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Optically transparent electrorheological fluid with urea-modified silica nanoparticles and its haptic display application

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ABSTRACT

A transparent electrorheological (ER) fluid was fabricated by dispersing urea-modified silica nanoparticles in a mixture of halocarbon oil and silicone oil, whose refractive index could be tuned to be the same as that of the dispersed particles. The ER fluid showed considerable enhancement in shear stress and shear viscosity, as determined by a rotational rheometer, as well as improved dielectric spectra measured using a LCR meter. Morphological and thermal characterization by scanning electron microscopy and thermal gravimetric analysis confirmed the modification by urea. The potential applications of the transparent ER fluid as haptic displays were also investigated.

1. Introduction

An electro-responsive electrorheological (ER) fluid is a type of intelligent material that exhibits a unique phase transition from a liquid-like to a solid-like state in the presence of an applied external electric field [1–4]. Generally, a typical ER fluid is composed of electrically polarizable particles dispersed in an insulating oil. In the absence of an external electric field, all particles are dispersed randomly in the medium phase. Once an electric field is applied to the suspension, however, all the dispersed particles become polarized immediately and attract to the adjacent particles to form chain-like structures with strong dipole–dipole interactions along the direction of the applied electric field [5,6]. During this rapid and electrically controllable process, the rheological properties of ER fluids change significantly, including a non-vanishing yield stress, enhanced shear viscosity and dynamic moduli. Therefore, ER fluids have great potential in a range of engineering applications, such as designing dampers [7], torque transducers, microfluidics [8] and tactile and polishing devices [9–11], which is the same as its magnetic analogue, the magnetorheological fluid [12,13]. In addition, the ER fluids were found to induce the phenomenon of viscosity decrease of crude oil transportation [14] which is related to that of turbulent drag reduction [15].

Many materials including both organic and inorganic particles display ER behavior, which is closely related to the dielectric and conducting properties of these suspended particles [16–20]. In addition, the particle shape and size have a significant effect on the ER efficiency [21–24]. Recently, special attention was paid to ER suspensions of very small particles on the nanoscale with core-shell structures, which showed extremely high ER performance due to the coated conducting polymer nanolayers or even polar molecules. An ER fluid containing 30 vol% polyaniline-coated silica nanoparticles showed a maximum yield stress of 4.5 kPa at 3 kV mm^{-1}. Similar results were obtained using other conducting polymers [25]. On the other hand, nanoparticles coated with polar molecules showed a more attractive increase in yield stress when dispersed in an insulating oil. Wen et al. [3] reported a giant ER effect using urea-coated barium titanyl oxalate particles. Thereafter, the polar molecule model was proposed, indicating that the polar molecules adsorbed on the surface of nanoparticles were aligned and attracted to each other along the electric field in the gap of the adjacent particles [26]. In addition to urea, other polar molecules, such as triethanolamine, acetamide and amino groups, were then applied to achieve a strong ER effect [27–30].

To expand the applications of ER fluids, the suspended ER particles need to possess special physical and chemical properties. This paper reports a transparent ER fluid with suspended urea-modified silica nanoparticles, which was prepared using a refractive index (RI) matching method [31]. RI matching of the oil to the silica particles was achieved by mixing oils of different RIs

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according to the Lorentz-Lorenz equation. The transparent ER fluid can be applied to touch display panels. The great change in viscosity of the ER fluid after the application of external electric field can be a feedback signal to fingers promoting a successful touch, and vice versa. This kind of touch screen can be used in a range of electronic products. In addition, the particle size is known to induce a significant effect on the transparency of the suspension. As the particles increase in size, transmittance of the suspension decreases. [32,33] Therefore, silica nanoparticles were selected for preparing transparent ER fluids in this study. Note that barium titanate nanoparticles based transparent ER fluid has been recently reported [24]. Furthermore, the urea-modified silica nanoparticles were characterized by scanning electron microscopy (SEM), Fourier transform infrared (FT-IR) spectroscopy and thermogravimetric analysis (TGA). Their rheological and dielectric properties in mixed oil (RI = 1.46) were examined using a rotational rheometer and LCR meter, respectively.

2. Experimental

2.1. Materials and preparation of urea-modified silica particles

Precipitated silica nanoparticles (Rhodoxane™34, ~20 nm) purchased from Rhodia were used. To modify them with urea, 10 g of these silica nanoparticles was dispersed in 500 ml de-ionized water at room temperature with magnetic stirring for 1 h. Subsequently, an aqueous solution of urea (1 M, 10 ml) was added slowly to the above suspension of silica nanoparticles followed by stirring for 16 h. The products were washed with de-ionized water and methanol by centrifuge, and obtained by drying at 70 °C in a vacuum oven for one day [34].

