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TECHNICAL NOTE

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The strengthening effect of guar gum on the yield stress of magnetorheological fluid

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Abstract
In this paper we present a novel approach for producing obvious strengthening of the magnetorheological (MR) effect of MR fluids. Carbonyl iron powders coated with guar gum were used as magnetic particles in the MR fluid. Experimental results showed that inducing a guar gum coating not only greatly improved the sedimentation stability but also strengthened the yield stress of the MR fluid. An intermolecular force based model was proposed for explaining the strengthening effect.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Magnetorheological (MR) fluid, invented by Rabinow in the late 1940s [1], is a complex fluid consisting of magnetic particles dispersed in liquid carrier media such as oil and water, showing a unique ability to change its rheological behaviors intensively, continuously and rapidly with external magnetic fields [2]. The process is completely reversible and the timescale for the transition is in the order of milliseconds, thus making the MR fluid an ideal material for use in valves [3], braking and clutch systems [4] and shock absorbing dampers [5].

The difference in density between magnetic particles and the carrier medium of the MR fluid make the magnetic particles tend to sediment and further form 'cake' under a magnetic field or static storage, which is the main reason for instability of the MR fluid. Using a viscoelastic medium [6], surfactant [7], nanoadditives [8] and coating on the magnetic particles can effectively improve the sedimental stability [9, 10]. On the other hand, the magnetorheological effect of MR fluid needs to be strengthened for its commercial application. Furthermore, many applications require the fluid to have a low off-state viscosity. This means that we need to select a well suited method to improve the sedimental stability of MR fluids combining with their MR effects and off-state viscosity.

Obviously, using a viscoelastic medium will increase the off-state viscosity intensively. The MR effect would decrease on using non-magnetic additives [11]. Inducing surfactant or coating on the magnetic particles could avoid the increase of the off-state viscosity and the decrease of the MR effect by controlling well the amount of surfactant or coating and processing the coating well. In our previous report [10], we have developed guar gum as a green additive for MR suspensions. The sedimental stability of the MR fluid was improved intensively, and the MR effect was almost unchanged. However, guar gum needs to be co-ball-milled with carbonyl iron powders for a long time, which is not appropriate for the commercializing of the MR fluid. Therefore, in our research, the carbonyl iron powders were firstly coated with guar gum instead of ball milling, and then

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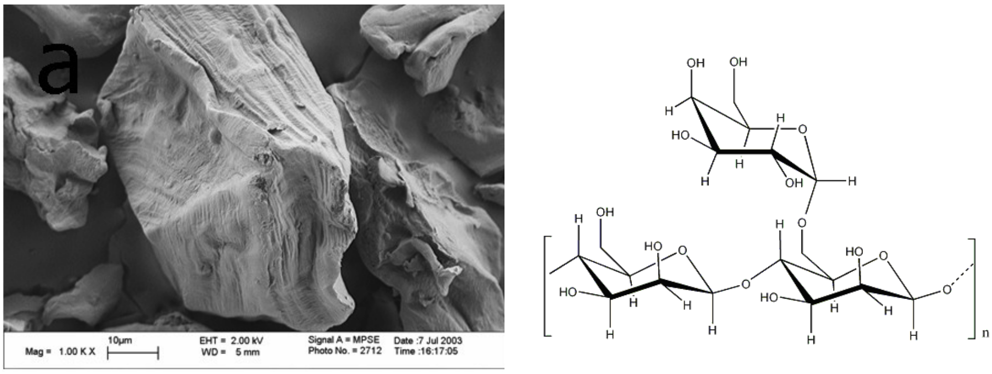


Figure 1. Scanning electron micrograph (1000×) and the molecular structure of guar gum.

mixed with silicone oil. It was found that the MR effect of the MR fluid was obviously strengthened in this way.

