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Analysis and Experimental Study on Rheological Performances of Magnetorheological Fluids

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1. Introduction

Magnetorheological fluids are suspension consisting of three parts: ferromagnetic particles, non – a magnetic carrier and additive. Without the action of a magnetic field, ferromagnetic particles are randomly dispersed in the non-magnetic fluid. Under the action of magnetic field, these ferromagnetic particles attract each other and form a chain structure along the magnetic field direction, resulting in the resistance to shear stress. The appearance is like a solid state [1-2]. The shear ability of the magnetorheological fluid varies with the magnetic field. After removing the magnetic field, the magnetorheological fluid immediately returns to the free flow state. The response time of the magnetorheological effect is very short, usually in milliseconds, and the transformation between solid and liquid is reversible. As a kind of intelligent material, magnetorheological fluid has many advantages, such as rapid change, continuous, high efficiency, safety and reliability [3]. Compared with other devices, magnetorheological fluid devices have the following advantages: control and adjustment have continuously changing performance, which can carry out precise real-time control [4]. The structure is simple, the work is soft, the noise is low, and the response speed is fast. Therefore, the use of new product development and magnetorheological effect compared to some products, has obvious advantages and market competitiveness in the use of performance, manufacturing, and price, has been used in aviation, aerospace, machinery, automobile, precision machining, control and other fields. With the development of research, magnetorheological fluids will be used in more fields and will show wide application prospects.

2. Constitutive model of magnetorheological fluid

Bingham model, Casson model and Herschel-Bulkley model are used to describe the rheological behavior for such fluids as magnetorheological fluids [5]. The Herschel-Bulkley model is a three variable model, and the computation is rather complicated. The Bingham model and Casson model have high computation accuracy and simple calculation method [6]. At present, the two models are used to simulate the rheological behavior of magnetorheological fluid. Bossis [7] and other have studied the yield stress of MR fluid. It is found that there is a dependency between yield stress and magnetic field. Alghamdi et al. [8] have analyzed the application of MRF in transmission technology. Zhao Chunwei et al. [9] observed the microstructure of magnetorheological fluidsand analyzed the formation and evolution of the microstructure of magnetorheological fluids under magnetic field [10]; rheological behavior of a magnetorheological fluid under the magnetic field in the experiment, using the Bingham model and Casson [11] model to fit the magnetic field under the action of magnetorheological fluid shear stress the relationship [12] between force and shear rate, analysis of the changes of magnetic field of magneto rheological fluid shear stress, with the actual reference value to engineering application of magnetorheological fluid.

The Bingham model can be expressed as [13]:

$$\tau = \tau_0\left(B\right) sign\left(\dot{\gamma}\right) + \eta\dot{\gamma}. \tag{1}$$

The Casson model can be expressed as:

$$\tau^{0.5} = \tau_0(B)^{0.5} sign(\dot{\gamma}) + \eta^{0.5}\dot{\gamma}^{0.5}. \tag{2}$$

Type: τ is shearing force of magnetorheological fluid; B is magnetic induction magnetic field; $\tau_0(B)$ is yield caused by magnetic field stress; η is magnetorheological fluid viscosity; γ is shear rate.

3. Preparation and experiment of magnetorheological fluid

3.1. Preparation of magnetorheological fluid

Magnetorheological fluid is the most widely used material for preparation of carbonyl iron powder. Because it is an industrial product, with large yield, low cost, high permeability and low magnetic coactivity, its magnetic saturation is about 2.1T, and has excellent soft magnetic properties. The liquid load of magnetorheological fluid should have the following characteristics: high boiling point, low freezing point, good chemical stability, non-toxic, no odor, low price and so on. At present, the non-magnetic carrier is mainly silicon oil, mineral oil, synthetic oil, water and ethylene glycol. In this experiment, two methyl silicone oils were used as the carrier liquid.

