

Study on magnetorheological shear thickening fluid

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Abstract

In this paper, a magnetic-field-controlled and speed-activated magnetorheological shear thickening fluid (MRSTF) is presented. We fabricated a kind of shear thickening fluid (STF) which was composed of nanosize silica particles suspended in a solvent, ethylene glycol, at high concentrations. Then the micron-size carbonyl iron particles with different volume fractions were added to the STF to fabricate the MRSTF. Their dynamic properties in different shear strain rates and magnetic fields were tested by using a rheometer. The suspension shows an abrupt increase in complex viscosity beyond a critical dynamic shear rate and a magnetic-field-controllable characteristic, as well as being reversible.

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

1. Introduction

The field of smart materials and structures is emerging rapidly with technological innovations appearing in engineering materials, sensors, actuators and image processing. Recently, a great deal of progress has been achieved in the development of advanced material systems using smart fluids such as electrorheological (ER) or magnetorheological (MR) fluids. As their rheological properties are reversibly and instantaneously changed by applying an electric or magnetic field, ER or MR fluids are widely investigated as actuating fluids and many applications, utilizing their variable flow rate or force characteristics in either damping or torque transfer scenarios, have been studied. These proposed applications include shock absorbers, clutches, brakes, actuators and artificial joints [1–4].

All these approaches have something in common in that they require an external power source to be activated. A way to avoid the need for an external power source is to use a material that changes its properties according to the loading conditions. Such behavior is a characteristic of shear-thickening fluids (STFs). STFs are concentrated colloidal suspensions composed of non-aggregating solid particles suspended in fluids, which exhibit a marked increase

in viscosity beyond a critical shear rate. In addition, this increased viscosity is seen as being both 'field-activated', due to the dependence on shearing rate, as well as reversible [5, 6].

Many earlier studies have focused on determining this 'field-activated' viscosity and other rheological properties of STFs under steady shear and oscillatory shear flow. Steady shear research indicated that the common feature of the materials' rheograms is a sharp increase in viscosity that decays at higher shear rates, often referred to as a discontinuity [7–11]. There have been some reports on the dynamic properties of STFs. Laun *et al* [12] reported the critical strain amplitude for dynamic shear thickening at a fixed angular frequency of a polymer latex dispersion. Raghavan *et al* [13] investigated the shear thickening response of a fumed silica suspension under both steady and oscillatory shear. Fischer *et al* [6] studied the dynamic properties of STFs based on a vibrating sandwiched beam. Strain-thickening refers to a sharp increase in the complex viscosity observed at critical combinations of strain amplitude and frequency.

The highly nonlinear behavior can provide a self-limiting maximum rate of flow that can be exploited in the design of damping and control devices, which was first investigated in the context of mountings for industrial machinery [12, 14]. More recently, Lee *et al* [11] and Decker *et al* [15] investigated

the ballistic properties of woven aramid fabrics impregnated with a colloidal, discontinuous shear thickening fluid (STF). Fischer *et al* [6] integrated STFs into a composite sandwich structure with the aim of inducing changes in the latter's dynamic properties under specific conditions. However, the applications of STFs are still limited because appropriate control strategies are hard to implement.

In this paper, we intend to combine the advantages of MRFs and STFs in an effort to present a novel smart material, which can provide a reasonable performance without a power supply and it still has the MR effect when an external magnetic field is applied.

Two main tasks will be reported in this paper. One is the fabrication of an STF base, which was composed of nanosize silica particles suspended in a solvent, ethylene glycol. Their steady and oscillatory shear properties will be tested by using a rheometer. The other task is the study of both the magnetorheological and shear thickening effect of an MRSTF composed of prepared STF and carbonyl iron particles. Using different weight fraction ratios of carbonyl iron particles and STFs, a series of magnetorheological shear thickening fluids will be prepared. Their dependences of viscosity on shear rate exposed to various magnetic fields will be tested. The effects of iron particle concentration, magnetic field and shear rate on rheological properties of the MRSTF will be discussed. The application of such novel materials will also be discussed.

