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Basic performance of ER gel on one-sided structured electrodes

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ABSTRACT

An electro-rheological Gel (ERG) is developed to overcome two shortcomings of Electro-rheological Fluid (ERF): sedimentation of ER particles and the seal structure required to allow the use of ERF in machine elements. The ERG shows a wide shear stress variation in response to an applied electric field. To apply an electric field to the ERG, it is necessary to sandwich the ERG between plane-parallel electrodes. However, it is impractical to wire both electrodes to a high voltage supply. In this study, one-sided electrodes are proposed to simplify the wiring structure. The basic characteristics of ERG on one-sided electrodes are evaluated experimentally. It is found that these electrodes exhibit nearly the same performance as the conventional plane-parallel type. The one-sided ERG mechanism is especially useful in applications involving rotating or sliding parts.

KEYWORDS

Electro-rheological Fluid, functional material, gel, one-sided electrodes

INTRODUCTION

Electro-rheological Fluids (ERF) [1, 2] are colloidal solutions whose viscoelastic properties vary with the applied electric field intensity. ERF are classified into two types, namely dispersed [3] and homogeneous [4], according to their flow behavior. Dispersed ERF and homogeneous ERF exhibit Bingham flow and Newtonian flow, respectively.

The research on homogeneous ERF has accelerated in recent years and its applications are put to practical use in the medical field, e.g., as assist devices for walking and rehabilitation [4]. On the other hand, the practical shortcomings of dispersed ERF remain: the separation and sedimentation of ER particles over long-term use caused by the difference in density between the particles and the base oil. This reduces the ER effect [5, 6] and results in low-stability of ER devices. Another shortcoming is that a mechanical seal is required for machine element applications.

The present study reports the development of an Electro-rheological Gel [7, 8] that will overcome these shortcomings. This new ER material is produced by the hydrosilylation reaction, whereby the hydrogensilicone and unsaturated compounds attach to the dispersed ERF via Si-H bonds. The ER particles are suspended in a gel component, and thus sedimentation of ER particles does not occur. This suppresses the decrease in ER effect associated with precipitation. A seal structure is not needed in ERG applications because this is a solid-state system.

The mechanism of shear stress formation in ERG (Fig. 1) differs from that in ERF [8]. The initial state of the ERG sheet sandwiched between a pair of electrodes is shown in Fig. 1(a). The shear force between the upper electrode and ERG is very low in the absence of an electric field because the upper electrode is supported by slippery ER particles protruding from the gel surface. By contrast, the upper electrode makes contact with the sticky gel surface under a high electric field because the protruding particles retract into the gel so that dielectric polarized particles can attract each other as shown in Fig. 1(b). These changes in contact conditions at the interface between the electrode and ERG result in the shear force variation observed in response to the change in electric field intensity.

To obtain the ER effect in ERG, it is necessary to apply an electric field to ERG, which is sandwiched between the plane-parallel electrodes. However, it is impractical to wire both electrodes to a high voltage supply. Thus, the present study proposes one-sided electrodes in order to simplify the wiring structure. Using one-sided electrodes, the generation of the ER effect in ERF is comfirmed by Furusho and Inoue [3]. In the present study, the basic characteristics of ERG on one-sided electrodes are evaluated experimentally and numerically.

STRUCTURE OF ONE-SIDED ELECTRODES

Figs. 2 and 3 show the structure and appearance of the one-sided electrodes fabricated. The aluminum electrodes are arranged alternately as cathode and anode on the insulating plate. Two types of one-sided electrodes having a different number of electrodes per unit length were designed: one with 10 electrodes where each electrode was 50×6.1×6 mm (L×W×H), the other with 15 electrodes where each electrode was 50×3.7×6 mm (L×W×H). The electrode gap in both types was 1 mm and the overall dimensions were 50×70 mm (L×W). An ERG sheet was formed on the electrodes with variable thickness. The ERG sheet was fixed on the one-sided electrodes because it was caught in slots between the electrodes.