Magnetorheological fluids with 10% carbonyl iron powder volume fraction were prepared. Carbonyl iron powder, base liquid and stearic acid were weighed according to the calculated ratio. The average particle size of carbonyl iron powder is 3.3 um. The base solution is dimethyl silicone oil with a viscosity of 25 cst. The surfactant is stearic acid and the mass fraction of stearic acid is 2% of carbonyl iron powder. The carbonyl iron powder and stearic acid are mixed into stainless steel container and stirred at high speed for several hours. The treated mixture is removed in real condition. The surface of magnetic particles is purified by drying in an empty drying chamber. Then the suspended phase powders after pretreatment and drying are mixed with dimethyl silicone oil in a stainless steel grinding tank and dispersed by high-speed grinding. The magnetorheological fluid is obtained.

3.2. Experiment condition

The test instrument used in this experiment is Antongpa Physica MCR 301 flat plate rheometer. During the experiment, the magnetorheological fluids were put between the upper and lower plates of the rheometer and sheared at a shear rate of 50 s^{-1} for 150 s without magnetic field to ensure good dispersion of the magnetorheological fluids. Then the shear stress of MRF was measured under different conditions.

The current is set to 1, 2, 3 and 4 A respectively. According to the data of the instrument manual, the magnetic induction intensity of the magnetic field is 0.23, 0.44, 0.65 and 0.86 T respectively. The shear rate is set to vary in the range of 0-1000s^{-1}. The temperature is 25°C and the shear time is 10 s. Sampling once every 0.1 s, the shear stress and the shear stress of magnetorheological fluid are measured. Changes in apparent viscosity. The shear rate is 300 s^{-1}, the magnetic field varies in the range of 0-0.5 T, the temperature is 25°C the shear time is 10 s, and the shear stress of MRF is measured every 0.1 s.

Table 1

Experimental conditions for measurement of shear stress and apparent viscosity of magnetorheological fluids

I, A	*B*, T	γ, s^{-1}	*T*, ℃	*t*, s
1	0.23	0~1000	25	10
2	0.44			
3	0.65			
4	0.86			

Table 2

Experimental conditions for measuring shear stress changes in magnetorheological fluids

I, A	*B*, T	γ, s^{-1}	*T*, ℃	*t*, s
1	0-1.5	300	25	10
2				
3				
4				

4. Experimental results and analysis

The relation between shear stress and shear rate of magnetorheological fluid is shown in Fig. 1 when the magnetic field is applied. It is shown that under the action of constant magnetic field, with the increase of shear rate, the shear stress first decreases slightly, then gradually increase and tends to be stable. The larger the magnetic field is, the more obvious the initial shear stress decreases. At the same shear rate, the shear stress increases with the increase of the magnetic field, and the range is 1.08~12 kPa. The relationship between apparent viscosity and shear rate of magnetorheological fluids is shown in Fig. 2. In Fig. 2, it can be seen that the apparent viscosity decreases significantly with the increase of the shear rate under the constant magnetic field. At the same shear rate, the apparent viscosity increases with the increase of the magnetic field, and the range is 2.5 Pa.s~ 28.7 kPa.s.