A typical MR fluid using carbonyl iron particles at 33% volume fraction produces a yield shear stress of about 25–35 kPa under a magnetic field of 0.4 T [4], which is not sufficient for some demands such as automobile clutches and manufacturing flexible fixtures. Using a higher volume loading of the particles [7, 12] or magnetic field B can enhance the MR response [13]; however, these methods will induce other problems such as increase of the zero-field viscosity, making the MR devices heavier and larger for getting a strong magnetic field [5]. Therefore, a lot of efforts at improving the quality of the dispersion phase such as using alloy particles [14] and nanoadditives [8] have also been developed to get MR fluids with higher yield stress. What we have found mentioned above has not been reported.

In this article, we present our experimental procedure and characterization results, and also make a attempt to explain the strengthening effect.

2. Materials and methods

In this research, methyl silicone oil with viscosity of 10 centipoises at 25 °C and pure water are used as the carrier fluids in the synthesis of MR fluids. The iron powder used throughout this work is a commercial product of HEBAO NANOMATERIAL Co., Ltd (Sichuan, China); its particle diameter is 2–4 μm and it typically consists of >96% pure iron and small quantities of carbon, nitrogen and oxygen as impurities.

In the synthesis of MR fluids, certain amounts of the water and guar gum power were mixed for 30 min at 400 rpm to get guar gum water solution. The carbonyl iron powder was first washed with acetone in an ultrasonic tank, then dried and added to the gel and mixed for 30 min at 600 rpm. Ethanol was then added slowly to the gelatinous mixture, which leads to guar gum precipitating and forming a coating layer on the iron powder. The proportion of the guar gum to the carbonyl iron powder by weight ranged from 1:100 to 14:100.

The precipitate was washed with acetone, filtered, milled and then vacuum dried to remove all trace water. MR fluids were then prepared by mixing the powder well with a certain amount of methyl silicone oil of 10 mPa s and ball milled for about one hour at 25 °C. The mass concentration of the powder was approximately 80%.

The morphologies of suspension particles in the MR fluids were observed with scanning electronic microscopy (SEM), JSM-6360LV JEOL, and transmission electron microscopy (TEM), Tecnai 20 S-TWIN Philips. The yield stress of the MR suspension was determined with a self-made parallel-plate rotational EMR rheometer. Stainless steel parallel-plate fixtures with diameters of 25 mm were used and the gap was set to 0.5 mm. The maximum magnetic field upon application of samples to be determined, which was produced by an iron core coil linking with a stabilized current supply, was not more than 0.5 T due to a limitation of the design. The fixture was strictly calibrated with the commercial MR product MRF-132LD of LORD Corporation and the relative error was found by examination to be no more than 5%. The sedimentation of various MR suspensions with different guar/Fe ratios was also studied with the measuring method used in [10].

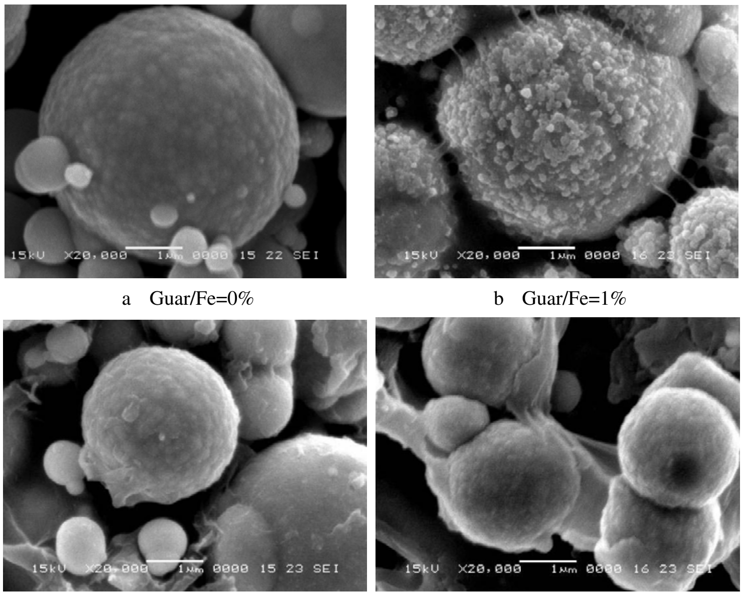
3. Results and discussion

3.1. The organic–inorganic composite particles

Guar gum is a rigid, non-ionic, polydisperse rod-shaped neutral carbohydrate polymer. Figure 1 show its scanning electron micrograph and molecular structure. As described in [10], the guar gum has a very large area of hydrogen bonds.

