Synthesis and Characterization of Nano-Particles Based Magnetorheological Fluids for Brake

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Magnetorheological (MR) fluids, to be used as brake friction materials, must have high heat transfer rate to dissipate the heat generated during the braking action. The aim of this manuscript is to synthesize MR fluids with nano-silver and nano-copper particles to increase the heat transfer rate and characterize the demagnetizing effect of those particles on the shear stress of MR fluids. Five different MR fluids, containing a different percentage of silver and copper nano particles, were synthesized. Shear stresses of all five MR fluids were measured using magnetorheometer and the results have been plotted. A flywheel based MR brake experimental setup was developed to analyze the performance of synthesized MR fluids. "T" type thermocouples were used to measure the temperature distribution of the fabricated MR brake. The results of the temperature distribution of brakes containing five synthesized MR fluids have been presented and compared.

Keywords: magnetorheological fluids, braking torque, synthesis of MR fluid, heat dissipation, nano-silver and copper particles

1. Introduction

MR fluid consists of micron sized magnetically permeable (i.e. soft iron) particles dispersed in the non-magnetic fluid carrier. In the ‘off’ state condition, MR fluids exhibit an apparent viscosity in the order of 0.1 to 1 Pa·s at low shear rates. When an external magnetic field is applied, the originally magnetic particles become magnetized and behave like tiny magnets [1]. Magnetic interactions between these particles can be minimized if the magnetic particles line-up along the direction of the magnetic field. A shear stress or a pressure difference is needed to disrupt this structure formed in energized MR fluids. The strength of the fluid i.e. the value of apparent yield stress, increases as the applied magnetic field (H) increases. The increase, however, is non-linear since the particles are ferromagnetic, and the magnetization in different parts of the particles occurs non-uniformly. Depending on their composition and the flux density (B) generated by the applied magnetic field, MR fluids can develop an apparent yield stress up to about 100 kPa. Higher saturation magnetization materials can lead to an increase in the maximum apparent yield stress. The yield stress development in MR fluids can also occur within a few milliseconds, provided that the electrical circuit generating the magnetic field is optimized. The response time of the overall device tends to be about 10-20 milliseconds, depending on the magnetic circuit design and the device. Multidisciplinary researches [2-6] on MR fluids have been increased considerably after 1990 due to promising applications coming up on the marketplace. The ability to control by a moderate magnetic field (magnetic induction B less than 1 T) the force or torque transmission in actuators, dampers and robotics components, is a consequence of the attractive magnetorheological behavior of MR fluids. The basic phenomena are related to reversible structural changes induced by an applied magnetic field. In MR brake [7-21], an increase in fluid’s shear stress restricts the rotational movement of the disk and increases braking torque on the disk. Under braking conditions, kinetic energy transfers into heat and thermal thinning of MR fluid occurs.

The increase in temperature of MR devices has been researched by various [22,23] researchers. Karakoc et al. [22] found an increase of 25°C temperature in 20 s of continuous braking at 200 rpm. Wiehe et al. [23]
Synthesis and Characterization of Nano-Particles Based Magnetorheological Fluids for Brake


indicated the possibility of 150°C as the maximum temperature of the MR brake. Liao [24] found sharp decay in the damping force on increasing operating temperature from 20 to 80°C.

In order to solve heat dissipation problem of MR devices, cooling methods have been proposed by researchers [25,26]. Dogruoz et al. [25] employed radiating fins in the shell to accelerate the heat dissipation from the MR fluid damper. Tian and Hou [26] proposed forced air cooling, using a rotating fan, of a MR clutch. Zheng et al. [27] utilized rotary heat pipes to achieve forced cooling of the MR transmission device. Wang et al. [28] proposed water cooling method for a high power MR brake. In the present study, mixing of nano-particles has been tried to increase the heat dissipation of MR fluid. Five MR fluid samples have been synthesized and characterized using MCR-102 magnetorheometer. To find the effect of synthesized MR fluid on braking torque and temperature distribution, a MR brake test rig has been designed and experiments have been performed. The schematic of MR brake [7] is shown in Fig. 1. The working principle and dimensions of the MR brake have been detailed by Sarkar and Hirani [7]. Here, \( r_1, r_2, r_3 \) are 10 mm, 44 mm and 45 mm respectively. The MR gap \( h \) is kept as 1 mm. The width \( w \) of the rotor is 10 mm.

