UDK 544.272
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 56(6)689(2022)

STUDY OF FACTORS INFLUENCING THE WALL SLIP OF A MAGNETORHEOLOGICAL FLUID

RAZISKAVA FAKTORJEV, KI VPLIVAJO NA DRSENJE POVRŠINE V MAGNETOREOLOŠKIH FLUIDIH

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Prejem rokopisa – received: 2022-10-07; sprejem za objavo – accepted for publication: 2022-11-04

doi:10.17222/mit.2022.643

The wall slip of magnetorheological (MR) fluids refers to a phenomenon that affects the application of mechanical properties of magnetorheological fluids due to the relative slippage between the magnetic particles and the transmission wall. In this paper, we analyze and experimentally verify the factors affecting the wall slip of magnetorheological fluids, which can limit the application of magnetorheological-fluid devices. Firstly, from the theoretical point of view, it is considered that the influencing factors are mainly divided into two parts: magnetorheological fluid's own parameters and transmission surface roughness, among which the parameters include viscosity, mass fraction, etc. When studying the influence of the transmission surface roughness, it is found that different surface morphologies have a great influence on the shear stress. Secondly, a magnetic field simulation analysis and shear yield stress experiments are conducted on shear blocks with different surface morphologies; the obtained results are compared and verified, confirming that different surface shapes affect the shear yield stress by changing the magnetic field distribution of the groove, which in turn changes the wall slip characteristics. These findings provide an effective basis for further research on the wall slip of magnetorheological fluids to improve the transmission effect.

Keywords: magnetorheological fluid, wall sliding characteristics, magnetic field distribution

Drsenje na stenah magnetoreoloških (MR; angl: magnetorheological) fluidov je pojav, ki vpliva na njihovo uporabnost v povezavi z njihovimi mehanskimi lastnostmi zaradi relativnega drsenja magnetnih delcev in stene. Opisana je analiza in eksperimentalna verifikacija faktorjev, ki vplivajo na drsenje magnetoreoloških fluidov na stenah. V prvem delu članka je obravnavan problem s teoretičnega stališča s poudarkom, da lahko vplivne faktorje razdelimo na dva dela: notranje oziroma lastne parametre magnetoreoloških fluidov (viskoznost, masni delež itd.) in parametre stične površine. Med raziskavo vpliva morfologije površine so avtorji ugotovili, da imajo različne morfologije površine velik vpliv na strižno napetost. Izvedli so tudi primerjave in preverili analize simulacij magnetnega polja in poizkusov strižne napetosti na meji tečenja s strižnimi bloki z različno površinsko morfologijo. Dobljeni rezultati in primerjave so pokazali, da razlike v obliki površine vplivajo na strižno mejno napetost tečenja v sozvočju s spremembo porazdelitve magnetnega polja površine, ki povratno vplivajo na drsne karakteristike stene. Ugotovili so, da izvedene raziskave predstavljajo dobro osnovo za nadaljnje raziskovanje obnašanja magnetoreoloških fluidov.

Ključne besede: magnetoreološki fluidi, drsenje stene, porazdelitev magnetnega polja

1 INTRODUCTION

With the rapid development of science and technology and the advancement of research methods, people gradually began to pay attention to the wall slip properties of MR fluids.[1] The wall slip properties of MR fluids started to receive attention when magnetorheological products were widely used, and more mature MR products appeared in the 21st century. The research on the wall slip properties of MR fluids is still in its initial stage and still needs a lot of theoretical knowledge for its support. The yield stress of MR fluids is an important basis for their application and an important indicator for determining the wall slip of MR fluids. However, due to the complexity of the working environment of MR fluids and the specificity of their own materials, the yield stress of MR fluids cannot be characterized more accurately at present. The accuracy of using the shear yield stress[2] to determine the occurrence of wall slip characteristics still needs to be improved.

The wall effect of MR fluids was first discovered by Lemaire et al.[3] at the University of Nice, France, who measured the yield stress of magnetorheological fluids with a rheometer and found that the yield stress values were always lower than the predicted values based on interparticle forces. And through further studies it was found that the type of material and surface roughness of a transmission wall had a great influence on the yield stress values of MR fluids. The MR fluid viscosity consists of magnetic particles and carrier fluid viscosity.[4] It is known from the Herschel-Bulkley[5] model that with an increase in the shear rate, a shear thinning[6] phenomenon occurs, leading to a decrease in the MR fluid viscosity. Shear thinning also has an impact on the occurrence of wall slip, so the viscosity of MR fluids must be carefully selected in order to control the wall slip. The mass fraction of MR fluids undoubtedly changes as a result of the

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formulation of MR fluids with different viscosities, which is also one of the main principles affecting the yield stress of MR fluids.

