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Magnetorheological fluid based on submicrometric silica-coated magnetite particles under an oscillatory magnetic field

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ABSTRACT

An experimental study conducted on the rheological properties of a magnetorheological fluid based on submicrometric silica-coated magnetite particles dispersed in silicone oil is presented. We investigated the rheological behaviour when the system is simultaneously exposed to a static field and a sinusoidal field used as a perturbation. The results show that the perturbation modifies the rheological behaviour of the system and can be used to control its physical properties; however, the changes that are induced are smaller than expected from previous results for the aggregation of particles under magnetic perturbations. We discussed this difference in terms of the ratio between the magnetic energy and the thermal energy. We observed that a threshold magnetic field exists; below it, the yield stress is practically zero, whereas above it, the yield stress grows quickly. We discuss this result in terms of a model based on chain length distribution.

1. Introduction

Smart materials are characterised by physical properties that can be reversibly controlled by external stimuli. Magnetorheological fluids (MR fluids) belong to this class of materials; they are dispersions of magnetisable particles in a low-viscosity liquid, such as oil [1–6]. These systems are particularly interesting because their physical properties depend not only on the relative composition of their components but also on the structures that form the particles due to the magnetic field. Depending on the structures formed, the system can modify its behaviour, from a Newtonian fluid in the absence of a magnetic field to a viscoelastic material in a high magnetic field [4,6–9]. The changes in both structure and rheological behaviour can be reversibly modulated by the magnetic field intensity. The rheological behaviour of MR fluids is usually described by the Bingham model for viscoelastic materials.

Currently, there is an enormous interest in using MR fluids in mechanical devices to improve their performance. These devices can be specifically used for vibration damping, transmission of forces in clutches, and optical finishing, among other applications [1,2,5]. The interest in these applications derives from their adaptability due to the characteristics of MR fluids. Currently, there are some technological applications of MR fluids; for example, some sport cars use MR dampers to improve their performance. If the technology based on MR fluids was more accessible, then they would be more widely used with regard to cars, buildings, bridges, seat belts, robots, and so on. The use of MR dampers is more promising in large structures because the movements are slower, thus allowing the MR fluids to perform better [10]. This feature is important in engineering because it allows, for example, large structures to be built that can withstand periodic wind gusts. The effects of earthquakes could also be decreased by MR dampers.

There is a great interest in finding MR fluids that exhibit even larger and faster changes in their mechanical properties [7,11–13]. To this end, recent studies have focused on producing more responsive soft magnetic particles and finding methods that allow the structural characteristics of the aggregates to be modified. Particles based on iron oxides are the most common selection in the preparation of MR dispersions; however, because of their high density, they tend to settle quickly, resulting in unstable dispersions. To diminish this problem, surfactants and polymeric coatings have been used to improve the stability of the dispersions.

We have recently shown that by exposing the system to a static field as well as a low-amplitude alternating field that are perpendicular to one another, it is possible to change the structure of MR fluids and their effective viscosity [11,12]. The effective magnetic field drives low-amplitude angular chain oscillation with regard to the direction of the static field. When chains oscillate angularly, the chain ends "sweep" around, leading more particles or chains to join them and thus forming longer and

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thicker chains than those formed without oscillation. Thus, the alternating field enhances the lateral aggregation. The inclusion of the alternating field affects neither the anisotropy defined by the static field nor the chains' stability. On the other hand, we have shown that the effective viscosity can be enhanced by an oscillatory field. Thus, there is a direct relationship between obtaining larger, thicker chains and enhancing the effective viscosity. Although higher-intensity alternating fields lead to larger changes in both structural and viscosity measurements, alternating field amplitudes greater than 25% of the static field, in combination with the frequency of the perturbation, cause the rupture and reformation of chains. In Refs. [11,12], we used relatively large particles in which the movements produced by thermal fluctuations, even in the absence of magnetic fields, are negligible, i.e., non-Brownian particles.

Herein, we present a study of the rheological behaviour of a MR fluid based on submicrometric magnetite particles coated with silica under various of field intensities, perturbation field frequencies, preconditionings, shear stresses and shear rates. In Section 2, we describe the procedure for obtaining magnetite particles coated with silica and the experimental setup used. In Section 3, we present the rheological measurements. Section 4 depicts a model for the yield stress based on previous results for the chain length distributions and compares our theoretical model and the experimental yield stress measurements. Finally, in Section 5, we present our conclusions and some comments.