2. Formation and testing of STF

2.1. Materials

The STF used was based on fumed silica (S5505, from Sigma-Aldrich) which has a primary particle size of 14 nm and a specific surface area of approximately $200 \text{ m}^2 \text{ g}^{-1}$. The carrier fluid was ethylene glycol [$\text{HOCH}_2\text{CH}_2\text{OH}$] with a density 1.113 g ml^{-1} (102466, ReagentPlus[®], from Sigma-Aldrich). In each case, the carrier fluid was added to the powder and a blender used to mechanically mix the two components for 1 h. The resulting suspensions were then placed in a vacuum chamber for several hours to eliminate bubbles. The other kind of particle was also used to mix with the carrier fluid for comparison. The silicon dioxide has primary particle sizes from 1 to $5 \mu\text{m}$ and density 2.6 g ml^{-1} (S5631, from Sigma-Aldrich). Solid contents of 20%, 30% and 40% w/w were selected for study.

2.2. Rheological measurements and results

A strain-controlled rheometer (MCR 301, Anton Paar Companies, Germany) was used to measure the shear-strain-dependent rheology of the STF. Steady-state strain rate sweeps, dynamic frequency sweeps and dynamic strain sweeps were carried out using 20 mm diameter parallel plates with a gap of $200 \mu\text{m}$.

The testing procedure for each measurement is illustrated below. Initially, the sample is sheared at a constant shear rate of 100 s^{-1} at zero field for half a minute to distribute the particles uniformly. Next, the desired magnetic field is applied and maintained for more than 30 s so that the testing

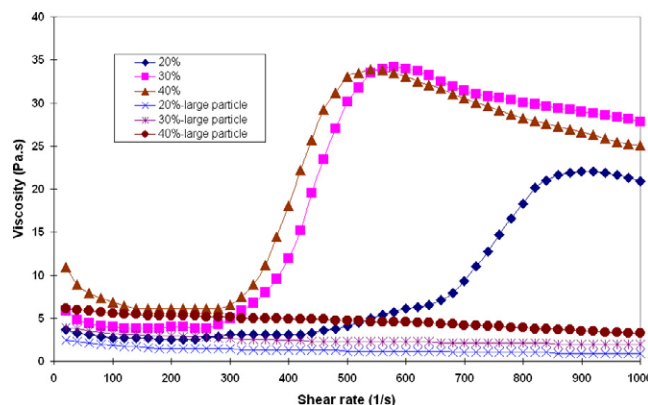


Figure 1. Viscosity as a function of shear rate.

sample forms a static structure. Then, both steady shear and dynamic oscillatory shear modes will be employed to measure rheological properties of the samples under steady and dynamic loading conditions.

For the old MR rheometer module, the testing gap is fixed as 1 mm, where the magnetic field shows a linear relationship with a coil current [16]. The new model (MR301) provides an improved function that the magnetic field versus sample gap can be calculated via a spreadsheet file. In our experiment, the testing gap is fixed as 0.2 mm. The relationship between the magnetic field and the coil current at this gap is obtained by calculating the spreadsheet.

Figure 1 shows the viscosity, η , as a function of shear rate. The colloidal suspensions with 'large' particles do not have a notable shear thickening effect until the shear rate of 1000 s^{-1} . At low shear rates, slight shear thinning can be observed. The rheograms of suspensions with 'small' particles show a sharp increase in viscosity that decays at higher shear rates. This increase occurs at a critical shear rate. It can be seen, as expected, that the viscosity of the STF increases with increasing volume fraction. In addition to affecting the viscosity, the critical shear rate is also dependent on this parameter, as 'thickening' occurs at lower shear-rate values when the suspension has a high volume fraction. However, the sample with 30% particles provides the optimum combination of relatively low viscosity at rest, marked shear thickening and high post-transition viscosity. Therefore, it was selected for further study.

The rheological behavior of the 30% fumed silica suspension is illustrated in figure 2 in terms of a strain sweep. The experiment was performed from low to high amplitude strains at different shear angular frequencies of 20, 40, 60, 80 and 100 rad s^{-1} , respectively. The STF exhibits strain thickening at high strain amplitudes, with its complex viscosity showing an abrupt jump to higher levels at particular strains for different shear frequencies. The data in figure 2 indicates that the transition to a strain-thickening (flow-blocking) behavior occurs at smaller strains as the frequency of the deformation is increased.

