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Short Communication

Generalized yield stress equation for electrorheological fluids

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ABSTRACT

A new generalized yield stress scaling equation for electrorheological (ER) fluids was developed by introducing the critical electric field (E_c) and material parameter. This equation can be used to describe the dependency of the yield stress on an electric field not only for conventional ER suspensions with a change in slope from 2.0 to 1.5, but also for giant ER fluids with a change in slope from 2.0 to 1.0. The yield stress data obtained from different ER fluid systems with different material parameters was collapsed onto a single curve for the entire range of electric field strengths using the proper scaling method proposed in this study.

1. Introduction

Electrorheological (ER) fluids, which are composed of higher dielectric and/or conducting particles dispersed in an insulating liquid in general, can be converted drastically from a liquid-like to a solid-like phase in the order of milliseconds when either an AC or a DC electric field is applied [1–6]. The rapid response to an external electric field is related to the formation of fibrillar structures aligned along the direction of the electric field due to dielectric or conductive mismatch between the particles and insulating liquid. ER fluids exhibit an increase in shear stress, shear viscosity and dynamic moduli according to the variation in structure. Interestingly, a liquid–solid transition is not only tunable, but also reversible when the electric field is removed. Therefore, ER fluids are also known as "smart materials", which have been used widely in a range of potential engineering applications, such as dampers, actuators, brakes and shock absorbers [2,7,8]. The yield stress of ER fluids as the critical design parameter in an ER device has attracted considerable attention [9]. Several models have been proposed in segmented regions of the electric field strength to study an electric field-dependent yield stress. The polarization model [10], which describes the dielectric response of both liquid media and solid particles arising from the Maxwell–Wagner's interaction, was introduced to predict the dependence of the yield stress on the applied electric field strength [2]. The yield stress (τ_y) was found to be proportional to the square of the applied electric field strength (E_0), which can be expressed as

$$\tau_y \propto \phi K_f E_0^2 f(\gamma) \tag{1}$$

where ϕ is the volume fraction of the particles and $\gamma = (K_p - K_f)/(K_p + 2K_f)$ is the dimensionless dielectric mismatch parameter [2]. K_p and K_f are the dielectric permittivities of the particles and fluid, respectively. This polarization model showed excellent agreement with the experimental data for small ϕ and low E_0 [9–11]. On the other hand, the conduction model [12,13] showed a power law dependency of the yield stress on the electric field strength, $\tau_y \propto E_0^{3/2}$, under high electric field strengths, which was attributed to the nonlinear conductivity effect induced by the electrical breakdown of ER fluids under high electric field strengths. This change in power law dependency from 2.0 of the polarization model to 1.5 of the conduction model of the ER fluids has been also observed for magnetorheological fluids under an applied magnetic field [14]. On the other hand, neither model can be used to describe the dependence of the shear stress on the entire range of electric field strengths. Previously, Choi et al. [15] proposed a simple scaling yield stress function by introducing the critical electric field strength (E_c) to depict the derivation of the yield stress from polarization, which was confirmed to be suitable for many conventional ER fluids [16,17]. Recently, Seo [18] proposed a new model to describe the electric field dependent yield stress. Compared to conventional ER phenomena, a giant electrorheological (GER) effect from a nanoparticle-based suspension whose static yield stress can reach 130 kPa, exceeding the theoretical upper bound shown by a conventional ER fluid, has been reported [19–21]. In this GER effect, saturation surface polarization in the contact regions of neighboring particles was considered and a almost linear relationship between the static yield stress and applied electric field was observed [21].

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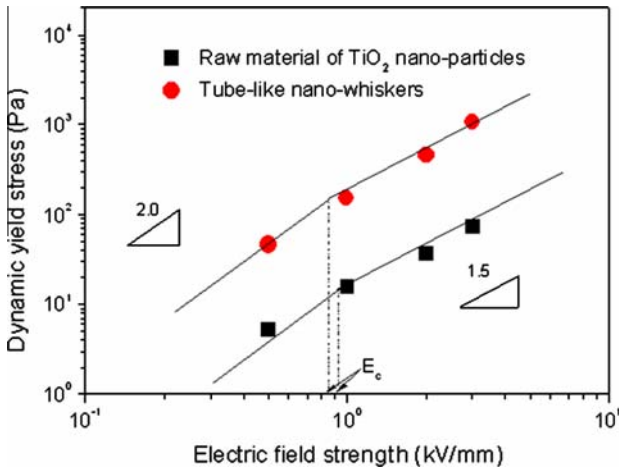

Fig. 1. Re-plotted dynamic yield stress of both tube-like nano-whiskers [23] and raw material of TiO_2 nanoparticles [22] as a function of applied electric field strengths on a log–log scale.

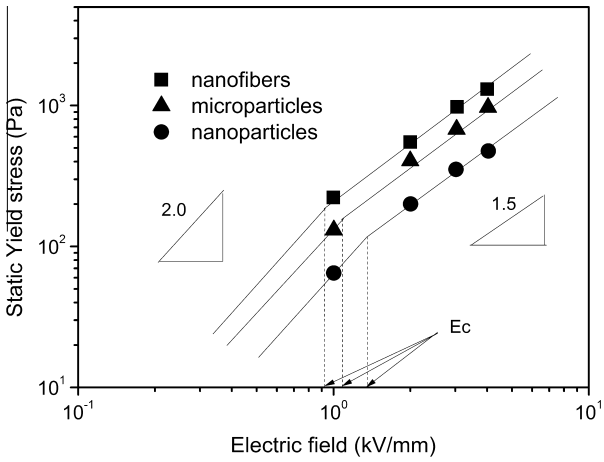

Fig. 3. Re-plotted static yield stress of 15 wt% PANI nanofibers (square point), nanoparticles (circle point) and microparticles (triangle point) [24] as a function of electric field on a log–log scale.

