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Research paper

Carbonyl iron suspension with halloysite additive and its magnetorheology

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ABSTRACT

The magnetorheological (MR) characteristics of a micron-sized soft magnetic carbonyl iron-based MR fluid were examined using halloysite nanoclay mineral, as an additive. The flow curves measured from a rotational rheometer revealed non-Newtonian Bingham fluid behavior under an applied magnetic field. The sedimentation of the MR fluid with and without the halloysite additive was also measured using a Turbiscan. It was found that the added rod-like hollow nanotubular-structured halloysite improved the sedimentation problem despite the decrease in MR behavior, as determined from the significant decrease in sedimentation rate.

1. Introduction

Magnetorheological (MR) fluids, consisting of soft magnetic micron-sized particles dispersed in a nonmagnetic fluid, such as hydrocarbon, silicone oil or aqueous carrier fluid, have been studied extensively for their interesting phase transition characteristics under an applied magnetic field strength and engineering applications in multidisciplinary areas (Andrei and Bica, 2009; Margida et al., 1996; Park et al., 2010). Their rheological properties can vary significantly with the magnetic field strength, allowing fine tuning of the material behavior (Alves et al., 2009). MR fluids in general exhibit Newtonian fluid characteristics in the absence of a magnetic field. On the other hand, in the presence of a magnetic field, these fluids exhibit continuous, rapid, and reversible changes from a fluid-like to a solid-like state within milliseconds (Bica, 2002; Dodbiba et al., 2008). This transformation is due to the dispersed magnetic particles forming chains that align in the direction of the magnetic field due to a magnetic-polarization interaction, which then return to their free-flowing liquid state after the external magnetic field is removed (Bica, 2012; Cheng et al., 2009; Genc and Phule, 2002; Pu et al., 2006; Svasand et al., 2009). In addition, the viscoelastic behavior of the CI-based MR fluids shows strong solid-like characteristics under an applied magnetic field strength (Chaudhuri et al., 2005; Fang et al., 2009).

MR fluids have been adopted in a range of engineering devices, such as shock absorbers, brakes, active dampers, etc., owing to their outstanding controllable mechanical characteristics with a typical yield stress value from 10 to 100 kPa (Bica, 2002; Hu et al., 2007). In addition to their high yield stress, because a magnetic field is more stable in an operation than an electric field, a much larger number of commercially available products of MR fluids have been developed compared to those using electrorheological (ER) fluids under an applied electric field strength (Chaudhuri et al., 2005; Lee et al., 1999; Sedlacik et al., 2012). Note that ER fluids have also been widely investigated as smart materials (Yin and Zhao, 2011).

Among the many magnetic particles available, soft magnetic carbonyl iron (CI) microspheres with excellent magnetic properties and proper particle sizes have been adopted widely for MR fluids and MR elastomers. On the other hand, the application of CI-based MR fluids in MR devices requires improvement in the fluid properties because the sedimentation problems caused by the large density mismatch between the CI particles and oil medium impede the MR device operation as well as their redispersion (Park et al., 2010). A range of strategies including the introduction of sub-micrometer sized additives or coating technology to the particles have been introduced to prevent the CI particles from caking or decrease the particle density, thereby reducing sedimentation. The addition of sub-micrometer sized fillers (Hato et al., 2011), such as polyhedral oligomeric silsesquioxanes, clays and carbon nanotubes (Fang et al., 2009; Hato et al., 2008; Lim et al., 2005), is an effective method for increasing the dispersion stability by providing a physical layer that improves the stability of MR fluids.

Halloysite, a clay mineral nanofiller, is a naturally occurring two-layered aluminosilicate with a predominantly hollow tubular structure (Du et al., 2010). The material is also environmentally friendly and biocompatible. Thereby, hollow halloysite can be used as a component in nanocomposites. Recently, a polyaniline-wrapped halloysite composite was reported to be an ER material (Zhang and Choi, 2012). Note that various clays, such as kaolinite, montmorillonite, laponite and

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fluorohectorite, have also adopted ER and MR fluids (Liu and Choi, 2012; Park et al., 2010).

The size of the additives for CI particles can affect their fluid properties, and nano-sized fillers appear to be one of the best options for stabilizing MR fluid suspensions. This paper reports the effect of nano-sized halloysite clay mineral additive on a CI based MR fluid. Halloysite reduced the level of CI particle settling and enhanced the flocculation stability of MR-based suspensions. The rheological properties of MR fluids under an applied magnetic field were examined using rotational and oscillatory tests. Sedimentation studies were also examined using a Turbiscan.

2. Experimental

2.1. Materials

Soft magnetic carbonyl iron (CI) (CD grade, mean particle size: 4.25 μm, density: 7.91 g/cm^3, BASF, Germany) particles (Fang et al., 2009) and silicone oil (KF-96, 100cs, Shin Etsu, Japan) were used as the dispersed phase and suspending medium for MR fluids, respectively. Halloysite nanopowder (Sigma-Aldrich, USA) with about 0.65 μm in length, 30–70 nm in diameter, and a surface area of 64 m^2/g was used as an additive.

2.2. Preparation of CI/halloysite MR fluid

Two MR fluids with the same volume fraction of particles were prepared by dispersing pristine and CI/halloysite particles in silicone oil. To prepare the MR fluids, the concentration of CI, with and without halloysite, was fixed to 70 wt.% for both systems. The concentration of halloysite was adjusted to 1.0 wt.% with respect to the total MR fluid (29 wt.% silicone oil). The MR fluids were sonicated for a few minutes to determine the required final homogeneity of the samples.