Figure 3 shows the complex viscosity as a function of angular frequency for the 30% w/w STF at various strain amplitudes. The transition was initiated at a relatively low

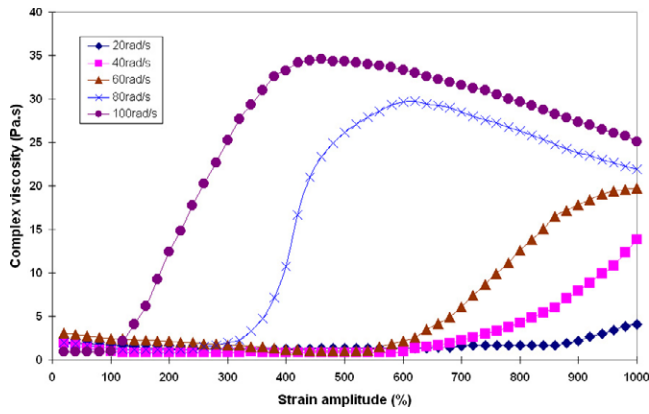


Figure 2. Dynamic strain sweeps at different angular frequencies.

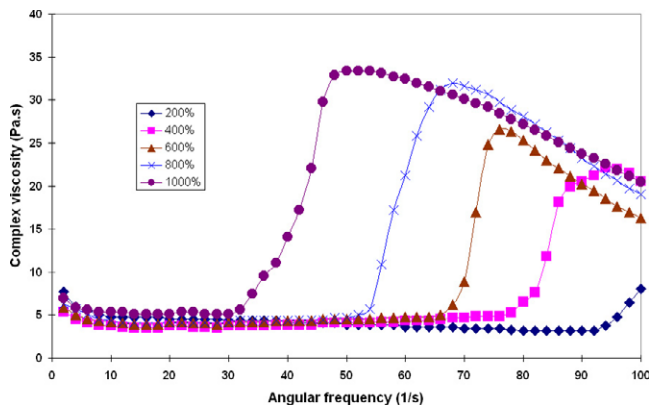


Figure 3. Dynamic frequency sweeps at different strain amplitudes.

frequency for high shear strain, but the critical frequency increased monotonically with decreasing shear strain. The data demonstrated that STF has a dramatic increase in viscosity at critical combinations of the amplitude and frequency. In a dynamic experiment conducted at frequency ω and strain amplitude γ_0 , the product $(\omega \cdot \gamma_0)$ corresponds to the maximum dynamic shear rate $\dot{\gamma}^{\text{dyn}}$. Thus, the parameter can be physically interpreted as a critical dynamic shear rate, which has also been demonstrated in a few earlier studies [6, 12, 13].

According to the experimental data, figure 4 gives the response of the 30% w/w STF for a critical shear strain γ_c and the strain at the end of the transition, γ_m , as a function of ω . This figure could be used to predict whether the STF was in the low viscosity state, in the transition state or in the shear-thickened state. The viscoelastic behavior of the sample as a function of dynamic shear rate is also plotted in figure 5. The viscous modulus G'' makes an abrupt transition to a higher level at the particular dynamic shear rate as well as elastic modulus G' .

The critical angular frequency can be modeled by the following equation [14]:

$$\omega_c = \frac{\dot{\gamma}_c^{\text{dyn}}}{\gamma_0 - \gamma_\infty} \quad (1)$$

where the parameter γ_∞ represents the critical strain at very high frequencies. For this STF sample, the value of $\dot{\gamma}_c^{\text{dyn}}$, $\dot{\gamma}_m^{\text{dyn}}$

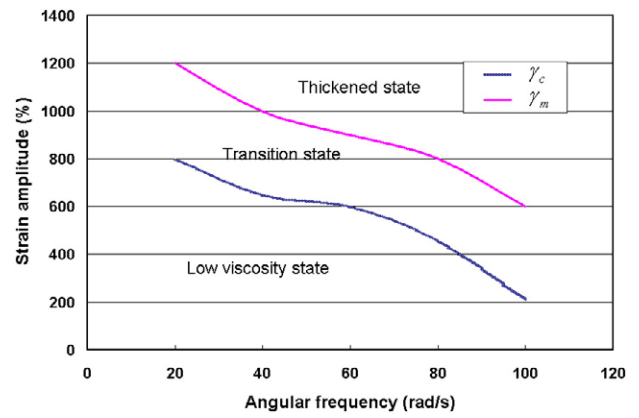


Figure 4. γ_c and γ_m as a function of angular frequency.

