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Properties of magneto-rheological fluids based on amorphous micro-particles

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Abstract: To improve the magneto-rheological (MR) properties of magneto-rheological fluids, self-made amorphous alloy particles, the composition of which was $Fe_{76}Cr_2Mo_2Sn_2P_{10}B_2C_2Si_4$, were used as the disperse phase to replace traditional carbonyl iron (CI) particles to prepare amorphous based magneto-rheological fluid (AMRF). Soft magnetic properties and densities of the amorphous particles and the CI particles were tested and compared. The results indicate the amorphous particles present a lower density but larger magnetization intensity and larger permeability at lower field levels. Properties of the AMRF with 20% particles in volume fraction were tested and compared with the CI based MR fluid (CMRF). The AMRF presents a saturation yield stress of 41 kPa at ~227 kA/m and a sedimentation ratio of 80%. The results indicate the magneto-rheological fluid based on amorphous micro-particles has better MR properties and sedimentation stability than that based on CI particles at lower field levels (0−200 kA/m).
Key words: magneto-rheological fluids; amorphous particles; carbonyl iron; soft magnetic properties; microstructure

1 Introduction

Magneto-rheological fluids (MRFs) are suspensions of magnetic micro-particles in a carrier fluid, usually mineral or silicon oil [1−3]. When placed in magnetic field, their apparent viscosities greatly increase. As a result, they change from linear viscous fluids (Newtonian fluid) with free flow to semi-solid materials (Bingham fluid) with controllable yield stress, and the process is reversible. Their ability of changing shear stress in an applied magnetic field gives rise to their many possible applications. Typically, they can be used in semi-active controllable fluid dampers for vehicles and for buildings protection against vibrations [4−6].

Carbonyl iron (CI) particles are widely used as the magnetic phase for MR fluids due to their high magnetic permeability and soft magnetic properties. The MR fluids fabricated with CI particles show great MR effect, whose yield stress even reaches ~100 kPa at 250 kA/m [7−9]. However, one serious drawback of the MR fluids with CI particles is that they subject to thickening after prolonged use and need replacing, because the density of the CI particles is too high [10,11]. Adding surfactant or coating polymer only solves the problem to some extent [12−14]. Another shortcoming of the fluids is their relatively large magnetic hysteresis, which is harmful for their longevity. Besides, in some applications, the maximum yield stress needed is only ~40 kPa, but the magnetic field required to reach the yield stress for the CI based MR fluids is large.

Applying magnetic particles with lower density, less magnetic hysteresis, and higher magnetic permeability may solve those problems [15−17]. Many amorphous magnetic materials show more excellent soft magnetic properties and lower density with respect to the carbonyl iron. In this work, a new MR fluid was fabricated by amorphous micro-particles, as $Fe_{76}Cr_2Mo_2Sn_2P_{10}B_2C_2Si_4$. Their magneto-rheological properties, sedimentation stability, and microstructure were investigated and compared with the CI based MR fluid with the same particle content.

2 Experimental

$Fe_{76}Cr_2Mo_2Sn_2P_{10}B_2C_2Si_4$ particles were used to fabricate the amorphous magneto-rheological fluid (AMRF). The original amorphous material was prepared

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by an in-rotating-water quenching technique. Then micro-particles were prepared by ball milling. Carbonyl iron micro-particles purchased from Jiangyou Hebao Nanomaterial Co., Ltd., were used to produce the carbonyl iron based magneto-rheological fluid (CMRF). Magnetic properties of the CI particles and the amorphous particles were tested at room temperature with vibrating sample magnetometer (VSM, JDM−13).

Silicon oil was used as the carrier liquid. Its density was 0.97 g/cm^3, and its kinematic viscosity was 0.5 Pa·s. Titanate coupling agent was chosen as the surfactant to increase the stability of the fluid.

The particles were dispersed in a sodium hydroxide solution for a few minutes to etch off a layer of surface, and then washed several times using distilled water. Titanate coupling agent in 2% of the mass of the particles was dissolved in an acetone solution. The washed dry particles were then dispersed in the solution. To ensure that all the particles were coated with the surfactant uniformly, an ultrasonic wave was applied until all the acetone was volatilized. Finally, the treated magnetic micro-particles were obtained. Then the treated particles were mixed with the silicon oil. The particles volume fractions were 20% for the two kinds of MR fluids based on the CI particles and the amorphous particles. Intense agitation was applied to the mixture for more than 60 min to obtain MR fluids with uniformly dispersed micro-particles.

