Magnetorheological fluids based on amorphous magnetic microparticles

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Abstract. Magnetorheological fluids were prepared using FeSiB particles with an irregular flattened shape and also spherical Fe particles commercially available. In this paper we point out that particles oxidation and particles size distribution can influence the MR fluid performance and measurements.

1. Introduction
Magnetorheological fluids are suspensions of magnetically polarizable particles in a magnetically neutral fluid, usually mineral or silicone oil. The main characteristic of magnetorheological fluids is their ability to reversibly change from a linear viscous fluid with free flow to a semi-solid material with controllable yield stress when placed in magnetic field. When magnetic field is applied, the dispersed particles in the fluid form oriented chains parallel to magnetic field and the result is an increase of the shear stress perpendicular to the magnetic field direction. Due to their ability to modify their properties (viscosity, shear stress) in an applied magnetic field, magnetorheological fluids are widely used in semi-active controllable fluid dampers for vehicles, machineries, for buildings protection against vibrations. [1]

Yield stress is very important in applications and depends on magnetic field applied, volume fraction of solid magnetic material and is limited by magnetic saturation of the magnetic material. Usually, spherical magnetic particles are used as they are easier to be obtained in this form. The preferred magnetic material is Fe due to high saturation magnetization [2]. We presumed that the magnetic particles blocking in magnetic field may be improved using non-spherical magnetic particles.[3] Our final goal is to study contribution of the particle size and shape to the performance of the MR fluids, and the FeSiB flattened particles are made for this purpose [5], [6], [7]. In this first stage of the study we only point out that particles oxidation and particles size distribution can influence the MR fluid performance and measurements.

2. Experimental
2.1. Particle preparation and characterisation
We prepared magnetorheological fluids with two types of magnetic particles: Fe and FeSiB particles.

FeSiB particles were obtained from amorphous microwires as they have convenient shapes. We used magnetic amorphous magnetic microwires prepared by an in-rotating-water quenching technique [4]. FeSiB wires were cut to pieces of millimeter sizes so that they could be milled in a Retsch
planetary ball mill. The purpose was to obtain particles of different sizes and shapes corresponding to different milling times. The particles were imaged by mean of SEM that revealed the particles dimensions and shapes. The wires were milled and then sieved by means of a sieve shaker from Retsch. The dimensional ranges of the particles used were < 20, 20-40, 40-60, 60-80 micrometers. SEM images show that they have irregular flattened shape as seen in figure 1.

![SEM images of the FeSiB particles](image1.png)

**Figure 1.** SEM images of the FeSiB particles a) 20-40 microns b) 40-60 microns

Fe particles used were commercially available spherical Fe particles (mesh 325) from Sigma-Aldrich. The powder was sieved and we obtained the following dimensional ranges: < 20, 20-40 and 40-60 microns. VSM measurements were performed for all the particles.

2.2. Magnetorheological fluid preparation and characterisation
All the magnetorheological fluids were prepared in volume concentrations of 10%, by mixing the mineral oil with the stabilizer (Al stearate) first and then with the magnetic particles using a grinding mortar. The fluid was homogenized afterwards by mean of a stirrer. Flow (viscosity) curves were measured in and out of magnetic field using a rheometer Physica MCR101 fitted with a magnetorheological module which can apply a magnetic field up to 1T corresponding to a 5A current. The measurements were performed using a parallel-plate system with a diameter of 20 mm at a gap of 1 mm and at 20°C for all tests. We applied different magnetic fields and flow curves were plotted for each magnetic field. The yield stress was calculated by the rheometer software for each flow curve according to Bingham model.

3. Results and discussions
Magnetorheological fluids were prepared in volume concentration of 10% using FeSiB particles with different dimensional range. Variation of the yield stress with applied field in the MR cell was plotted for each MR fluid based on the measured flow curves. The values of the yield stress for each magnetic field were calculated by the rheometer software according to Bingham model. As seen in figure 3, a direct dependence between the particles size and the maximum yield stress was found. Further VSM magnetic measurements shown in figure 2 revealed that the saturation magnetization of the particles was greater as the particles were bigger. This could mean that the particles were affected by oxidation. The degree of oxidation was larger as the particles were smaller due to their larger surface in contact with air. Smaller particles were more affected by oxidation leading to lower saturation magnetization and thus to lower yield stress. Our EDS analysis reveals that the particles were indeed oxidized. Thus it cannot be clearly separated the influence of the oxidation from the influence of the dimension of the particles. Further investigations have to be made taking into consideration the particles oxidation.

Saturation magnetization for each particle dimensional range is given in Table 1. It can be seen also in Figure 3 that although the dimensional ranges of 20-40µ and 40-60µ have notable different saturation magnetizations they present almost the same yield stresses. Starting with this observation and other results with the same type of MR fluids we assumed that there could be another factor that alters the resulting yield stress and that would be the particle size distributions.
Table 1. Saturation magnetization for each FeSiB particle dimensional range

| Particle size range | Ms(emu/g) |
|---------------------|-----------|
| <20 µ              | 149.69    |
| 20-40 µ            | 161.32    |
| 40-60 µ            | 172.20    |
| 60-80 µ            | 174.17    |

For a better understanding of the particle size distributions we made MR fluids using Fe particles. The Fe particles were Mesh325 commercially available from Sigma-Aldrich. The particles were sieved identically as in the case of the FeSiB particles. Thus we obtained Fe particles with size ranges of < 20, 20-40 and 40-60 microns. Over 60 microns there was a negligible quantity after sieving.

MR fluids were prepared using the same procedure as in the case of FeSiB particles. The magnetization curves are shown in figure 4. Yield stress dependence with applied field has been plotted after flow curves measurements. The result is shown in figure 5. We note that the MR fluid with particles in range of 20-40µ presents maximum yield stress higher in the case of ranges <20µ and 40-60µ.
The size distribution has been measured with a Microtrac S3500 particle size analyzer. A maximum in the range 20-40 µ, and an ascending respectively descending slope distribution in the ranges <20µ and 40-60µ were observed. We presume that there is a link between the particle size distribution and yield stress curves shown in figure 5. This could mean that a strictly ascending or descending slope distribution has a negative role for the performance of the MR fluid. Also, it is probably that a more uniform particle size distribution leads to more homogenous and strong structure in the MR fluid when magnetic field is applied. Further investigations have to be done.

4. Conclusions
Magnetorheological fluids were prepared using FeSiB particles with an irregular flattened shape and also spherical Fe particles commercially available. FeSiB particles in four dimensional ranges were obtained by milling magnetic amorphous microwires and sieving the resulting powder. Rheological measurements were performed for each MR fluid: flow curves having the magnetic field as parameter and yield stress vs. applied magnetic field curves were calculated using Bingham model. In order to highlight the influence of the particle dimension and shape on the performance of the MR fluid it is necessary to eliminate or keep constant the other influencing factors. We found that two factors were influencing our measurements: particles oxidation and particles distribution. The degree of oxidation was higher as the particles were smaller leading to lower magnetic saturation and hence to lower yield stresses in magnetic field. The influence of the particle distribution was better evidenced using commercially available Fe particles with a known particle distribution and sieved in the same dimensional range as the FeSiB particles. Our hypothesis is that a strictly ascending or descending slope-like distribution has a negative effect on the performance of the MR fluid.

Further experiments have to be done regarding the role of the size distribution to the MR fluid performances. In order to study the particles dimension and shape contribution to the properties of a MR fluid we must take into account the above mentioned influences.

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