2.3. Characterization and MR measurement

The morphology of the pristine CI, halloysite and CI/halloysite particles was observed by scanning electron microscopy (SEM, S-4300, Hitachi, Japan), while particle size distribution of the halloysite was examined using a particle size analyzer (Zetasizer, ELS-800, Otsuck, Japan). The MR performance of the two MR fluids were measured using a rotational rheometer (Physica MCR 300 Anton Paar, Germany) equipped with a magnetic field supplier and a 25 mm parallel plate measuring system. The rheometer system is equipped with a MR cell having a parallel plate configuration. Approximately, 0.32 ml sample mass is filled in a constant gap of 1 mm between two parallel plates during the experiment. While a lower plate is stationary, an upper plate was rotating at the same time a torque was measured. The magnetic field applied was in the perpendicular to the flow field which is parallel to the rotating axis. A controlled shear rate (CSR) mode over a shear rate range of 0.01–200 1/s was applied for all tests under different magnetic field strengths. The sedimentation behavior of the pure CI and CI/halloysite MR fluids was examined using a Turbiscan (MA200, Turbiscan Laboratory, France).

3. Results and discussion

Fig. 1 presents SEM images of the CI, halloysite and CI/halloysite surface, in which Fig. 1(a), (b) and (c) show the pure CI particle, neat nanotubes of raw halloysite and halloysite attached to CI, respectively. When the CI/halloysite particles constructed columnar structures under an applied magnetic field, the nano-sized halloysite around the CI particles could decrease the attractive force between the CI particles, resulting in slightly poorer MR performance. On the other hand, without the magnetic field, the nano-sized halloysite

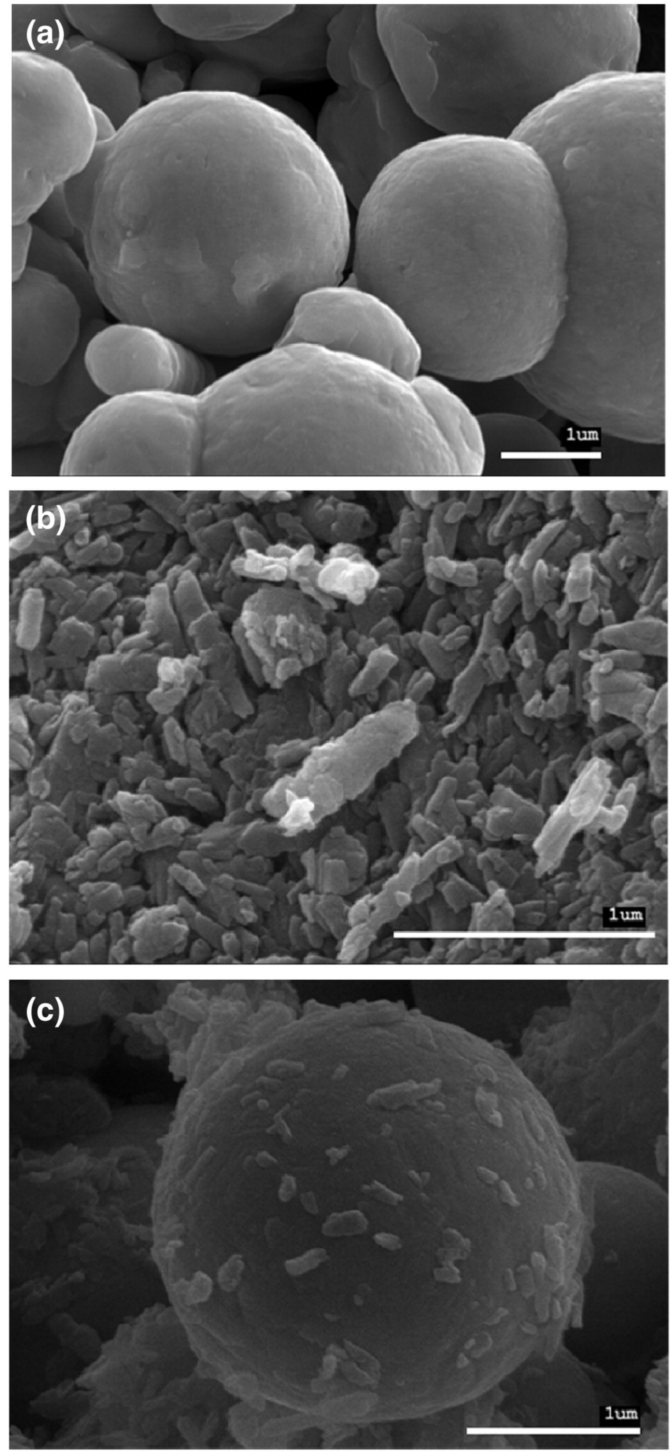

Fig. 1. SEM image of CI/halloysite particles.

inhibited direct contact of iron particles and prevented the hard caking of magnetic particles.

Fig. 2 displays particle size distribution of the halloysite clay mineral measured using a particle size analyzer (Zetasizer, ELS-800, Otsuck, Japan), exhibiting that the halloysite nanoparticles have some particle size distribution with average size of about 650 nm. In the case of CI particles, their particle size distribution of several different grades can be found from previously reported (Bombard et al., 2002; Medina-Esquivel et al., 2012).

The rheological properties of the MR fluid were examined at magnetic field strengths ranging from 0 to 342 kA/m using a rotational