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The methods for measuring shear stress of polar molecule dominated electrorheological fluids

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Recently, a series of electrorheological (ER) fluids with high yield stress up to hundreds of kilopascals, which is named as polar molecule dominated electrorheological (PM-ER) fluids, has been developed. The mechanism of PM-ER fluids is quite different from that of conventional ER fluids. The normal rheometer cannot be used anymore to measure the shear stress of PM-ER fluid because a slide occurs at the interface between PM-ER fluids and metallic electrodes. In this paper, a proper technique for measuring the yield stress of PM-ER fluids is presented. By using this method, the intrinsic yield stress and the shear modulus of PM-ER fluids can be obtained conveniently, and the boundary effect at electrodes can be eliminated. [DOI: 10.1063/1.2756515]

INTRODUCTION

Electrorheological (ER) fluids are a class of materials whose rheological property is controllable by applying an electric field.[1–5] How to measure and characterize the mechanical properties of ER fluids is one of the key issues in the study and application. For conventional ER fluids, of which the yield stress is usually less than 10 kPa,[4] the shear stress is commonly measured with a parallel-plate or coaxial cylinder rheometer consisting of metallic electrodes. In those methods the boundary condition at the interface of ER fluid and electrode is similar to that inside ER fluids based on the electric image effect at the metallic surface when an electric field is applied [Fig. 1(a)]. Though the chains in such ER fluids are slightly easier to be broken at either end, the resulted difference of the shear stress is quite small[6] so that the measured parameters are able to well reflect the rheological properties of conventional ER fluids.

In recent years, a type of ER fluids, named as polar molecule dominated electrorheological (PM-ER) fluids, has been developed,[7] in which the polar molecules adsorbed on the particles play a crucial role. The static yield stress of PM-ER fluids can be as high as hundreds of kilopascals and their dynamic shear stress is also enhanced tremendously, much higher than that of conventional ER fluids.[7–11] The PM-ER effect comes from the interaction of polar molecule-charge instead of that of the particles themselves as in conventional cases. When the suspended particles are polarized by an external electric field and aligned until they form chains, the high local field in the gaps between the particles causes the polar molecules to turn to the field direction and interact with the polarization charges of the neighboring particles. The attractive force of the polar molecule-charge can be orders higher than that of pure polarized particles occurring in conventional ER fluids.[7]

At the interfaces of PM-ER fluids and the electrodes the boundary condition is not same as the inside of the fluid. The image effect of the electrode at the boundary only offers a half real distance of that in between particles, where the polar molecules on the particles can hardly be aligned along the direction of the electric field as in the gap of two particles [Fig. 1(b)]. Usually there are not polar molecules adsorbed on the metallic electrodes of a rheometer, and then the interaction of the particle and the electrode is much decreased comparing to the interaction of the polar molecule-charge in between the particles. By using the normal rheometer to measure the shear stress of PM-ER fluid, a slide must occur at the surfaces of metallic electrodes and result to the measured shear stress being much lower than the intrinsic value of the fluids. Therefore, finding a proper way to measure the intrinsic rheological property of PM-ER fluids is necessary in characterizing and applying the PM-ER fluids.

In this paper, we provide a method for measuring the intrinsic yield stress of PM-ER fluids, with which the slide of the fluids on the electrodes can be avoided. In principle, because the yield stress of PM-ER fluids is up to 200 kPa, almost as high as that of solids, the methods for measuring the yield stress of them can follow that for measuring the solid materials.

EXPERIMENT

Figure 2(a) illustrates the design for measuring the high shear stress of PM-ER fluids. Two metallic electrodes are

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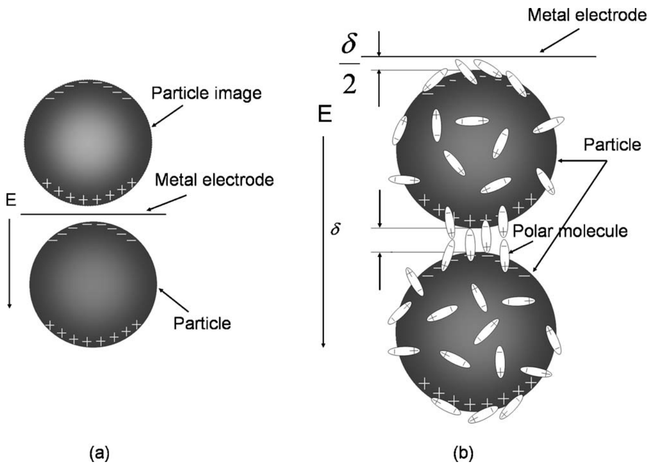

FIG. 1. (a) For conventional ER fluids, the interface of the ER fluid and the electrode is similar to that inside ER fluids based on the electric image effect at the metallic surface when an electric field is applied. (b) For PM-ER fluids, the image effect of the electrode at the boundary only offers a half real distance of that in between particles, where the polar molecules on the particles can hardly be aligned along the direction of the electric field as in the gap of two particles.

embedded into two grooves of insulating blocks. The materials of insulating blocks could be chosen from nylon, Teflon, ceramics, etc. ER fluid is filled in the gap between the electrodes. When a high voltage is applied to the electrodes and the step motor drives upper insulating block moving, the force sensor attached can detect the shear force F. The shear stress τ can be calculated with $\tau=F/S$, where S is the cross section area of the ER fluid. In our measurement, the moving velocity of the block was 0.01 mm/s, the distance of two electrodes was 3.3 mm, the cross section area of filled ER fluid was $S=7\times 2\ \text{mm}^2$, and the gap width of two parallel insulating blocks was about 0.1 mm.

