Rheological properties of plate-like shape carbonyl iron particles compositions based magnetorheological grease in oscillatory mode

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Abstract. This paper investigates dynamic viscoelastic properties of magnetorheological (MR) grease with different fractions of plate-like Carbonyl Iron (CI) particles (MRGP). The plate-like CI particles were prepared through milling process. Subsequently, three types of MRGP was developed by dispersing 30 to 70 wt% of plate-like CI particles into grease using mechanical stirrer. The rheological test was performed using oscillatory shear rheometer under flux density influence of 0 to 0.7T and strain amplitude ranging from 0.001 to 10% at constant temperature of 25°C. The experimental results show that the storage and loss moduli of the MRGP is dependent on the fractions of the plate-like CI particles. The enhancement in the MR effect in the plate-like CI particles based MR grease is observed due to the anisotropy shape which leads to the strong inter-particle configuration and chain formations.

1 Introduction

Magnetorheological (MR) fluid consists of dispersion of magnetic particles in a carrier fluid [1]. It can be considered as a smart material that have controllable rheological properties on the variation of external magnetic field [2]. MR fluid has unique characteristics that are reversible and tunable from liquid-like to solid-like state [3]. MR fluid is widely investigated in many industries for the application of shock absorbers, brakes, dampers, valves and torque transfer devices [4–6]. Therefore, many researchers have studied the MR fluid due to its potential to be applied in many fields. The rheological properties of the MR fluid are mainly influenced by the features of the magnetic particles such as size, shape and saturation magnetization. There are some researchers investigated about the plate-like of magnetic particles in MR fluid. For example, Shah et al. [7] had studied the effect of different size of plate-like magnetic particles in MR fluid. The result showed that the rheological properties of MR fluid was affected by the size of magnetic particles. The larger
diameter of plate-like magnetic particles with 19 µm exhibited high yield stress compared to the smaller diameter of plate-like Carbonyl Iron (CI) particles which is 2 µm. In addition, study done by Upadhay et al. [8] stated that the plate-like MR fluid has a higher storage modulus of 6 MPa compared to sphere-based MR fluid. This is due to the field-dependent solid friction between the CI particles. The plate-like magnetic particles can be easily magnetize even though at low magnetic field due to the long axis aligned with the external field that contributed for the formation of strong structures [9]. However, the sedimentation rate in MR fluid can only be reduced up to 20% by using plate-like CI particles [10]. Therefore, the researchers have come up with MR grease that has ability to eliminate the sedimentation problem which occur in MR fluid.

MR greases are identical to the MR fluid that it can be stimulated by the magnetic field [11]. The difference between the MR fluid and MR grease is the viscosity of the carrier fluids [11]. The MR grease is able to suspend the magnetic particles in equilibrium in the grease medium [12]. Recently, MR grease had received a great attention from researchers by investigating the rheological and characteristics of MR grease under various magnetic field strengths. Sahin et al [11] studied the rheological behavior of MR grease and found that the shear stress of MR grease increases with the increment of magnetic field, up to 50 kPa at 0.53T. Another study conducted by Park et al. [13] reported that the maximum dynamic yield stress of the MR grease under influence of magnetic field was 10 kPa. The study was continued by investigating the viscoelastic properties of MR grease under different weight percentages of magnetic particles and magnetic field strengths by Mohamad et al. [14]. The result showed that the MR grease with 70 wt% of magnetic particles exhibited the highest viscosity which was up to 120 kPa with the increment of applied current, yet decreases as the shear rate increases. The viscoplastic properties of MR grease can be described by referring to its yield stress [15]. This MR grease exhibited a maximum yield stress for a similar amount of applied current of 5A which was 52.7 kPa. Besides that, it was found that MR grease has a certain value of yield stress although in the absence of magnetic field due to the intrinsic grease property [13].

Another researcher [16] found that the hexagon shape of magnetic particles in MR grease has a higher shear stress compared to spherical shape of magnetic particles through simulation study. The shear stress of the hexagonal shape particles increased from 7.4 to 21.7 kPa whereas for the spherical shape particles, the shear stress increased from 6.2 to 16.6 kPa. This phenomenon was due to the contact area between the particles. Although many researchers have investigated the synthesis and characterization of MR grease, so far, there are no investigation and experimental work have been done related to MR grease with plate-like CI particles. Therefore, in this paper, the investigation about the effect of different fractions of plate-like shape CI particles on the dynamic viscoelastic properties of MR grease is presented.