Gorodkin et al.[7] studied the effect of the radial groove wall surface and smooth wall surface on the magnitude of yield stress of MR fluids. They established through experiments that the effect was most visible under certain small particle volume fraction and strong magnetic field conditions, and that the yield stress was increased by 2.8 times. The radial groove effectively inhibited the occurrence of a wall defect. Laun et al.[8] studied the effect of magnetic wall materials, nonmagnetic wall materials, and the effect of wall roughness on the wall slip characteristics of MR fluids. The results showed that increasing the roughness and number of grooves of nonmagnetic wall materials could increase the shear stress transferred by them. While under magnetic wall conditions, the wall roughness had no effect on the magnitude of the shear stress generated. T. Zuzhi et al.[9] studied the mechanism of the wall slip generation and the influencing factors from both theoretical and experimental aspects. They investigated the effect of wall slip characteristics on the transfer capability of MR fluids on different experimental benches. The results showed that the transfer-wall material type and surface roughness have a significant impact on the transfer capability of MR fluids. C. Fei et al.[10] studied the effect of wall morphology on the slip phenomenon. The results showed that different wall morphologies have different effects on the slip. As a result, the viscosity and mass fraction of MR fluids, as well as the roughness of the transmission wall surface can have an impact on the wall slip effect. The role of different transmission surface topography features on the prevention of slip is complex.

According to the above, the existing research on wall slip characteristics is mainly qualitative experimental research. The analysis of the mechanism of occurrence and quantitative research on the influencing factors are limited. In the process of measuring the shear yield stress, the centrifugal and inertia forces have an impact on the measurement results. As a result, the accuracy with which the shear yield stress is used to determine the degree of wall slip needs to be improved. The wall slip phenomenon is unstable, having an impact on the rheological properties of MR fluids.[11] In this paper, a quantitative experimental study was conducted to verify the effect of the MR fluid viscosity and mass fraction on the shear yield stress based on various indicators affecting the wall slip. A simulation of the magnetic field distribution of shear blocks with different surface morphology characteristics was carried out using the COMSOL software. The results of the shear stress predicted by the simulation were compared with the experimental results to find and verify how the magnetic field distribution of shear blocks affects the wall slip effect, thus giving a transmission solution for attenuating the wall slip effect.

2 EXPERIMENTAL PART

2.1 Preparations of experiments

MR fluids with (67, 72 and 77) % mass fraction were configured using the base fluid replacement method and placed in beakers with labels.

An experimental table was built. A magnetic field generation device, shearing device and force measuring device were used for this experiment. During the experiment, the magnets were placed symmetrically at both ends of the fixed base in order to produce as uniform a magnetic field as possible. The drive mechanism, transfer mechanism and reservoir were all part of the shear device. The model of the stepper motor acting as a power source was YZ-57BLS120 (Hangzhou Yizhi Technology Co., Ltd.). In addition, we used a matching driver and

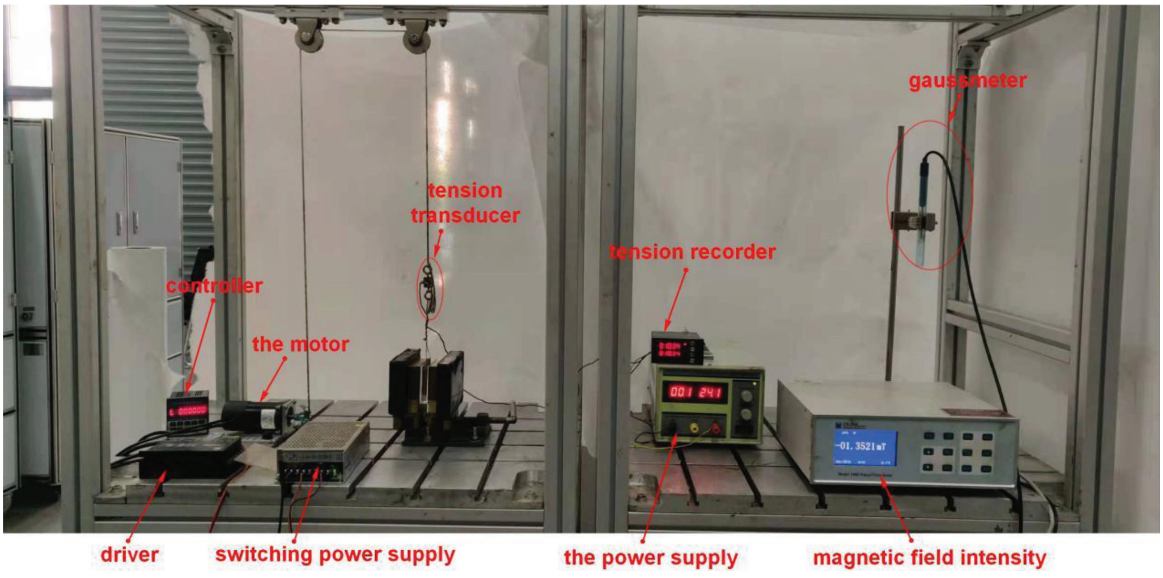

Figure 1: Experimental bench

controller to control the speed and lifting distance of the stepper motor. The role of the transfer mechanism is to convert the motor rotational force into pulling force, mainly including a pulling rope and fixed pulley. The reservoir is a device that holds the MR fluid so that the shear block can be pulled out of the device, fixed by the fixed base. For the material of the reservoir we selected a transparent acrylic plate. In addition to allowing us to visually observe the shear block pulling process, it is also a non-conductive material. It does not have an impact on the reservoir magnetic-field distribution uniformity. The length, width and thickness of the reservoir volume were (60, 60 and 10) mm, respectively. The force measuring device included a tension sensor and recorder (Shanghai Longlv Electronic Technology Co., Ltd.). Finally, the test stand was built with the above experimental equipment. Its structure and location are shown in **Figure 1**.