The MR brake surface temperature has been measured using eight thermocouples, placed on the surface of the MR brake housing. The comparison among temperature rise and braking for the five MR fluid samples has been presented.

2. Synthesis and characterization

2.1. Samples preparation

Normally MR fluid consists of carbonyl iron (CI) particles (diameter 3-10 µm, 20-40% by volume), additives and base oil [29]. In this research work, three MR fluid samples have been synthesized using 99% pure iron particles having micron sizes (2 to 212 µm) purchased from SIGMA-ALDRICH. Impurities contain As: \( \leq 5 \) mg/kg, Cu: \( \leq 100 \) mg/kg, Mn: \( \leq 1000 \) mg/kg, Ni: \( \leq 500 \) mg/kg, Pb: \( \leq 20 \) mg/kg and Zn: \( \leq 50 \) mg/kg. To avoid settling of particles, 3-10 microns sized particles [30] are preferred, but to increase the shear stress larger sized particles are recommended. MR applications having relative rotating bodies (such as brakes, clutches), settling of the particle does not arise and larger sized

(a) Nomenclature of MR brake

(b) Dimensions of MR brake

Fig. 1 Nomenclature and dimensions of the MR brake
particles may be permitted.

First synthesized MR fluid sample, MRF85, contains 14.5% by mass silicone oil, 0.5% by mass oleic acid, and 85% by mass carbonyl iron powder. The second sample, MRF85_0.25Ag, is made of 14.25% by mass silicone oil, 0.25% by mass silver nano-particle, 0.5% by mass oleic acid, and 85% by mass carbonyl iron powder. The third sample, MRF85_0.50Ag, is composed of 14% by mass silicone oil, 0.50% by mass silver nano-particle, 0.5% by mass oleic acid, and 85% by mass carbonyl iron powder. The fourth sample, MRF85_0.25Cu, is made of 14.25% by mass silicone oil, 0.25% by mass copper nano-particle, 0.5% by mass oleic acid, and 85% by mass carbonyl iron powder. The fifth sample MRF85_0.50Cu is made of 14% by mass silicone oil, 0.50% by mass copper nano-particle, 0.50% by mass oleic acid, and 85% by mass carbonyl iron powder as shown in Table 1.

Silver nano-particles were purchased from EPRUI Nanoparticles & Microspheres Co. Ltd. The average silver particle size is 50 nm. Nearly spherical silver particles are black in color with some impurities (Impurities are Sb: 0.0065%, Bi: 0.0086%, Fe: 0.0076%, Zn: 0.0043%, Cu: 0.0074%, In: 0.0043%, Ni: 0.0015% and Cd: 0.0001%). Copper nano-powder suspensions, purchased from Reinste Nano Ventures, contains the copper particle size of 40 ± 5 nm in ethanol (30% by mass) and metal impurities lesser than 0.1% including Fe (< 0.02%).

<table>
<thead>
<tr>
<th>MR fluid samples</th>
<th>Silicone Oil (% by mass)</th>
<th>Iron particle (% by mass)</th>
<th>Oleic acid (% by mass)</th>
<th>Silver particles (% by mass)</th>
<th>Copper particles (% by mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRF85</td>
<td>14.50</td>
<td>85</td>
<td>0.50</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MRF85_0.25Ag</td>
<td>14.25</td>
<td>85</td>
<td>0.50</td>
<td>0.25</td>
<td>0</td>
</tr>
<tr>
<td>MRF85_0.50Ag</td>
<td>14</td>
<td>85</td>
<td>0.50</td>
<td>0.50</td>
<td>0</td>
</tr>
<tr>
<td>MRF85_0.25Cu</td>
<td>14.25</td>
<td>85</td>
<td>0.50</td>
<td>0</td>
<td>0.25</td>
</tr>
<tr>
<td>MRF85_0.50Cu</td>
<td>14</td>
<td>85</td>
<td>0.50</td>
<td>0</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Fig. 2 Comparison of shear stress of MRF85M1, MRF85M1_0.25Ag, MRF85M1_0.25Cu, MRF85_0.50Ag and MRF85_0.50Cu
To mix in the carrier fluid (silicone base oil), silver nano-particles and silicone oil were homogenized at 35% pulsation power and 70°C temperature for the duration of 2 hours. The homogenized mixture of silicone base oil and silver nano-particles were blended in the mixture of CI powder and oleic acid to prepare MR fluid samples. Similarly, for MRF85_0.25Cu and MRF85_0.50Cu, copper nano-particles, and silicone oil were homogenized.