Figure 2 shows the morphology of carbonyl iron powders coated with different contents of guar gum. Obviously, with the increase of the content of guar gum, the coating was formed gradually and finally became smooth membrane-like coating surfaces. As shown in figure 2(b), the guar gum deposited on the surface of the carbonyl iron particles in the form of spots. The coatings become continuous until the guar/Fe ratio reached 3% or above. The thickness of the encapsulations significantly increases with the guar/Fe ratio, and finally the coating layers connected with each other, which made the particles bind to each other to form large conglomerations.

The transmission electron microscope (TEM) images shown in figure 3 also indicate that these particles have a shell–core composite structure. The surface of the composite particles is completely covered by guar gum layers. The thickness of the coating layer is tens of nanometers, much thinner than the radius of the particles.



a Guar/Fe=0% b Guar/Fe=1%

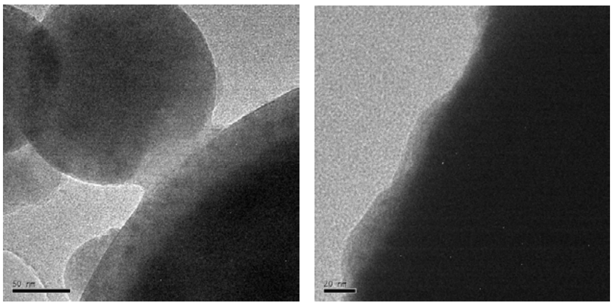
c Guar/Fe=3% d Guar/Fe=14%

Figure 2. Morphology evolutions of composite iron particles with guar gum encapsulations (20 000×).

Table 1. Zero-field viscosity of MR suspensions (shear rate: 100 s^{-1}) in terms of the guar/Fe ratio.

Guar gum/Fe ratios		0%	1%	3%	5%	8%	11%	14%
Zero-field viscosity (Pa s)	Well coated with guar gum	0.29	0.32	0.70	0.98	0.67	0.59	0.24
	Simple mechanical mixing		0.30	1.16	1.24	0.93	1.27	1.97
Final sedimentation ratio[a] (%)		25	3.3	2.55	3.2	4	4.5	5.9

[a] MR fluid with carbonyl iron powders well coated with guar gum.



a b

Figure 3. Images of composite particles (guar/Fe = 3%).

3.2. MR effect

The effect of the external magnetic field strength (B) on the magnetic field induced shear stress (τ) for the MR suspension of 20% (by weight) coating composite particles with different guar/Fe ratios in methyl silicone oil at a shear rate (γ) of 100 s^{-1} is presented in figure 4. Obviously, the MR suspension based on guar/Fe coating composite particles shows the MR effect; its shear stress increased linearly with incrementation of the magnetic field strength B ranging from 0 to 0.30 T but shifted to a nonlinear form when the magnetic field was higher (see figure 4).

As shown in figure 4, the MR effect of the MR fluid with guar gum coated carbonyl iron particles is obviously higher than that of the other two kinds of MR fluids without using guar gum coated carbonyl iron particles. It can also be found that the ratio of guar gum to the carbonyl iron powder influenced the MR effect of the MR fluid. Figure 5 indicates more clearly the relation between the value of guar/Fe and the MR effect.