2.2 Viscosity test

An NDJ-5S digital rotational viscometer (Shanghai Star Optical Instrument Co., Ltd.) was selected. The surface of the measuring rotor of the viscometer was covered with 60, 120, 240 and 400 grit sandpaper, respectively. The MR fluid with the 72 % mass fraction was selected and placed in a beaker to measure the viscosity change under rotational speeds of (6, 12, 30 and 60) min^{-1}.

2.3 Mass-fraction experiment and surface-roughness experiment

Shear-yield-stress experiments were conducted at different magnetic field strengths using MR fluids with different mass fractions, in which a shear block without sandpaper and the one covered with 60 grit sandpaper were used.

The shear yield stresses of these two types of shear blocks were measured at different magnetic field strengths using the 72 % mass fraction MR fluid and shear blocks covered with 60 or 400 grit sandpaper.

2.4 Simulation and experimental analysis of surface morphological features

The magnetic field distribution of each groove on the transmission surface is changed by different machining shapes and sizes of the grooves on the surface, resulting in a change in the force between the magnetic particles and the transmission surface. The magnetically induced shear yield stress is affected by the wall slip of MR fluids. In other words, the surface topography has an impact on the wall slip characteristics of MR fluids. The surface processing of certain morphological features is a promising and feasible method for attenuating the wall slip characteristics. The types of shear block grooves are shown in **Figure 2**:

Shear blocks are semicircular, triangular, rectangular and trapezoidal in shape, with each shear block having the same number of grooves on one side and a direction that is perpendicular to the shear direction. The parameters of shear blocks are shown in **Table 1**.

Table 1: Model parameters of different slot shapes

Shear blocks	Depth of grooves (mm)	Width of grooves (mm)	Number of grooves		
Length (mm)	Width (mm)	Thickness (mm)			
50	50	6	1	2	24

There are three directions of the grooves (horizontal, 45 degrees, vertical). The information of the shear blocks is shown in **Table 2**.

Single-sided processing with 3, 6 and 12 vertical rectangular grooves is applied.

The rectangular groove width of the shear block is 2 mm, and the depths are 1 mm and 2 mm, respectively.

Figure 2 shows how the shear block models were imported into the COMSOL software for a magnetic field analysis. The set uniform boundary conditions included room temperature, 101.3 kPa (1 atm), spherical air domain outside the shear block and an air boundary radius of 50 mm. The magnetization direction was perpendicular to the surface of the shear block, and the intensity was 200 kA/m. A steady-state solution was used to ob-

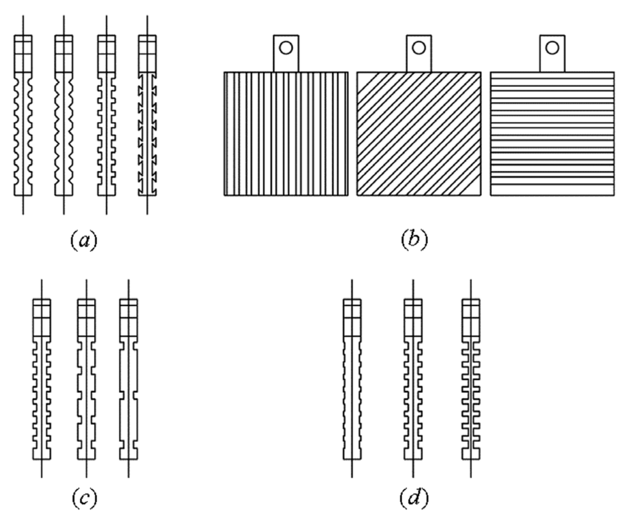

Figure 2: Different slotting types of shear blocks: a) different shapes, b) different directions, c) different densities, d) different depths

Table 2: Parameters of different slotting directions

Size of shear blocks (mm × mm × mm)	Material	Shape of grooves	Number of grooves	Size of grooves width (mm) × depth (mm))
50 × 50 × 6	Aluminum	Rectangle	24	2 × 1

serve the magnetic field distribution around the shear block grooves by dividing the tetrahedral mesh freely.

Then, on the constructed experimental table, a MR fluid sample with 72 % mass fraction was measured under the conditions of different surface characteristics of the shear block, and a lifting experiment was performed to obtain the variation in the shear yield stress with the magnetic field.

