Effect of Cluster Formation on Dynamic Response of an Electrorheological Fluid in Shear Flow

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Abstract. Transient shear stress responses of an electrorheological fluid to step-wise electric fields are investigated experimentally. The characteristic time constants of the electrorheological fluid sheared between two concentric cylinders are obtained under various electric field strengths and shear rates. Especially, two experimental modes are adopted to investigate the effect of the cluster formation on the dynamic response of the fluid; one is that the electric field is induced before shearing, and the other is the electric field is induced after shearing. The cluster formation time is obtained from the difference in the response times between the two modes. The cluster formation time is monotonously increased with the increase of shear rate and converged on a constant value.

1. Introduction

An electrorheological (ER) fluid is a kind of suspensions which consist of polarizable particles dispersed in insulation solvents. The ER particles which are induced by the electrostatic interaction upon applying electric field are aligned to form chains or columns along the field direction. Due to the controllability of the apparent viscosity, ER fluids are increasingly being considered in a large variety of devices such as shock absorbers, vibration insulators, brakes or clutches. In order to effectively design and control devices based on ER fluids, the knowledge of the behaviors and properties of the ER fluids during the phase transition is required inevitably. [1]

The previous researches on the dynamic response of the ER fluid have been achieved through the rheological stress behavior or the microstructural configuration change based on optical visualization or the simulation. [2, 3] However, it is difficult to quantitatively specify many of the parameters employed in the simulation as well as the flow visualization conditions are rather different from the operating conditions in the real situation. Especially, such studies have focused on the ER fluid at quiescent state because of the limited size of the inspection window. Therefore, in this study, the dynamic stress behavior of the ER fluid sheared between two concentric cylinders is investigated under various electric field strengths and shear rates.

In general, the dynamic response of the ER fluid is determined by the microstructural behavior of the ER particles in the competition of the electric-field induced particle attractive interaction (electrostatic
force) and the hydrodynamic force. [4, 5] Such a microstructural behavior is mostly separated by the formation, the deformation, the destruction and the reformation processes of the cluster. While the static response of the ER fluid is determined by the circulating close-loop process including the cluster destruction and reformation, the dynamic response is closely related to the cluster formation and deformation processes. Specifically, the cluster formation can be also divided by the particle polarization, the particle aggregation and the cluster densification. [6]

In this study, two experimental modes are adopted; one is that the electric field is induced before shearing (EH mode), and the other is the electric field is induced after shearing (HE mode). Compared to the HE mode, the cluster formation process in the EH mode can be considered to be already completed prior to the cluster deformation due to the hydrodynamic force. Consequently, the cluster formation time of the ER fluid in shear mode can be obtained from the difference in the response times between the two modes.

2. Experimental setup
The ER fluid used for the investigation of the shear stress response is TX-ER8 composed with sulfonated polymer particles dispersed in a mixture of fluorine oil and silicone oil. This fluid sample has a viscosity of 115 mPa s and a density of 1.6 g/cm$^3$ at room temperature (about 25°C). [6] Figure 1 depicts the schematic diagram of the experimental apparatus. The switching module installed in a high voltage power supplier is used to turn on or off DC electric fields, whose operation can be controlled by a micro-processor. The switching time of the module is about 2 msec, which is in the negligible order.

As seen in figure 2, a concentric type cylindrical rheometer is fabricated to investigate the shear stress response of ER fluid. The gap size between the internal (cathode) and outer (anode) cylinders which are used for electrodes is designed to be 1.5mm, considering low viscous effect due to the ER fluid. The length of the electrode is designed to be 70mm. The internal cylinder is designed in the form of a cup to reduce its inertial load. A shaft-supporter system is employed to keep the gap size of between the cylinders constant. The internal cylinder is rotated at a certain velocity in one direction by a DC servomotor, where the inverter is used to keep the rotational velocity of the DC servomotor uniform irrespectively to an external load torque. And, the output torque is measured by the rotary-type torque sensor connecting the rheometer with the DC servomotor and recorded using a PC-based data acquisition system with the sampling speed of 1 kHz.

The characteristic time constants of the ER fluid are obtained from the transient stress behaviors at various rotating velocities and electric field strengths.

3. Results and discussions
Figures 3 and 4 show the shear stress response of the EH mode and the HE mode, respectively. The shear rate and the electric field strength are changed in the ranges of 4-125 s$^{-1}$ and 0-3kV/mm,
Figure 3. Shear stress of ER fluids where Electric field is induced before shearing

Figure 4. Shear stress of ER fluids where Electric field is induced after shearing

Figure 5. Rising time constant of ER fluids

Figure 6. Cluster formation time of ER fluid

respectively. There is no significant difference in the steady state response of the shear stress according to those two experimental modes. As can be seen in these figures, the shear stress is increased with the increase of the electric field strength. However, it is hardly influenced by the shear rate, with the exception of low shear rate region having relatively high stress. At the relatively low shear rate, the cluster formation is easily achieved because of small hydrodynamic force. Therefore, the cluster structure at the low shear rate is similar to that of quiescent state. In addition, the attracting force between cluster structure and two electrodes might be larger than that of ER particles. Therefore, the slipping phenomenon between the clusters and the electrodes hardly take place at the relatively low shear rate. [7] At the moment that cylinder is about to rotate from the quiescent state, a relatively large torque is required to destroy the cluster structure due to the friction between the clusters and the electrodes. Because the friction can be considered as the sticking friction, the yield stress is highly affected by the static yield stress. Instead, as the shear rate is increased, the cluster structure is less dense than those at the relatively low shear rate. Also, the strength of the cluster structure becomes weak gradually due to large hydrodynamic force. Therefore, the slip phenomenon is occurred in the high shear rate. [7] The friction can be considered as the sliding friction. The yield stress of this case is known as dynamic yield stress.