2.2. Preparation of transparent ER fluid

Two oils, halocarbon oil (Halocarbon, kinematic viscosity: 0.8×10^{-6} m^2/s, density: 1.71×10^3 kg/m^3) and HIVAC F-4 silicone oil (Shinetsu, kinematic viscosity: 37×10^{-6} m^2/s, density: 1.065×10^3 kg/m^3), with different RIs of 1.383 and 1.555, respectively, were mixed to prepare the medium oils with the required RI. The volume fractions of the two oils were calculated using the following well-known Lorentz–Lorenz equation.

$$\frac{n^2-1}{n^2+1} = \left(\frac{n_1^2-1}{n_1^2-2}\right)\phi_1 + \left(\frac{n_2^2-1}{n_2^2-2}\right)\phi_2 \quad (1)$$

where n_1, n_2 and n represent the RI of pure halocarbon oil, pure HIVAC F-4 and the mixture of them, respectively; and ϕ_1 and ϕ_2 are the volume fraction of the corresponding oil. Three mixed oils (n = 1.45, 1.46 and 1.47) were prepared according to Eq. (1).

The optically transparent ER fluids were prepared by dispersing a dry powder of urea-modified silica nanoparticles in the mixed oil with the same volume fraction of 10 vol%. The suspensions were shaken mechanically by a vortex and then stored in a vacuum oven for 30 min to remove the bubbles in the suspension.

2.3. Characterization

The morphology of the silica nanoparticles before and after modification by urea was observed by field emission-scanning electron microscopy (FE-SEM, Hitachi S-4300, Japan). The mass composition and thermal stability of both pure and urea-modified silica nanoparticles were detected by TGA (Perkin Elmer, USA) at a heating rate of 10 °C min^{-1} from 25 to 800 °C under a nitrogen atmosphere. Fourier transform infrared spectroscopy (FT-IR, Perkin Elmer, USA) was used to examine the change in the chemical structures in the nanoparticles and confirm the successful modification by urea. A spectrometer (LAMBDA-900, Perkin Elmer) was used to estimate the transparency of the ER fluid containing urea modified silica particles.

The ER properties of the ER fluid in steady shear flow were observed using a rotational rheometer (MCR 300, Physica, Austria) with a cylindrical cone-plate geometry (CC17 ERD, the gap between cup and bob was 0.71 mm) and a DC high voltage generator. The flow curves of shear stress vs. shear rate and shear viscosity vs. shear rate were measured in controlled shear rate mode over a shear rate range of 0.1–1000 s^{-1} with a controlled electric field strength. To support the ER performance data, the dielectric spectra of the prepared ER fluid was examined using a LCR meter (HP 4284A) with a HP 16452A liquid test fixture at AC electric field frequencies ranging from 20 to 1 MHz at room temperature.

Fig. 1 shows the schematic side view of the transparent ER fluid-contained touch panel and force measurement configuration. The size of the panel was 40 mm by 40 mm with a dam of 300 μm, and the thickness of the PET film was 125 μm. The upper side of the PET film and lower side of the glass were coated with transparent polyethylenedioxylthiophene/polystyrene sulfonate (PEDOT/PSS) and applied as electrodes to work on the ER fluid between them. The ER suspension was injected into the panel through the corner of the dam, and the injection hole was then sealed [35]. When the voltage was applied to the electrodes, the particles in the injected ER fluid were polarized and aligned to the chain or column structures perpendicular to the electrodes. The push rod, acting as a finger of the user, was moved down to the panel to sense the increased repulsive force due to the increasing viscosity in the ER fluid. The diameter of the push rod was 10 mm and the push speed was 30 μm/s. The position and speed of the push rod were controlled using a universal testing machine (Model 5948 MicroTester, Instron) and the push force was measured using the load cell. The applied voltage was turned off at some point during push, which was controlled with an equipped unit, the aligned particle chains were released and the push force was decreased to some

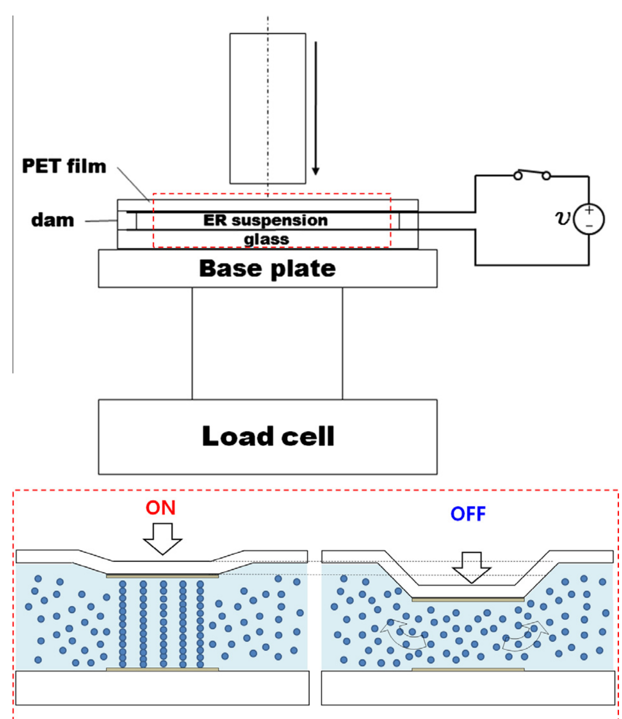

Fig. 1. Schematic diagram of the force measurement configuration of the ER touch panel and details in the ER fluid as the touch panel operate.