3 SIMULATION RESULTS

3.1 Different slotting shapes

Magnetic field concentration is generated at the recesses, as shown in **Figure 3**, in the magnetic field simulation of the above four slotted shapes. A concentrated magnetic field is located on both sides of a groove. The concentrated areas of the magnetic fields in the semicircular groove and rectangular groove are larger than those in the trapezoidal groove and triangular groove. The magnetic field distributions of the trapezoidal and rectangular recesses fluctuate greatly and the maximum values of the magnetic field are also large, so wall slips occur easily. The magnetic field distribution of the semicircle is small, as is the maximum value, and a wall slip is easy to occur. According to the above analysis, the magnetic particles produce greater magnetic adsorption on both sides of a groove than at its bottom. It means that it is easier for them to anchor at the sides (i.e., there is stronger adsorption between the particles at the end of the particle chain and the drive surface). It can be predicted that the shear blocks with trapezoidal grooves and rect-

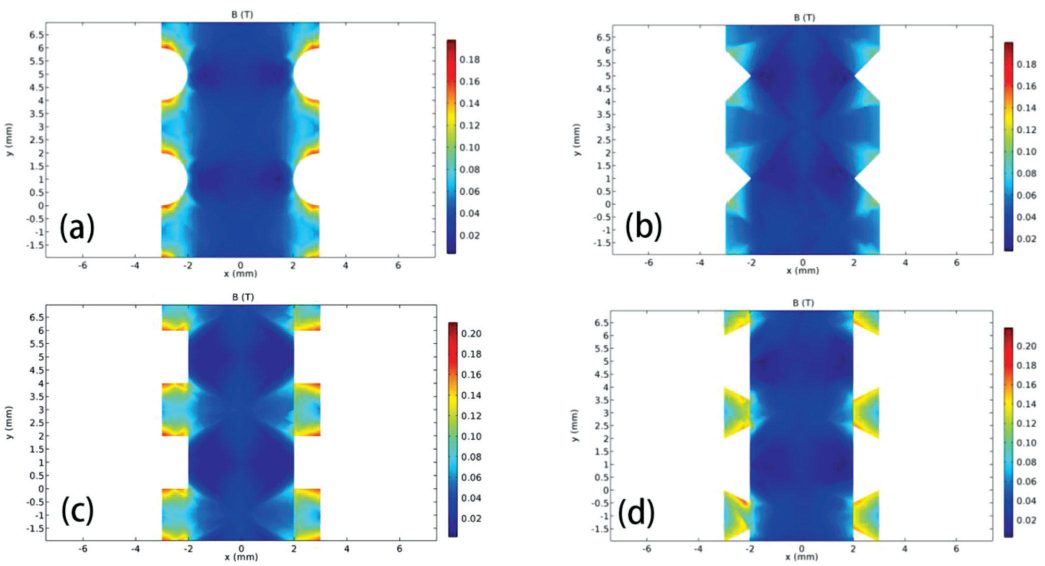

Figure 3: Magnetic field distribution at the grooves with different shapes: a) semicircular, b) triangular, c) rectangular, d) trapezoidal

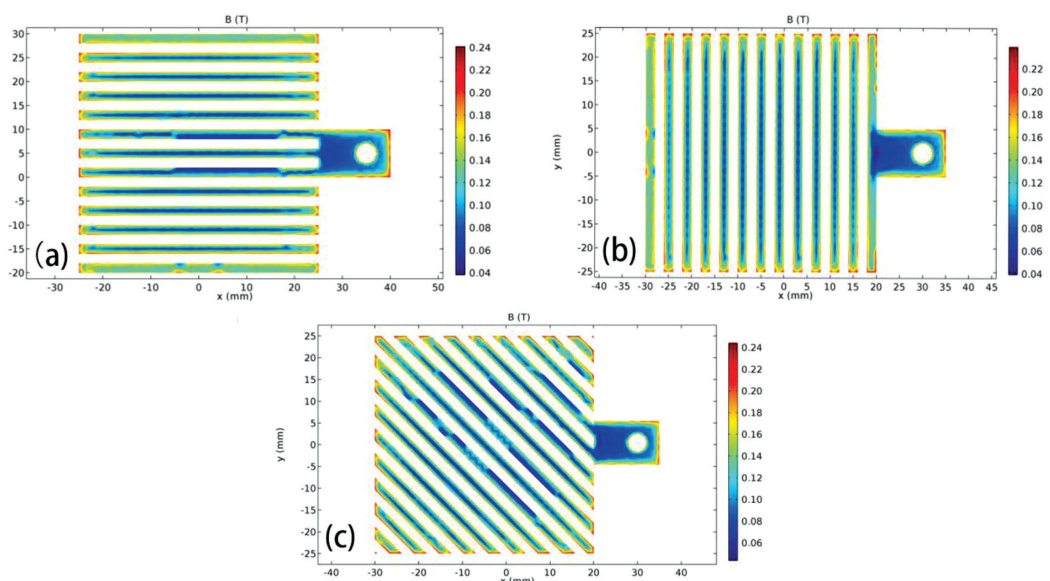

Figure 4: Magnetic field simulation of shear blocks in different grooving directions: a) horizontal, b) vertical, c) 45° direction