The viscosity—shear rate curves at zero magnetic field, shear stress—shear rate curves at constant magnetic field, and yield stress—magnetic field strength curves at constant shear rate were measured using a rheometer Physica MCR301 fitted with a magneto-rheological module which can apply different magnetic fields by changing direct current. As shown in Fig. 1, the diameter and the gap of the parallel-plate system were 20 mm and 1 mm, respectively. All the measurements were performed at room temperature.

A self-made system including two permanent-magnets, a stereomicroscope, a computer and a chase filling with MR fluids, as shown in Fig. 2, was used to observe the microstructure of the MR fluids in magnetic field.

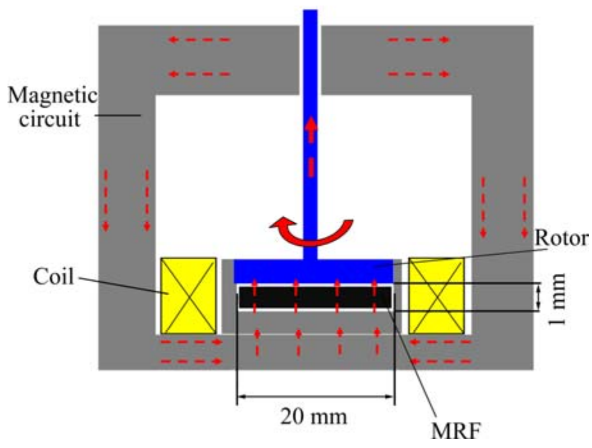

Fig. 1 Test system of MR properties

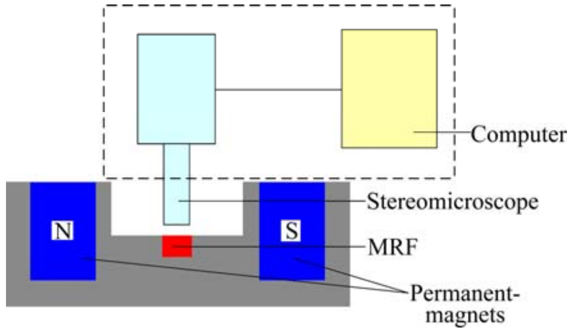

Fig. 2 Self-made microstructure observation system

The sedimentation experiments were carried out at room temperature using graduated flask. The sedimentation ratio, defined by the height percentage of the particle-rich phase relative to the total suspension height, was used to evaluate the sedimentation stability of the MR fluids.

3 Results and discussion

3.1 Properties of amorphous particles

As shown in Fig. 3, the amorphous particles are spherical and moderately polydisperse. The average size of the amorphous particles was ~5 μm. Figure 4 shows the X-ray diffraction pattern of the amorphous particles. The broad band between 30° and 60° confirms the amorphous structure.

The magnetic hysteresis cycles of the CI particles and the amorphous particles are shown in Fig. 5. It reveals that both particles have a similar behavior, but they differs in saturation and remnant magnetization, saturation magnetic field, and coercive field. As shown in Table 1, compared with the CI particles, the amorphous particles present lower density, lower saturation and remnant magnetization, lower saturation magnetic field and lower coercive field. The squareness ratio given by the ratio of M_r/M_s is essentially a measure of the soft magnetic properties for magnetic materials. The squareness ratios of the CI particles and the amorphous particles were 0.014 and 0.007, respectively, which indicates that the magnetic hysteresis of the amorphous particles is less than that of the CI particles.

The comparison of the initial M—H curves and the initial μ_r—H curves between the CI particles and the amorphous particles is shown in Fig. 6. At low field levels, the amorphous particles present larger magnetization intensity and larger permeability than CI particles.

