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Short Communication

The electrode effect on polar molecule dominated electrorheological fluids

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ABSTRACT

The polar molecule dominated electrorheological (PM-ER) fluids are based on the interaction of polar molecule-charge in between the particles, of which the yield stress can be orders higher than that of conventional ER fluids. In the case of PM-ER fluids unlike conventional ER fluids the surfaces of ordinary metallic electrodes can no longer satisfy the boundary condition. A slide must occur at the interface between PM-ER fluids and electrodes leading to the much lower measured shear stress than its intrinsic value. According to the principle of PM-ER fluids modified electrodes are designed for increasing the adhesion of fluids to the electrodes and weakening the slide in shearing. Ions induced in the ER fluids are much harmful to the application of modified electrodes and should be avoided.

1. Introduction

Electrorheological (ER) fluids are complex suspensions consisting of nanometer or micron particles mixed with insulating oil, of which the shear stress can be continuously tunable under an applied external electric field. Such peculiar character of ER fluids has attracted much attention both in science and technology because of its wide potential applications in various industries such as for clutch, brake and damping systems, robotics. A great deal of research interest in ER fluids and ER devices has been stimulated since the ER effect discovered by Winslow [1].

The behavior of conventional ER fluids [2–7] is based on the interaction of polarized particles in the electric field, of which the yield stress is usually less than 10 kPa. The low yield stress of such ER fluids has strongly limited their applications for decades. In recent years, a new type of ER fluids has been developed, of which the yield stress can reach hundreds of kPa [8–11]. To explain the physical mechanism of the giant ER effect a model based on the interaction of polar molecule-charge in between the particles was proposed and the new ER fluids were defined as polar molecule dominated ER (PM-ER) fluids [8]. The character of the high shear stress exhibited by those ER fluids is much attractive for the applications. However, it was found that a serious slide always occurred at the electrodes made of common smooth metal in measuring the dependence of the yield stress on the electric field for PM-ER fluids, quite different from the conventional ER fluids. Especially in the dynamic measurement authentic shear stress data could hardly ever be obtained. This situation must be an obstacle for the applications of PM-ER fluids and urged us to understand the reason and to search the suitable electrodes for PM-ER fluids.

Firstly we consider the difference of the principle for conventional ER fluids and PM-ER fluids. In the case of conventional ER fluids, the ER effect comes from the interaction of polarized particles. According to the electric principle, the electric image effect of the particles at the metallic surface of electrodes as plotted in Fig. 1a indicates that the condition at the boundary of metallic electrodes can be taken for the same as inside ER fluid. The attractive interaction between the particle and its image is equal to that of the particles in fluid when an electric field is applied. The measured shear stress can reflect the intrinsic one of the ER fluids. Therefore the ordinary metallic plates is basically suitable to be used to measure the shear stress of conventional ER fluids and satisfied for their applications, although some related experiments about the effect of grooved electrodes for conventional ER fluids were studied [12,13].

However, PM-ER effect comes from the interaction of polar molecules adsorbed on the particles and the polarized charges of the neighboring particles in the gap between particles, where the high local field (about three orders higher than the applied electric field [4–6]) causes the polar molecules turning to the field direction [8]. The attractive force of the polar molecule-charge in PM-ER fluids can be orders higher than that of pure polarized particles in conventional ER fluids. As shown in Fig. 1b, in the gap between electrode and particles the condition is quite different from that between particles. The polar molecules are absent on the surface of electrode and the gap size is only half of that between particles. Therefore, the polar molecule-charge interaction cannot be well realized and the attractive force at the bounder is much weaker than that inside of particle chains where the interactions are caused by polar molecule-charge. Then at the surfaces of the

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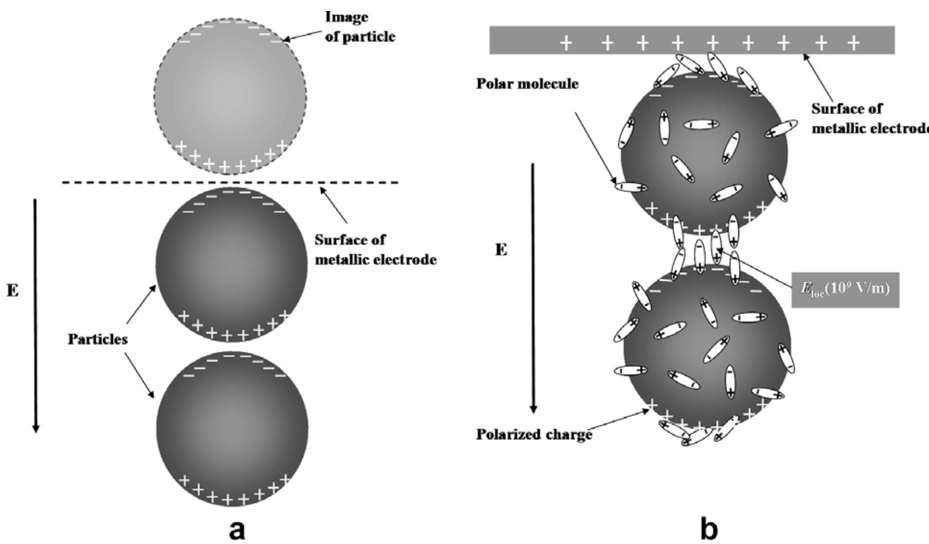