The ER effect generated in the form of bridge-shaped electric field lines between the one-sided electrodes goes through the ERG sheet. To examine the ER effect on the one-sided electrodes, phenomena at the boundary between the ERG and the upper plate of the ITO glass were observed. As shown in Fig. 4, that the ERG surface changes into an adhesive surface under a 1.5-kV/mm electric field indicates that the ER effect of ERG is obtained using the one-sided electrodes.

STATIC PERFORMANCE OF ERG ON ONE-SIDED ELECTRODES

Shear test: experimental setup and procedure

Static performance of ERG on one-sided electrodes under an electric field was evaluated by the simple test

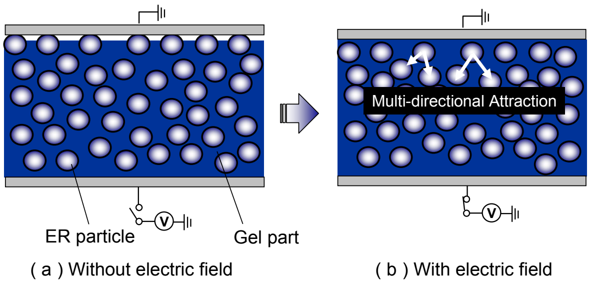

Figure 1 Mechanism of ER effect in ERG

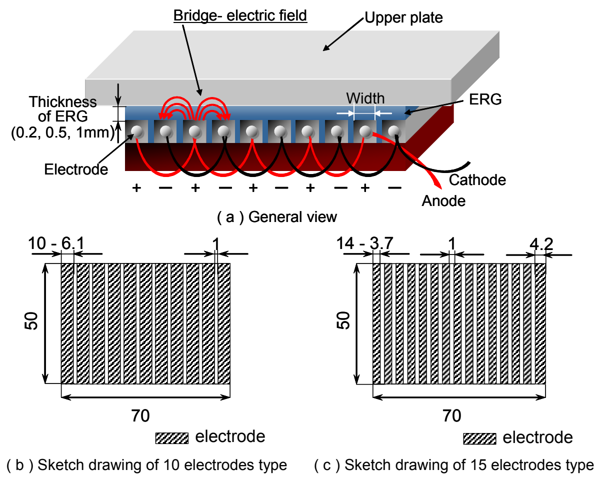

Figure 2 Structure of one-sided electrodes

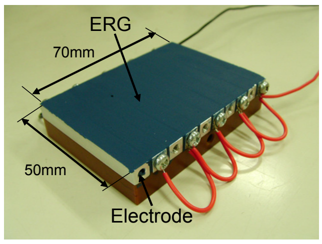

Figure 3 ERG sheet on one-sided electrodes

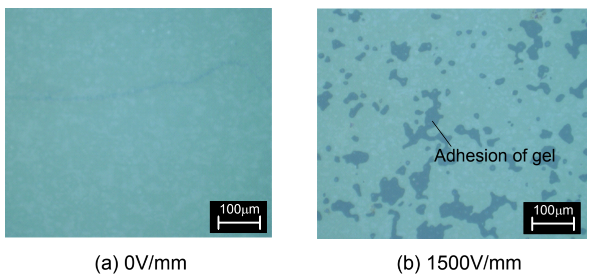

Figure 4 Observation at the boundary between ERG and the glass

stand schematized in Fig. 5. The upper plate made of Al was set on the ERG sheet formed on the one-sided electrodes. The variation in shear force between the upper plate and ERG sheet was measured while applying an electric field to the ERG. Shear motion was applied to the upper plate by a micrometer screw with motor-drive equipment. The shear force was measured by a strain gauge load cell attached to the slider plate. The displacement of the upper plate was measured by an eddy current displacement sensor. The behavior of shear force was monitored while varying the electric field intensity from 0 to 1.5 kV/mm. The shear length was set to 600 μm, and the shear speed was adjusted to 30 μm/s.

