Dynamic Shear Flow Behavior of Magneto-Rheological Fluid between Two Rotating Parallel Disks under Relatively Weak Magnetic Field*

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The transient shear stress variation and the flow patterns of an MR fluid have been investigated simultaneously under constant shear rate and relatively weak magnetic field using a parallel disk rotary rheometer. The effects of magnetic field, shear rate and gap height on the induced shear stress and the flow behavior of the MR fluid were evaluated. The behavior of shear stress changes remarkably and various flow patterns (cracks in packed MR fluid structure, grain-like particle’s agglomeration, line of grains, etc.) with MR fluid leakage out of the gap can be observed, depending on these parameters. The amount of the MR fluid leakage due to the centrifugal force also depends on these parameters. Both the evolution of pattern and the leakage of MR fluid might be responsible for the transient variation of shear stress.

Key Words: Non-Newtonian Fluid, Magneto-Rheological Fluid, Multi-Phase Flow, Unsteady Shear Flow, Flow Visualization, Flow Pattern

1. Introduction

Magnetorheological (MR) fluids are suspensions of micron-sized magnetizable particles dispersed in medium fluid, which have the distinguished ability to change their rheological properties in a rapid and reversible manner on the application of an external magnetic field. The MR fluids behave like a Bingham fluid having magnetically changeable yield stress and are expected to be applied to various kinds of industrial device such as dampers, breaks, clutches, etc.\(^{1)–4}\), because their response to the magnetic field is very fast. When the magnetic field is applied to the MR fluid, the particles in the fluid are magnetically polarized and form chain structure parallel to the magnetic field direction. These chains form columns due to the attractive force between them. They cause a drag to the flow normal to the field direction, which is appeared as the increase of the yield stress from a macroscopic viewpoint. Formation and destruction of the columns are considered to recur while the MR fluid flows in shear flow mode under the magnetic field. Thus, it is quite important for understanding the flow structures of the MR fluid and applying to industrial devices to observe the change of the morphology and compare with the rheological properties.

Simultaneous measurement of the morphology and shear stress for the shear flow of electrorheological (ER) fluid between two rotating parallel disks was reported by Nakano et al.\(^{5)–6)\). They suggested that the hysteresis phenomenon and the time variations of the shear stress were due to the lamellae formation of ER particles in the direction of shear, and strongly depended on the narrow gap between two disks less than 0.3 mm. However, the similar measurement for MR fluid has not been done yet.

In this study, the transient characteristics of an MR fluid shear flow between two rotating parallel disks were investigated under the simultaneous stimulus of a constant shear and weak magnetic field perpendicular to the direction of the shear flow. The shear stress was measured with time from just after applied the rotational shear and the dynamic flow behavior of the fluid was visualized simultaneously, to clarify the relationship between the shear stress and the changes of the flow morphology. The effects of
magnetic field strength, shear rates and gap height on the shear stress and the dynamic flow behavior were studied. This study is very important regarding the use of MR fluids in brakes and clutches, which may be submitted to constant shear rates for long periods of time.

2. Experiment

The MR fluid used in the experiments is composed of micron-sized, magnetically polarizable carbonyl iron particles dispersed into hydrocarbon oil (Lord, MRF-132LD). The average diameter and volume fraction of the particles are 3 microns and 32 vol%, respectively. The density ratio of the particle to the oil is about 9.

The magnetorheological properties are evaluated using a parallel disk rotary rheometer (HAAKE, Rheostress RS150). Figure 1 shows the experimental apparatus to measure the shear stress and visualize the shear flow behavior of the MR fluid between two rotating parallel disks under relatively weak magnetic field. An upper rotating disk of \(d = 20\) mm diameter is made of aluminum. A lower fixed disk of 20 mm diameter is made of glass to visualize the flow pattern from a bottom side. The gap height \(h\) between two disks is set 0.1, 0.2 and 0.3 mm, since the induced shear stress of the ER fluid strongly depended on the narrow gap between two disks less than 0.3 mm in our previous study(5), (6). The MR fluid is filled up between two disks, and relatively weak effective magnetic field strength \(H\) less than the maximum of 5.90 kA/m at 5 A to the Helmholtz coil is applied in a stable condition, to investigate in the condition of the high fluidity and the almost same shear stress as for the ER fluid. The shear rate defined at the outer edge of disk is set 50, 100 and 150 s\(^{-1}\), where the observation of the flow behavior is enable using a normal video camera. The shear stress is defined as \(\tau = \frac{16T}{\pi d^3}\), where \(T\) is the measured torque acting on the shaft of the upper rotating disk, so that it includes the effects of flow pattern evolutions including a phase separation and fluid leakages out of the disks. In the experiments, the upper disk starts rotating just after the application of the magnetic field. The shear stress is measured for two minutes under constant magnetic field strength and shear rate. The flow pattern evolution of MR fluid with time is observed through the lower transparent disk from the bottom side to be recorded on VTR using a CCD camera.