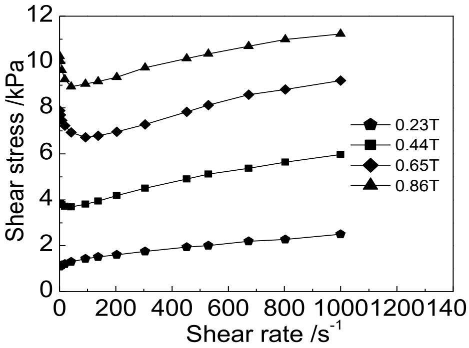

Fig. 1 Dependence of shear stress on shear rate

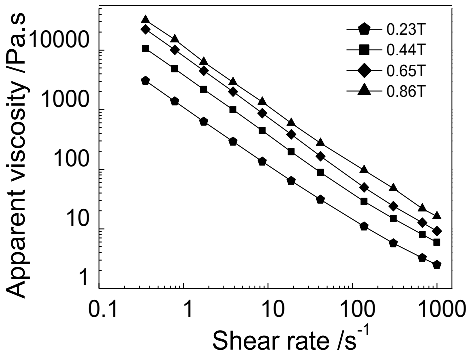

Fig. 2 Dependence of apparent viscosity on shear rate

4.1. Using Bingham model for fitting

The rheological behavior of magnetorheological fluid using Bingham model fitting calculation, as shown in Fig. 3, the fitting results are shown in Table 1, see from Fig. 3 and Table 3, magnetorheological fluid shear stress has the good linear relationship between stress and shear rate, the magnetic field increased from 0.23 T to 0.86 T, cut by Bingham model the calculated stress increased from 1369 to 8825 Pa, the magnetic field is increased by 274%, the shear yield stress increases 545%.

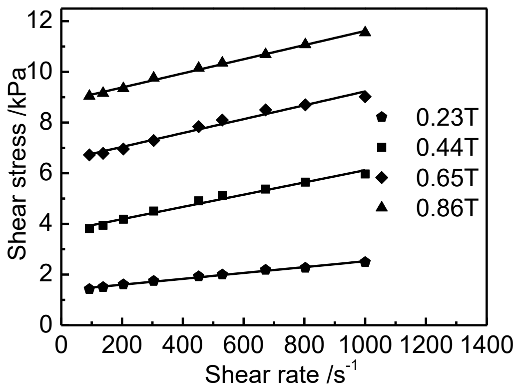

Fig. 3 Using Bingham model to fit the shear stress of MRFs

Table 3

Fitting calculation results on shear stress of MRFs using Bingham model

B, T	Fitting equation	R^2	τ_y, Pa	*H*, Pa s
0.23	y=1.15x+1369	0.991	1369	1.15
0.44	y=2.41x+3703	0.980	3703	2.41
0.65	y=2.73x+6491	0.976	6491	2.73
0.86	y=2.79x+8825	0.995	8825	2.790

4.2. Using Casson model for fitting

The Casson model is used to fit the rheological behavior of magnetorheological fluids. As shown in Fig. 4, the fitting results are shown in Table 2. From Fig. 4 and Table 2, it can be seen that there is a good linear relationship between the shear stress and the shear rate of magnetorheological fluids. The magnetic field increases from 0.23 T to 0.86 T, and the shear yield stress calculated by Casson model fits follows. 1043 Pa increased 7624 Pa, 274% and shear yield stress 631%. It can be concluded that the results of the two models fitting the MRF shear stress all have good linear correlation, and the shear yield stress obtained by Bingham model is slightly higher.

Under the action of magnetic field, the ferromagnetic particles in magnetorheological fluids are arranged in a chain structure. When the magnetorheological fluids begin to shear, the grain chains between the plates are suddenly destroyed and cannot be restored in time. The macroscopic manifestation is that the shear stress decreases. With the increase of shear rate, new particle chains are formed under the action of magnetic field, shear stress increases gradually, and apparent viscosity decreases. When the shear rate increases to a certain extent, the fracture and formation of grain chains will reach equilibrium, and the shear stress will reach a stable value. The larger the magnetic field is, the stronger the interaction force between particle chains in MRF is, and the larger the shear stress is. It can be concluded that with the increase of shear rate, the shear stress increases and tends to stabilize, and there exists a shear thinning phenomenon in the shear stress.