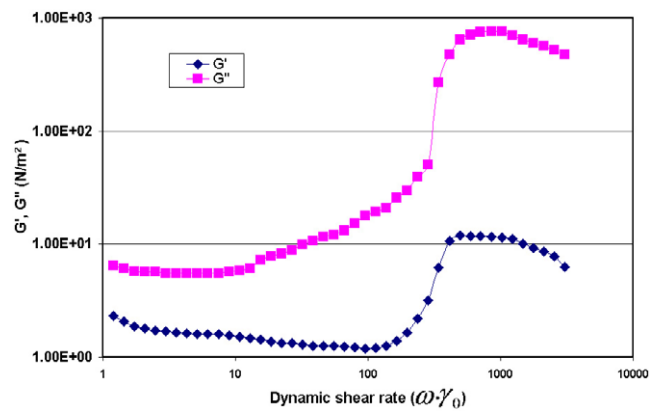


Figure 5. The viscous and elastic modulus of the STF versus dynamic shear rate.

and γ_∞ is about 350 s^{-1} , 600 s^{-1} and 90%, respectively. These experimental results and equation are similar to those observed and used by Raghavan [13].

3. Formation and testing of MRSTF

3.1. Preparation of MRSTF

Carbonyl iron particles (carbonyl iron, C3518, Sigma-Aldrich Pty LTD) with $5 \mu\text{m}$ mean particle size were chosen as the magnetic particle in the MRSTF. The carrier phase is the STF which was previously prepared. The preweighed solid iron microspheres were added in weighed amounts to form the several weight fraction mixtures of MRSTF. The particles were thoroughly mixed with a base fluid under a high shear condition for approximately 10 min. The air bubbles in the resultant mixture were removed in a vacuum chamber before testing. Four kinds of MRSTFs were prepared. Their weight ratios of iron particles and STF were 5:100, 10:100, 50:100 and 200:100, respectively.

3.2. Magnetorheological and shear-thickening measurement

Similarly, both steady shear and dynamic shear modes were employed to measure rheological properties of the MRSTF.

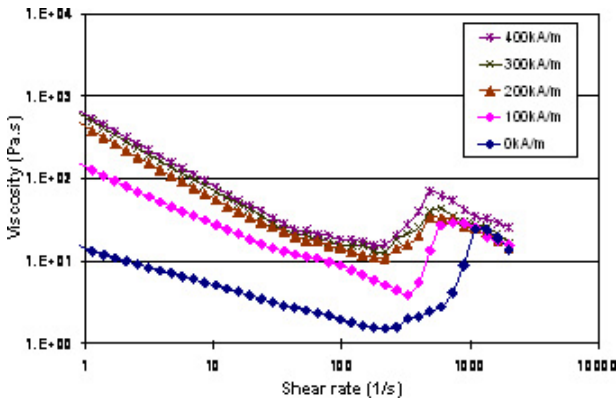


Figure 6. Viscosity as a function of shear rate and magnetic field (sample 1).

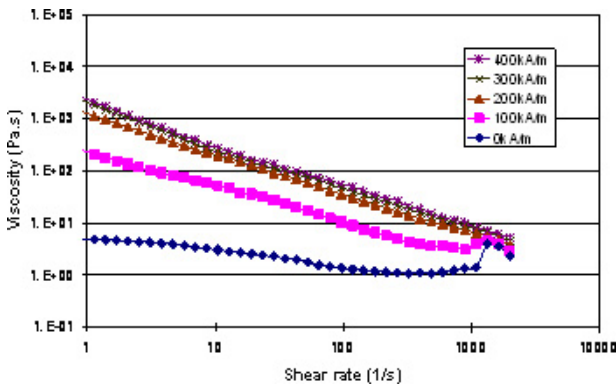


Figure 7. Viscosity as a function of shear rate and magnetic field (sample 2).

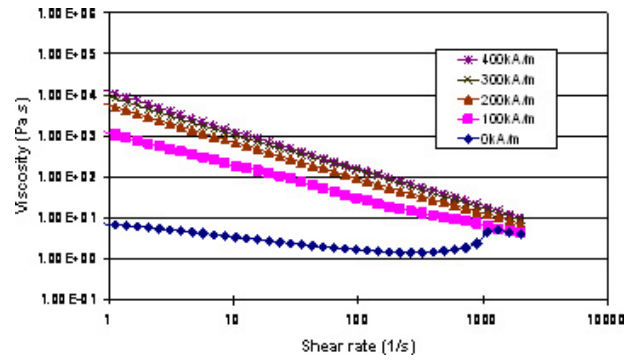


Figure 8. Viscosity as a function of shear rate and magnetic field (sample 3).

