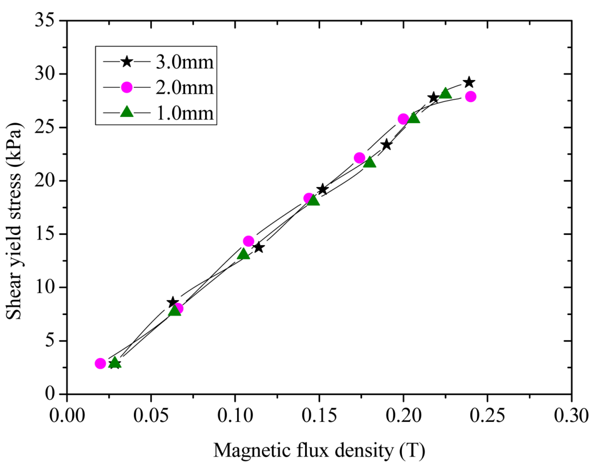


Fig. 7. (Color online) Shear yield stress of MR fluids with different groove depths.

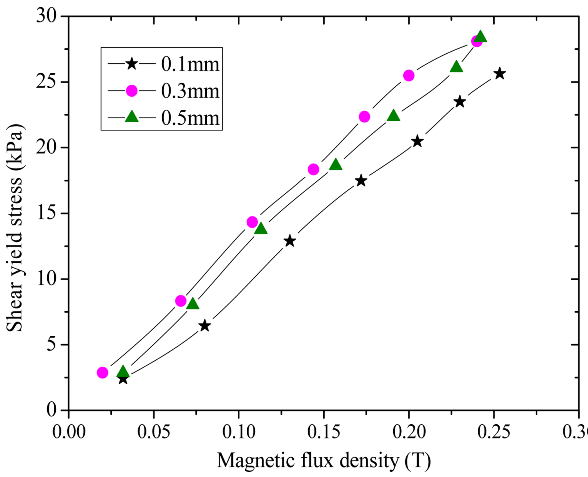


Fig. 8. (Color online) Influence of radial groove depth on shear yield stress.

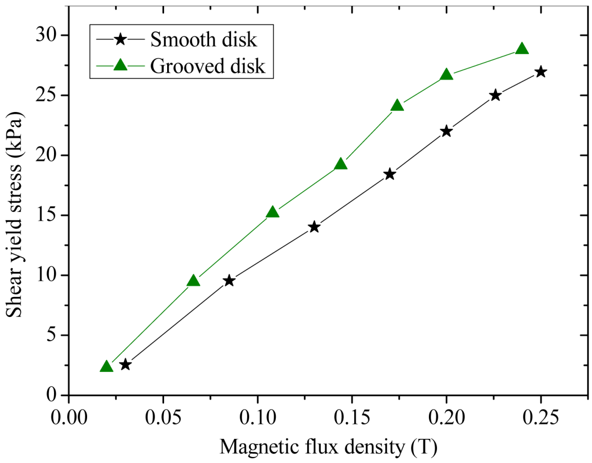


Fig. 9. (Color online) Shear yield stress obtained by smooth disk and grooved disk.

3.5. Shear yield stress testing

To evaluate the optimized disk surface, the smooth disks are also designed and manufactured, and the shear yield stress of self-prepared MR fluid can be obtained, as shown in Fig. 9.

The shear yield stress tested by the grooved disk is obviously higher than that by the smooth disk, which indicates that the grooved disk can suppress the slip of particles and effectively improve the precision of the yield stress instrument. Moreover, when the magnetic flux density is 0.2 T, the shear yield stress of prepared MR fluid is 26 kPa, and based on the relationship between shear yield stress and magnetic flux density, the maximum shear yield stress can reach up to 65 kPa as the magnetic flux density is 0.5 T.

4. Conclusions

Shear yield stress is the most important property of MR fluid and should be measured precisely, while the measurement precision strongly depends on the wall slip effect. Therefore, to suppress the wall slip effect, different grooved disks are manufactured and experimented. The experimental results indicate that the groove type has a slight influence on the shear yield stress measurement, and the measured shear yield stress is enhanced with an increasing groove number. The surface groove width has a slight effect on the shear yield stress of MR fluid while attractive of the groove depth. The optimization surface groove manufacturing process is obtained, that is, the groove number is 32 (or much more), the groove depth is 0.3 mm, and the groove width is 2 mm (or less, depending on the manufacturing capacity). Furthermore, the average measured shear yield stress of MR fluid can be improved by 18 % through the optimized grooved wall, and the yield stress of self-prepared MR fluid can reach up to 65 kPa, which can satisfy most of the application requirements.

Acknowledgment

The support of National Natural Science Foundation of China (No. 51405488, 51575512) the Postdoctoral Science Foundation of China and Jiangsu Province (No. 2013M541754 and 1302074C) and the Priority Academic Program Development of Jiangsu Higher Education Institutions in carrying out this research is gratefully acknowledged.

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