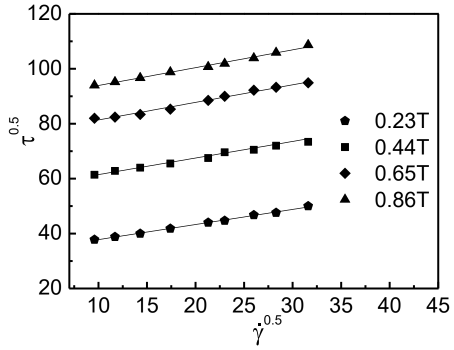

Fig. 4 Using Casson model to fit the shear stress of MRFs

The relationship between shear stress and magnetic field of magnetorheological fluid is shown in Fig. 5. It shows that with the increase of magnetic field, the shear stress increases significantly, and its range is 200 Pa ~ 11 kPa. When the magnetic field is relatively small, the ferromagnetic particles in magnetorheological fluid do not reach magnetization saturation. Under the action of magnetic field, particles interact with each other, forming the chain column structure. The macroscopic expression is that the shear stress increases rapidly, showing a rapid growth. With the increase of magnetic field, the ferromagnetic particles in magneto rheological fluid are magnetized locally, and the shear stress increases steadily. The macroscopic stress is approximately linear growth of shear stress. It can be predicted that if the magnetic field continues to increase and the particles are close to full magnetization saturation, the shear stress will change very little, and the shear stress will reach a stable value when the particles are completely magnetized. It can be concluded that the shear stress of the magnetorheological fluid increases significantly with the increase of the applied magnetic field.

Table 4

Fitting calculation results on shear stress of MRFs using Casson model

B, T	Fitting equation	R^2	τ_y, Pa	H, Pa s
0.23	y=0.55x+32.3	0.997	1043	0.30
0.44	y=0.60x+55.5	0.992	3080	0.36
0.65	y=0.64x+75	0.985	5625	0.41
0.86	y=0.65x+87.4	0.992	7627	0.42

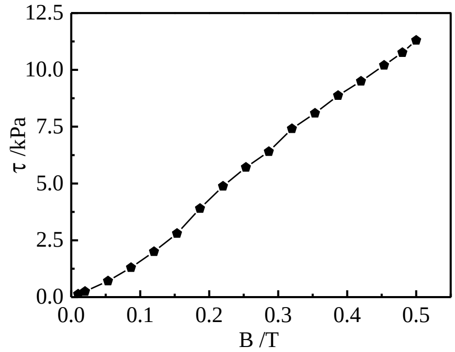

Fig. 5 (Similar number of figures) Dependence of shear stress on magnetic field

5. Conclusions

1. Under the action of magnetic field, the stress shear of magnetorheological fluid of hydroxyl iron powder increases slowly with the increase of shear rate, and the apparent viscosity decreases exponentially; the magnetic field remains unchanged, and the shear stress increases with the increase of shear rate. It tends to be stable and shear thinning exists.

2. Under the action of magnetic field, the shear stress and apparent viscosity of magnetorheological fluid increase significantly, the range of shear stress is 1.08~12 kPa, and the apparent viscosity range is 2.5 Pa.s~28.7 kPa.s. The shear yield stress calculated by Bingham and Casson model is 1043~8825 Pa. With the increase of the magnetic field, the shear stress of the magnetorheological fluid increases significantly, and the change range is 200 Pa ~11 kPa.

3. The relationship between shear stress shear rate and apparent viscosity of MRF is analyzed, and various factors affecting the response characteristics of MRF materials, design parameters and optimization design of MRF materials are analyzed. It provides a theoretical basis for improving the properties of magnetorheological materials. According to the characteristics of magnetorheological fluids, the rheological characteristic curves are provided for the design of related products.

References

1. **Zhang, H. H.; Luo, M. Q.; Li, D. H.; Zhong, Y. F.; Bu, D. C.** 2016. Effect of different volume fraction of carbonyl-iron-powder on properties of magneto-rheological fluid, Experimental Technology and Management 33(4): 61-64, 67 (in Chinese). http://dx.doi.org/10.16791/j.cnki.sjg.2016.04.018.