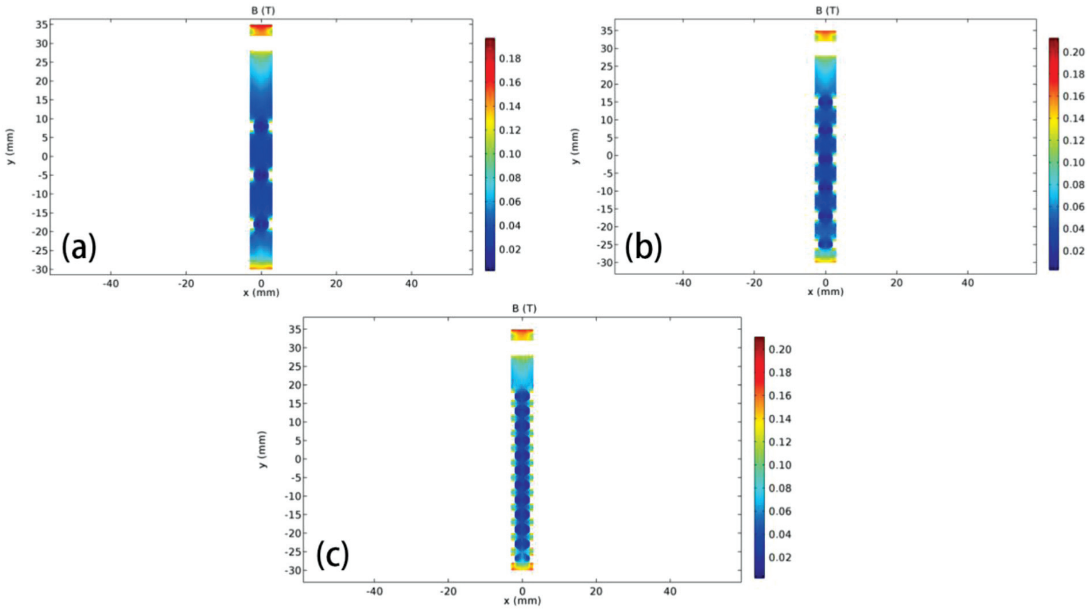

Figure 5: Magnetic field simulation of shear blocks with different grooving densities: a) 3 grooves, b) 6 grooves, c) 12 grooves

angular grooves have more difficulties with the wall slip than those with semicircular and triangular grooves.

3.2 Different slotting directions

As can be seen from **Figure 4**, the magnetic field in the groove position is the smallest for all three grooving directions. Magnetic field concentration is generated at the ends of both faces of a groove. It demonstrates that irrespective of the grooving conditions used, the end of the magnetorheological fluid particle chain is under the action of an anchor bolt.

In an actual working process, both vertical slotting and 45° slotting have a certain blocking effect on the movement of the particle chain. According to a comprehensive analysis and comparison, the order of the wall slip characteristics of an MR fluid from difficult to easy should be: vertical direction > 45° direction > horizontal direction.

3.3 Different slotting densities

According to the previous analysis, processing rectangular recesses on the surface of a shear block produces a magnetic field concentration effect at the rectangular recesses. From the specific analysis from **Figure 5**, it can be seen that machining different numbers of rectangular recesses on a surface can effectively produce the above phenomenon at each recess. The larger the number of rectangular recesses, the larger is the number of the positions where the magnetic particles can be anchored. The greater the shear yield stress, the more obvious is the effect on suppressing the MR-fluid wall-slip phenomenon.

3.4 Different slotting depths

The magnetic field distribution for the two grooves in the shear block transverse center is shown in **Figure 6**. The magnetic field concentration in the 2-mm-deep groove is more uniform, and the concentration area is more evenly distributed on both sides of the groove. On the other hand, the magnetic field concentration in the 1-mm-deep groove is mainly concentrated near the outer

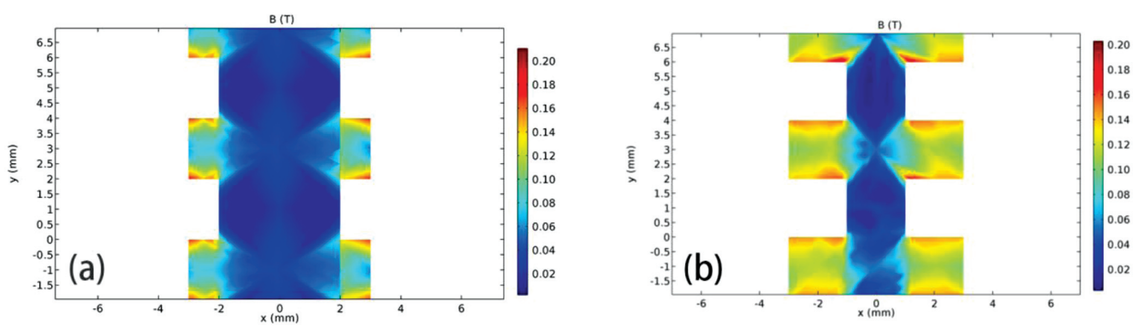

Figure 6: Magnetic field simulation of shear blocks with different grooving depths: a) 1 mm, b) 2 mm

surface of the groove. The magnetic field concentration becomes more visible as you get closer to the sharp corner of the outer surface. The maximum magnetic field generated by the 1-mm groove is larger than that generated by the 2-mm groove on the whole groove surface of the shear block. The magnetic field concentration location of the 1-mm groove is close to the outer surface of the shear block, which is more likely to produce the anchor bolt phenomenon. So it can be predicted that the 1-mm-deep recess should theoretically be more difficult to generate a wall slip than the 2-mm-deep recess.

