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Electrorheological response measured with pectinated electrodes

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Pectinated electrode has been designed to measure the rheological property of electrorheological (ER) fluids. The principle of this measurement is based on the effect that the outside electric field near the edges of parallel electrode can contribute a considerable value of the field. The relations of the yield stress and the gap between pectinated electrode and workpiece, as well as the variations of the yield stress versus the parameters of pectinated electrodes have been obtained. It is found that the yield stress can be much enhanced when the gap is small and decreases with the gap increasing. The mechanism of those phenomena is explained. This knowledge of the ER behavior by using pectinated electrode must be helpful for the design of device in the applications of ER fluid. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4901832]

I. INTRODUCTION

The yield stress of electrorheological (ER) fluid can be changed from liquid-like to solid-like state by applying electric field.[1–5] A new type of ER fluid which is called Giant electrorheological (GER) fluids or polar molecule dominated ER (PM-ER) fluids has been developed in recent years.[6–11] The yield stress of the GER (or PM-ER) fluids can be as high as more than 100 kPa, much higher than that of the traditional ER fluids. Thus, the applications of such new ER fluids are promising. However, comparing with the applications of magnetorheological (MR) fluids,[12] some technical issues should be resolved besides the improvement for GER materials. In the case of applying MR fluids, the magnetic field can be provided in one side, while two electrodes are usually needed in operating ER fluids. For instance, in the application of precision polishing, which is enabling technology that can produce surface accuracy of the order of 10 nm by using MR fluids,[13,14] however, the electrodes should not be arranged in two sides as usually for polishing an insulating workpiece in the case of using ER fluids. There must be a new design of the electrodes to satisfy the requirement for such applications of ER fluids.

In this paper, we present a study on the ER response by using a pectinated electrode based on the principle that there must be a certain value of electric field contributed in the region outside the edges of the parallel electrode. It is observed that the ER response is very considerable by using a system consisted of a pectinated electrode and insulating workpiece. The yield stress of ER fluids increases with decreasing the gap width between pectinated electrode and workpiece. It is also found that when the distance between pectinated electrode and workpiece is small the measured yield stress of ER fluid is even much higher than that measured with a rheometer made up of conventional electrodes at a same electric field. A simulation about the distribution of electric field and ER response in this design has been performed and is consisted with the measured results. We believe that the knowledge of pectinated electrodes and the ER behavior between the electrode and workpiece are beneficial in the application of ER fluid for ER fluid-assisted polishing, as well as other device designs such as dumpers and clutches, etc. This also provides a method for the measurement of the ER behavior, especially for measuring the shear stress of ER fluids at high shear rate.[15]

II. EXPERIMENTAL

The nanometer-size calcium titanate (CTO) particles used in the experiment were synthesized by a co-precipitation procedure. The detailed process for material preparation and the composition of CTO particles were described in our previous work.[9,16] The powders were dried at 120 °C for 2 h in atmosphere, of which the average size was about 70 nm estimated with SEM. The dried CTO particles are suspended in aviation hydraulic oil with volume fraction of $\phi = 47\%$.

The fabricating method of pectinated electrodes and the arrangement for measuring ER behaviors are described as follows. As illustrated in Figure 1(a), the copper slices with same thickness are parallelly and uniformly spaced embedded into a piece of insulating nylon. Those copper slices are alternately separated into two groups and connected to two larger copper pieces respectively for applying the electric field. After assembling the copper slices to nylon framework, the surface of whole pectinated electrode is carefully ground to be smooth. Three sets of pectinated electrodes with different w and l are used in the measurement, where w is the width of the copper slices and l is the width between neighboring copper slices. They are nominated as electrodes 1#, 2#, and 3# with

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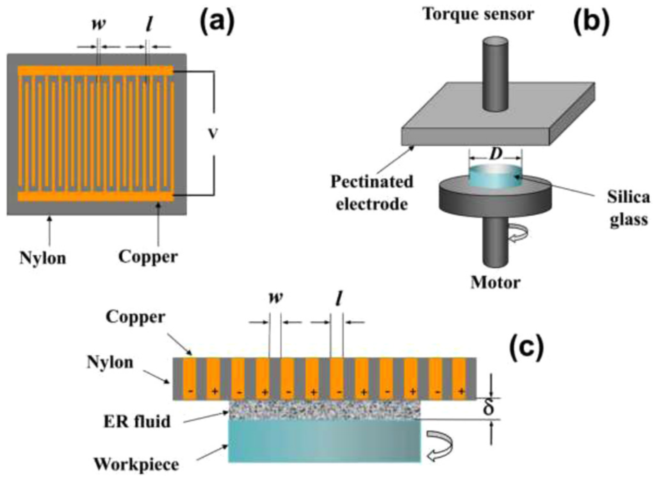

FIG. 1. (a) Sketch of pectinated electrode. (b) Sketch of the arrangement for measurement. (c) The sectional view of the arrangement for electrodes, ER fluid, and workpiece.

