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An experimental study on the effect of fatty acid chain length on the magnetorheological fluid stabilization and rheological properties

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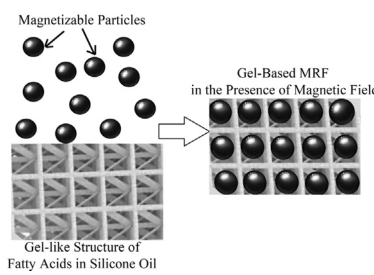
HIGHLIGHTS

- Improving MRF stability and MR effect by using stearic acid additive.
- Fatty acids with longer carbon chain as additive creates stronger gel structure.
- Stronger gel structure improves stability and yield stress, consequently more efficient MRF.

GRAPHICAL ABSTRACT



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ABSTRACT

An experimental study was conducted on the effect of acid additives on the stability and rheological properties of a suspension of carbonyl iron (CI) microparticles dispersed in silicone oil. A series of acids with the same carboxyl group but different carbon chain lengths (C12, C14, C16 and C18) were added to magnetorheological fluids (MRFs) to investigate their effect on the stability and rheological behavior. MR effect was measured with the aid of a magnetorheometer and stability measurements were made by simple determining the height of the transparent layer in the MRF over a 6-month period. Experimental results showed that by increasing carbon chain length of acids, yield stress and stability increased up to 22 times (at $H = 362$ kA/m) and 7 times, respectively, in comparison to the additive-free MRF. Model fitting confirmed that all of the acid-based MRFs showed a yield stress with shear thinning behavior and followed Herschel–Bulkley model. Further investigations suggested that 3 wt% stearic acid was the most promising additive in increasing MR effect and stability. The results of stability and rheological tests showed that further increase in stearic acid fraction improved stability slightly and, at the same time, increased the off-state viscosity to a huge extent undesirably.

1. Introduction

Magnetorheological fluids (MRFs) are a class of smart materials whose rheological properties vary considerably in the presence of an external magnetic field [1]. The viscosity of these materials can increase to a huge extent when they are exposed to a magnetic field. MRFs consist of three main parts; a continuous phase, magnetizable particles, and stabilizer additives [2]. When an external magnetic field is applied to an MRF, magnetizable particles build a chain-like structure in the direction of magnetic field lines and restrict the fluid flow. This behavior is recognized by a sudden increase in the fluid viscosity and a yield stress [3]. In the literature, this change in the MRF state, shear stress and viscosity is mostly interpreted as MR effect which plays an important role in MR technologies [4,5].

Magnetorheological fluids are used in a broad range of industrial applications from MR valves in chemical engineering [6,7] to seismic dampers in civil engineering [8,9]. They have attracted great attention in some industries such as automobile shock absorbers

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Nomenclature

k	Consistency parameter, Pa s^n
n	Power law index
α	Field-constant parameter, Pa
β	Field-consistency parameter, Pa s^n
$\dot{\gamma}$	Shear rate tensor, s^{-1}
τ	Stress tensor, Pa
τ_y	Yield stress, Pa

[10,11]. Two important challenges in MRF-based technologies are their low MR effect and the fluid instability. Like any other dispersed systems, MR suspensions face sedimentation problems. Many studies have attempted to resolve the problem of MRFs instability by using proper additives [12,13], reducing particle size [14] or density [15], synthesizing more elongated particles [16], coating magnetizable particles [17–19], using ionic [20,21] or polymeric liquids [22] as carrier fluids and so on. Unfortunately, most of these methods reduce the MR effect or increase the off-state viscosity of fluid undesirably [23].

In any application, a specific MR effect and stability are needed; so the composition of MRFs for any application must be chosen carefully and consciously [4]. In MR dampers, for example, improving stability is the first and the most important problem and MR effect is of secondary importance. Also in most applications, some limitations restrict the MRF composition; in polishing applications, considering the cooling characteristics of surface and some other parameters, water is the best candidate to be used as the carrier phase in MR suspension preparation [17].

Some researchers like López-López et al. [24] focused on the effect of dispersion on the magnetorheological behavior. They used different surfactants and observed that when particles were dispersed well in the suspension, the change in the viscosity was more significant. They also showed the quality of dispersion had no important effect on the yield stress. However, in the presence of a magnetic field, the change from liquid-state to semi solid-state is more rapid when the particle dispersion is poor.