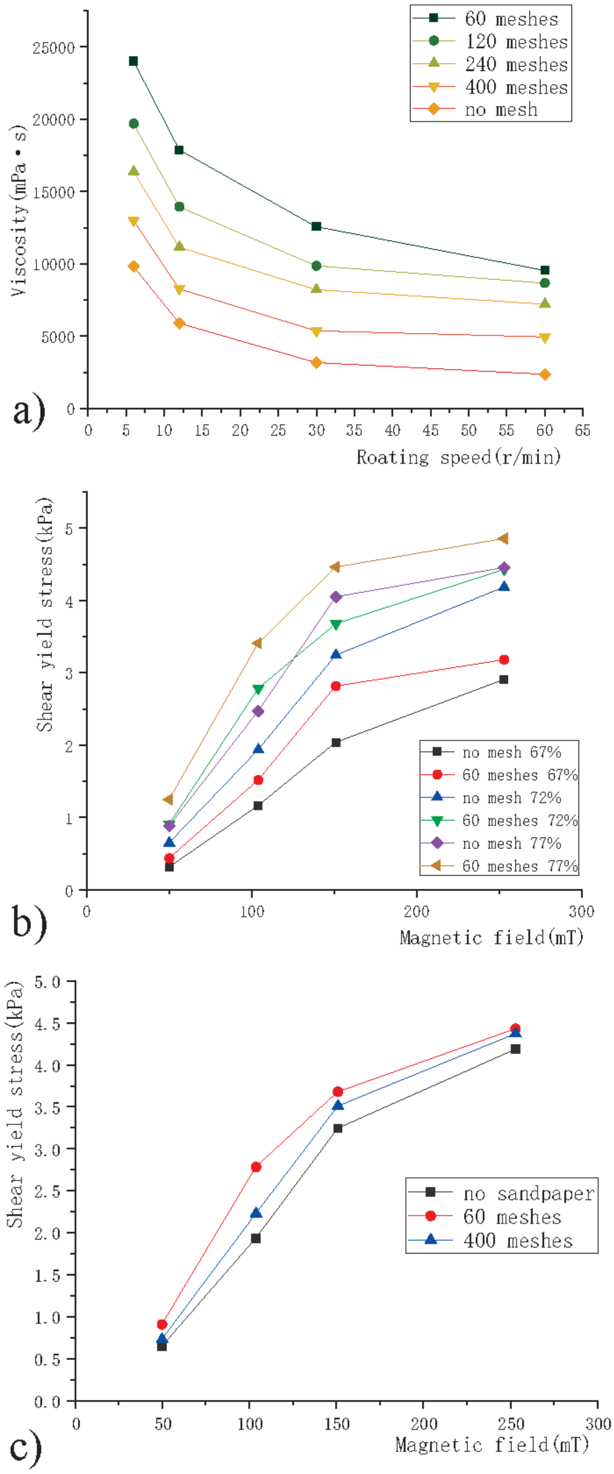

Figure 7: Variation of: a) zero-field viscosity under different roughness surfaces, b) shear yield stress under different mass fractions, c) shear yield stress under different surface roughness values

4 EXPERIMENTAL RESULTS

4.1 Viscosity experimental analysis

The viscosity of the MR fluid as a function of shear rate is depicted in **Figure 7a**. The viscosity value of the MR fluid varies with different-surface roughness values. The rougher the surface, the higher is the viscosity value at the same speed. At the same roughness of the rotor, the zero-field viscosity value of the MR fluid decreases as the shear rate increases, which is due to the shear thinning phenomenon when the MR fluid is shearing. Therefore, the viscous resistance can be increased by increasing the roughness of the transmission surface, which in turn weakens the wall-slip phenomenon.

4.2 Experimental analysis of the mass fraction and roughness

Figure 7a represents the variation in the shear yield stress at different mass fractions. The shear yield stress increases as the mass fraction of the MR fluid increases, as can be seen in the figure. This is due to the increase in the mass fraction, which increases the number of magnetic particle chains. The measured yield stress increases with the increase in the surface roughness of the shear block. This indicates that the surface roughness has a certain inhibitory effect on the wall slip of the MR fluid. The degree of increase in the shear yield stress varies between the two types of mass fractions, indicating that the influence on the MR fluid wall slip varies between the two types of mass fractions.

At low mass fractions, the wall slip of the MR fluid can be better suppressed by changing the external roughness. This phenomenon is caused by a small number of magnetic particles, poor chain aggregation under the magnetic field, and a simple chain structure, which is more likely to cause a wall slip. In this case, increasing the surface roughness can have a better inhibition effect. However, as the mass fraction of the MR fluid decreases, the shear yield stress decreases, which has an impact on practical applications. Although the average improvement rate decreases as the mass fraction of the MR fluid increases, the decrease is small and can still reduce the wall slip within a certain range. In summary, a MR fluid with a medium to high mass fraction should be used as the working fluid. As can be seen from **Figure 7b**, when the surface of the shear block is coated with sandpaper, the shear yield stress of the MR fluid is greater under the same magnetic-field working conditions, indicating that an increase in the surface roughness effectively suppresses the occurrence of a wall slip of a magnetorheological fluid. The shear yield stress gradually increases with an increase in the magnetic field strength. But the increasing trend is gradually slowed down, indicating that the effect of roughness on the wall-slip phenomenon starts to weaken under the working conditions of a high magnetic field strength.