Fig. 1. Scheme of particles and metallic electrodes (a) in conventional ER fluids and (b) in PM-ER fluids.

electrodes the slide of the fluids must occur resulting in the measured yield stress much lower than the intrinsic one of PM-ER fluids [14].

2. Experimental and discussions

2.1. Effects of electrode surface roughness on ER effect

The essential difference between the PM-ER and conventional ER fluids both in principle and characters must reasonably make the difference on their measuring method. Roughening the surfaces of electrodes should be a direct way to avoid the slide between electrodes and PM-ER fluids to a certain extent. Three ranks of metallic electrodes with different roughness were adopted to examine the effect on the shear stress measurement of PM-ER fluids: (A) Polished smooth metallic electrodes. (B) Rough metallic electrodes, of which the surfaces were ground with a sand paper. (C) The surfaces of the metallic electrodes were grooved in the shape of file, of which the protuberant tips were insulated with epoxy resin to avoid point discharge.

The yield stresses of calcium titanate (CTO) nano-particle PM-ER fluid [11] with a volume fraction $\phi \approx 40\%$ were measured with a parallel-plate rotating rheometer, in which the nano-CTO particles were prepared in near spherical shape with diameter range of 50–100 nm. The surface roughness effect of electrodes on the measured yield stress is shown in the Fig. 2. For a comparison the intrinsic shear stress of PM-ER fluids is also shown in Fig. 2 (curve E), which was measured with a direct cutting method to eliminate any surface influence of the electrodes [14]. It is seen from Fig. 2 that the higher the measured yield can be obtained, the rougher the electrodes are used. The measured yield stress with smooth metallic electrodes (curve A) is far less than the intrinsic one, for instance only 30 kPa (one-sixth of real value) under a field of 5000 V/mm. The rough metallic electrodes can slightly resist the boundary slide and increase the measured yield stress (curve B) to a double magnitude of that done with smooth ones. With file like electrodes the measured result (curve C) is much better and close to the real one at low electric field. In order to give a visual picture for the effect of rough electrodes on ER fluid in the case of electric field applying, the conglutinative degree at the boundary is illustrated in the right panel of Fig. 2. It is distinct that the ER

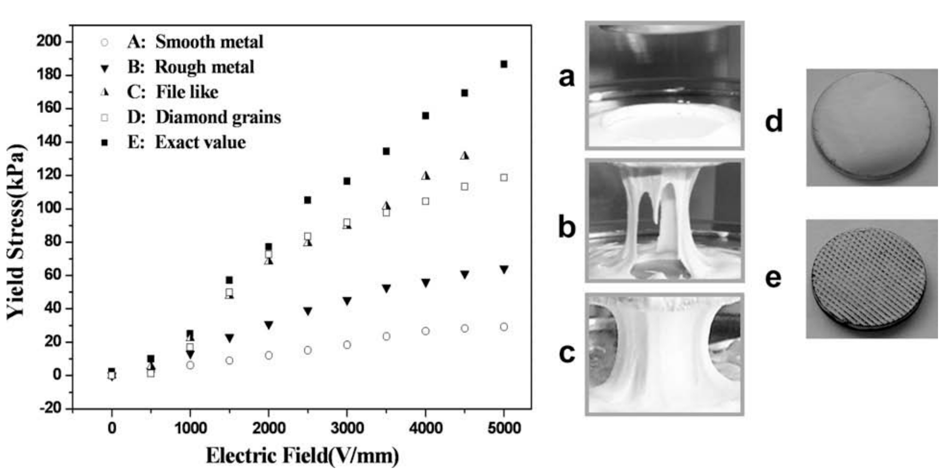

Fig. 2. The variation of yield stress vs. electric field measured with different electrodes. Curve A–D represents the data measured with smooth metal, rough metal, file like and diamond grains coated electrodes, respectively. Curve E indicates the intrinsic yield stress. In right panel, (a)–(c) show the visual appearance of the sample and electrodes at 2000 V/mm for smooth metallic electrodes, only the upper electrode being file like and both the upper and bottom electrodes being file like, respectively; (d) and (e) show the surface of smooth metallic electrodes and file like electrodes after electric field is removed.