2 Experimental

2.1 Materials

Soft magnetic CI particles in spherical shape with OM series purchased from BASF Germany were used to produce plate-like CI particles. The average size and density of the spherical CI particles were 5 µm and 7.874 g/cm³, respectively. The plate-like CI particles were attained from milling process by utilizing rotary ball mill (QM-5 model from Tencan Company). The details of procedure is according to the method described by Shilan et al. [10]. In this work, the duration of milling is 40 hours. Three types of MR grease (will refer as MRGP after this) with different ratios (30, 50 and 70 wt%) were prepared between plate-like CI particles and commercial grease (NPC Highrex HD-3 Grease, Nippon Koyu Ltd, Japan). Firstly, commercial grease was stirred for five minutes using mechanical stirrer. Subsequently, the plate-like CI particles were added and stirred another two hours at room temperature until the suspension is homogeneous.
2.2 Characterization

MRG-P samples were characterized using commercial rheometer (Anton Paar, Physica, MCR 302) equipped with electromagnetic apparatus (MRD 70/1T) under rotational and oscillatory mode. A 20-mm diameter parallel plate measuring system at a gap of 1-mm was used. The storage modulus and loss modulus of MRGP samples were measured in dynamic oscillation test with strain amplitude ranging from 0.001 to 10%. The applied magnetic field is varied from 0 to 0.7T by adjusting the coil applied current from 0 to 5A at room temperature.

3 Results and Discussions

Figure 1 shows storage modulus ($G'$) and loss modulus ($G''$) as function of strain amplitude under influence of different fractions of plate-like CI particles at applied current 3A. It was found that storage and loss moduli of MRGP is dependent on the fractions of the plate-like CI particles. The storage and loss moduli of MRGP increased by increment of the plate-like CI particles fractions at constant applied magnetic field strength. This outcome is expected to be occurred in MRGP due to the larger surface contact areas which leads to the strong attraction between plate-like CI particles [10,17]. In addition, strong attraction between CI particles is rearranged in line to form chain structures; parallel to the applied magnetic field. The chain formations become strong and thick as the applied magnetic field increases. As results, the separation gap between particles has decreased which resulted in hard chain structures formation and indirectly increase the suspension storage modulus [18].

![Figure 1](image_url)

**Figure 1** Storage and loss modulus as a function of strain amplitude under influence of fractions of plate-like CI particles at constant (3A) applied current

The effect of strain amplitude towards storage modulus of MRGP under variation of applied current is depicted in Figure 2. The storage modulus of MRGP-50 increase by increasing current applied. This pattern is also observed for samples MRGP-30 and MRGP-70. The increment of storage modulus is an indication of strong chain structures formation in the suspension [19]. By increasing the strain amplitude, the chain structures initiate to break and slowly starts to flow when exceed the linear viscoelastic (LVE) region [8]. From Figure 2, the LVE region of MRGP-50 is determined at strain amplitude 0.1%. In addition, it has been noticed that the increment of applied magnetic field strength has almost insignificant effect on the LVE...
range of the MRGP, while the storage modulus is promptly changed with the presence of magnetic field strength. Besides, this phenomenon is closely related to the dipole-dipole interactions which occurs in the shape anisotropy due to the stimulated magnetic field in which irregular shape particles can be only attained. The shape anisotropy can produce one or more axis along the long axis of plate-like shape particles which depends on the favorable direction of magnetization. Otherwise, the demagnetization field for shape anisotropy is more complex due to the three-dimensional inhomogeneity of magnetization [20]. Therefore, a greater value of retentivity is stimulated for the plate-like shape particles due to their easy magnetization axis and smaller demagnetization factor in their long direction [20,21].

![Figure 2](image)

**Figure 2** Storage modulus as a function of strain amplitude under various applied current for MRGP-50

Consequently, the relative MR effect of MRGP for all samples were calculated from storage modulus were shown in Table 1. As mentioned earlier, the shape anisotropy that are in the plate-like CI particles responsible to the inter-particles configuration of chain formation and indirectly promotes the higher relative MR effect [21].

| Samples   | Zero-field modulus, MPa | Absolute MR effect, MPa | Relative MR effect, % |
|-----------|-------------------------|-------------------------|-----------------------|
| MRGP-70   | 0.149                   | 1.05                    | 708.03                |
| MRGP-50   | 0.160                   | 0.232                   | 144.59                |
| MRGP-30   | 0.129                   | 0.064                   | 49.54                 |

**4 Conclusion**

Three types of MRGP with 30 to 70 wt% of plate-like CI particles have been synthesized via mixing process using mechanical stirrer. The plate-like particles itself are prepared from the spherical particles which have undergone milling process. The rheometer test under oscillatory mode has been conducted to
measure the rheological properties of the samples. The experimental results have shown a significant increment of the storage modulus which is parallel to the increment of plate-like CI particles fractions and magnetic field strength. Meanwhile, the LVE of the MRGP which is determined at 0.1% strain has insignificant effect towards increment of magnetic field strength. In addition, the MR effect of 708.03% is achieved by utilizing 70 wt% of plate-like CI particles which proves that the anisotropy shape, which obtained in the plate-like CI particles, has improved the interactions between inter-particles. The anisotropy shape also indirectly improves the particles configurations during on-state condition. Finally, it can be concluded that the rheological characteristics of MRGP is showing advantage for practical applications which require high MR effect.

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