2. Experimental setup

To obtain magnetite particles, we use the following chemical reaction in aqueous media: $FeCl_2 \cdot (H_2O)_4 + FeCl_3 \cdot (H_2O)_6 + HCl + NH_4OH + H_2O \rightarrow Fe_3O_4 + subproducts$. In a 100 ml glass beaker, a solution of 2.0 M of $FeCl_2 \cdot (H_2O)_4$ and 2.0 M of HCl was prepared. In another glass beaker, 1.0 M $FeCl_3 \cdot (H_2O)_6$ and 2.0 M of HCl was prepared. Both solutions were mixed under shaking for 10 min. A solution of 50 ml of 0.1 M of NH_3 was poured slowly into this solution during 5 min. The black precipitate formed consists of magnetite powder. The particles were cleaned using deionised water and then dried at 70 °C for 30 min. The characteristic shape of the material was determined from the SEM images. Agglomerates of several sizes, between 0.05 and 15 μm, were observed. To coat the magnetite with silica, a dispersion of 200 mg of magnetite, 15 ml of ethanol, and 5 ml of deionised water was shaken in an ultrasonic bath for 10 min. A mixture of 4 ml of TEOS (tetraethyl-orthosilicate) in 30 ml of ethanol was poured into the solution at room temperature and shaken for 24 h. Spherical particles (approximately 0.5 μm) were obtained. The density was estimated to be 3.48 g/cm^3. Fig. 1 shows a SEM image of the magnetite–silica particles obtained, indicating their regular spherical shape and very narrow size distribution, as illustrated in the histogram displayed below the particles. The average particle diameter was 0.48 μm, with a dispersion of 0.05 μm.

A MR fluid was prepared by dispersing the magnetite–silica particles in silicone oil at a viscosity of 0.350 Pa s. The concentration of the particles was indicated by the fraction of the total volume ϕ occupied by the particles; in our experiments, we used $\phi = 0.10$. To measure the yield stress, we used a Bohlin CVO 120 HR rotational rheometer in controlled-stress mode. The experimental setup, shown in Fig. 2, involves a parallel-plate geometry with a diameter of 55 mm made of a non-magnetic material. A 2 ml sample of the MR fluid was placed between the plates and allowed to stand for a few minutes to reach thermal equilibrium. Because the rheological behaviour depends strongly on temperature, the temperature was maintained at 20 °C using a Peltier plate, which allowed us to control the temperature with an accuracy of ± 0.1 °C. The MR fluid sample was exposed to a static magnetic field and, in some cases, a sinusoidal field as well, transverse to the static field. A solenoid was used to generate the

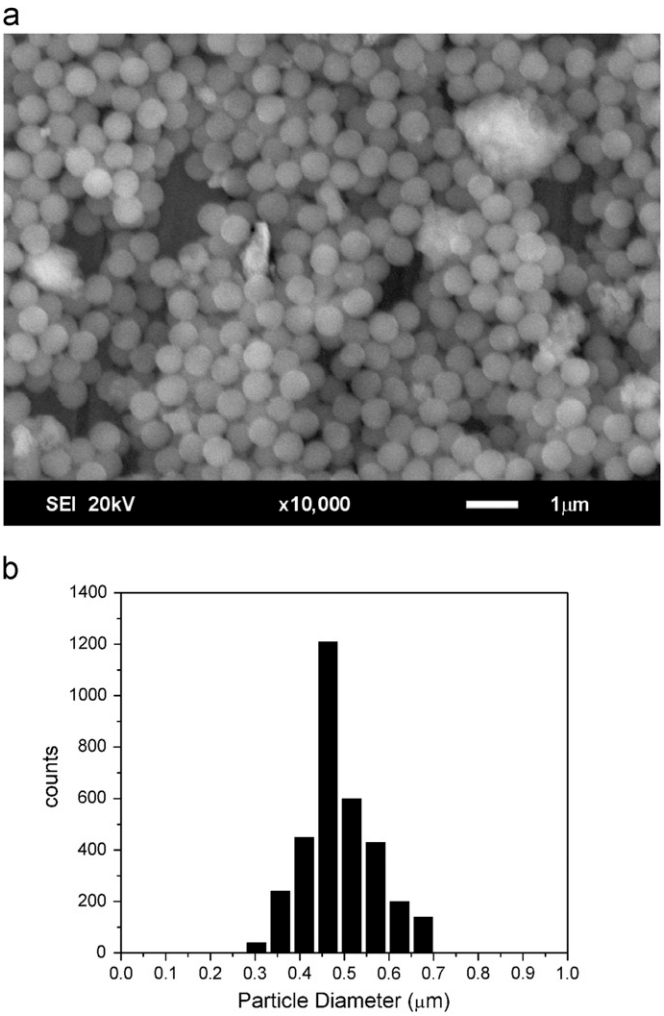

Fig. 1. (a) SEM photograph of the magnetite–silica particles. (b) Histogram of the particle sizes.

Fig. 2. Experimental setup used for rheological measurements.