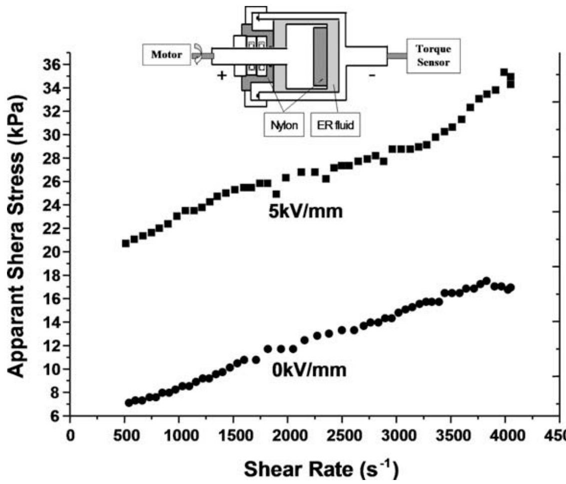

Fig. 3. Dependence of the apparent shear stress on the shear rate under different electric field. Upper inset is a configuration of the sealed cylindric rheometer.

fluid does not adhere to the surface of a smooth metallic electrode and can well adhere to the file like electrodes.

The reason of the accidented surfaces being effective is easy to be understood. As seen in right panel of Fig. 2, there is a considerably part of PM-ER fluid can be hold in the gaps of the rough electrode as shown in picture (e), but none on the smooth metallic electrode as shown in picture (d). The inbuilt nano-CTO particles confined in the gaps on the rough surface can keep PM-ER interaction with other particles in ER fluid as applying an electric field. Accordingly, the rough electrodes can bear the flow with strong shear stress and result in the measured yield stress much higher than that of using a smooth surface. It is obviously that in the case of file like electrodes the inbuilt sample can occupy most area of whole electrode leading to the measured yield stress close to the intrinsic value.

However, for improving the measurement of the yield stress with the rough electrodes, the current density rises markedly and even the electric breakdown takes place at a higher electric field due to the discharge of rough surface. Illumined by the effect of rough surface and considering the problem about point discharge, we proposed a series of modified electrodes for the PM-ER fluid prepared by adding the modified layer on the surfaces of metallic electrodes by mechanical processing, spraying, chemical depositing, adhesive bonding, plating, sintering, or infiltrating [15]. Therein, the modified electrodes coated with diamond and alumina grains not only avoid the slide effectively in improving the measured stress, but also reduce the current density greatly, which are favorable for measuring and applying the PM-ER fluids. The yield stress vs. electric field measured with diamond grains coated electrodes is also shown in Fig. 2 (curve D).

2.2. Effect of modified electrodes on dynamic characteristics of ER fluid

The electrodes coated with diamond grains are succeeded in the dynamic measurement of PM-ER fluid, because diamond grains are wear-resisting enough at high rotating speed. The apparent shear stress of PM-ER fluid with a volume fraction of 20% was measured with a sealed cylindric rheometer shown as the inset of Fig. 3. In this clutch like rheometer the radius and the length of the inner cylinder both are 20 mm, while the gap between inner cylinder and outer cylinder is 1 mm. The surfaces of two cylinders were both coated with diamond grain layers, of which the grain size was 100 μm and the layer thickness was 200 μm. In Fig. 3 the apparent shear stress represented by the left axis is obtained from the conversion of the torque indicated by the right axis which can be collected from the torque sensor directly. When the electric field of 5 kV/mm is applied, the apparent shear stress is enhanced obviously and behaves an increasing dependence on shear rate, exhibiting a character of Bingham fluid. Even the shear rate reaches as high as 4000 s^{-1}, the apparent shear stress can still keep stable. For the CTO ER fluid of volume fraction 40% the apparent shear stress was measured to be 117 kPa at shear rate 775 s^{-1} under the electric field of 4 kV/mm, while the apparent shear stress is about 10 kPa at zero field. In the measurements the appreciably high shear stress at zero electric field is mainly ensued from the friction of sealing ring of cylinders. The difficulty for measuring the higher shear stress of ER fluid at high shear rate is the calorific problem from the intense resistance of the material, which causes the temperature rapidly increasing and fluid expanding. Typically at rotating rate of 1000 rpm, a toque of 3 N m can induce a power of about 300 W. This fact has baffled us to collect higher dynamic shear stress data systematically for PM-ER fluids, especially at high shear rate. We should make more efforts to improve the design of the measurement.

In contrast to above results, the shear stress is unable to be measured successfully when the electrodes are made of smooth metal due to the slide of the ER fluid on the electrodes.