3. Results and Discussion

3.1 Typical flow patterns

Figure 2 shows two typical flow patterns of the MR fluid observed with time under constant magnetic field and shear rate \((H = 4.72\) kA/m, \(h = 0.2\) mm and \(\dot{\gamma} = 100\) s\(^{-1}\)). The left pattern was obtained at 10 sec after the beginning of rotation, and another one was at 120 sec. In the presence of magnetic field, the particle chains are formed in the field direction, and the aggregation of these chains is caused to form columns by the interaction of the chains(7), (8). When the upper disk rotates and the MR fluid is sheared under constant shear rate, these structures are destroyed by the hydraulic force and various flow patterns are formed. In the condition of Fig. 2, the packed MR fluid cracks spirally at a few second after the beginning of rotation, and then
the MR fluid leaks out of the gap due to the centrifugal force. After that, arm-like structures, grain-like particle’s agglomeration (which is called “grain” in this study), line of grains, etc., are formed and destroyed. Finally “quasi-steady” pattern (explained in next subsection) shown in the right image of Fig. 2 can be established. In this pattern, the flow morphology does not change a lot and the amount of leak is very small. This quasi-steady pattern consists of a circular large packed structure with uneven but apparent boundary, many grains rotating independently and lines of grains around the circular structure. The grains might be mainly composed of a high-density column of particle chains, and spirally separate from the circular large packed structure due to the centrifugal force. The characteristics of the flow patterns, initial cracks and the leakage of MR fluid depend on the parameters such as effective magnetic field strength \( H \), gap height \( h \) and shear rate \( \dot{\gamma} \). In the following subsections, this case \( (H = 4.72 \text{ kA/m}, h = 0.2 \text{ mm} \) and \( \dot{\gamma} = 100 \text{ s}^{-1}) \) is compared with other cases in order to investigate the effects of the parameters on the time evolutions of the flow behavior and the time variation of shear stress.

### 3.2 Effect of magnetic field strength

Figure 3 shows the time evolution of the flow behavior in terms of the effective magnetic field strength \( H \). The gap height \( h \) and the shear rate \( \dot{\gamma} \) are set constant value \( (h = 0.2 \text{ mm}, \dot{\gamma} = 100 \text{ s}^{-1}) \). For the case of relatively small magnetic field \( (H = 3.54 \text{ kA/m}) \), the packed MR fluid cracked spirally in the early stage. The arm-like structure created by the crack moved to the outer edge of the disks, and then leaked out. After that the stable large circular structure was formed at the center of the disk and the leakage stopped, then the size of this structure was kept ever after. No grains were observed all through the experimental period. For the case of relatively large magnetic field \( (H = 4.72 \text{ kA/m}) \), the cracks generated initially were small compared with that for the weak magnetic field case, but the leakage of the MR fluid was caused in the same manner. The remarkable feature for this case was the formation of grains around the circular structure, caused by the centrifugal force acting on the high-density aggregated column of the particle chains. The grains detached from the edge of the circular structure, and then they slowly moved with rotation to the edge of the disk and leaked out. The “complete” stable state with grains cannot be obtained because the grains generated and leaked out continuously. Thus, this state is called as a quasi-stable state, in which the total amount of MR fluid between the disks keeps decreasing slowly. For the case of \( H = 5.90 \text{ kA/m} \), the grains could be observed just after the generation of the crack. In the quasi-stable state, many smaller grains rotated around the circular structure. Generally, as the magnetic field strength increases, the number of grains increases, their size becomes smaller and they become to form the line structure. The circular structure at the center becomes smaller and its boundary becomes unclear. These phenomena might be closely related to the aggregation strength of the particle chains; the density of the

![Fig. 3 Effect of magnetic field strength on pattern evolution of MR fluid shear flow \((h = 0.2 \text{ mm} \) and \( \dot{\gamma} = 100 \text{ s}^{-1}) \)](image-url)
aggregated particles, depending on the applied magnetic field.

