MATEC Web of Conferences **67**, 03032 (2016) DOI: 10.1051/matecconf/20166703032
SMAE 2016

Effect of Surface Roughness on the Stick-slip Behavior of Magnetic Field Controlled-dipolar Suspensions in Simple Linear Shear Mode

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Abstract. The effect of surface roughness on the stick-slip motion of Magnetorheological (MR) fluids under a simple linear shear mode has been experimentally reported. The shear stress of the MR fluids could be modulated by the changing of the surface roughness. The rate of energy accumulation and releasing during stick-slip motion changed with respect to the shear plates of different surface roughness. The changing of the stick-slip motion based on the different surface roughness was ascribed to the evolution of internal particle structures when shear motion was applied to the aggregates of the particles exposed to the external magnetic field.

1. Introduction

Various phenomena [1, 2] have been involved during the friction process, indicating the properties of the rubbing materials and mechanism of interaction. Stick-slip is one kind of the phenomenon that has been studied with help of the modern apparatus, revealing the interfacial friction in much smaller scale. Various factors [3-4] have great impact on the process of accumulating energy in "stick" part while releasing the energy in "slip" part when the two surfaces rubbing together. Research concerns more about the properties and mechanisms of the stick-slip motion due to the characterization of the materials and some focus on controlling and modulations[5,6]. Mechanical properties of electrorheological(ER) and magnetorheological (MR) fluids can be dramatically changed once exposed to the external electric/magnetic field [7,8]. This provides two controllable phases of one matter, the possibility in the modifying the energy consuming process.

Stick-slip during the shearing of ER fluids was ascribed to the reformation of the chain structure [9] in the first place, along with sufficient discussion on the important role of the chain structure to the shear behavior of the ER/MR fluids [10,11]. What should be noted is that the traditional rheological properties of the MR/ER fluids are studied under imposed shear motion in the geometry of co-axial cylinder or two parallel plates with unidirectional shearing or oscillation and smooth surface. So a linear shearing motion especially with low

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velocity with changeable surface will provide a simpler imagine revealing the details of the stick-slip [13].

The experimental study of stick-slip motion of MR fluids reported here are based on a linear shearing motion accompanied by the shear plates with different roughness of Ra 0.08 μm~31μm, demonstrating that the shear behavior, especially the stick-slip behavior of MR fluids during shearing is impacted by the external magnetic field and the morphology of the shearing plates. Both the accumulation of the energy in "stick" process and the releasing of the energy in "slip" process were by the viscosity of the carrier phase of the MR particles. Also the state transition due to shear thickening will influence stick slip behavior. The stick slip behavior can be possibly dramatically restrained when the carrier fluids is different from silicon oil undergoing a slow linear shearing motion.

2. Material and Methods

The MR fluids used in this study were mixture of carbonyl iron particles (average diameter3 μm, TianYi Corp., China) and silicone oil (10cSt, Beijing Chem. Corp., China) with the volume fraction of 30%. The external magnetic field is generated by a coil with 935turns under the maximum voltage of 16 V and the maximum value is 16k A/m. The lower shearing plate (surface roughness: Ra 0.03 μm~31μm) is driven by a motor while the upper plate fixed with the coils. The force sensor is attached to the lower plate with a sample frequency of 5 kHz. The nominal gap between the plates is 1 mm, controlled by a grating scale with a resolution of 1μm. The MR fluids will be sheared for 50 s or 100 s at a constant shear rate (forward) and then sheared back (reverse) to the original position. The nominal shear rate is 0.01~0.2 s^{-1}. Nominally the magnetic field is perpendicular to the surface of the shearing plate and the direction of the shearing.