2.3. Influence of ions

In the case of the modified layers made of insulated or semi-insulated grains on the metallic electrodes, if ER fluid comprises of ions or some substance easy to be decomposed under an applied

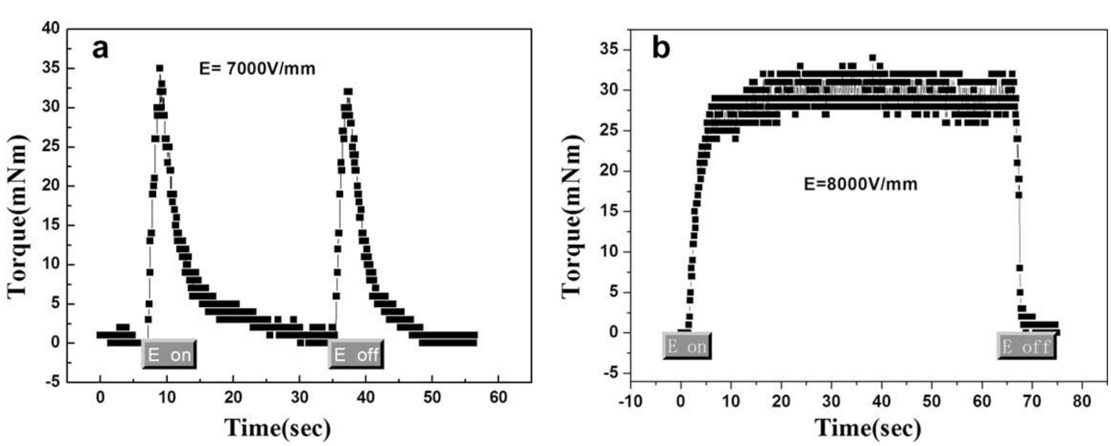

Fig. 4. The feature of the torque measurements using the electrodes covered by an insulating tape for ER fluid with ions contained (a) and without ions contained (b).

electric field, the ions will congregate on the electrodes. An additional electric field opposite to the external one will form, which must counteract the applied field strength and weaken the ER effect. Moreover, the inverted electric field will strengthen gradually due to the continuous deposit of ions on the surfaces of electrodes. On the other hand this additional counter field still exists and discharges gradually after turning off the external electric field.

In order to examine the influence of the ions deposited on the electrodes, an experiment was carried out. The surfaces of metallic electrodes of the parallel-plate rheometer were covered by insulating tape of 50 μm. The behavior of the yield stresses for the ER fluids with ions and without ions contained were inspected, respectively, when the external electric field was turned on and turned off. The variation of torque is shown in Fig. 4, in which (a) and (b) represent the ER fluids with ions and without ions contained, respectively. In the case of the ER fluids with ions contained, the measured torque rises rapidly as the electric field applying and decreases gradually in about 10 s as shown in Fig. 4a. Then the torque is even diminished close to the magnitude as in a zero electric field. It is the aggregated ions on the surfaces of the electrodes creating an inner opposite electric field and counteracting the external electric field. When the electric field is turned off, however, instead of the torque vanishing, the torque arises again abruptly and then disappears in 10 s. This indicates that the additional opposed electric field still exists as shutting off the external field and then discharges with time. On the other hand for an ER fluid without ions contained, the measured torque increases promptly and can be stable in a long period as the electric field turning on, and the torque vanishes as the applied electric field turning off, of which the features are shown in Fig. 4b.

Accompanying with the results described above for the ER fluids containing ions or substance easy to be ionized, we observed that the current density of the fluids continuously rose at a certain applied electric field when the conducting electrodes were used. It even brought a breakdown due to the ionic conduction causing an overlarge current. Therefore we must carefully manufacture the ER fluids to avoid any ions or molecules which are easily to be decomposed. For instance, in the ER fluid consisted the particles coated with urea molecule such phenomena is usually can be observed because of the rather low decomposition energy of urea molecule.

3. Conclusions

In conclusion the PM-ER fluids with high shear stress are newly developed [8] based on the interaction of polar molecule-charge in between the particles. The slide of the fluids inevitably exists on the surfaces of metallic electrodes because the interfaces cannot satisfy the boundary condition of polar molecules' aligning and interaction. By comparing the influence of different metallic electrodes with different surface roughness on the ER effect, a series of modified electrodes were fabricated which succeed in increasing the adhesion of fluids to the electrodes and weakening the slide in shearing. Especially, the modified electrodes coated with diamond grains are favorable for measuring and applying PM-ER fluids, which are easy to be processed and can bear a high shear stress at high shear rate. On the other hand it is found that the ions contained in the ER fluids are much harmful and should be avoided.

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