Figure 4 shows the time variation of shear stress $\tau$ in terms of the magnetic field strength. The maximum value of $\tau$ was obtained just after the beginning of rotation, and then it monotonically decreases mainly due to the leakage of MR fluid out of the gap. The curve moves upper as the magnetic field increases. For $H = 3.54$ kA/m, the decrease of $\tau$ stops around $t = 30$ sec, after that almost constant value is obtained. For $H = 4.72$ and 5.90 kA/m, $\tau$ decreases remarkably in the early stage and keeps decreasing gradually. As seen from Fig. 3, the stable circular structure is formed and no grains are generated for $H = 3.54$ kA/m so that the decrease of $\tau$ stops because of no leakage of MR fluid. However, a lot of grains are generated and leak out of the gap for $H = 4.72$ kA/m so that the $\tau$ keeps decreasing gradually. Small fluctuation of $\tau$ becomes to be distinctive as $H$ increases. That is perhaps attributed to the pattern evolution with time, but we cannot discuss in detail because the perturbation of $\tau$ due to the leaked fluid adhering to the outer edge of disks cannot be neglected.

### 3.3 Effect of shear rate

Figures 5 and 6 show the time evolution of the flow patterns and the time variation of shear stress $\tau$ in terms of the shear rate, respectively. The effective magnetic field strength $H$ and the gap height $h$ are set constant value ($H = 4.72$ kA/m, $h = 0.2$ mm). For $\dot{\gamma} = 50$ s$^{-1}$, the packed MR fluid cracked spirally in the early stage, and then the circular structure with uneven boundary can be seen. The shape of this structure varied with time. A few individ-
ual grains can be seen around it, but almost all the grains were adhered to the boundary of it. For \( \dot{\gamma} = 100 \text{ s}^{-1} \), there are many grains and the lines of grains around the circular structure. For \( \dot{\gamma} = 150 \text{ s}^{-1} \), the small-cracked pattern in the early stage changed to the circular structure with clear boundary. There are a few small grains during the transient term, but they cannot be seen in the quasi-stable state. The beginning of fluid leakage was relatively earlier because of high-speed rotation so that, in Fig. 6, the period of rapid decrease of \( \tau \) in the early stage is distinctively shorter than that for other cases. The \( \tau \) in the quasi-stable state (\( t > 100 \text{ sec} \)) increases as \( \dot{\gamma} \) increases. Especially the difference of \( \tau \) between the cases of \( \dot{\gamma} = 100 \text{ s}^{-1} \) and \( 150 \text{ s}^{-1} \) is about 50 Pa, which cannot be explained by the "original" plastic viscosity of the MR fluid. It is considered that the amount of the fluid leakage depends on the shear rate. Actually much amount of MR fluid remains for \( \dot{\gamma} = 150 \text{ s}^{-1} \) than for \( \dot{\gamma} = 100 \text{ s}^{-1} \) at \( t = 120 \text{ sec} \) as seen in Fig. 5. However, there is the distinct difference of \( \tau \) just after the beginning of rotation although the MR fluid does not leak yet. Therefore, the manner of the pattern evolution seems to depend on the shear rate.

3.4 Effect of gap height between two disks

Figure 7 shows the time evolution of the flow patterns in terms of the gap height \( h \). The effective magnetic field strength \( H \) and the shear rate \( \dot{\gamma} \) are set constant value \( (H = 4.72 \text{ kA/m}, \dot{\gamma} = 100 \text{ s}^{-1}) \). For \( h = 0.1 \text{ mm} \), the large-cracked pattern in the early stage changed to the unstable circular structure having many spiral arms with time. These arms consist of the lines of minute grains. As the gap increased to 0.2 and 0.3 mm, the initial cracks became smaller and many large grains were generated around the circular structure in the quasi-stable state because of the increase of the disk rotational speed, probably suggesting that the aggregation of the particle chains might be enhanced. Thus, the difference between the flow pattern evolutions for \( h = 0.1 \text{ mm} \) and \( h = 0.2 \text{ mm} \) is clearly distinctive, while the flow pattern evolution for \( h = 0.2 \text{ mm} \) is almost the same as that for \( h = 0.3 \text{ mm} \). Corresponding to these changes of the flow pattern evolution with the gap height, as seen in Fig. 8 the time variation curve of the shear stress \( \tau \) for \( h = 0.1 \text{ mm} \) is obviously located below the two curves for \( h = 0.2 \text{ and } 0.3 \text{ mm} \) which are not

![Fig. 7](image_url)

![Fig. 8](image_url)
greatly different. Thus, it is likely that the strength of shear stress strongly depends on the flow patterns.