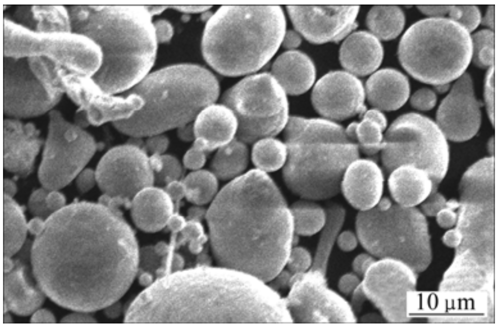

Fig. 3 SEM image of amorphous particles

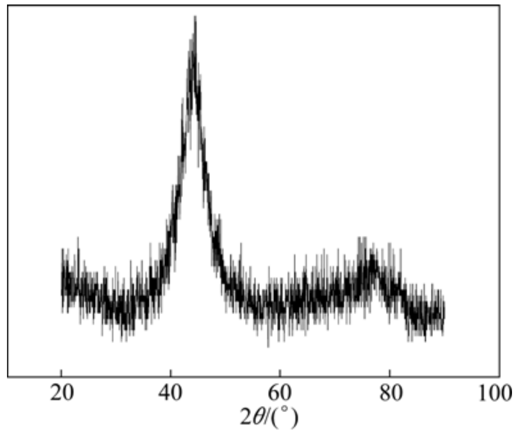

Fig. 4 X-ray diffraction pattern of amorphous particles

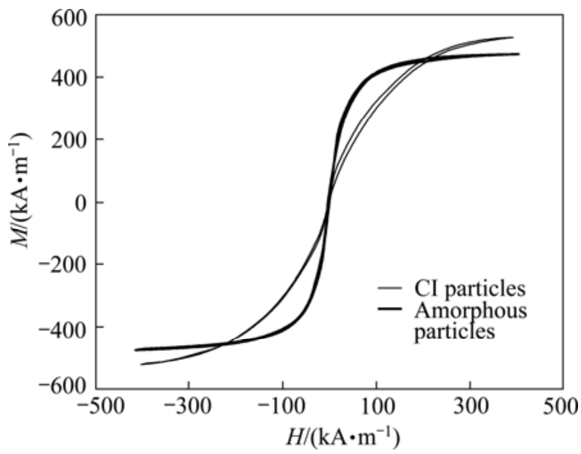

Fig. 5 VSM data of CI particles and amorphous particles

3.2 Properties of amorphous MR fluid

Figure 7 presents the typical flow curves for MR fluids containing 20% (volume fraction) CI particles and amorphous particles, respectively. Due to the shear-thinning effect, the viscosities of the two fluids decrease

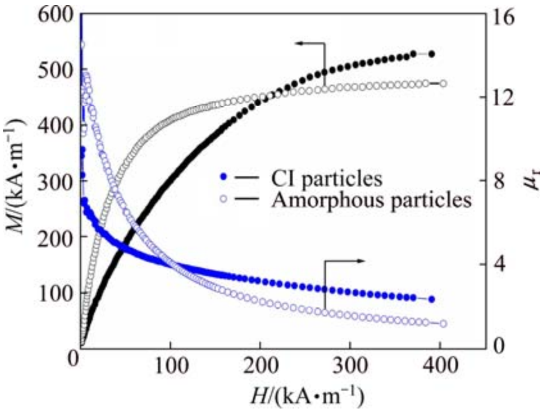

Fig. 6 Dependence of magnetization and permeability on magnetic filed of CI particles and amorphous particles

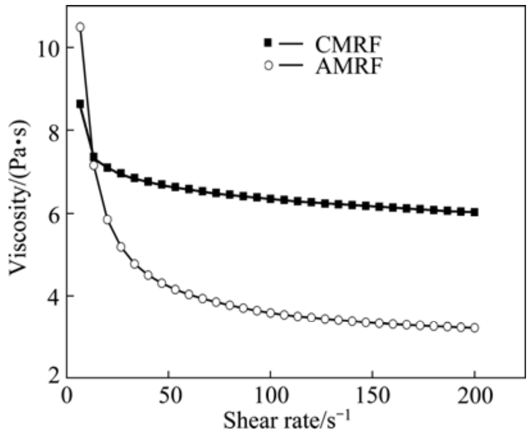

Fig. 7 Viscosity versus shear rate for AMRF and CMRF in the absence of magnetic field

dramatically with increasing the shear rate at low shear rate level, and then the changes become gentle and reach a constant value at high shear rate level. When the shear rate exceeds 10 s^{-1}, the AMRF presents much lower viscosity than the CMRF.