Relation between electric field intensity and shear stress

The behavior of shear stress under a variable electric field in both the 10- and 15-electrode-type electrodes are summarized in Figs. 6(a) and 6(b). An ERG sheet was formed on both one-sided electrodes with 0.2 mm thickness. When the displacement of the upper plate exceeds a certain value, the ERG sheet yields. Higher yield stresses are obtained under higher electric field intensities. Up to the yield point, the shear stress varies linearly with displacement because the upper plate and ERG are bonded by the ERG, which was rendered adhesive by the electric field. Above the yield point, the shear stress increases only gradually. This is due to the slip between the surface of the upper plate and the ERG sheet. Though the generated shear stress is lower than in double-sided electrodes, it is clearly possible to obtain the ER effect using an ERG on one-sided electrodes. Fig. 7 shows the relation between the applied electric field and generated yield stress. The generated yield stress increases exponentially with the applied electric field. By contrast, in the case of double-sided electrodes, the generated yield stress varies linearly with the applied electric field. This difference can be ascribed to the electric field lines going through the ERG, which increase exponentially in the case of one-sided electrodes, but linearly in the case of double-sided electrodes.

As shown in Fig. 7, the generated shear stress increases with the number of electrodes. To investigate the effects, if any, of the electrode structure on the generated shear stress, FEM analysis of the electric field is performed in one-sided electrodes at an electric field intensity of 1.5 kV/mm. Fig. 8 shows the FEM analysis results for the 15-electrode type. Clearly, the bridge-shaped electric field lines go through the ERG sheet. Perpendiculars dropped from the center of the cathode and anode to the boundary line between the ERG and the upper plate intersect the boundary at points A and B, respectively. In order to investigate the electric field distribution on line segment AB, 20 points are taken on the segment at equal intervals and the electric field intensity at each point is determined. Fig. 9 shows the distribution of the electric field intensity on segment AB. The average of the electric field intensity between A and B is equal to the average electric field intensity at the boundary between the ERG and the upper plate. The average electric field intensity is given by