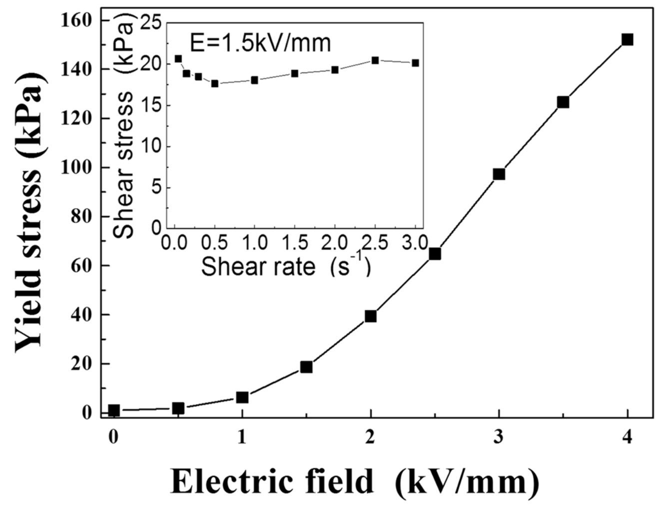

FIG. 2. The yield stress versus electric field of CTO ER fluid measured using the ordinary parallel-plate rheometer (Anton Paar Physica MCR 501). The inset is the shear stress of the sample at 1.5 kV/mm in the region of 0.1 to 3 s^{-1} of shear rate.

$w = 0.15$ mm and $l = 1$ mm, $w = 0.6$ mm and $l = 1$ mm, and $w = 0.15$ mm and $l = 1.5$ mm, respectively.

As same in a rheometer of parallel mode, the pectinated electrode is installed as the upper plate of the rheometer connected to a torque sensor, and a silica glass disc is installed on the lower platform driving by a step motor, as shown in Figure 1(b). The diameter and thickness of silica glass disc are 26 mm and 3 mm, respectively. The size of the pectinated electrodes is $35 \times 35\ mm^2$, which is large enough to ensure the electric field in effective region is basically uniform. The gap δ between the pectinated electrode and silica glass disc can be adjustable. A schematic diagram of the electrodes, ER fluid, and workpiece is shown in Figure 1(c).

III. RESULTS AND DISCUSSION

In order to compare the effect of pectinated electrode on the ER behavior, original yield stress versus electric field of CTO ER fluid is measured with an ordinary parallel-plate rheometer (Anton Paar Physica MCR 501) as shown in Figure 2. The dynamic yield stress is measured at a low shear rate of 0.2 s^{-1}. It can be seen that the yield stress is about 150 kPa at 5 kV/mm and 20 kPa at 1.5 kV/mm. The shear stress of the sample at 1.5 kV/mm in the region of 0.1 to 3 s^{-1} of shear rate is also plotted as inset in Figure 2, and it shows that the variation of shear stress is slight in this region. In the following statement, the yield stress is approximately defined as the measured shear stress at low shear rate. As measuring the yield stress by using pectinated electrode, the change of distance δ between pectinated electrode and silica glass must cause the change of the shear rate. Corresponding to δ changing from 0.1 mm to 1 mm, the shear rate varies from 2.7 s^{-1} to 0.27 s^{-1} in our measurements. Because shear stresses keep almost same in this region of shear rate as seen in inset of Figure 2, we can ignore the influence of shear rate on yield stress in the process of changing δ in the measurement.

The yield stress of the above ER fluid sample versus electric field and δ are measured employing pectinated electrode as described in Figure 1. Figure 3(a) indicates that the yield stress increases with electric field rising as common