2. **Chen F.; Tian Z. Z.; Wang, J.** 2014. Influence of temperature on the performance of magnetorheological fluid, Journal of Functional Materials 45(20): 20095-20098 (in Chinese). http://dx.doi.org/10.3969/j.issn.1001-9731.2014.20.020.
3. **Huang, L.; Cha, C. S.** 2016. Mechanical properties of magnetorheological elastomers, Journal of Materials Science and Engineering 34 (1): 139-141 (in Chinese). http://dx.doi.org/10.14136/j.cnki.issn1673-2812.2016.01.028.
4. **Wang Y. F.; He, L.; Yang, X.; Shuai, C. G.** 2010. Study on the development of magnetorheological elastomers and its application in engineering, China Elastomerics 20(3): 62-66 (in Chinese). http://dx.doi.org/10.3969/j.issn.1005-3174.2010.03.016.
5. **Chen, F.** 2013. Research on MRF preparation and power transmission technology, PhD dissertation of China University of Mining and Technology (in Chinese).
6. **Wei, Q. L.; Wang, C.; Luo, Q.; HE, J. G.** 2013. Rhelogical behaviors of a magnetorheological fluid in magnetic fields, Journal of Magnetic Materials and Devices 44(1): 6-9 (in Chinese). http://dx.doi.org/10.3969/j.issn.1001-3830.2013.01.004.
7. **Bossis, G.; Khuzir, P.; Lacis, S.; Volkova, O.** 2003, Yield behavior of magnetorheological suspensions, Journal of Magnetism and Magnetic Materials 258-259: 456 -458. http://dx.doi.org/10.1016/s0304-8853(02)01096-x.
8. **Alghamai A. A.; Lostado, R. l.; Olabi, A. G.** 2014. Magneto-rheological fluid technology, Modern Mechanical Engineering 252(1-3):43-62. http://dx.doi.org/10.1007/978-3-642-45176-8_3.
9. **Zhao, C. W.; Peng, X. H.; Shi, X. D.** 2014. Experimental observation the micro-structure of MRF, Journal of Functional Materials, 45(10): 10049-10054 (in Chinese). http://dx.doi.org/10.3969/j.issn.1001-9731.2014.10.010.
10. **Wu, J. R.; Li, X. Q.; Li, X. H.; An, H.** 2014. Preparation of the magneto-rheological fluid and experimental study on its surface tension coefficient, Micronanoelectronic Technology 51(3): 146-150 (in Chinese). http://dx.doi.org/10.13250/j.cnki.wndz.2014.03.002.
11. **Yao, J.; Zhang, J. Q.; Peng, Z. Z.; Zhang, G. L.** 2014. Influence of Fe content and particle size of carbonyl iron powder on shear yield stress of magnetorheological fluids, Chinese Journal of Material Research 28(12): 955-960. http://dx.doi.org/10.11901/1005.3093.2014.361.
12. **Ren, Z. P.; Yuan, M. T.** 2016. Analysis of harmonics measurement based on the multiplier and LabVIEW simulation, Journal of Qingdao University (Engineering & Technology Edition) 31(1): 34-39 (in Chinese). http://dx.doi.org/10.13306/j.1006-9798.2016.01.007.
13. **Choi, S. B.; Han, Y. M.** 2012. Magnetorheological Fluid Technology-Applications in vehicle systems. CRC Press.

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ANALYSIS AND EXPERIMENTAL STUDY ON RHEOLOGICAL PERFORMANCES OF MAGNETORHEOLOGICAL FLUIDS

S u m m a r y

Silicone-based Magnetorheological Fluids (MRFs) were prepared with 10% volume fraction of carbonyl iron powder. Rheometer Physica MCR 301 was used to test the rheological performances of MRFs.The experimental results show Bingham model and Casson model could well describe rheological behaviors of MRFs. Shear stress of MRFs increases but apparent viscosity is significantly decreased and tends to be stable with the increase of shear rate in the presence of magnetic field. The results also show that MRFs are shear thinning fluids. The dependence of shear stress on magnetic field was tested under the condition of constant shear rate and increasing magnetic field, shear stress of MRFs increases remarkably.

Keywords: magnetorheological fluid, rheological performance, magnetic field, structural model.

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