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Research paper

Effect of $CoFe_2O_4$ nanoparticles on a carbonyl iron based magnetorheological suspension

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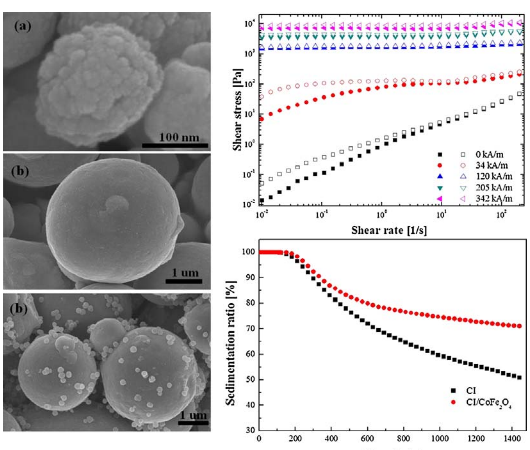
GRAPHICAL ABSTRACT

Magnetic CoFe2O4 nanoparticles were successfully fabricated by a non-aqueous hydrothermal method and used as an additive in a micron-sized, carbonyl iron (CI) based-magnetorheological (MR) fluid. The magnetorheological characteristics and dispersion stabilities for two kinds of CI based-MR fluid with and without CoFe2O4 additives were investigated.



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ABSTRACT

Magnetic $CoFe_2O_4$ nanoparticles were successfully fabricated by a non-aqueous hydrothermal method and used as an additive in a micron-sized, carbonyl iron (CI) based-magnetorheological (MR) fluid to improve its dispersion stability and MR characteristics. The morphology and magnetic properties of $CoFe_2O_4$ were demonstrated by using X-ray diffraction, scanning electron microscopy, and vibrating sample magnetometry. The results showed that $CoFe_2O_4$ was synthesized successfully with a nearly spherical morphology and excellent crystalline structure. The saturation magnetization (Ms) of the $CoFe_2O_4$ was also about 74.4 emu/g. The CI MR fluid was prepared by dispersing 50 wt% of CI particles in silicone oil, and the CI/$CoFe_2O_4$ MR fluid was prepared by adding 0.1 wt% of $CoFe_2O_4$ nanoparticles to the CI MR fluid. The MR characteristics of both MR fluids were tested via a rotational rheometer at various magnetic field strengths. The CI/$CoFe_2O_4$ MR fluid showed enhanced MR characteristics with higher yield stress, shear viscosity, and dynamic modulus than that of the CI

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MR fluid. Furthermore, the dispersion stability of both MR fluids were also investigated via a Turbiscan optical analyzer system, and these results showed that the sedimentation ratio after 24 h had improved by about 21%.

1. Introduction

Magnetorheological (MR) fluids are the colloidal suspensions of magnetizable soft-magnetic particles dispersed in a nonmagnetic medium including aqueous carrier fluids, lubricant, hydrocarbons, mineral oil, and silicone oil [1–4]. They can be transformed rapidly and reversibly between a fluid-like and a solid-like state by applying or removing a magnetic field. When the magnetic field is applied, the dispersed magnetizable particles aggregate into an ordered chain-like structure in the same direction as the external magnetic field due to the induced magnetic dipole–dipole interactions between particles. Thus, the shear viscosity, yield stress and dynamic modulus of the MR fluids increase significantly. Conversely, if the magnetic field is removed, the particles in a chain-like structure recover back to the free dispersed state in the medium [5–7]. MR fluids have been widely studied because of the above properties and have been considered very promising materials in many applications, such as brakes, clutches, dampers, shock absorbers, isolators, and precise polishing [8–12].

Many metal and metal oxide magnetic materials such as Fe_3O_4, Fe_2O_3, $BaFe_{12}O_{19}$, $MgFe_2O_4$, carbonyl iron (CI) [13–20] and magnetic composite materials such as $CoFe_2O_4$/GO and $MnFe_2O_4$/GO [21,22] have been reported to be used as MR fluids. Among these candidate materials, soft-magnetic CI particles have been especially attractive owing to their spherical shape, proper particle size, and high saturation magnetization [23,24]. Nevertheless, the high density of CI particles always causes serious sedimentation problems for the MR fluid system. There are many strategies to overcome this shortcoming such as coating the magnetic particles with a low density layer or introducing different kinds of additives [25–27]. Compared with the relatively complex coating process, the introduction of additives is a fast and effective method to improve the dispersion stability by filling the free space between CI particles and increasing the repulsive forces. When nonmagnetic materials have been used as the additive, the MR performance was found to be slightly reduced, but the dispersion stability improved [28]. Therefore, magnetic particles have been considered an effective additive that can enhance not only the dispersion stability but also the MR characteristics of the fluid [29–31].