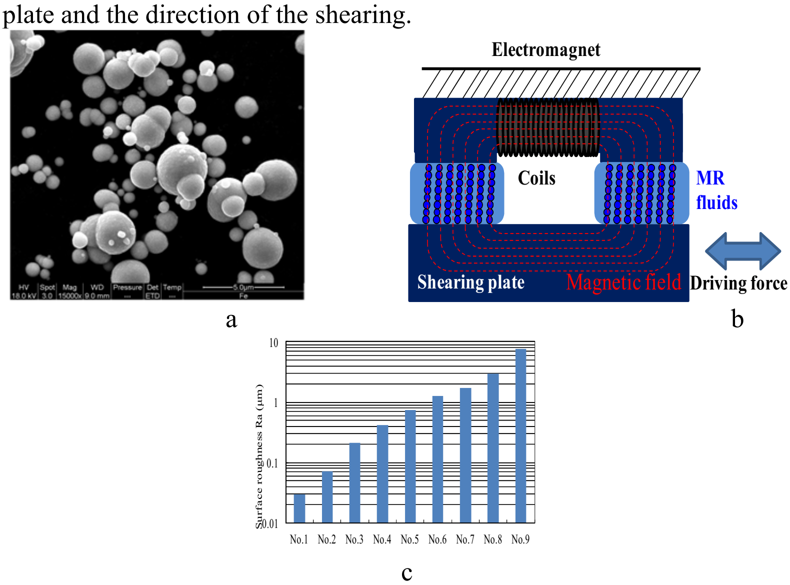
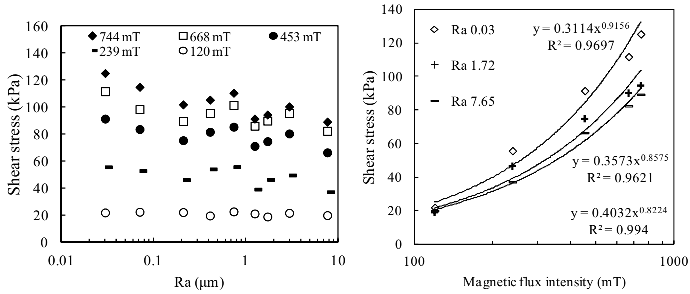


Fig.1 a: SEM image of carbonyl iron particles; b: Schematic of the experimental setup. The Magnetorheological fluids were filled in the gap between the electromagnet and the shearing plate with a certain amount of volume with assistance of a syringe; c: surface roughness of the shear plates from No.1 to No.9.

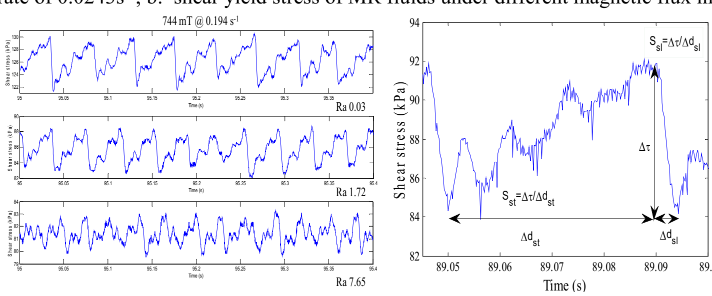
3. Results and Discussions

Considering the morphology of the shear plates used in the experiments, the shear stress should be noted. According to the results shown in Fig.2a, the shear stress gradually decreased with the increase of the surface roughness of the lower shearing plates. But around Ra 1μm a slice increase of the shear stress can be observed. The relative changing of the shear stress can be more obvious when the higher external magnetic field was applied. For example the fluctuation of the shear stress under 120 mT was very limited. But the change of the shear stress under 744 mT was over 20%. with respect to the different surface roughness. As shown in Fig.2b, the shear stress with respect to the shear plate of Ra 0.03 will change more sharply with the increase of the magnetic field. So the level of solidification has impacted on the response of the shear resistance of the MR fluids to the surface roughness. Another important aspect of the results is the shear stress with respect to the low surface roughness was normally higher than the one sheared by the plates with high surface roughness. This result shows the smooth shear plates will be better for the high performance of the devices based on MR effect.



a b

Fig.2 a: Shear stress of MR fluids Vs. Surface roughness under the magnetic flux intensity of 744 ~120mT at the shear rate of $0.0243s^{-1}$; b: shear yield stress of MR fluids under different magnetic flux intensity.



a b

Fig. 3 a：Different shear curves of MR fluids with surface roughness at shear rate of 0.194 s-1; b: Definition of Sst and Ssl in the phenomenon of stick-slip during the shear of MR fluids under magnetic field.Δdst is the product of the shearing time and the shearing velocity (product of shear rate and gap distance of 1 mm)

Not only the shear stress changed with respect to the surface roughness but the stick slip behavior of the MR fluids under linear shear motion changed as well. As shown in Fig.3a the same MR fluids were sheared under the shear rate with the same magnetic field applied, regarding to the different shear plates with different surface roughness introduced. The stick slip behavior was more obvious when the surface of the shear plates were much smoother.

To investigate characterization of the stick-slip motion, two defined parameters are proposed here.

$$S_{st}=|\Delta\tau/\Delta d_{st}| \quad (1)$$

$$S_{sl}=|\Delta\tau/\Delta d_{sl}| \quad (2)$$

The meanings of $\Delta\tau$， Δd_{st} and Δd_{sl} are demonstrated in Fig.4. $\Delta\tau$ is the amplitude of the stick-slip spike. Δd_{st} is the distance that the shearing plates move with the increase of the shear stress. Δd_{sl} is the distance that the shearing plates move with the decrease of the shear stress. Both of S_{st} and S_{sl} are the absolute value of the slope of the saw-tooth-like spike in "stick" part and "slip" part, respectively. The energy is accumulated in a short duration if S_{st} is relative larger, and released in a short duration when S_{sl} large.

