LETTERS

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A new net-like structure formed by a metal/oil electrorheological fluid

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(Received 6 June 1996; accepted 23 July 1996)

A new kind of net-like structure formed by the metal spheres suspended in a metal/oil electrorheological (ER) fluid is reported for the first time in this Letter. The experimental results show that this structure is totally different from that formed by dielectric particles. After comparing the two formation patterns, it is found that the dielectric particles in certain ER fluids align themselves into chains or columns in the direction of the external electric field. The metal particles in a metal/oil ER fluid, on the other hand, form a net-like structure of chains and no column could be observed even when the ER fluid has been exposed to a high electric field. We attribute the net-like structure of the metal ER fluid to the strong interaction between dipole fields induced on the metal particles under the external electric field. Finally, the dielectric properties of the different structures were measured and are discussed in this paper. [S1070-6631(96)01511-5]

Electrorheological (ER) fluids consist of fine solid particles suspended in an insulating oil. The effective viscosity of ER fluids increases dramatically when an external electric field is applied. These phenomena occur rapidly and are reversible. It has been thought that the increment of apparent viscosity of ER fluids is due to the interactions between dipoles induced on the dielectric particles.[1–3]

According to the conventional polarization model, as an external electric field is applied to an ER fluid, the particles obtain an induced dipole moment p which is given below:

$$p = a^3 \epsilon_f \beta E_l, \tag{1}$$

where

$$\beta = \frac{(\epsilon_p - \epsilon_f)}{(\epsilon_p + 2\epsilon_f)}, \tag{2}$$

and E_l is the local effective field acting on the particles and satisfies $E_l = E + \Delta E$, where E is the applied external electric field and ΔE is the induced dipole field, and ϵ is the complex dielectric constant, with the subscripts p and f indicating the particle and fluid, respectively.

The force f_d between dipoles has been calculated rigorously for the case of two spherical particles separated by a distance R much greater than their radius a,

$$f_d = \left(\frac{6}{4\pi\epsilon_f} \right) \frac{p^2}{R^4}. \tag{3}$$

The f_d will lead to the particles attracting each other if their interparticle axis is parallel to the applied field or repelling each other if their interparticle axis is perpendicular to the applied field, which gives rise to the chain or column structures when the applied electric field surpasses the threshold values, respectively.[4–6] However, all solid particles commonly used in the experiments are assumed to be nonconductive, but a few of them performed with high conductivity, especially in the case of the metal particles. In a previous experiment carried out with a metal/oil ER fluid system, we found an unusual phenomena in which the increment rate of the shear stress would decrease when the strength of applied electric field surpassed a certain value.[7] The reason for this was thought to be the effect of a large dielectric loss of the metal ER fluid which results in an increase of the temperature of the ER fluid; in this case, the square relationship between the shear stress and the strength of applied electric field, which were observed in most kinds of ER fluids,[8,9] was no longer satisfied. Furthermore, recent work has shown that the rehological properties of the metal and dielectric particles are totally different.[7,10]

In this paper, a new kind of structure formed by a metal/oil ER fluid is reported for the first time. The experimental results show that the structure of ER fluids composed of metal particles is different from that of ER fluids composed of dielectric particles, where the particles line up to form chains or columns in the direction of the electric line under an external electric field. But the directions of the chains in the metal/oil ER fluids are random. Moreover, all chains there form a net-like structure and no columns could be observed. We consider the physical mechanisms of structure

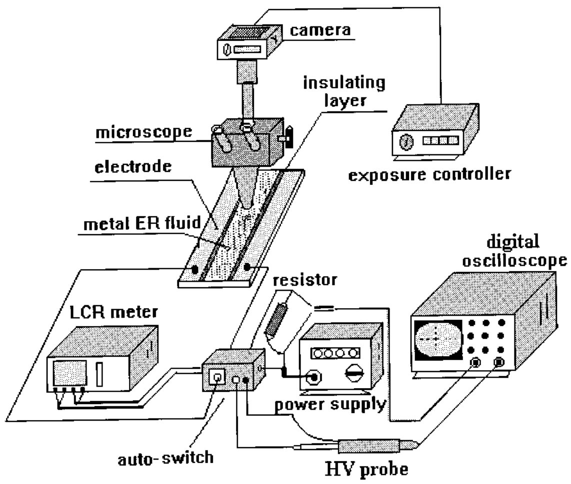

FIG. 1. Schematic diagram showing the experimental setup.