The effect of the gap height on the shear stress $\tau$ is probably related to the mechanism of the flow pattern formation and the amount of leakage. Figure 9 shows the shear stress against the gap height at $t=1$ and 60 sec and Fig. 10 does the change of the flow patterns with the gap height for $H=2.36$ and 4.72 kA/m at $t=60$ sec. According to the visualization of flow patterns in Fig. 10, there is the remarkable difference in the gap effect on the patterns and the leakage at $t=60$ sec, while there is no leakage at $t=1$ sec (which is not shown here). Especially, the flow pattern for $h=0.1$ mm is obviously distinguished from the flow patterns for $h=0.2$ and 0.3 mm in both cases of $H=2.36$ and 4.72 kA/m. As shown in Fig. 9, the shear stress for $H=2.36$ kA/m increases as the gap increases, while for $H=4.72$ kA/m it increases with the increase of gap from $h=0.1$ to 0.2 mm and then slightly decreases with the increase of gap from $h=0.2$ to 0.3 mm. These trends are obtained at both $t=1$ and 60 sec. Therefore, the mechanisms of the initial destruction of the packed MR fluid and the succeeding pattern evolution seem to differ with the gap height, depending on the magnetic field strength.

On the other hand, the decrease of $\tau$ during the period from the beginning of rotation to the quasi-stable state is considered to mainly depend on the amount of leakage. Therefore, the effect of the gap height on the amount of leakage is investigated with the reduction rate of the shear stress ($R\tau$) defined as follows,

$$R\tau = \left(\frac{\tau_1 - \tau_{60}}{\tau_1}\right)$$

where $\tau_1$ and $\tau_{60}$ are the shear stress at $t=1$ and 60 sec, respectively. Figure 11 shows the changes of $R\tau$ with the gap height at $\dot{\gamma}=100$ s$^{-1}$. In the case of relatively weak magnetic field of $H=2.36$ kA/m, the $R\tau$ decreases as the gap increases, suggesting that the leakage probably decreases with increasing gap. This is consistent with the flow images for $H=2.36$ kA/m in Fig. 10, characterized by the unstable circular structure with spiral arms which are diminished as the gap height increases from 0.1 mm to 0.3 mm. When the magnetic field strength $H$ increases to 3.54 and 4.72 kA/m, the $R\tau$ increases exhibiting no apparent dependence on the gap height although the flow patterns differ with the gap height as seen from the images for $H=4.72$ kA/m in Fig. 10. The further increase of $H$ to 5.90 kA/m leads the increase of $R\tau$ for $h=0.2$ and 0.3 mm and the slight decrease of $R\tau$ for $h=0.1$ mm, resulting in the trend to increase $R\tau$ with the increase of the gap height contrary to the weak magnetic field case.
of \( H = 2.36 \text{kA/m} \). In general, it can be clearly said that the amount of leakage remarkably increases when the MR fluid flow forms the circular large packed structure having many grains rotating independently and line of grains around it for \( H \geq 4.72 \text{kA/m} \) and \( h = 0.2 \) and 0.3 mm.

In the future, the experiments for the wide range of the gap height less than 0.1 mm and more than 0.3 mm should be done in order to precisely determine the dependence of the gap height on the shear stress, the flow pattern evolution, the leakage flow and the \( R \tau \).

In the MR fluid devices such as clutches and brakes, which have equivalent configuration to this experimental one excepting the open end of the gap between disks, the variation of the shear stress due to both the flow pattern evolution and the fluid leakage flow has to be taken into consideration. It can be easily expected from the fluid leakage flow observed in this experiment that in the practical MR clutches and brakes having the closed end of the gap the particles of high density might move to the outer part of the disk due to the centrifugal force. In the future, the apparatus with the closed end of the gap has to be investigated in order to evaluate the effect of the leakage flow.

4. Concluding Remarks

The shear stress of MR fluid shear flow between two rotating parallel disks was measured and the flow patterns were simultaneously visualized under constant shear rate and relatively weak constant magnetic field. The effects of magnetic field, shear rate and gap height on the transient behavior of MR fluid were evaluated. The results were summarized as follows;

(1) In general, the maximum value of the shear stress \( \tau \) is obtained just after the beginning of rotation, and then it gradually decreases mainly due to the leakage of MR fluid out of the gap.

(2) Both the flow pattern evolution and the MR fluid leakage are responsible for the transient variation of the shear stress. So, the time variation and the level of the shear stress \( \tau \) mainly depend on the effective magnetic field strength \( H \) and the gap height \( h \).

(3) The flow pattern evolution of the MR fluid shear flow is characterized by the crack, the spiral arm, the grain-like particle’s agglomerations (grains), the leakage of MR particles out of the gap, and the packed circular structure.

(4) The occurrence of grain-like particle’s agglomerations (grains) and their leakage out of the gap seems to be mainly due to the interactive forces acting to the particles consisting of the magnetic force and the centrifugal force.

References