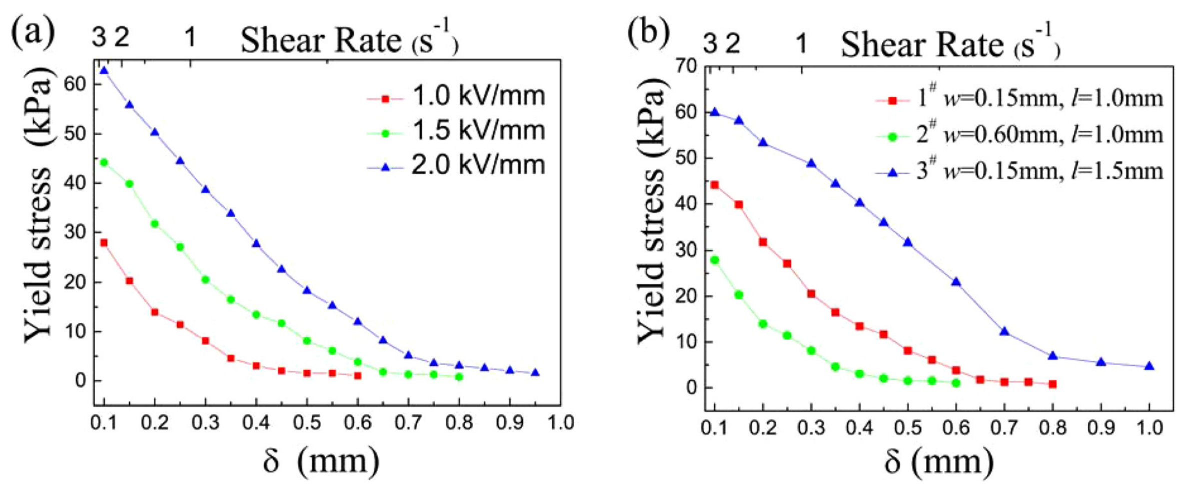

FIG. 3. The dependences of the yield stress on electric field and δ measured with pectinated electrodes. The top scale in figures indicates the shear rate for different gap δ. (a) The yield stress measured with 1# pectinated electrode under different electric fields. (b) The yield stress at 1.5 kV/mm measured with different pectinated electrodes.

ER behavior and decreases with δ increasing measured with $1^{\#}$ pectinated electrode. In the measurement, the shear rate becomes smaller as increasing the gap δ and is also plotted in top scale of Figure 3 corresponding to δ.

It also can be seen in Figure 3 that the measured yield stresses of ER fluid with pectinated electrodes exhibit a significant behavior. The yield stresses are much larger than the original values measured by ordinary rheometer as shown in Figure 2 when δ is small under a same electric field. For instance, the yield stresses are 28 kPa, 44 kPa, and 62 kPa measured with electrode $1^{\#}$ at $\delta = 0.1$ mm when the electric fields are 1 kV/mm, 1.5 kV/mm, and 2 kV/mm, respectively. Correspondingly, the original values of yield stress are 6.3 kPa, 19 kPa, and 39 kPa under respective electric field as shown in Figure 2. The results indicate that an enhancement of yield stress occurs as using pectinated electrode with small distance δ, meaning smaller the δ larger the enhancement.

To understand the observed ER behavior in using pectinated electrodes, an explanation is presented as follows. The basic difference for the ordinary electrodes and pectinated electrodes is that the electric field is uniform in the former but is not in the latter. For comparing with the measured results by using pectinated electrodes, a calculation is made. Considering the metal slices periodically arranged in pectinated electrode, a finite difference method is applied to calculate the electric potential distribution in the outside region of electrodes. By solving two-dimensional Laplace equation of static electric field in a periodic boundary condition, the distribution of the electric field in the region can be obtained. The calculated electric flux lines of pectinated electrode are illustrated in Figure 4(a). The electric field near the edges of a pectinated electrode is stronger, where the electric flux lines are dense and tend to be parallel to the surface of electrode. As an ER response, the particles must be aligned into chains along the electric flux lines in the region as shown in Figure 4(b). The larger proportion of parallel flux lines component near the surface of electrode generates more particles arranged in the form of chains in this region. Thus, the ER effect must be larger as δ is small and decreases with the increase of δ. Another factor for enhancing the ER response at the region of small δ may be due to more particles paralleling to the surface of electrode. If the applied shear direction is parallel to the surface of electrodes, there is an additional strain pressing the parallel chains. Even though the pressure only contributes a component to the chain direction, this situation is distinct from ordinary yield stress measurement in which the shear direction is perpendicular to particles chains. This additional strain along the direction of chains could induce an enhancement of yield stress as reported in the literatures.[17,18] This kind of enhancement of yield stress in MR fluids has been also observed and explained with compression assisted-aggregation process,[19] although the mechanism of this phenomenon should be further studied.

Therefore, when δ is small, i.e., near the surface of pectinated electrode more particles are arranged in parallel chains and also the average electric field is stronger. Those two effective factors become weaker as δ is larger, thus the average electric field and ratio of parallel chains both decrease with δ increasing as shown in Figure 4(b). From the distribution of the electric field in the region near pectinated electrode as shown in Figure 4(a), the stresses can be calculated in x and y directions, respectively. A calculation is adopted with the approach that the stress of GER is proportional to electric field strength.[7–9] As shown in Figure 4(c), the calculated torques of ER fluids by using pectinated electrode decrease with δ increasing, as a condition of $w = 1.00$ mm is considered. This behavior is in accord with the measurements.