formation for these two ER fluids to be very different. The effect of the induced dipole field of one particle on other adjacent particles cannot be ignored when metal particles are involved. In this case, the local field depends strongly on the dipole field. As the result of a nonuniform local field, the metal chain arrangement is completely random. On the other hand, the dipole field induced on the dielectric particles is very small and the local field is thought to be homogeneous in two parallel electrodes. So the directions of all chains would line up in the direction of the external electric field. In addition, the dielectric properties corresponding to different structures of metal/oil ER fluids were measured and are discussed in this Letter.

The ER fluid used in our experiment consists of silicon oil containing indium microspheres with a radius of 25 μm. At first, the indium spheres were immersed in an NaOH solution with a concentration of about 2% for 15 min to clean the sphere's surfaces and then they were placed into a vacuum oven for 2 h. The dried particles were mixed with silicon oil immediately after they were taken out of the oven. The volume fractions of the spheres are about 0.2. Before taking any measurements, the ER fluid was stirred in order to keep it uniformly mixed. A schematic of our experiment setup is shown in Fig. 1, where two- and three-dimensional structures of the ER fluid were observed with different sizes of ER fluid cells under an optical microscope, and their corresponding dielectric properties were measured with an LCR meter (HP 1345A). The digital oscilloscope with a high voltage probe was used to measure the strength of the applied electric field.

Two-dimensional structures of the metal ER fluid are shown in Fig. 2. As can be seen from Fig. 2(a), the particles were distributed randomly in the area between the two parallel electrodes if no electric field was applied. When the field strength was increased to 100 V/mm, some short chains were formed near the two electrodes [Fig. 2(b)]. When the electric field strength was further increased to 300 V/mm, the chains began to grow from the two electrodes [Fig. 2(c)]. But the aggregation of chains was stopped when two chains came into contact with each other, as can be seen in Fig. 2(d). If the electric field was applied to the metal ER fluid suddenly, then the final state of the structure pattern was as shown Fig. 2(e). This pattern is totally different from that shown in Fig. 2(f) which was the result of the same experimental procedure performed with glass spheres. This structure formation is the same as that observed by other authors.[11,12]

The physical mechanism for the structural differences between metal and dielectric particles can be explained as follows. According to Eq. (1), the induced dipole moment, as well as their polarization directions, are determined by the local field. If an ER fluid is composed of glass particles, the induced dipole field ΔE_{glass} is very small and is thought to be negligible, so the local field $E_{l\ \text{glasss}}$ is mainly determined by the external electric field **E**. In this situation, the electric field acting on each and every particle may be considered to be uniform and is equal to the external field strength. So the direction in which the chains arranged is the same as that of the electric line produced by the external electric field [Fig. 2(f)]. On the other hand, when the metal spheres are distributed randomly in the parallel electric field, as a result of the effect of the large dipole field ΔE_{metal} acting on the metal

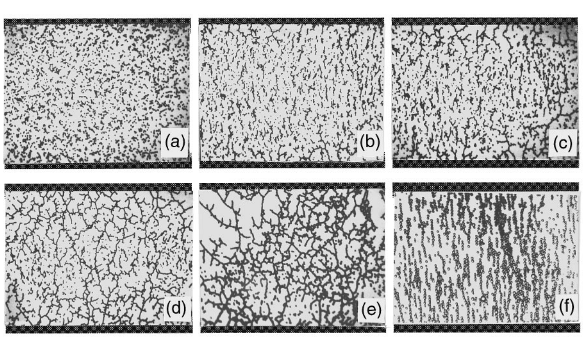

FIG. 2. Development of the two-dimensional structure of a metal/oil ER fluid containing 0.2 volume fraction of indium spheres with increasing electric field. (a) $E=0$, (b) $E=200$ V/mm, (c) $E=500$ V/mm, (d) $E=700$ V/mm, (e) and (f) are the structural patterns formed with metal and glass spheres when the electric field is applied suddenly. In both of these cases, the experiments are performed under the same conditions.