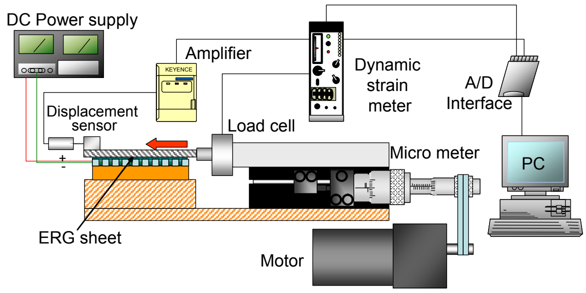

Figure 5 Experimental setup for shear test

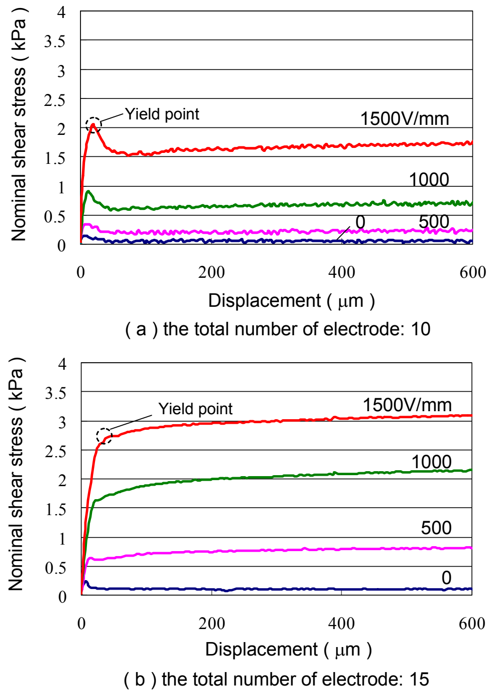

Figure 6 Behavior of shear stress under variable electric field

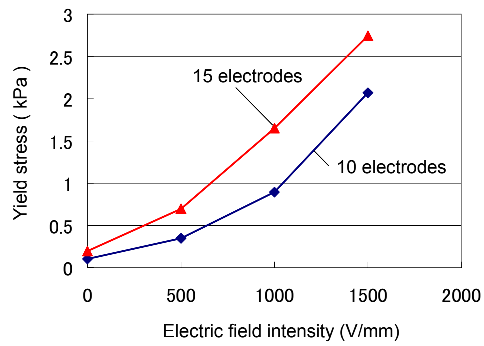

Figure 7 Relation between the generated yield stress and applied electric field

$$E_{ave} = \frac{\sum E_i}{20} \quad (1)$$

where E_{ave} is the average electric field intensity between the upper plate and the ERG sheet and E_i is the electric field intensity at each point on segment AB. The average electric field intensities using 10 and 15 electrodes are 336 and 465 kV/mm, respectively. The thinner the electrode width is, the higher the average electric field intensity, and hence, the higher the generated shear stress.

Based on the electric field analysis, a way to solve the yield stress from the average electric field intensity is proposed. In the case of the double-sided electrodes, the generated yield stress is roughly proportional to the applied electric field intensity. Fig. 10 shows the shear stress behavior in double-sided electrodes using the same ERG material. Under an applied electric field intensity of 1.5 kV/mm, the yield stress is about 9 kPa. Using this and the FEM analysis results, the relation between the estimated yield stress and average electric field intensity is formularized:

$$\tau_{est} = \frac{9}{1500} \times E_{ave} \quad (2)$$

where τ_{est} is the estimated yield stress. The estimated yield stress in the case of 10 and 15 electrodes is 2.0 and 2.79 kPa, respectively. These values determined by Eq. 2 match the results shown in Fig. 6 almost exactly. It appears that the generated yield stress depends on the average electric field at the boundary.

The average electric field intensity at the boundary seems to be determined by the ratio of the electrode gap to the electrode width. To generate the highest yield stress possible the ratio that gives the highest average electric field intensity at the boundary is determined. Then, at a constant electrode width, the influence of the electrode gap on the average electric field intensity is investigated by means of FEM analysis of the electric field. Fig. 11 illustrates the relation between the electrode gap and average electric field intensity, for an electrode width of 3.7 mm. The average electric field is calculated by Eq. 1. The maximum average electric field intensity occurs at an electrode gap of about 0.5 mm. That is, the most efficient design in terms of the generated yield stress would presumably be one-sided electrodes with an electrode gap of 0.5 mm and an electrode width of 3.7 mm.

From these results, it is possible to estimate the yield stress by FEM analysis, which helps in designing any device that incorporates the ERG.

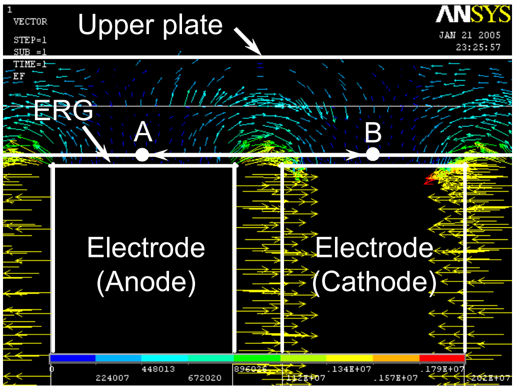

Figure 8 Distribution of electric lines

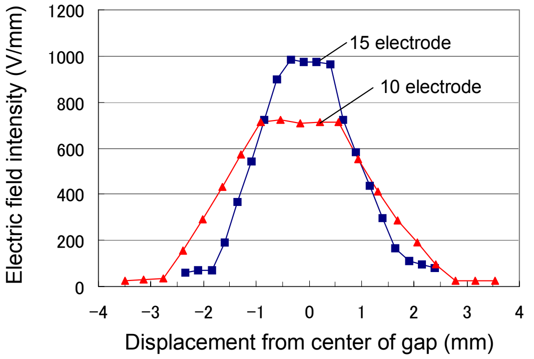

Figure 9 Distribution of electric field at the boundary between ERG and the upper plate