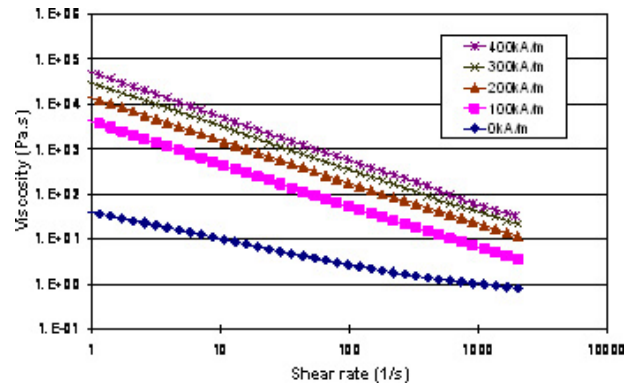


Figure 9. Viscosity as a function of shear rate and magnetic field (sample 4).

In the steady shear, steady-state strain rate sweep mode from shear rate 1 to 1000 s⁻¹, and five different magnetic fields of 0, 100, 200, 300 and 400 kA m⁻¹ were applied.

The dependence of viscosity on shear rate for sample 1 exposed to various magnetic fields is illustrated in figure 6. At relatively low shear rate, the fluid shows an obvious shear thinning behavior. At a shear rate close to 1000 s⁻¹, the viscosity begins to increase steeply. However, the critical shear rate of the STF has been increased because of the addition of micron-size iron particles. The figure also clearly shows that, at a given shear rate applied to the MRSTF, the associated viscosity increases with increasing strength of magnetic field, thus demonstrating an obvious MR effect. It can also be observed that the magnetic field intensity can slightly decrease the critical shear rate of shear thickening. Therefore, the MRSTF material combines the MR and shear-thickening effects. In other words, it has magnetic-field-dependent and speed-activated viscosity characteristics.

Figures 7 and 8 show the viscosity of samples 2 and 3 as a function of shear rate and magnetic field. It can be observed that the increase of iron particle concentration and magnetic field obviously restrain the shear thickening phenomenon. The shear thickening can only be observed at higher shear rate and zero field (sample 2) or very low magnetic field (sample 3). Obviously, the MR effect was improved because of the higher iron fraction.

A similar trend was observed in figure 9, where the concentration of iron particles in this sample is close to the value in conventional MR fluids. The shear thickening cannot be observed in this experiment because of the high micron-size particle concentration. The fluid shows an obvious shear thinning behavior and the viscosity increased with magnetic field strength as expected, i.e. it shows the MR effect like conventional MR fluids. It is recognized that the fumed silicas act as a thixotrope in the fluid. For the gap-filling component and nonmagnetic suspending medium, a high shear dispersion of the ultrafine silica particles in the fluid provides a thixotropic medium for stabilizing the dispersion of the magnetic particles. For the high concentration of fumed silica in the fluid, no sedimentation can be observed in this material. Figure 10 shows the MR effect of the MR fluid sample has the same iron particle concentration as sample 4 and has no fumed silica. It can be found that the viscosity of sample 4 at zero field is higher than that of the conventional MR fluid because of the high concentration of fumed silica. But the field-induced viscosity has no noticeable difference. This demonstrates that the high micron-particle-based MRSTF has similar behavior to conventional MR fluids.

For sample 1, the complex viscosity against shear strain amplitude for sample 1 in a magnetic field and without a magnetic field is shown in figure 11. Without a magnetic field, the results are very similar to the STF dynamic properties, as shown in figure 2. This demonstrated again that the low

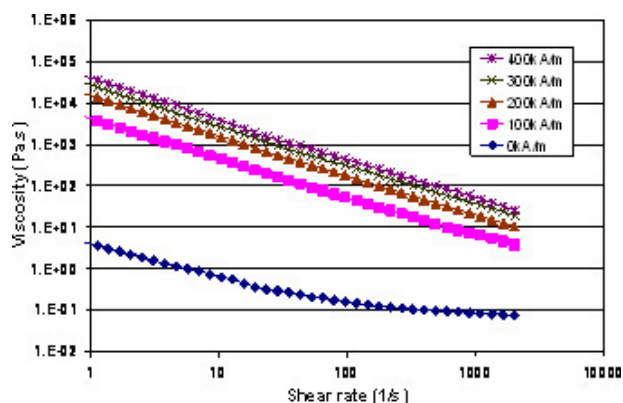


Figure 10. Viscosity as a function of shear rate and magnetic field (MR fluid).