Nano fluids are expected to exhibit superior heat transfer properties when compared with conventional fluids mixed with micron-sized particles. Nano particles have extremely large surface areas and, therefore, have a great potential for application in heat transfer. In addition to better heat transfer capabilities, nano-particles provide better stability of the suspensions (Choi and Eastman [31]). As the main purpose of the using silver/copper particles is to enhance the heat transfer properties of MRF, therefore nano-sized particles of Ag/Cu have been used.

2.2. Characterization using magnetorheometer

Shear stress flow curve of these MR fluid samples have been measured in ANTON PAAR modular compact rheometer MCR-102 at different magnetic fields in controlled shear rate (CSR) mode. The measurement was performed in a parallel plate system with a diameter of 20 mm at a gap of 1 mm for various input currents (0.1 to 4.8 A). The resulting flow responses have been examined as a function of magnetic field strength ranging from 0 to 152.4 kA/m. The magnetic field strength (A/m) has been calculated from the magnetorheological cell 70/1T MRD. The temperature was set at 30°C during the measurement. Table 2 shows the data of shear stress measurement for MRF85 at various input currents at 100 s⁻¹ shear rate. There are 15 measuring points for an interval of 10 seconds and shear rate is fixed at a constant value. Temperature is set at 29°C during the measurement. The minimum shear stress is 876.80 Pa at 5.316 kA/m magnetic field and 101, 100 Pa at 152.40 kA/m magnetic fields. The results of shear stresses are plotted in Fig. 2. The experiments have been done for three different trials. Based on the different trials, average and standard deviations have been calculated. The graphs have been plotted based on the average and error bars indicate the standard deviation value. The
shear stress of each sample was measured thrice. Due to the diamagnetic property of silver nano-particles and copper nano-particles, shear stress of MR fluid may decrease. However, Fig. 2 shows that the shear stress of all MR fluids samples lies within the error bar. There is no significant variation in the stress values. On other hand, it is important to find the effect of silver particles and copper particles on temperature distribution, which is the main aim of using nano particles. As per SEM images the iron particles are poly-disperse (Sarkar and Hirani).
Hirani [19]). Some iron particles are spherical in shapes and some are flake type. Due to variation in size and shape of iron particles, no definite structure of iron particles can be expected. Variation in structure will increase with increase in the high magnetic field. In addition, shearing of structure break and reform chains/clusters randomly without any particular orientation (Sarkar and Hirani [19]). This leads to deviations of shear stress results with high error bar compared to at that low magnetic field (Kittipoomwang et al. [32]).

To observe the effect of temperature on shear stress, experiments have been performed and results at various magnetic fields are plotted in Fig. 3. There is a common trend of reduction in shear stress of MR fluid with an increase in temperature. In other words, the MR fluid undergoes thermal thinning behavior due to increasing in temperature.

Both Silver (Ag) and Copper (Cu) are diamagnetic material. Diamagnetism is expressed by magnetic susceptibility ($X_v$) of diamagnet. The magnetic susceptibility ($X_v$) of silver (Ag) and copper (Cu) is $-2.6 \times 10^{-5}$ and $-1.0 \times 10^{-5}$ respectively. Hence, silver (Ag) is more diamagnetic than the copper. In other words, due to the higher susceptibility of Silver (Ag), MR fluid containing Cu provide higher stress than that of MR fluid containing Ag particles.

2.3. Characterization using scanning electron microscope

The scanning electron microscope photographs of three samples have been captured by Scanning Electron Microscope.
Microscope Zeiss EVO 50. The ZEISS EVO 50 is a versatile analytical microscope with a large specimen chamber. The EVO 50 series can handle large specimens at the analytical working distance of 8.5 mm owing to a combination of the inclined detectors and the sharp conical objective lens. The class leading X-ray geometry allows for the addition of an EDS detector. It has the resolution in the range of 2.0 mm $\phi$ 30 kV, and acceleration voltage 0.2 to 30 kV. The magnification range is from 5, to 1,000,000. The field of view is 6 mm at the analytical working distance (AWD). The X-ray analysis has been done at 8.5 mm AWD and 35° take-off angle. The dimensions of the chamber are the diameter ($\phi$) 365 mm and height (h) 255 mm. The system is controlled by Smart-SEM software. Iron particles (Sigma-Aldrich) are shown in Fig. 4(a). These iron particles are spherical in shape with various sizes. The iron particles were extracted from MRF85_0.50Ag; MRF85_0.50Cu and the scanning electron microscopic photograph of these iron particles have been captured and shown in Fig. 4 (b) and 4 (c). The EDX analysis of iron particles extracted from MRF85_0.50Ag and MRF85_0.50Cu is shown in Fig. 5. It shows that there is some presence of Ag nano-particles and Cu nano-particles with the iron particles.