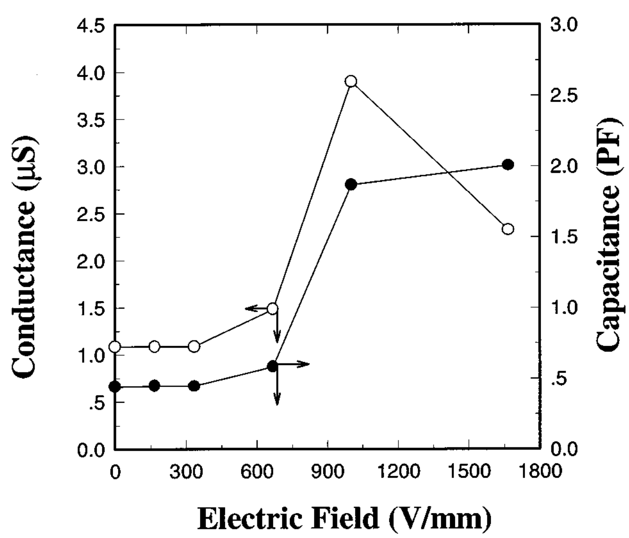

FIG. 3. Dielectric properties and energy of the metal ER fluid as the electric field was increased. The measured frequency was fixed at 200 kHz. The volume of the ER fluid cell used here is 70 mm×2 mm×1 mm.

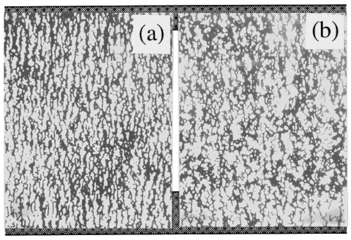

FIG. 4. The structural changes when the electric field strength is below and above a certain threshold value.

spheres, the local field for each particle is decided not only by the external electric field **E** but also by the induced dipole field ΔE_{metal}, which is expressed as $E_{l\ \text{metal}} = E + \Delta E_{\text{metal}}$. In this case, the direction of the local field acting on each and every particle is no longer uniform due to strong effect that the one induced dipole field has on that of the adjacent particles. As a result, the directions of all chains are, in most cases, different from the direction of the external electric field. This fact can be observed clearly in Fig. 2(e).

Corresponding to the structural changes of the metal ER fluid, the dependence of the conductance and capacitance (the dielectric constant and dielectric loss are proportional to these two parameters at fixed measured frequency. Here, it is difficult to calculate dielectric constant and dielectric loss exactly due to the effect of the insulating film. However, the variation tendency of them can be observed) on the strength of external electric field has been measured *in situ*. The results in Fig. 3 show that the conductance and capacitance increase as the electric field is increased. The increases of these two parameters are thought to be the structure changes under the different electric field strength. When the electric field is above 1000 V/mm, the capacitance remains almost unchanged, but the conductance starts to decrease sharply which means that the dielectric loss of the metal ER fluids decreases. This phenomenon is highly unusual and differs from that observed in our previous experiments carried out with low dielectric loss materials. The decrease in the dielectric loss is due to the change of the structure when the electric field surpasses a threshold value which can be seen in Fig. 4. Figure 4(a) and 4(b) are the structural patterns observed when electric field was below and above the threshold value, respectively. The actual physical mechanism is unclear at present. We can suppose from the structure change that this may be another reason why the shear stress of metal ER fluids begins to decrease when the electric field strength surpasses a certain value. Finally, we recommended that further theoretical work be conducted to explain this structural formation.

ACKNOWLEDGMENTS

The authors would like to thank Xiao Nan for providing us the metal spheres and Dr. Raymand A. Dragan for his editorial suggestions.

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