On the other hand, the enhancement of yield stress also depends on the design of pectinated electrode with different w and different l when δ is fixed. As seen in Figure 3(b), for electrodes $1^{\#}$ and $2^{\#}$, the widths of nylon are the same

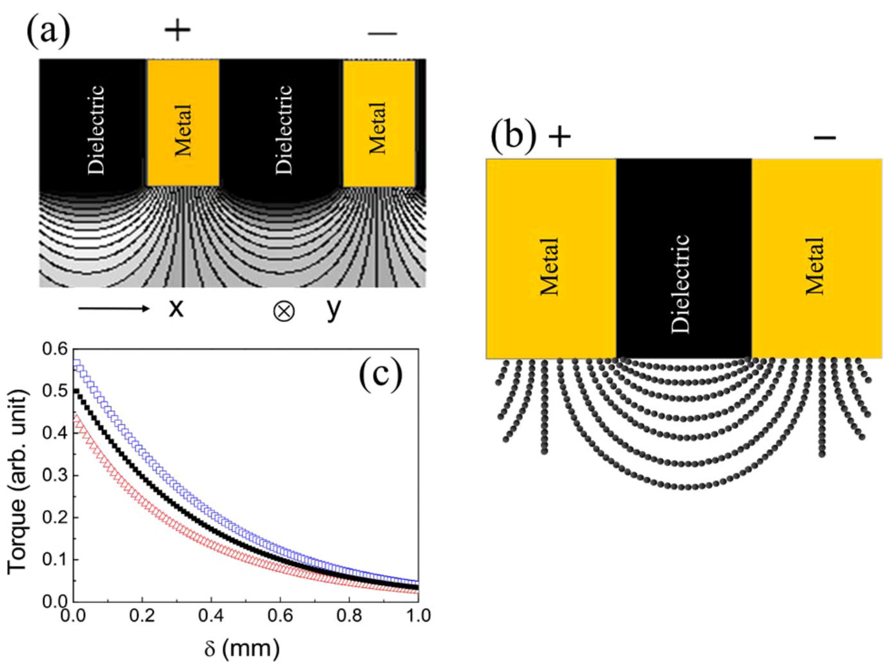

FIG. 4. (a) The field distribution near the edges of parallel electrodes. x and y indicate the directions in the plane and perpendicular to the plane, respectively. Arrow indicates the shear direction. (b) The schematic of particle chains arranged follows the electric flux lines of electrodes. (c) The calculated results: relation of the relative torque changing with δ. Blue open square, red open triangle, and black solid square represent the torques in x, y directions and the mean of them, respectively.

($l = 1.00$ mm), while the widths of copper slices are different ($w = 0.15$ mm and $w = 0.60$ mm, respectively), the yield stress measured with electrode $1^{\#}$ is larger than that measured with electrode $2^{\#}$. It implies that the smaller w causes a stronger yield stress when l is the same. On the other hand, by comparing the measured results with electrodes $1^{\#}$ and $3^{\#}$ it is found that wider separation l of the pectinated electrode can induce higher ER effect even with same w of copper slices. In this case, the widths of copper slices are same ($w = 0.15$ mm) and separations of them are different ($l = 1.50$ mm and $l = 1.00$ mm, respectively). Those observed dependences of the yield stress on w and l are easy to be understood. It can be seen in Figure 4 that the outward electric flux lines from metal are mostly perpendicular to the surface. Smaller width w of copper slices and larger separation l can provide relatively higher ratio of flux lines paralleled to the surface, and consequently induce more chains in shear direction, which results in higher yield stress.

IV. CONCLUSIONS

The rheological behaviors of ER fluids have been studied by using a system consisted of a designed pectinated electrode and an insulating plate. It is found that the measured yield stresses with this method depend on the distance δ between pectinated electrode and insulating plate as well as on the design of pectinated electrode. The yield stress can be much enhanced when the distance δ is small and decreases with the distance δ increasing. The large enhancement of yield stress comes mainly from the denser contribution of the electric field near the surface of pectinated electrode, where more particles are in the chains parallel to the plane of shear direction. The decrease of measured yield stress with δ increasing is due to the average electric decreasing and less particles in the chains parallel to the plane of shear direction. Smaller width w of the copper slices and larger separation l are beneficial to the enhancement of yield stress in the design of pectinated electrode. The obtained results are beneficial for the applications of ER fluid, such as for the ER fluid assistant polishing and the device designs of dumpers, clutches, etc.

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