3. Experimental study on temperature measurement of MR brake

3.1. Experimental setup

The block diagram of the MR brake test rig is shown in Fig. 6. A 5 hp D.C. motor has been used a source of the motion of the shaft of MR brake. A flywheel (20 kg) is connected between the 5 hp D.C. Motor and MR brake through bearing brackets and jaw couplings. The speed of the D.C. motor has been controlled by the speed controller up to 1500 rpm. However in the present research work tests have been carried out up to 600 rpm due to the vibration of the experimental table. A D.C. power supply (30 V and 5 A) to control the current to the electromagnet of MR brake; a tachometer to measure the rotational speed have been used. The temperature readings of thermocouples have been recorded using eight thermocouples to measure the heat dissipation of different MR fluids. The temperature readings of thermocouples have been recorded in the computer using Agilent 34972A LXI data Acquisition/switch unit. To find the temperature profiles at various operating conditions, magnetic field H varying from 0 to 350 kA/m and speed at 200 rpm and 600 rpm were conducted. After completing each experiment, forced cooling using table fan was used to bring back the MR brake at the normal temperature.

Figure 7 shows the photograph of the MR brake test rig. Figure 8 shows the position of the thermocouples on the surface of the MR brake housing.

3.2. Working principle
Braking torque and surface temperatures in each experiment were measured by adopting following step by step procedure:

- Run the D.C. motor at constant rpm using speed controller.
- Note down the reading of the voltmeter and ammeter of the speed controller of the D.C. motor.
- Estimate the power loss. Supply current in the electromagnet of MR brake.
- In the presence of magnetic field, brake actuation happens and the speed of the disk of MR brake reduces. Therefore, regulate the voltage using the speed controller to maintain the same speed (rpm) of the MR brake shaft.
Record the reading of the voltmeter and ammeter of the D.C. motor speed controller. Calculate the power loss. Braking torque \((BT)\) is calculated using the following formula [7]

\[
BT = \frac{PW_f - PW_i}{\omega}
\]

Where, \(PW_i\) and \(PW_f\) are initial and final power loss; \(\omega\) is constant angular speed.

- Record temperatures using thermocouples after the stabilization of temperature in the desktop computer using data logger.
- After completing temperature reading, switch off the power supply to the electromagnet and reduce the rpm of the D.C. motor to zero.
- Switch on the table fan to cool the MR brake to get back to the initial temperature. Repeat the same procedure for another experiment (different current electromagnet and different motor speed). Each experiment was performed thrice.

4. Results and discussion

When the speed of the MR brake is maintained at 200 rpm (applied magnetic field in the MR brake is zero), the voltmeter and ammeter of the D.C. motor speed controller shows 59 V and 1.1 A. Therefore, the power loss (V.A) of the 5 hp D.C. motor is 64.9 Watt. Figure 9 shows the braking torque and surface temperature of the MR brake housing using three MR fluids (MRF85, MRF85_0.25Ag, and MRF85_0.25Cu) in shear mode at 200 rpm. At zero magnetic field, the braking torque is zero and maximum temperature on the MR brake housing for different MR fluids is same (22°C). When the rotor is rotating at specified speed the iron particles are randomly oriented as shown in Fig. 10 (a). Due to centrifugal force, the iron particles get staggered at the periphery of the rotor and help to dissipate the zero-field frictional heat. The maximum temperature (22°C) had been observed at the Thermocouple T4 on the housing surface of the MR brake for all the different samples of MR fluids. When the magnetic field is applied at the central electromagnet, the iron particles get aligned along the direction of the magnetic field and sheared due to the constant rotation of the rotor. The thermocouple T4 shows the temperature 37°C, 30°C and 27°C for MRF85, MRF85_0.25Cu, and MRF85_0.25Ag respectively as shown in Fig. 10 (b).