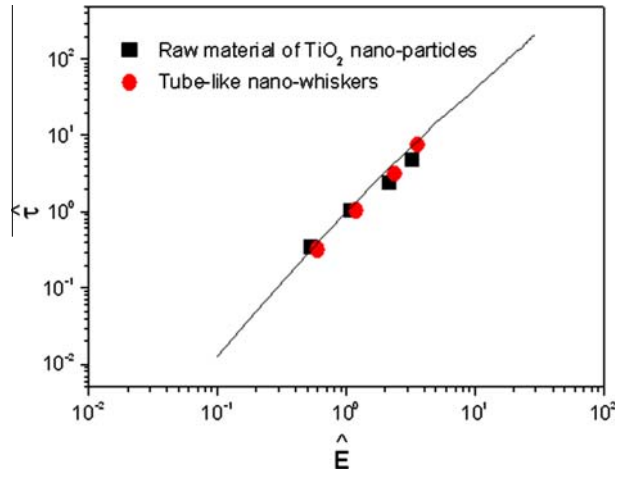

Fig. 2. Plot of $\hat{\tau}$ versus $\hat{E}$ for both tube-like nano-whiskers and raw material of TiO_2 nanoparticles based ER fluids. The solid line is obtained from Eq. (5).

Until now, there is no scaling function that can be used to describe the dependence of the shear stress on an applied electric field for both conventional ER and GER fluids. This communication proposes a generalized scaling function for the normalized yield stress by scaling the applied electric field strengths, which is suitable for describing the correlation between the yield stress and applied electric field for both conventional ER and GER fluids, indicating that the experimental data of the yield stress could be fitted closely to a single line for the entire range of electric fields.

To describe the yield stress dependence on the electric field strength for a broad range of electric field strengths, Choi et al. [15] proposed a simple scaling function as follows:

$$\tau_y(E_0) = \frac{\alpha E_0^2 \tanh\sqrt{E_0/E_c}}{\sqrt{E_0/E_c}} \tag{2}$$

where the parameter depends on the dielectric property of the fluid and the particle volume fraction. E_c is the critical field strength where the correlation between the yield stress of the ER suspension and electric field strength bridges the polarization model and conduction model.

Eq. (2) manages the following asymptotic characteristics at both low and high electric field strengths:

$$\tau_y = \alpha E_0^2 \propto E_0^2, \quad E_0 << E_c \tag{3}$$

$$\tau_y = \alpha\sqrt{E_c}E_0^{3/2} \propto E_0^{3/2}, \quad E_0 >> E_c \tag{4}$$

Eq. (3) suggests that τ_y depends quadratically on the electric field strength at low electric fields, as expected by the polarization model [10], and Eq. (4) shows that τ_y is proportional to $E_0^{3/2}$ at high electric fields, which is in agreement with the results obtained from the nonlinear conduction model [12,13].

Eq. (2) can be scaled as follows:

$$\hat{\tau}_y(E_0) = \frac{\tau_y(E_0)}{\tau_y(E_c)} = 1.313\hat{E}^{3/2}\tanh(\sqrt{\hat{E}}) \tag{5}$$

where $\hat{E} = E_0/E_c$ and $\hat{\tau} = \tau_y(E_0)/\tau_y(E_c)$ with $\hat{\tau} = \alpha E_c^2 \tanh(1) = 0.762\alpha E_c^2$.

The dynamic yield stress data from two references on the ER effect of TiO_2 nanoparticles [22] and titanate nanowhiskers [23], respectively, was used to examine the effect of Eq. (5). The dynamic yield stress of Fig. 6 from Ref. [22] and the dynamic yield stress in Fig. 7 from Ref. [23] were replotted as a function of the applied electric field strengths on a log–log scale, as shown in Fig. 1. E_c was obtained at the crossover of two slopes, i.e. the slope of the polarization model (slope = 2.0) and that of the conduction model (slope = 1.5), which are 0.84 kV/mm for titanate nano-whiskers and 0.93 kV/mm for TiO_2 nano-particles. The plot of $\hat{\tau}$ versus $\hat{E}$ for both titanate nano-whiskers and TiO_2 nano-particle-based ER fluids were rearranged and plotted in Fig. 2. Eq. (5), which is represented by a solid line, can normalize the dynamic yield stresses.

In addition, polyaniline (PANI) systems with different morphologies were also investigated. Yin et al. [24] synthesized nano-fibrous PANI via a modified oxidative polymerization, which possesses a diameter of hundreds of nanometers and several micrometer lengths. Note that the nano-fibrous PANI based ER fluid exhibits improved suspension stability and larger ER effect when compared to conventional granular PANI [25], PANI nanoparticle [24] and PANI microparticle based ER fluids [24]. To obtain the single scaling function for these two different systems, we first replotted Fig. 7(a) (Ref. [24]) on a log–log scale, and then chose data of 1.35 kV/mm, 1.08 kV/mm, and 0.92 kV/mm as E_c for ER fluid containing PANI nanoparticles, microparticles and nanofibers (as shown in Fig. 3), respectively. The scaling curves ($\hat{\tau}$ versus $\hat{E}$) for these systems are plotted as shown in Fig. 4, finding that Eq. (5) fits the experimental data well in the broad range of electric field strengths for different morphology of PANI based ER fluids. This