It can be clearly seen that the MR effect of the MR fluid with the coated iron powder reached its maximum (about 52.5 kPa) when the guar/Fe ratio was equal to 3%, and then dropped slightly until the guar/Fe ratio was up to 14%. The maximum value is much higher than those for the other samples in this paper and the reference [10], which proves the strengthening effect of the guar gum coating layer on the surface of the carbonyl iron particles. The strengthening effect is beyond our estimate. To our mind, the inducing of the coating on the iron powders will reduce the magnetism of the iron powders; therefore, the MR effect of the MR fluid will also be reduced. Furthermore, the iron volume fraction declines from 33% to 29.50% as the ratio of guar/Fe increases from 1% to 14%. According to classical theoretical and experimental predictions, the yield stress would suffer a remarkable decrease as it is proportional to the volume fraction

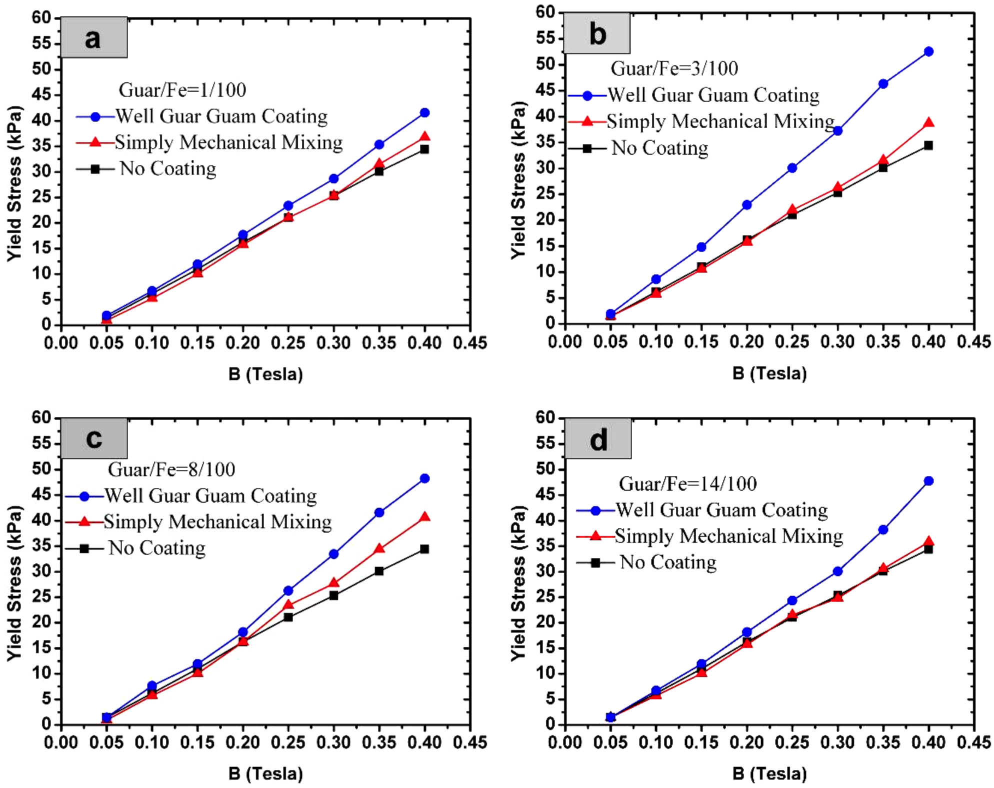


Figure 4. The response of the shear stress for MR suspensions of three different coating states upon application of a stepwise magnetic field at 25 °C and $\gamma = 100\ s^{-1}$. No guar gum coating (■), good guar gum coating (●) and simple mechanical mixing (▲) are presented.

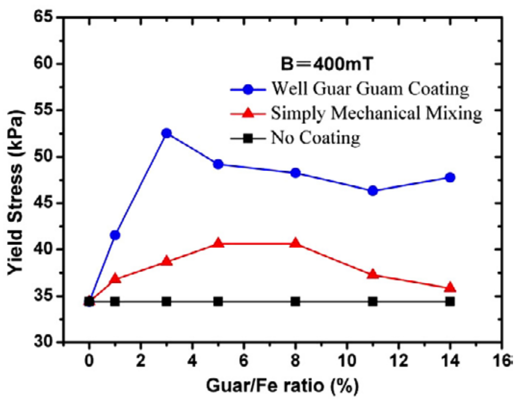


Figure 5. The response of the shear stress for a MR suspension of 80% (by weight) coating composite particles with different guar/Fe ratios (1%–14%) in methyl silicone oil ($B = 400$ mT).