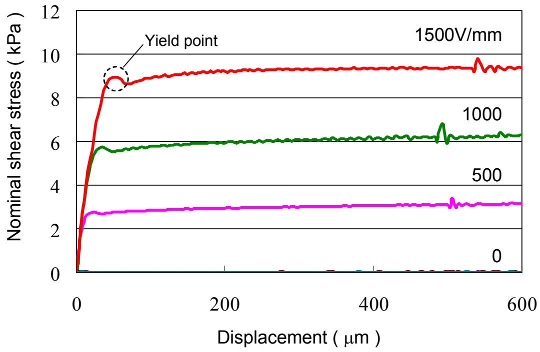

Figure 10 Result of shear test with both-sided electrodes

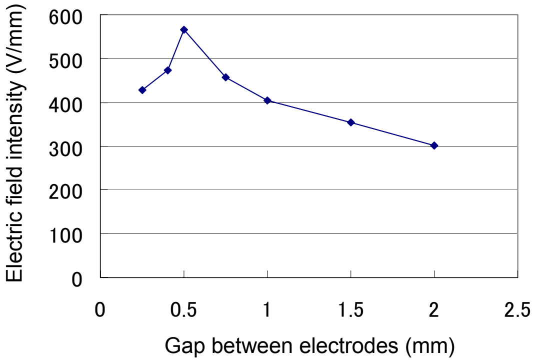

Figure 11 Relation between the electrode gap and average electric field intensity at the boundary

DYNAMIC PERFORMANCE OF ERG ON ONE-SIDED ELECTRODES

Procedure

The static performance assessment reveals that the ER effect can be obtained without wiring the upper plate. Then, to investigate the feasibility of using the ERG in a given device, e.g., as a clutch in a torque transfer device, its dynamic performance is analyzed experimentally. Fig. 12 shows the experimental setup for the vibration test. A 0.2-mm-thick ERG sheet and 15 one-sided electrodes are prepared. When vibrations are applied to the slider, the upper plate connected to it through a load cell is vibrated. In the absence of an electric field, the amplitude remained constant at 100 μm, while the frequency was varied from 5 to 100 Hz. The displacement amplitude and generated shear force were measured while applying an electric field to the ERG under vibration conditions. From the results of this test, the response of the ERG to the applied electric field is obtained.

Vibration test results

Fig. 13 shows the measurement results obtained at a frequency of 25 Hz. The electric field shown on the right vertical axis does not refer to the field at the boundary between the ERG and upper plate, but rather, to that between the electrodes. The vibration of the upper plate is quickly suppressed by the applied electric field as shown in Fig. 13(a): the amplitude of the electrode drops from 100 μm to less than 10 μm as a result of the applied electric field on the ERG. The shear stress is increased by the applied electric field as shown in Fig. 13(b); the shear stress amplitude increases from 1 kPa to more than 2.5 kPa.

Table 1 shows the dynamic responsiveness of the ERG on one-sided electrodes (the 15-electrode type), which differs little from the responsiveness of double-sided electrodes. ERG exhibits a very high ON responsiveness. However, the responsiveness of ERG in the CUT OFF operation is rather low. This is because the ERG is a passive material so that releasing the polarization charge in ER particles naturally requires time when the power supply is cut off.

Fig. 14 shows the relation between displacement of the electrode and shear stress over a period of cyclic vibration. When the applied electric field is relatively low, a hysteresis is observed between the displacement and the shear stress. This is presumably caused by the viscous damping of the ERG sheet, i.e., the damping effect due to the energy dissipation of viscous friction loss. By contrast, the vibration energy is converted into elastic energy as the electric field intensity exceeds 750 V/mm.

Fig. 15 shows the effect of the applied electric field intensity on the dynamic compliance of the upper plate.