For both the fluids increase in braking torque as well as temperature with increase in current supplied to the central electromagnet can be observed. It is important to notice that the braking torque for three MR fluids is same. The increasing order of temperature on the MR brake housing is: MRF85 > MRF85_0.25Cu > MRF85_0.25Ag. This proves that the heat transfer rate of the MRF85_0.25Ag is higher than MRF85_0.25Cu and MRF85. It can be said that the silver nano-particles helps heat dissipation and reduces the temperature of MR brake.

To observe the effect of silver particles and copper particles at relatively higher speed, experiments were performed at 600 rpm. Figure 11 (a) shows the braking torque and surface temperature of MR brake operated at 600 rpm. It can be said that with increase in rpm, braking torque of MR brake decreases. MR fluid containing silver nano-particles is sensitive toward the thermal thinning behavior of MR fluids. The increasing order of the temperature on the surface of the MR brake housing is: MRF85 > MRF85_0.25Cu > MRF85_0.25Ag.
To observe the effect of particle percentage (0.50% by mass) of silver and copper, experiments had been conducted at 600 rpm and plotted in Fig. 11(b). It shows that there is a decrease in braking torque for the silver nano-particle based MR fluids though there is an increase in heat transfer of MR brake. Therefore, MRF85_0.50Cu is a better option than MRF85_0.50Ag.

To understand the effect of silver and copper nano-particles on MR fluids, equation (Eq. 1) related to the effective thermal conductivity ($K$) of multi-component given by Brailsford and Major [33] has been used.

$$K = \frac{4k_1 k_2 D}{3k_1 + k_2} \left(1 - \nu \right) + k_1 \left(1 - \nu \right)$$

(2)

Where $k_1$ and $k_2$ are the thermal conductivities of the particle and the suspending medium respectively; and $\nu$ is the particle volume fraction. As per this equation, the effective thermal conductivity of MRF85 ($K_{MRF85}$) can be estimated using thermal conductivity of suspending
medium silicone oil \(k_2\) equal to 0.1 W/(m·K), thermal conductivity of CI powder \(k_1\) equal to 80 W/(m·K), and the particle volume fraction, \(\nu = 0.3548\). The value of \(K_{\text{MRF85}}\) comes out to be 0.319 W/(m·K). In order to estimate the thermal conductivity \(K_{\text{MRF85}_0.25\text{Ag}}\) of MRF85_0.25Ag using equation (1), it was assumed that silver nano-particles make a layer on the surface of the iron particles and particle volume percentage \(\nu\) remains almost same \(\sim 0.3556\). With this assumption, \(K_{\text{MRF85}_0.25\text{Ag}}\) comes out to be 0.3259. This value is slightly higher than that of \(K_{\text{MRF85}}\); therefore temperature rise will be reduced by using \(K_{\text{MRF85}_0.25\text{Ag}}\). Similarly the value of thermal conductivity \(K_{\text{MRF85}_0.25\text{Cu}}\) of MRF85_0.25Cu will be almost equal to that of MRF85_0.25Ag. Here, particle volume percentage \(\nu\) remains almost same \(\sim 0.3557\) and \(K_{\text{MRF85}_0.25\text{Cu}}\) comes out to be 0.3259. Therefore, the exact mechanism of heat dissipation for both of MRF85_0.25Ag and MRF85_0.25Cu is still unknown. There is a need of a detailed theoretical study on thermal conductivity measurements of MR fluids which is beyond of this research work.

Figure 12 shows the maximum temperature on the MR brake housing surface, using five different MR fluids. Thermocouples T3, T4, T5, T6, and T7 are placed on the same pitch circle diameter of MR brake housing surface. The temperature difference (maximum temperature reading-minimum temperature reading) for MRF85, MRF85_0.25Cu, MRF85_0.25Ag, MRF85_0.50Cu and MRF85_0.50Ag are 18°C, 12°C, 14°C, 16°C and 9°C respectively. Therefore the increase in silver nano-particle percentage helps in uniform temperature distribution on the MR brake. The difference in the temperature around the periphery of the disk of MR brake may be due to misalignment between the disk and the MR brake housing.

The behavior of MR brake due to the misalignment has been sketched in Fig. 13. It shows there is minimum MR gap \(h_{\text{min}}\) and maximum MR gap \(h_{\text{max}}\) over the circumference of MR disk. Due to the difference in the MR gap, non-uniform distribution of MR particles occurs and non-uniform distribution of temperature even on the same PCD occurs.

References

Synthesis and Characterization of Nano-Particles Based Magnetorheological Fluids for Brake