Figure 8 represents shear stress as a function of shear rate for CMRF and AMRF under five different magnetic field strengths (0, 82, 142, 186, and 206 kA/m). The range of shear rate tested was from 6.67 to 200 s^{-1} linearly. Both the two MR fluids represent typical Bingham behavior under a magnetic field. The shear stress strongly depends on the magnetic field strength. To further illuminates this phenomenon, for the two MR fluids, the dependences of yield stress at constant shear rate of 200 s^{-1} on the magnetic field strength ranging

Table 1 Main characteristics of carbonyl iron particle and amorphous particle

Sample	Density/($g\cdot cm^{-3}$)	M_s/($kA\cdot m^{-1}$)	M_r/ ($kA\cdot m^{-1}$)	M_r/M_s	H_s/ ($kA\cdot m^{-1}$)	H_c/ ($kA\cdot m^{-1}$)	μ_r
Carbonyl iron particles	7.87	518.57	7.36	0.014	~346	2	9.2
Amorphous particles	7.05	473.65	3.29	0.007	~227	1	13.4

M_s: Saturation magnetization; M_r: Remnant magnetization; H_s: Saturation magnetic field; H_c: Coercive field; μ_r: Relative initial permeability.

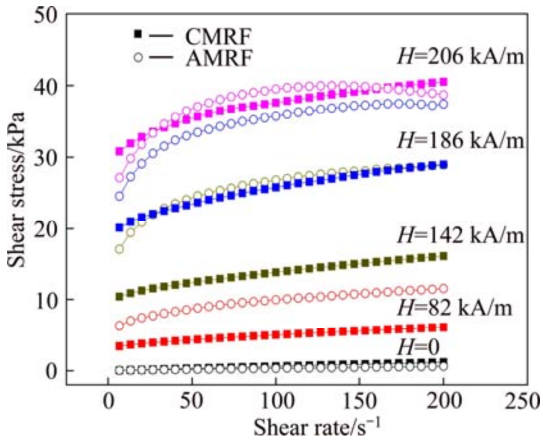

Fig. 8 Shear stress—shear rate curves for CMRF and AMRF under different magnetic field strengths

from 0 to 206 kA/m were tested, which are shown in Fig. 9. It indicates the yield stress increases with increasing magnetic field strength, initially slow, and then becomes dramatic, and finally becomes slow. This phenomenon is caused by the formation of robust columns due to the strong dipole-dipole interaction among the adjacent magnetic particles. The saturation yield stresses for CMRF and AMRF obtained by extrapolating the fitting curves are 70 kPa at 346 kA/m, and 41 kPa at 227 kA/m, respectively. Although the AMRF presents much lower saturation yield stress with respect to the CMRF, its yield stress at low field levels (0−200 kA/m) is larger than that of the CMRF. This observation can be explained by their microstructures. As shown in Fig. 10, under a magnetic field of 80 kA/m, the columns formed by the amorphous particles in silicon oil are more robust than those formed by the CI particles. The results indicate that the AMRF produces more excellent MR properties than traditional CMRF at low field levels. The reason is that the magneto-rheological effect was caused by the strong attraction force between the adjacent magnetic particles,

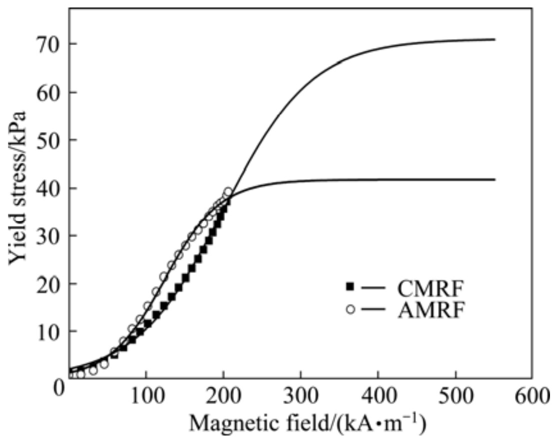

Fig. 9 Yield stress—magnetic field curves at shear rate of 200 s^{-1} for CMRF and AMRF