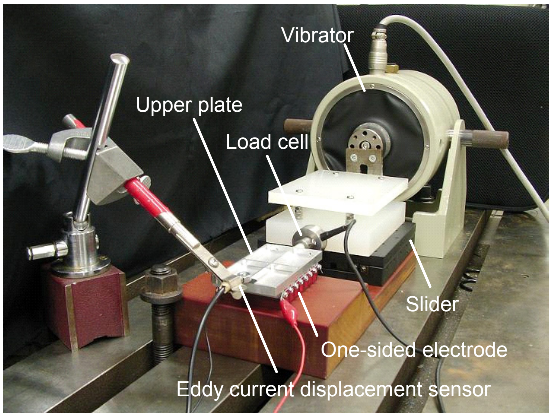

Figure 12 Experimental setup for vibration test

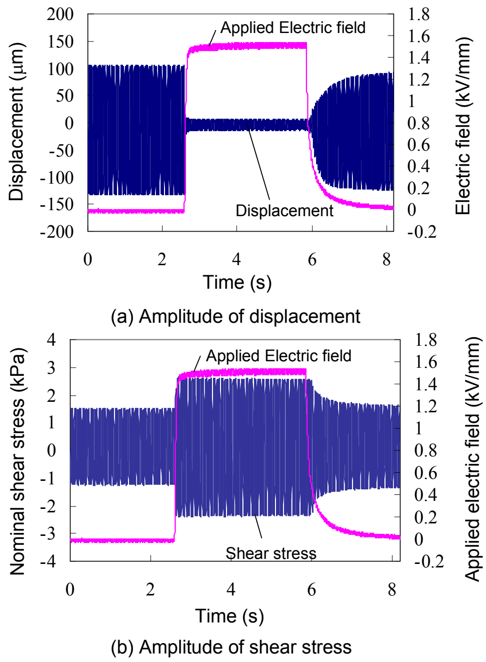

Figure 13 Result of vibration test at 25Hz

Table 1 Response time of ERG

	ON-response (ms)	OFF-response (ms)
ERG on one-sided electrodes	20~30	100~200

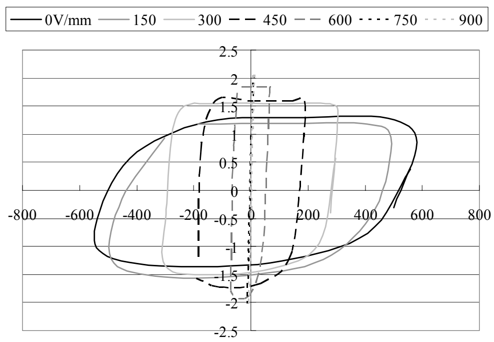

Figure 14 Influence of electric field intensity on hysteresis characteristics

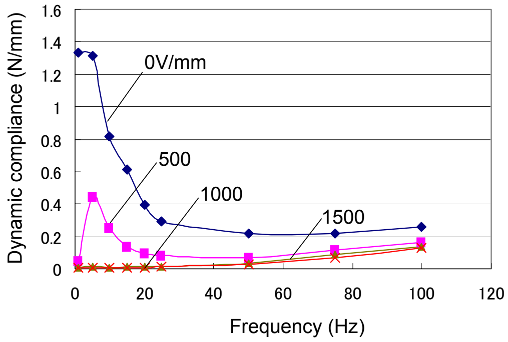

Figure 15 Relation between dynamic compliance and frequency of vibration

The peak value of the dynamic compliance curve decreased with increasing electric field intensity, indicating that the vibration of the upper plate can be effectively suppressed by the ERG on one-sided electrodes.

CONCLUSION

Using the developed ERG in a device with a rotating mechanism is problematic in that the ERG needs to be wired to the rotating part. To simplify the wiring mechanism, one-sided electrodes were proposed and applied to the ERG. The basic performance of the ERG on one-sided electrodes was analyzed experimentally and numerically. The relation between the generated shear stress and applied electric field was investigated via shear tests. Results indicated that the ERG on a large number of electrodes per unit length showed a large variation in shear force in response to changes in applied electric field intensity. Moreover, the yield stress clearly depends on the average electric field at the boundary between the ERG and the upper plate. Dynamic characteristics of the ERG on one-sided electrodes were determined through a simple vibration test. The results of this test showed the suitability of the ERG for use in vibration attenuators. It is expected that ERG on one-sided electrodes will find applications in, for example, clutch mechanisms, damping devices, and braking systems.

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