A primary x-ray investigation of the turning of ferroelectric microspheres contained in electrorheological fluids under a direct current electric field

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An x-ray diffraction method is introduced to probe the turning of ferroelectric singlecrystal microspheres suspended in electrorheological (ER) fluids. The microspheres used in the experiment have their permanent dipoles polarized in the same direction. Our initial results show that the x-ray diffraction amplitude in some crystal planes will increase when a fixed dc electric field is applied to the ER fluids. We argue that the enhancement of the diffraction is due to the reorientation of the crystal planes which is caused by the turning of the permanent dipoles in the ferroelectric microspheres under an external electric field. The particle turning has not attracted much attention in the past. We propose that further work should be performed. © 1996 American Institute of Physics. [S0003-6951(96)04208-3]

Electrorheological (ER) fluids, which consist of microscopic particles suspended in an insulating liquid, can be transformed into a solidlike state when an electric field is applied. It is thought that this phenomenon is caused by the structural change of ER fluids. A widely accepted model is the polarization theory which assumes that the interaction between the electric dipoles induced on the particles by the external electric field will lead to the formation of chain and column structures which cause an increase in the shear stress of ER fluids. Many papers have proved this view.1–8 However, certain other parameters appear to have been overlooked because there is as yet no clear explanation for the quantitative difference between the experimental results and theoretical predictions.

Another significant phenomenon is that ER fluids composed of waterless ferroelectric material display a totally different frequency response and the shear stress of this kind of ER fluid increases when the frequency of an ac electric field is increased.9 In contrast, ER fluids composed of nonferroelectric materials show the opposite frequency response.10 The reason for this is probably due to some difference in their structure. The permanent dipole of a ferroelectric particle turns continuously when an ac electric field is applied. The turning of the dipole causes the particle’s vibration to deviate from the direction of the applied electric field and at the same time leads to a change in the force branch of the shear direction of ER fluid. However, the effect of vibrating on the shear stress only appears in a low frequency range from a few Hz to about 3 kHz. In a previous experiment, we observed under a microscope that the microspheres contained in ER fluids turned when an electric field was applied. However, quantitative results have not been obtained.

In this letter, we introduce an x-ray diffraction method to investigate the turning of the particles suspended in an insulating oil. In order to get quantitative results, special ferroelectric spheres with a single-crystal structure and a unified polarization direction were fabricated. Our experiments revealed that the diffraction spectra in some crystal planes of the particles were enhanced when a fixed dc electric field was applied. The changes in the x-ray diffraction spectra are thought to be caused by the reorientation of the dipoles in the crystal microsphere when a fixed dc electric field is applied.

The cell (Fig. 1) used in our experiment is made of a piece of glass with a 10 mm×20 mm×1.5 mm window on which two pieces of Al foil are mounted to serve as electrodes. The ER sample consists of silicon oil containing BaTiO3 single-crystal spheres with a radius of 20 μm. These ferroelectric microspheres were specially fabricated for the experiment so that their permanent dipoles are all polarized in the same direction.11 The volume fraction of the spheres is 31.5%. Before taking any measurements, the ER fluid was stirred in order to keep it uniform. An x-ray measurement was carried out with a Cu target. The voltage and current were fixed at 40 kV and 150 mA, respectively. An optical microscope was used to observe the structure of the ER fluid and found that the ferroelectric microspheres can easily form a chain structure even when exposed to a very low electric field.

The measured results of the x-ray diffraction spectra at the electric strengths $E_0$=0 V/mm and $E$=2500 V/mm are shown in Figs. 2(a) and 2(b), respectively. We can clearly see the differences between the two spectra. The reason can be explained from Fig. 3. At $E_0=0$ [Fig. 3(a)], the distribution of the microspheres suspended in the oil was random, and the

![FIG. 1. Schematic of the cell employed in the x-ray diffraction experiment.](image-url)
orientation of their dipoles and that of their fixed crystal planes were random as well. Therefore, the diffraction spectra in Fig. 2(a) are the average results of all random orientations of the crystal plane, which give weak diffraction peaks. We can see from Fig. 3(b) that when the electric field was applied to the ER fluids, the dipoles as well as the fixed crystal planes of the suspended microspheres would turn toward the direction of the external field. The reorientation of the crystal planes gives rise to the observed change in the diffraction spectra. This fact can be seen in Fig. 2(b), where the spectra amplitudes in some crystal planes increase dramatically.

The relative difference between \( E=0 \) and \( E=2500 \) V/mm is plotted in Fig. 4, where \( I_j \) and \( I_n \) represent the x-ray diffraction amplitudes with and without the electric field, respectively. From the plot we can see that the diffraction from the (102) and (104,110) planes increases dramatically, while diffraction in the high-angles range remains unchanged.

In conclusion, an x-ray diffraction method to probe the turning of the ferroelectric microspheres suspended in ER fluids is presented in this letter. Our initial results show that the particles first turn and then remain in a certain position when a fixed dc electric field is applied. We argue that this phenomenon is due to the turning of the dipoles in the ferroelectric microsphere under a dc electric field. The turning of the particles was actually observed under an optical microscope. This phenomenon involving turning of the ferroelectric particles in ER liquids under the electric field especially in the ac electric field has not attracted much attention up to now. We propose that further theoretical and experimental work be performed in the future.

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