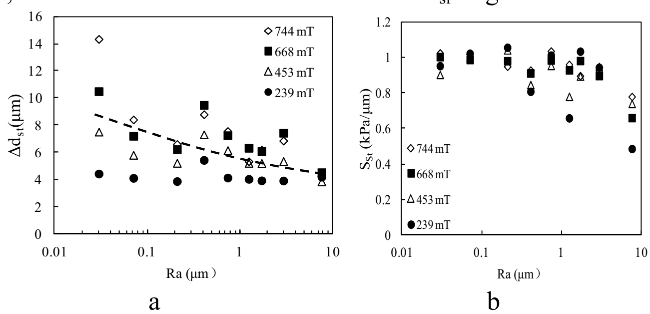


Fig. 4 a: Slip distance of the MR fluids Vs surface roughness under the magnetic field of 744~239 mT; b: Sst Vs surface roughness under the magnetic field of 744~239 mT.

The slip distance of the stick-slip behavior gradually decreased with respect to the increase the surface roughness. Similar to the results of the shear stress shown in Figure 2, the changing of the slip distance can be omitted when the MR fluids were sheared under the low magnetic field. The large slip distance of the stick slip behavior indicates the strong resistance of the aggregates structure to the external driving force. If the large slip distance occurs only if the shear plates of small surface roughness are used, the stronger particle structure can expected when shear plates were rather smooth.

Since the shear stress of the MR fluids is induced by the external magnetic field, the accumulation of the energy in "stick" part will be originated by the magnetic field. As shown in Fig. 5, possible yield region can be expected near the shear plate. Two reasons can be proposed here. First the surface roughness of the lower shearing plate will change the distribution of the local magnetic flux intensity. The magnetic field will determine the local structure of the particles inside MR fluids. A well distributed magnetic field will result in a BCT structure of the aggregates, which leads to the maximum energy of the structure. If the distribution of the modified magnetic field is different from the one of nominally well distributed field, the shear resistance of the structure of particles inside MR fluids will be smaller. Comparing to the shearing gap between the two electrodes, the average height of the asperities on the low shear plate was much smaller. So the weak structures of the aggregates are near the shear plates. Secondly the asperities of the low shear plate will destroy the structure of the aggregates inside MR fluids near shear plate once the shear motion is applied. Then the shear resistance of the MR fluids will decrease if the destruction occurs. When the destruction completed the reconstruction of the aggregates in the form of BCT structure will be initiated, which leads to the increase of the shear force in the process of stick. But sometimes the interaction between the asperities and the aggregates will be beneficial to the increase of the shear stress. Maybe that is the reason that the shear stress will increase when a large surface roughness of the shear plate is introduced to the experiments.

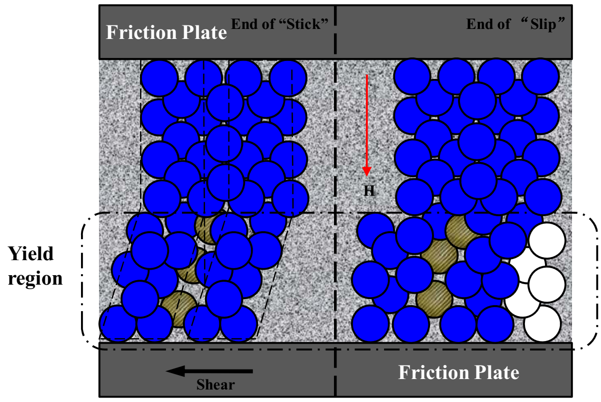


Fig.5 Structure Evolution of aggregates in MR fluids during shearing

4. Summary

In this study the influence of the surface roughness of the shear plates to the shear behavior of the MR fluids were studied in a simple linear shear mode. The MR fluids under magnetic field exhibit the increase of the shear stress when the large surface roughness was introduced. The typical stick-slip motion will be masked if the large surface roughness was introduced. The energy accumulation rate will decrease when the large asperities available on the shear plates. These stick-slip behaviors of MR fluids under pure shear mode demonstrate similar mechanism as solid matters. And the large shear resistance with respect to the smooth shear plates indicates a way of designing MR effect devices with high performance.

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