4.3 Experimental analysis of surface morphological characteristics

4.3.1 Different slotting shapes

As can be seen from **Figure 8a**, all four grooving shapes have an effect on the wall slip of the MR fluid. Among them, the shear yield stress of the shear block with semi-circular grooves is slightly lower than that of the shear block without grooves, indicating that the semi-circular grooves have limited effect on suppressing the occurrence of a wall slip. On the other hand, the triangular grooves, rectangular grooves and trapezoidal grooves all increase the shear yield stress to a certain extent. Rectangular and trapezoidal grooves have a better effect, which is consistent with the simulation results. As a result, rectangular or trapezoidal grooves on a wall surface can be used to effectively reduce the wall-slip effect.

4.3.2 Different slotting directions

Figure 8b shows that under the same magnetic-field operating conditions, the rectangular groove in the vertical direction produces the highest shear yield stress and the lowest stress in the horizontal direction, which is the same as predicted by the simulation. The rectangular groove in the horizontal direction does not improve the shear yield stress of the MR fluid because the horizontal groove direction is the same as the shear direction. The magnetic particle chain of the MR fluid contributes to the occurrence of a wall slip during the shear process. As a result, grooves in the drive wall can be made in the vertical direction or at an angle of 45° to the shear direction to suppress the wall-slip effect.

4.3.3 Different slotting densities

According to **Figure 8c**, the shear yield stress of the MR fluid does not increase significantly when the shear block has 3 grooves on one side. The stress increases significantly when the groove density reaches 6 and 12 on one side. The simulation results are consistent with the experimental results. The suppression effect, on the other hand, decreases as the magnetic field strength increases, indicating that the magnetic field strength has begun to dominate. In summary, in order to effectively suppress

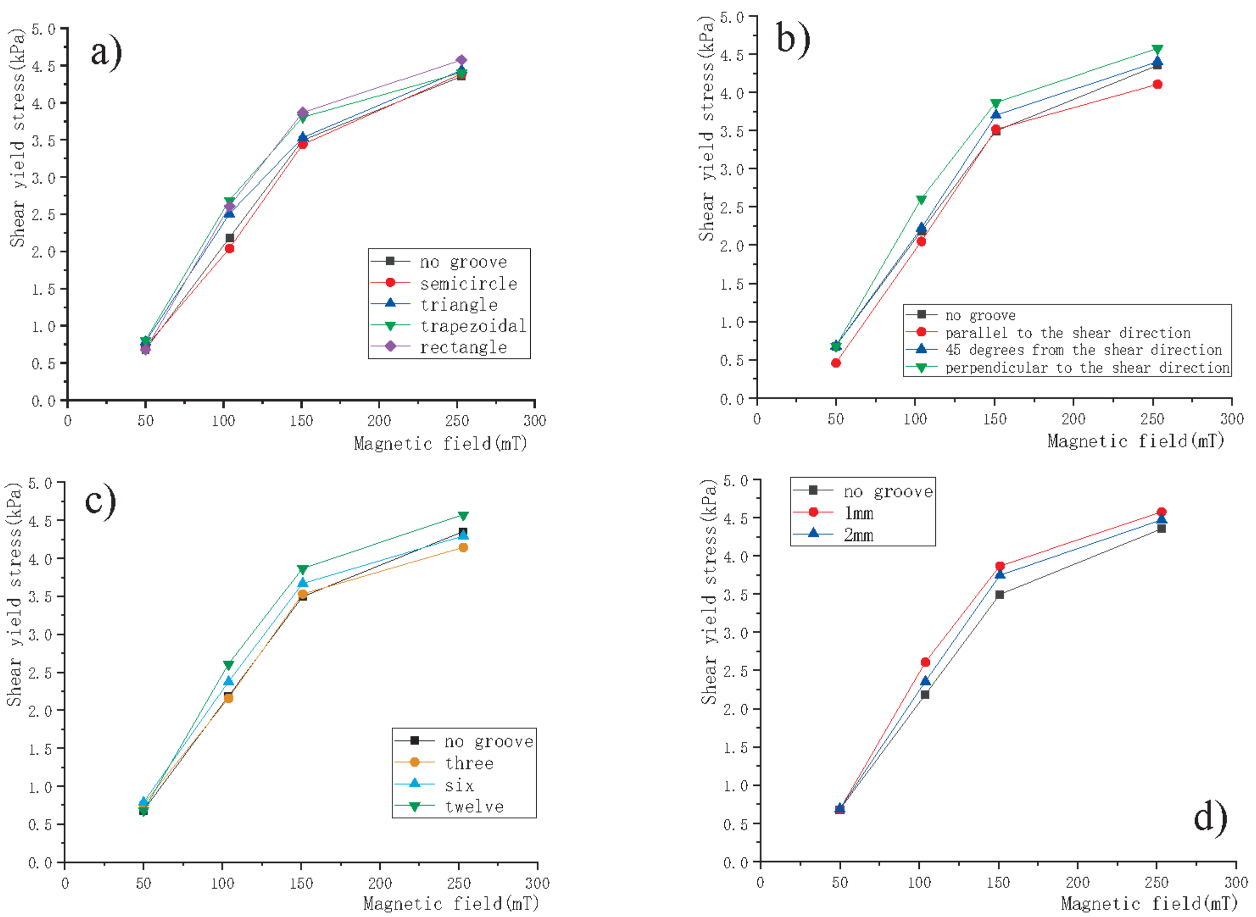

Figure 8: Variation in the shear yield stress under different surface morphologies: a) different shapes, b) different directions, c) different densities, d) different depths, e) different widths

the slip, more grooves should be machined on the transmission surface.