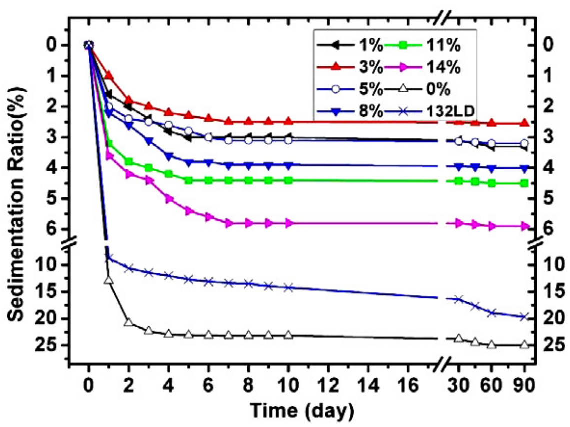


Figure 6. Sedimentation ratios versus time; each curve corresponds to a certain value of the guar/Fe ratio. The ratio of sedimentation is defined as (volume of the supernatant liquid)/(volume of the total suspension).

at not too high volume fractions and increase rapidly at higher volume fraction. However, the results of the experiments showed that the MR effect of the MR fluids not only did not become lower, but also became much stronger.

3.3. Stability of the MR fluid

Table 1 shows the measured apparent viscosity under 100 s^{-1} shear strain rate for the samples. It was found that the MR fluid containing guar gum coated iron powders had not only excellent sedimental stability but also low zero-field viscosity.

The sedimentation behaviors of various MR fluids with or without guar gum coatings are compared in figure 6. When the guar/Fe ratio is 3%, the sediment of the MR fluid is the lowest, only 2.2% after 3 months. And obviously, the coating of guar gum improves the sedimental stability of the MR fluids.

From the strengthened MR effects and the low ratio of sedimentation of MR suspensions shown in figures 5 and 6, it could be concluded that the inducing of the guar gum coating on the iron powders improves the properties of the MR fluid, which should be attributed to some factor related

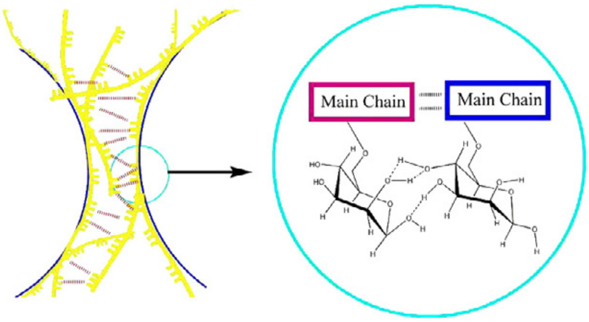


Figure 7. Schematic diagram of inter-polymer attractions in the contact region of the neighboring spheres.

to the physical and chemical structures of the guar gum. The hydrogen bonds of the guar gum may play a very important role, because they can build a network throughout all the particles coated with the guar gum (as shown in figure 7). Deeper research and more analysis need to be done for clarifying the mechanism of the strengthening effect of the guar gum coating.

4. Summary and conclusions

On changing the coating method from ball milling guar gum powder with carbonyl iron powder to precipitating guar gum on the surface of the carbonyl iron powders from guar gum water solution, a strengthening effect of the guar gum coating on the MR effect of the MR fluids was found, and also the sedimental stabilizing function of the guar gum was reinforced. The best amount of guar gum induced is 3% to the amount of the iron powders, which leads to a MR fluid with about 52.5 kPa at 0.4 T and only 2–3% sedimentation after 3 months.

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