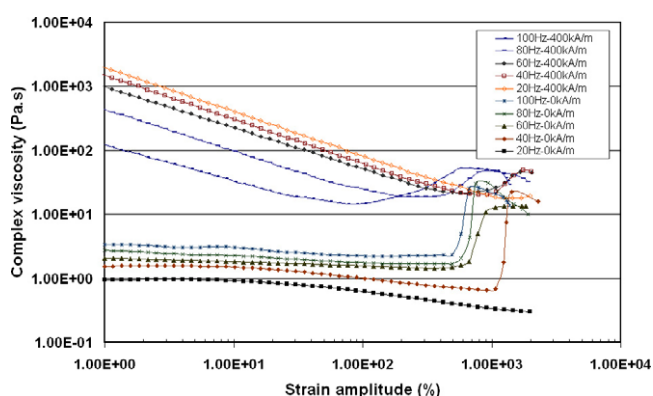


Figure 11. Complex viscosity as a function of strain amplitude without and with a magnetic field (sample 1).

volume MRSTF works as a normal STF without a magnetic field. At a magnetic field of 400 kA m^{-1} , the results show a vast difference to that without a magnetic field. It is very hard to find the transition amplitude unless the driving frequency is very high. Also, the complex viscosity without a magnetic field shows an increasing trend with frequency while it shows a decreasing trend with frequency. These results demonstrate that the MRSTF exhibits an MR effect where the shear-thinning effect plays a dominant role in the magnetic field.

4. Discussion

Rheological studies of the MRSTF and conventional MRF under steady shear, as shown in figures 9 and 10, demonstrated that these two materials have similar MR effects. Our further experiment indicates that the MRSTF has much better stability than the conventional MRF. In conventional MR fluids, due to the density mismatch between the particle and the carrier fluid, particle settling is a big problem. However, the MRSTF has a super-stable merit that no settling is observed even after a few weeks. The gap-filling nanosized particle between the micron-sized iron spheres might be the main reason for such an improvement. It means that the MRSTF can be used as an effective no-sedimentation MR fluid without hampering its MR properties.

The applications of such an MRSTF would be exciting. Generally, all MRF-related devices can be replaced with such materials, including dampers, shock absorbers, engine mounts, etc. Besides, this material can also work as a field-activated material, so viscoplastic dampers using this material are now under development in our group.

5. Conclusion

In this study, a novel magnetic-field-dependent and speed-activated fluid was presented. This kind of smart material is based on a shear thickening and magnetorheological fluid. Its rheological properties can be controlled by magnetic field and shear rate.

In the first step, we fabricated a kind of STF which was composed of nanosize silica particles suspended in a solvent, ethylene glycol, at high concentrations. Their dynamic properties at different shear strain rates were also tested by using a rheometer. This suspension behaves as a quasi-Newtonian fluid during a large spectrum of dynamic shear rates, except for the transition shear rate period that causes the fluid's specific critical shear rate transition and, again, with a quasi-Newtonian behavior but with a much higher viscosity after the transition. The viscous modulus G'' makes an abrupt transition to a higher level at the particular dynamic shear rate as well as the elastic modulus G' .

In the second step, by using different weight fraction ratios of carbonyl iron particles and STF, a series of magnetorheological shear thickening fluids were prepared. Their dependences of viscosity on shear rate exposed to various magnetic fields were tested. When the weight fraction of iron particle is lower than a specific value, both the magnetorheological effect and shear thickening behavior can be observed. It means this novel smart fluid can be controlled by both magnetic field and shear rate. With the increase of iron particle concentration, the shear thickening is restrained and the magnetorheological effect becomes more obvious. For high iron particle concentrations, the MRSTF can be used as an effective MR fluid with a high MR effect and without sedimentation.

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