A similar configuration is also as shown in Fig. 2(b), which is suitable for measuring the thick ER fluids. Two

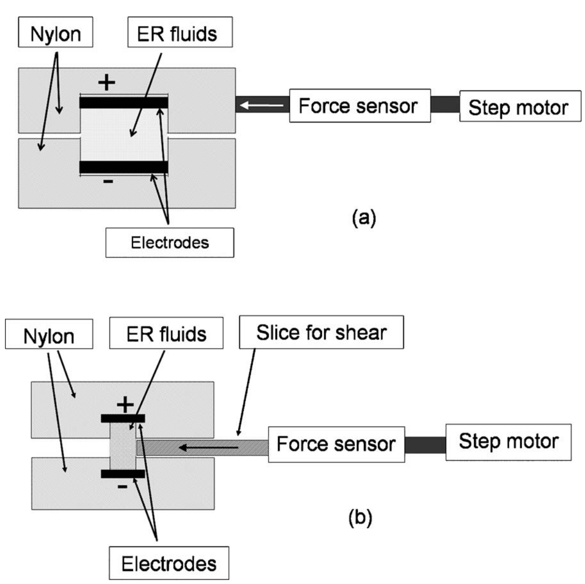

FIG. 2. (a) Sketch of unilateral shear configuration. The upper electrode moves, whereas the lower electrode is fixed. (b) Sketch of double shear configuration. Two insulating blocks with electrodes are fixed, whereas the slice moves to shear the PM-ER fluid.

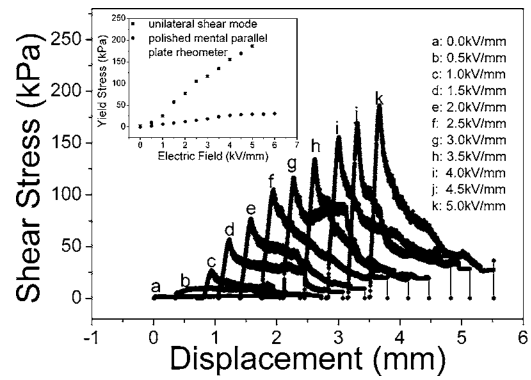

FIG. 3. The relationship of the shear stress vs the displacements under different electric fields for CTO/silicone oil ER fluid. The inset is the dependence of the shear stress on electric field for CTO/silicone oil ER fluids. For a comparison, the yield stress vs the electric field of the same fluid measured with ordinary parallel-plate rheometer is also shown.

insulating blocks with embedded metallic electrodes are perpendicularly mounted on the table. An insulating slice of cross section of 1 mm in thickness and 10 mm in height is driven by a step motor. By measuring force F acted on the slice, the shear stress $\tau=F/2S$ can be obtained, where S is the cross section area of the ER fluids. $S=1\times 4\ \text{mm}^2$ in our measurement.

RESULTS AND DISCUSSIONS

The rheological properties of calcium titanate (CTO)/silicone oil PM-ER fluid have been measured by using the experimental setups. The CTO nanoparticles were synthesized with O–H and C=O polar groups contained[7,11] and the CTO particles were suspended in silicone oil with the volume fraction about 38%. By using the method of unilateral shear mode, we measured the shear stress as function of the displacements under different electric fields, as shown in Fig. 3. The maximum value of each scan represents the yield stress. Then, the dependence of the yield stress on the field strength can be obtained as shown in the inset of Fig. 3. For a comparison, the yield stress versus the electric field of the same fluid measured with ordinary polished metal parallel-plate rheometer is also given in the inset of Fig. 3. It can be seen that the yield stress measured with the present method is several times higher than that measured with normal parallel-plate rheometer. Obviously, the results measured with the present technique reflect the real rheological values of our PM-ER fluid; however, the slide occurs in between the fluid and electrodes in using the conventional rheometer and causes the measured yield stress to be much lower. It can also be seen that a near linear dependence of the yield stress on electric field in PM-ER fluid is different from the quadratic one in ordinary ER fluids.