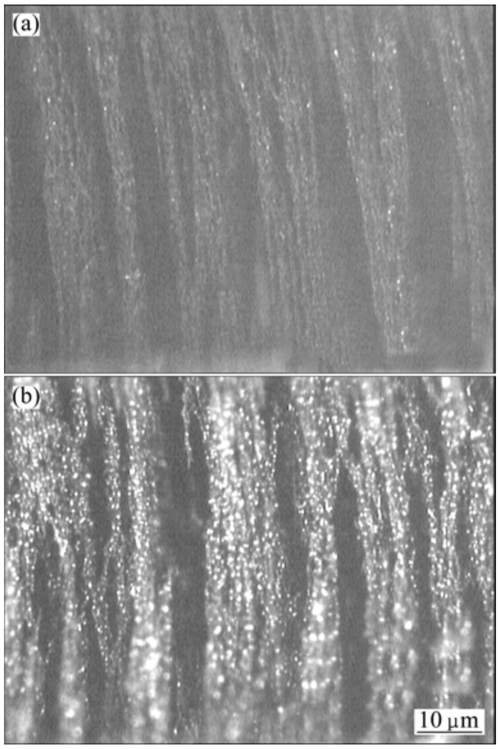

Fig. 10 Microstructures of CMRF (a) and AMRF (b) at 80 kA/m

and the amorphous particles present better soft magnetic properties than the CI particles. In applications, it is difficult to get a high magnetic field strength. Therefore, the advantage of the AMRF under low field levels is meaningful.

Figure 11 shows the sedimentation ratio with the time for the two MR fluids containing different particles. CI particles settle down rapidly within the initial 5 d, while amorphous particles settle down slowly. Although the average particle size of the amorphous particles is larger than that of the CI particles, the AMRF shows improved sedimentation stability. The most likely reasons for such discrimination may include two aspects. First, the density of the amorphous particles is lower

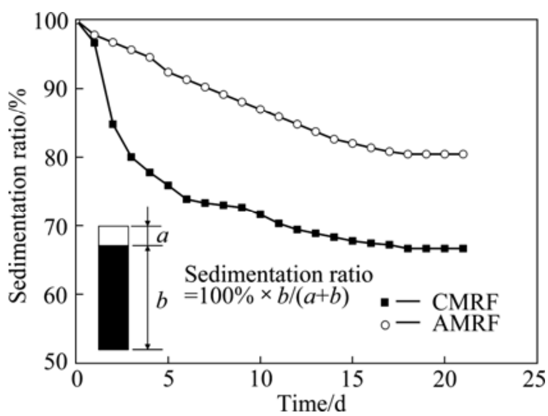

Fig. 11 Time dependence of sedimentation ratio of CMRF and AMRF

than that of the CI particles. Second, CI particles are easier to congregate to form conglomerations.

4 Conclusions

1) The amorphous particles present less magnetic hysteresis, larger permeability at low magnetic field levels, and lower density than the CI particles.

2) The AMRF presents much lower viscosity in the absence of a magnetic field than the CMRF. The AMRF achieves a saturation yield stress of 41 kPa at ~227 kA/m. Although it is much lower than the saturation yield stress of the CMRF, the MR property at low field levels (0−200 kA/m) for the AMRF is better than for the CMRF.

3) Due to its low density and being difficult to congregate, the AMRF presents improved sedimentation stability with respect to the CMRF.

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基于非晶微米颗粒的磁流变液性能

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摘 要：采用成分为 $Fe_{76}Cr_2Mo_2Sn_2P_{10}B_2C_2Si_4$ 的自制非晶颗粒取代传统羰基铁粉作为分散相，制备非晶型磁流变液，以提高磁流变液的性能。对比非晶颗粒和羰基铁粉的软磁性能和密度，发现非晶颗粒具有较低的密度，在低磁场中具有较高的磁化强度和磁导率。测试颗粒体积含量为 20%的非晶磁流变液和羰基铁粉磁流变液的性能，可知非晶磁流变液在 227 kA/m 磁场强度下其饱和剪切屈服强度达 41 kPa，抗沉降率为 80%。在低磁场中(0~200 kA/m)基于非晶颗粒的磁流变液具有比羰基铁粉磁流变液更优的磁流变性能和沉降稳定性。

关键词：磁流变液；非晶颗粒；羰基铁粉；软磁性能；微观结构

(Edited by YANG Hua)