Effect of different volume fraction magnetorheological fluids on its shear properties

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Abstract. In order to study the relationship between shear stress and volume fraction and shear rate of MRFs, four kinds of MRFs with different volume ratios were prepared. The shear stress of MRFs at different shear rates was tested by rheometer. The shear stress expression of MRFs is obtained by fitting and analyzing the experimental data. The experimental results show that under the same volume fraction, the shear stress of MRF increases slowly, and the apparent viscosity decreases exponentially with the increase of shear rate.

1. Introduction

Magnetorheological Fluid (MRFs) are a new kind of intelligent material, which is a suspension formed by dispersing micron-sized ferromagnetic particles in liquid polymer[1]. MRFs can flow freely and show the characteristics of Newton fluids without the presence of magnetic field. The magnetorheological effect of MRFs occur in the presence of magnetic field with the ferromagnetic particles gather themselves along the field direction and the fluids turn to solid-like within a few milliseconds. MRFs have not only good abilities of easy control, fast response and reversibility[2,3], but also the advantages of simple preparation, low cost and wide temperature range for use, MRFs can be widely used in vibration absorb mechanism control and other fields[4-6].

The research on MRFs is mainly focus on properties of shearing. Bossis studied the shear stress of MRFs with different volume ratio under different magnetic field, and obtained that the shear stress is proportional to the volume fraction and the square of magnetic field strength[7]. By studying the particle coating process, Liu found that the shear stress and apparent viscosity of the coated MRF increased by half under the same magnetic field strength[8]. Kim study shows that the shear stress of MRF is directly proportional to the magnetic field strength[9]. Chiranjit Sarkar's study found that the shear stress of MRF was also related to the particle size. The larger the particle size, the better the shear performance[10]. Yi et al obtained similar conclusions through finite element analysis. These studies show that the shear stress of MRF is closely related to volume fraction, magnetic field strength and particle size[11].

In this paper, the rheological behavior of MRFs in presence of magnetic field was studied, and the relationship between shear yield stress and shear rate of MRFs with different volume fraction was analyzing.

2. Paterial preparation and testing

2.1 Sample preparation

The MRFs samples consist of four components: ferromagnetic particles, base carrying fluids, surfactants and additives. The composition, size and volume fraction of ferromagnetic particles have
great influence on the properties of MRFs. The carbonyl iron powder MRS-MRF-35 that manufactured by Jiangsu Tianyi Ultra-fine Metal Powder Company was used as the ferromagnetic particles. The shape of the particles is spherical and the average size of the particle is 3.14 micrometer. The matrix carrier is generally selected from a material with small viscosity to facilitate uniform dispersion of the carbonyl iron powder particles. Dimethyl silicone oil is selected as the matrix carrier. It can be used in the temperature range of -50 to 300 °C. Surfactants of sodium dodecyl sulfate was added during the preparation to prevent sedimentation. Polyvinylpyrrolidone used as the dispersant with mass ratio to matrix carrier was 1:10. Fig.1 shows the preparation processes in which a high-speed stirring is carried out using a KQM-X4 planetary ball mill, and the DZF-6020 vacuum drying oven is used for vacuuming. MRFs with ferromagnetic particle volume fractions of 10%, 20%, 30%, and 40% were prepared for subsequent experiments.

2.2 Particle structure observation

The particle microstructure of the MRFs were observed at the presence of a uniform magnetic field by Keyence's VHX-600 optical microscope. The self-made magnetic field source was fixed on the microscope's observatory. The magnetic field source is an electromagnetic solenoid with a wide air gap. The magnetic field was modified by DC power. Fig.2 is the observing system and Fig.3 shows the observed pictures. It can be seen that the carbonyl iron powder particles are randomly distributed under the zero field. After the application of the magnetic field, the carbonyl iron powder particles rapidly aggregate into the chain along the direction of the magnetic field.

Microscopic view of the internal structure observed by electron microscopy: With the increase of the volume ratio of magnetorheological fluid, based on the minimum energy state, the magnetic particles gradually form a continuous single row of long chains of particles. The arrangement between the particles and the particles is more and more dense, the spacing is reduced, and the magnetic field force between the particles is increased. As the volume ratio continues to increase, a network structure
will eventually form, the structure becomes denser, and the macroscopic performance is greater the shear stress. Therefore, as the volume fraction increases, the shear yield stress of the magnetorheological fluid increases at the same shear rate.

2.3 Colour illustrations
The shear properties of MRFs were tested by Aaton Paar Physica MCR 301 with the magnetic component. In the experiments, the shear rate was set in the range of 0-1000s\(^{-1}\), the magnetization current was set to 1A, the temperature was set to 18°C, and the shear time is set to 30 s. The shear stress of MRFs was measured automatically every 0.1s. The effect of different volume fraction on the shear stress was studied by changing the test sample and shear rate in turn.