The shear modulus of ER fluid for different electric fields can be calculated from the slope of the shear stress increasing with strain from each shear stress-displacement curve. As shown in the inset of Fig. 4, typically the shear modulus of CTO ER fluid at 4 kV/mm can be calculated with a formula of shear modulus $\kappa=\Delta\tau/\delta$, where $\Delta\tau$ is the increment of shear stress and δ is the shear strain. Approximately, the shear strain δ is the ratio of the displacement and

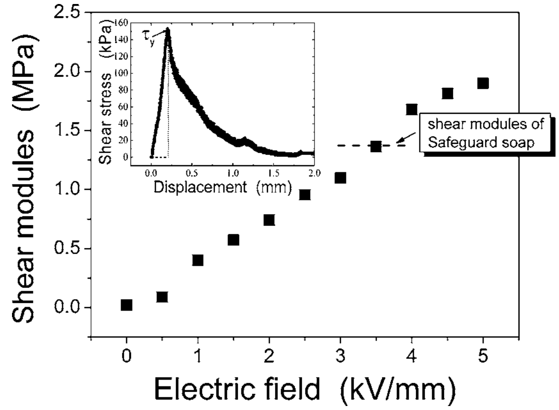

FIG. 4. The shear modulus vs electric field for CTO/silicone oil ER fluid. The inset is the calculation of shear modulus for CTO ER fluid at 4 kV/mm.

the half gap length of two electrodes. Figure 4 plots the relation of the shear modulus and electric field for CTO/silicone oil ER fluid. The shear modulus of CTO/silicone oil ER fluid also shows a near linear dependence on electric field. The reason for the linear dependence of the shear stress of PM-ER fluids has been discussed in Ref. 7.

The same result can be obtained by using slice shearing mode, as shown in Fig. 2(b). The variation of the yield stress measured with two methods is about 5%.

The shear modulus of CTO/silicone oil ER fluid can reach about 2 MPa when the applied electric field is 5 kV/mm. For a comparison the shear modulus of Safeguard soap produced by P&G Co. measured with the same apparatus is 1.3 MPa. Obviously, the CTO/silicone oil ER fluid and other our PM-ER fluids[7,10] show the real solid character when a high enough electric field is applied. In the case of PM-ER fluids with high shear stress, the normal rheometer is not adaptive anymore to be used for measuring the shear stress of them. As shown in Fig. 3 the yield stress measured by using normal rheometer is much lower than that measured by using the present technique. Therefore, the method we presented is suitable for measuring the PM-ER fluids and can give their intrinsic rheological properties. However, the applicability of the normal rheometer is for measuring conventional ER fluid. The differences in the measurements come from the fact that the principle of PM-ER fluid is quite different from conventional ER fluid as described above.

In the applications of PM-ER fluids the electrodes must be modified instead of that made of flat metal as in the applications of conventional ER fluids. A detail description will be published elsewhere.[12]

CONCLUSIONS

The physical mechanism of PM-ER fluids is quite different from that of conventional ER fluids. By using a developed technique the intrinsic yield stress and the shear modulus of PM-ER fluids have been measured. For a comparison the yield stress of the same fluid is also measured by using the normal rheometer, which is much lower than the intrinsic yield stress measured by the present method. This fact indicates that the normal rheometer is not suitable to be used anymore to measure the shear stress of PM-ER fluid because a slide must occur at the interface between the fluid and metallic electrodes.

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[1]T. C. Halsey and W. Toor, Phys. Rev. Lett. **65**, 2820 (1990).
[2]T. C. Halsey, Science **258**, 761 (1992).
[3]R. Tao and J. M. Sun, Phys. Rev. Lett. **67**, 398 (1991).
[4]H. R. Ma, W. J. Wen, W. Y. Tam, and P. Sheng, Phys. Rev. Lett. **77**, 2499 (1996).
[5]T. Hao, Adv. Colloid Interface Sci. **97**, 1 (2002).
[6]R. Tao, J. Zhang, Y. Shiroyanagi, X. Tan, and X. Zhang, Int. J. Mod. Phys. B **15**, 918 (2001).
[7]K. Q. Lu, R. Shen, X. Z. Wang, G. Sun, W. J. Wen, and J. X. Liu, Chin. Phys. **15**, 2476 (2006).
[8]W. J. Wen, X. X. Huang, S. H. Yang, K. Q. Lu, and P. Sheng, Nat. Mater. **2**, 727 (2003).
[9]K. Q. Lu, R. Shen, X. Z. Wang, G. Sun, and W. J. Wen, The electrorheological fluids with high shear stress, Int. J. Mod. Phys. B **19**, 1065 (2005).
[10]R. Shen, X. Z. Wang, Z. Y. Wang, W. J. Wen, and K. Q. Lu, Int. J. Mod. Phys. B **18**, 1104 (2005).
[11]X. Z. Wang, R. Shen, W. J. Wen, and K. Q. Lu, Int. J. Mod. Phys. B **18**, 1110 (2005).
[12]X. Z. Wang, R. Shen, G. Sun, W. J. Wen, and K. Q. Lu (unpublished).