Fang et al. [12] added single-walled carbon nanotube (SWNT) to a suspension of carbonyl iron (CI) particles in lubricant oil. They showed that adding SWNT could improve both MRF stability and the MR effect. They attributed this behavior to the more robust chain-like structure of the SWNT-containing MRF in the presence of a magnetic field. Wang and Gordaninejad [14] compared the rheological properties and apparent viscosity of three suspensions of a commercial MRF, a polymeric gel-based MRF and a ferrofluid-based MRF at high shear rates. They showed that the gel-based MRF enhances yield stress more in comparison to the commercial MRF by somehow increasing the off-state viscosity. The ferrofluid-based MRF showed an MR effect enhancement similar to that of the gel-based ones. However, it resulted in a sharp increase in the off-state viscosity which hampers its usage.

Jiang et al. [16] used stearic acid (3 wt% of the mass of CI) as the stabilizer additive in a suspension of iron nanowires and CI spherical microparticles in silicone oil. Cheng et al. [17] coated CI particles with a hydrophilic acid (N-glucose ethylenediamine triacetic acid) and claimed that by dispersing these composite particles in water, stability of the suspension increases up to 25%. In an attempt to synthesize an efficient MRF with long lifetime, Premalatha et al. [13] used grease as the stabilizer additive and observed that by increasing the fraction of this agent up to 0.5 wt%, MRF sedimentation decreased. However, MR effect decreased with the increase in grease weight percentage.

Based on the best author's knowledge, the effect of carbon chain length of fatty acids on the strength of the network formed as a result of adding additives to MRF has not been investigated thoroughly, yet. There are few researches on the relation between carbon chain length and kinetics of some specific reactions [25]. Aramaki et al. [26] reported that by increasing carbon chain length of alcohols, the viscosity and shear stress of the micellar solution increase. Yu et al. [27] found that by decreasing carbon content of magnetizable particles, MR effect is enhanced. Morrow et al. [28] examined the influence of acyl carbon chain length on the mean orientational order parameter of liquid to gel transition and found a linear relationship between them. The effect of acid carbon chain length on the rate of crystallization [29] and on some other structures [30–33] have also been investigated.

In this study with the aim of synthesizing a stable MRF with a promising MR effect, four hydrophobic acids with the same functional group but different numbers of carbon atoms were added to the suspension of carbonyl iron and silicone oil. The rheological behavior of the prepared MRFs was monitored using a well-known rheological model.

Table 1
Samples composition.

Sample no.	CI particles (wt%)	Silicone oil (wt%)	Additives (wt%)
MRF1	62	38	–
MRF2	62	35	Lauric acid (3)
MRF3	62	35	Myristic acid (3)
MRF4	62	35	Palmitic acid (3)
MRF5	62	35	Stearic acid (3)
MRF6	72	28	–
MRF7	52	48	–
MRF8	42	58	–
MRF9	62	36	Stearic acid (2)
MRF10	62	37	Stearic acid (1)
MRF11	62	33	Stearic acid (5)
MRF12	62	28	Stearic acid (10)

2. Materials and methods

Spherical carbonyl iron particles (average particle size less than 5 μm, density: 7.86×10^3 kg m^{-3}, CS grade, BASF, Germany) were used as the dispersed phase without further purification. In all samples, magnetizable carbonyl iron particles were dispersed in polydimethylsiloxane (silicone oil, viscosity: 3.50×10^{-4} m^2 s^{-1}, KCC, Korea). Four fatty acids with different carbon chain lengths were added to the MRFs to improve their stability. The additives employed in this study were stearic acid (MIT, Malaysia), myristic, palmitic and lauric acid (MERCK, Germany).

In an attempt to determine a composition of MRF which has an efficient MR effect as well as promising stability, four samples with different weight fractions of CI particles were synthesized and examined. For stabilizing the MRFs, different acids were added to the MRF suspensions. The sample compositions with and without additives are presented in Table 1.

For synthesizing samples, each acid was added to the base fluid (silicone oil). Each mixture was then stirred and heated at 100 °C for half an hour until a homogeneous solution was obtained. All of the acids used in this study produced a gel-like structure in silicone oil. This structure increases the base fluid density and the MRF stability. Afterwards, magnetizable CI particles were added to the sample which was then stirred at 1000 rpm with the aid of an overhead stirrer (Heidolph, RZR 2102, Germany) for more than half an hour to ensure suspension uniformity.

3. Results and discussion

The main focus of this study is on the synthesis of a stable MR suspension. However, if an MRF is stable for more than several months with no efficient MR effect, it is worthless; rheometry