In this work, we fabricated magnetic $CoFe_2O_4$ nanoparticles and used them as an additive in a CI based MR fluid. The MR characteristics of CI based MR fluid both with and without $CoFe_2O_4$ additives were investigated via a rotational rheometer, and the MR characteristics of the CI based MR fluid with $CoFe_2O_4$ additive were enhanced. The CI based MR fluid with $CoFe_2O_4$ additive also was proven to have better dispersion stability by using a Turbiscan optical analyzer system.

2. Experimental

2.1. Preparation of $CoFe_2O_4$ nanoparticles and MR fluid

The $CoFe_2O_4$ nanoparticle additive was fabricated by a non-aqueous hydrothermal method [32]. $CoCl_2{\cdot}6H_2O$ and $FeCl_3$ were initially dissolved in ethylene glycol at a molar ratio of 1:2, and then urea was added to the mixture with stirring for 2 h to obtain a homogeneous solution. The mixed solution was transferred into a Teflon-lined autoclave and maintained at 200 °C for 24 h. Finally, the obtained black precipitate was washed with ethanol and water and was dried at 60 °C for 12 h.

Two kinds of MR fluids were prepared. At first, the CI based MR fluid was obtained by dispersing the CI (CM grade, average particle diameter: 4 μm, density: 7.96 g/cm^3, BASF, Germany) particles (50 wt%) in silicone oil (KF-96-100cSt, Shin-Estu, Korea). The other fluid was prepared by adding 0.1 wt.% of the $CoFe_2O_4$ nanoparticles as an additive while the concentration of CI particles was maintained at 50 wt% in silicone oil. The latter fluid is referred to as CI/$CoFe_2O_4$ MR fluid hereafter.

2.2. Characterization

The surface morphology of the $CoFe_2O_4$ nanoparticles was examined via scanning electron microscopy (SEM, S-4300, Hitachi, Japan). X-ray diffraction (XRD) patterns were obtained using an X-ray diffractometer (DMAX-2500, Rigaku) with 2θ ranging from 10° to 80°. The transmission electron microscopy (TEM) (CM-220, Phillips, USA) was used to analyze the microstructure of the $CoFe_2O_4$ nanoparticles. The magnetic properties of $CoFe_2O_4$ were measured by a vibrating sample magnetometer (VSM) at 25 °C, and the density was measured via a gas pycnometer (AccuPyc 1330, micromeritics). The MR characteristics of both kinds of MR fluids were investigated using a rotational rheometer (Physica MCR 300, Anton Parr, Germany) equipped with a magneto-rheological device. The suspension stabilities were observed using the Turbiscan (Formulation, France) for 24 h at 25 °C.

3. Results and discussion

The XRD pattern of the $CoFe_2O_4$ particles is shown in Fig. 1, with 2θ angles ranging from 10° to 80° with a step size of 0.02°. The sharp peaks shown in this figure indicate excellent crystalline structure, and the diffraction peaks at 18.22° (111), 30.04° (220), 35.44° (311), 37.12° (222), 43.06° (400), 53.48° (422), 57.02° (511), 62.70° (440), 71.10° (620), and 74.10° (533) are consistent with the standard pattern of spinel $CoFe_2O_4$ (JCPDS No. 22-1086) [33], suggesting that the $CoFe_2O_4$ particles were successfully fabricated.

The SEM images of the fabricated $CoFe_2O_4$ nanoparticles, pure CI particles, and CI/$CoFe_2O_4$ mixture are shown in Fig. 2(a), (b), and (c), respectively. Fig. 2(a) shows that the $CoFe_2O_4$ nanoparticles exhibit nearly spherical morphology with a rough surface and average diameter of about 180 nm and the particles appear to consist of many tiny nanocrystals. As shown in Fig. 2(c), after mixing the $CoFe_2O_4$ and CI particles, $CoFe_2O_4$ nanoparticles attached to the CI microparticles and occupied the interspace between the CI particles. The attached $CoFe_2O_4$ nanoparticles prevented direct contact of pure CI particles and improved the dispersion stability of the CI/$CoFe_2O_4$ MR fluid, as expected. When the magnetic field was applied, the CI particles aggregated into a

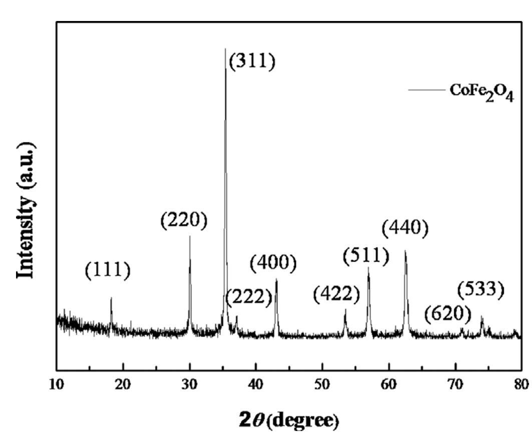

Fig. 1. X-ray diffraction pattern of fabricated $CoFe_2O_4$ particles.