4.3.4 Different slotting depths

Figure 8 shows that all the shear blocks increase the shear yield stress after machining the grooves. However, the shear block with 2-mm grooves produced less yield stress than the shear block with 1-mm grooves, indicating that the grooving depth should not be too large. The magnetic field concentration phenomenon is more obvious in the shear block simulation for the 1-mm notch shear block. It means that the magnetic field concentration can make the magnetic particle chain anchor tighter and generate a greater yield stress. This is due to the fixed position of the magnetic field generating device and the fixed working gap on the outer surface of the shear block. When the depth of the groove increases, the working gap on the inner surface of the groove becomes larger, resulting in a loss of the magnetic field inside the groove and a reduction in the stress. As a result, in order to effectively suppress the phenomenon of the MR-fluid wall slip, the depth of groove wall should not be too large, and good results can be achieved at 1 mm.

5 CONCLUSIONS

The article experimentally confirms that the MR fluid parameters and transmission surface roughness can influence the wall slip characteristics. Both the viscosity and mass fraction of a MR fluid can effectively improve the yield stress during shear by increasing the viscosity and mass fraction of the MR fluid. The research demonstrates that changing the viscosity and mass fraction can be beneficial. The roughness of the transmission surface has an impact on the wall slip. The viscous resistance of the MR fluid increases with an increase in the surface roughness. In addition, the shear yield stress is greatly influenced by surface morphological characteristics. As different groove shapes lead to different magnetic field distributions, the structure of the magnetic particle chain varies. The thicker and tighter the magnetic particle chain, the greater is the anchor bolt force, and the more likely it is to prevent the occurrence of a wall slip.

6 REFERENCES

[1] X. J. Zhang, R. C. Wu, K. H. Guo, P. Y. Zu, M. Ahmadian, Dynamic characteristics of magnetorheological fluid squeeze flow considering wall slip inertia, Journal of Intelligent Material Systems and Structures, 31 (**2019**) 2, 229–242, doi:10.1177/1045389X19888781

[2] M. I. Varela-Jimenez, J. L. Vargas, J. A. Cortes-Ramirez, G. Song, Constitutive model for shear yield stress of magnetorheological fluid based on the concept of state transition, Smart Materials and Structures, 24 (**2015**) 4, 045039, doi:10.1088/0964-1726/24/4/045039

[3] E. Lemaire, G. Bossis, Yield stress and wall effects in magnetic colloidal suspensions, Journal of Physics D: Applied Physics, 24 (**1991**) 8, 1473–1477, doi:10.1088/0022-3727/24/8/037

[4] E. Esmaeilnezhad, S. H. Hajiabadi, H. J. Choi, Effect of medium viscosity on rheological characteristics of magnetite-based magnetorheological fluids, Journal of Industrial and Engineering Chemistry, 80 (**2019**), 197–204, doi:10.1016/j.jiec.2019.07.049

[5] I. Bahiuddin, S. A. Mazlan, I. Shapiai, F. Imaduddin, Ubaidillah, S. B. Choi, Constitutive models of magnetorheological fluids having temperature-dependent prediction parameter, Smart Materials and Structures, 27 (**2018**) 9, doi:10.1088/1361-665X/aac237

[6] W. N. Zhu, X. F. Dong, H. Huang, M. Qi, Iron nanoparticles-based magnetorheological fluids: A balance between MR effect and sedimentation stability, Journal of Magnetism and Magnetic Materials, 491 (**2019**), 165556.1–165556.6, doi:10.1016/j.jmmm.2019.165556

[7] S. Gorodkin, N. Zhuravski, W. Kordonski, Surface shear stress enhancement under MR fluid deformation, International Journal of Modern Physics B, 16 (**2002**) 17–18, 2745–2750, doi:10.1142/S0217979202012931

[8] H. M. Laun, C. Gabriel, C. Kieburg, Wall material and roughness effects on transmittable shear stresses of magnetorheological fluids in plate–plate magnetorheometry, Rheologica Acta, 50 (**2011**) 2, 141–157, doi:10.1007/s00397-011-0531-8

[9] Z. Z. Tian, F. Chen, D. M. Wang, Influence of wall characteristics on transmittable torque of magnetorheological fluid, Journal of Intelligent Material Systems and Structure, 25 (**2014**) 15, 1937–1949, doi:10.1177/1045389X13512189

[10] F. Chen, Y. F. Hou, Z. Z. Tian, Influence of wall texture on slip effect of magnetorheological fluids, Journal of Functional Materials, 44 (**2013**) 3, 451 (in Chinese), doi:10.3969/j.issn.1001-9731.2013.03.036

[11] J. L. Jiang, G. Hu, Z. M. Zhang, Y. G. Meng, Y. Tian, Stick-slip behavior of magnetorheological fluids in simple linear shearing mode, Rheologica Acta, 54 (**2015**) 9–10, 859–867, doi:10.1007/s00397-015-0877-4