Figure 5 shows the dynamic response time of the two modes. As can be seen in the figure, the response times and their decreasing rates are decreased with the increase of the shear rate and are unchanged with the electric field strength applied. At the shear rates more than about 15 s⁻¹, the response times tend to be kept nearly constant. The inverse relationship between the stress response time and the shear rate is similar to the previous researches.
In addition, it is observed that the EH mode has much shorter response times than the HE mode under the same shear rates. The ER particles under an external electric field are polarized and then chains or columns are formed between the two electrodes due to the dipole interactions (cluster formation). By applying shearing load, the ER chains and columns exhibit the elastic behavior where its shear stress is proportional to the shear strain (cluster deformation). After this yielding region, the clusters are repeatedly destructed and reformed. Here, the cluster formation and deformation processes are closely related to the dynamic response of the ER fluid, while the cluster destruction and reformation processes give an effect on the static response. At the EH mode, the hydrodynamic force is applied after having enough time to form the stable cluster structure. On the contrary, at the HE mode, the cluster begins to form the quasi-stable structure as the electric field is induced on the ER fluid already subjected to the hydrodynamic force. In other words, the dynamic response at the EH mode is determined only by the cluster deformation process, while the cluster formation and deformation are occurred simultaneously at the HE mode. Therefore, it is concluded that the cluster formation time of the ER fluid in shearing can be found from the difference in the dynamic response time between the EH mode and the HE mode, as shown in figure 6. The cluster formation time is monotonously increased with the increase of shear rate and converged on a constant value. This is because the collision chance among the aggregated ER particles and the deformation rate of the cluster structure are increased with the increase of hydrodynamic force. [8] Therefore, It is also verified that shearing force inactivates the cluster formation of the ER fluid and promotes the cluster deformation, but consequently results in the decrease of the ER response time.

On the other hand, it is verified that there is an overshoot phenomenon in the shear stress rising process, as shown in figures 7 and 8. The magnitude of the overshoot at the EH mode is relatively large, compared to the HE mode. In the microstructural viewpoint, the cluster formation can be divided by the particle polarization, the particle aggregation and the cluster densification. The cluster structure of the EH mode is fully stable because of the cluster densification process at the quiescent state, as reported in the previous visualization study. [3] However, the cluster structure of the HE mode is less densely formed because its formation and deformation is occurred simultaneously. In other word, the chains or columns at the HE mode are mainly formed by the particle aggregation, but not the cluster densification. Therefore, the clusters at the EH mode are stronger than the counterpart, leading to the overshoot in the shear stress rising process. Also, it can be seen at the EH mode that the overshoot magnitude tends to be increased with the increase of the shear rate. It is considered that it is closely related to relatively high shear stress at the low shear rate. In other word, because the shear rate at the EH mode is increased from the quiescent state to the constant level, the corresponding shear stress is reached at its steady state via the yielding region at the low shear rate. Therefore, the
overshoot at the EH mode can be also considered as the effect of the static yield stress in relatively high level.

4. Conclusions
The dynamic response of the ER fluids in shear flow to step wise electric fields is investigated experimentally. With the characteristic time constants of the ER fluid obtained under various experimental conditions, the relationship between the ER response and the cluster formation is examined. The conclusions drawn from this research can be summarized as follows.

(1) The shear stress at the steady state is increased with the increase of the electric field strength. And, the shear stress at low shear rate is larger than those at relatively high shear rate. This is because the clusters subject to weak hydrodynamic force are relatively densely formed as well as the stick friction between the clusters and the electrodes drives the static yielding stress to the ER fluid.

(2) If the electric field is induced before shearing (EH mode), the response time of the ER fluid is dominated by the deformation process of the cluster structure. When the electric field is induced after shearing (HE mode), the response time is determined by the cluster formation and deformation processes. The cluster formation time can be derived from the difference in the response time between the two modes.

(3) The cluster formation time is increased monotonically and then converged constantly with the increase of the shear rate. Instead, the dynamic response of the ER fluid is decreased with the increase of the shear rate. Under the hydrodynamic field, the increased cluster deformation rate has more effect on the dynamic response time of the ER fluid than the increased collision chance of the ER particle.

5. References
[1] Rhee E J, Park M K, Yamane R and Oshima S 2003 “A study on the relation between flow characteristics and cluster formation of electrorheological fluid using visualization” Experiments in Fluids 34 316-23
[2] Ginder J M 1993 “Diffuse optical probes of motion and structure formation in an electrorheological fluid” Physical review E 47(5) 3418-29
[3] Wen W, Zheng D W and Tu K N 1999 “Chain/column evolution and corresponding electrorheological effect” Journal of applied physics 85(1) 530-33
[4] Tian Y, Zhang M, Meng Y and Wen S 2005 “Transient response of compressed electrorheological fluid” Journal of Colloid and Interface Science 290 289-97
[5] Tian Y, Meng Y and Wen S 2004 “Dynamic responses of zeolite-based ER fluid sheared between two concentric cylinder” Journal of Intelligent Material Systems and Structures 15 621-26
[6] Nam Y J, Park M K and Yamane R 2008 “Dynamic responses of electrorheological fluid in steady pressure flow” Experiments in Fluids 44 915-26
[7] Ryoichi H, Koji H, Hidenobu A, Koji S and Shinichi K 2000 “Internal structure and ER properties in ER suspensions of disperse system under DC electric field” Electrical Engineering In Japan 132(4), pp. 9-18
[8] Tanaka K, Hashimoto S, Takenouchi T, Sugimoto I, Kubono A and Akiyama R 2001 “Shearing effects on the electrorheological response” Intelligent. Journal of Modern Physics B 15 930-37