3. Analysis and discussion
Fig.4 shows the different volume fractions of MRF, and the shear stress varies with shear rate. It can be seen that as the shear rate increases, the shear stress increases gradually and is basically linear. When the volume ratio is 40%, the shear stress increases significantly when the shear rate is between 100s\(^{-1}\) and 500s\(^{-1}\). At the same shear rate, the shear stress increases significantly with the increase of volume ratio. The shear stress increases slowly between 20% and 30%. The extent of the increase in the remaining stages is significantly faster. It can be seen that when the shear rate is constant, the magneto-rheological fluid increases with the volume fraction from 10% to 40%, and the yield stress increases from 3.9KPa to 14.2KPa, and the stress increases significantly.

![Figure 4. Effect of Shear Rate on Shear Stress of MRFs](image)

According to the research, a generalized Bingham model and a nonlinear model are established, which can accurately reflect the shear thinning phenomenon of MRF[12].

\[ \tau = \tau_0(B) + \eta \gamma \tag{1} \]

\(\tau\) -Shear stress;
\(\tau_0(B)\) -Shear stress under magnetic field
\(\eta\) -Apparent viscosity
\(\gamma\) -Shear rate

A double exponential fit was performed on the experimental data.
Figure 5. Shear rate fitting curve of shear stress of MRFs

Under the action of an external magnetic field, the magnetorheological fluid has a relatively large shear stress due to the aggregation of its magnetic solid particles to form a certain structure. According to the formula, the shear stress of the magnetorheological fluid is divided into two parts, one is the shear stress generated by the magnetic field force under the action of the magnetic field, and the other part is related to the apparent viscosity and the shear rate.

The shear stress generated by MRFs under the action of magnetic field is further analyzed and studied. By fitting the shear stress with the volume fraction, the relationship between the formula \( \tau_0(B) \) and the volume fraction is obtained:

\[
\tau_0(B) = 32.913\varphi + 0.5848 \tag{2}
\]

Figure 6. Fitting curve of shear stress with volume fraction

Apparent viscosity is a physical concept that refers to the quotient of the shear stress divided by the shear rate at a given velocity gradient. Therefore, the apparent viscosity can be expressed as:

\[
\eta = \eta(\varphi, \gamma)
\]

By fitting the curve of apparent viscosity with volume fraction, the relationship between \( \eta \) and volume fraction is obtained:

\[
\eta(\varphi) = 0.3526\ln(\varphi) + 4.1189 \tag{3}
\]
Figure 7. Approximate curve of apparent viscosity with volume fraction

Figure 8 shows the shear rate as a function of MRFs apparent viscosity at different volume fractions. It can be seen from the figure that the shear rate is between 100 s\(^{-1}\) and 300 s\(^{-1}\), the apparent viscosity drops rapidly, and the change is slow and tends to be flat after 300 s\(^{-1}\). At the same shear rate, the apparent viscosity increases with increasing volume fraction. When the shear rate is 100 s\(^{-1}\) and the volume fraction is increased from 10% to 40%, the apparent viscosity increases from 40.91 to 139.9 Pa\(\cdot\)s. When the shear rate increases to 1000 s\(^{-1}\), the apparent viscosity is stable at 6.131 and 18.16. The volume fraction of carbonyl iron powder in the magnetorheological fluid increases, and the zero field viscosity of the magnetorheological fluid increases. The mechanism is that the magnetorheological fluid increases its internal friction due to the presence of ferromagnetic particles. Therefore, the viscosity of the magnetorheological fluid becomes large. The higher the density of the ferromagnetic particles, the greater the internal friction per unit volume, resulting in a larger zero field viscosity of the magnetorheological fluid.

Figure 8 Apparent viscosity changes with shear rate
Analysis and calculation of the above data, available

\[ \eta(\dot{\gamma}) = 8113.1 \dot{\gamma}^{-0.882} \]  \hspace{1cm} (4)

Bring formula (2),(3),(4) into (1) respectively:

\[ \tau = \tau_0(B) + \eta \dot{\gamma} \]
\[ = 32.913\phi + 0.5848 + [(0.3526\ln(\phi) + 4.1189)8113.1 \dot{\gamma}^{-0.882}] \dot{\gamma} \]

Therefore, the shear stress is related to the volume fraction and shear rate, which is consistent with the proposed influencing factors, and the test results are in line with the previous theory.

4. Conclusion

Through theoretical and data analysis, the following conclusions can be drawn:

1. The Bingham model was used to fit the shear stress and shear rate of MRF under different volume fractions. As the volume fraction increases from 10% to 40%, the yield stress of MRF increases from 3.9 kPa to 14.2 kPa. When the volume ratio is constant, the shear stress of MRF increases slowly with the shear rate, but the change is not very obvious.

2. Through the experimental data, you and the analysis, the calculation formula of the shear stress and volume fraction and shear rate of MRFs is derived, which is the basis for the subsequent stress calculation.

3. When the volume ratio is constant, the surface viscosity of MRF decreases exponentially with the increase of shear rate.

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