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Effect of compression on the response of a magneto-rheological suspension

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Abstract

A carbonyl iron-based magneto-rheological suspension was compressed in the direction of the applied magnetic field and the change in rheological properties was measured. It was found that the compression did not have a large effect on the magneto-rheological response, which is in contrast to recent reports in the literature describing an almost order of magnitude increase in the shear yield stress. The difference can be attributed to the latter test's use of a sliding wedge apparatus which imparts considerable shearing to the sample during the compression.

Keywords : particle suspension, magneto-rheological suspension, MRS, magneto-rheological fluid, compression, micro-structure

1. Introduction

A magneto-rheological suspension (MRS) consists of magnetisable particles dispersed in a carrier liquid and displays a large but reversible increase in flow resistance upon application of an external magnetic field (usually expressed as magnetic flux density B). This material is also sometimes referred to as "magneto-rheological fluid" or "MRF". The tunable flow properties of MRS offer many potential engineering applications e.g. tunable vibration damping systems (Carlson *et al.*, 1996; Carlson, 2000; Stix, 2001). MRS has been the focus of much research attention in recent years and presently there are available several review articles (Ashour *et al.*, 1996; Ginder, 1998; Phule, 1998; Rankin *et al.*, 1998; See, 2001; Klingenberg, 2001) and conference proceedings (Bullough, 1996; Nakano and Koyama, 1998; Tao, 2000; Bossis, 2002). The essential physical mechanism for this change in flow properties is that the external field causes magnetic polarisation of each particle, leading to strong magnetostatic interparticle forces and the rapid formation of elongated aggregates in the direction of the field. The presence of these aggregates greatly increases the resistance to an imposed flow. The rheological response of these fluids under shear flow is often modeled as a Bingham fluid, with the field-induced solid-like behaviour expressed by a field-dependent yield stress. Although this basic picture has been known for some time, there are still many unresolved issues related to the physical mechanisms governing the field-induced rheological response.

One of the major goals in MRS development is to maximize the increment in the flow resistance induced by the magnetic field. Towards this end, Tao, Tang and co-workers (Tang *et al.*, 2000; Tao, 2001) have reported that compression of the samples in the field direction can lead to a considerable increase in the solid-like nature of these materials. These workers used the difference in the shear yield stress before and after the compression to characterize this phenomenon. This enhancement of the response arising from compression could prove useful if it could be incorporated in the design of magneto-rheological engineering devices. To date, these reports appear to have been the only ones published on this "compression-enhancement" effect in MRS, despite its potential practical significance, and there is certainly a need for more information on this behaviour. The present paper reports experiments carried out using a parallel plate rheometer to investigate the rheological properties of an MRS before and after compression, up to compressive strains of 0.05.

At this point, it is appropriate to briefly describe the compression measurements carried out by Tao, Tang and co-workers (Tang *et al.*, 2000; Tao, 2001). These workers studied a MRS comprised of carbonyl iron particles in silicone oil with volume fractions of 46 to 50%. The compression of the MRS in the field direction was accomplished as follows: An aluminium container containing the MRS was placed between two electromagnetic poles, which were horizontally opposed. Inside the container, the MRS was sandwiched between two sliding wedges, each of which was able to translate vertically over a fixed guiding wedge (the wedge angle was 12° to the vertical). Thus, as the two sliding wedges were moved downwards, the fluid between them became compressed. To

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characterise the mechanical properties of the MRS (before and after compression), these researchers used an aluminium test bar inserted vertically in the middle of the fluid sample, midway between the wedges. The minimum force required to pull out the test bar was converted to a yield stress. The extent of the compression of the MRS was expressed via the compression pressure calculated from four strain gauges mounted on the test bar in a Wheatstone bridge circuit. With this method, they found that the yield stress induced under a constant field increased dramatically from approximately 100 kPa (prior to compression) to over 600 kPa (after compression). Tao, Tang and co-workers attributed this change to the formation of thicker (and hence stronger) aggregate structures induced by the compression. Indeed, this picture was supported by their microscopic examination of the structures formed before and after compression (facilitated by inducing the formation of aggregates in an epoxy which was subsequently set). It should be pointed out that, due to the motion of the wedges to facilitate the compression, the apparatus of Tao and Tang involves simultaneously subjecting the sample to considerable shearing deformation. Further, it must be noted that the extent of compression in these papers was reported via the value of the compressive pressure as described (up to 2.5 MPa), and no data was presented on the actual displacement of the compression.

For completeness, we note that there are reports in the literature describing the effects of compression on electro-rheological fluids, which are the electrical analogues of MRS (Kim *et al.*, 1999; Tian *et al.*, 2002a; 2002b; 2003; Tao *et al.*, 2002). For example, Tian and co-workers (Tian *et al.*, 2003) have extensively looked at the compressive stresses arising in electro-rheological fluids, and have concluded that continuum-based models (e.g. Bingham fluid model) are unable to explain the phenomenon observed. However, it should be kept in mind that under strong fields ERF and MRS have fundamental differences - for example, the response of ERF can be considerably modified by effects arising from electrical conductivity in the particles (Sung and Choi, 2004) and carrier matrix, which is an effect that does not occur in magnetic systems. Henceforth, this paper will focus on the MRS systems.

This paper will examine the behaviour of an iron-based magneto-rheological suspension under compression and magnetic fields, using a parallel plate rheometer modified for this purpose. The results will be compared to the behaviour reported by Tao, Tang and co-workers obtained using their wedge compression approach (Tang *et al.*, 2000; Tao, 2001). It needs to be pointed out that this paper does not present a direct comparison, in the sense that we do not use the same wedge geometry as Tao, Tang and co-workers. Further, we will not be using the yield stress to characterise the material: to monitor the changes in the rheology of the MRS, in particular the extent of the solid-like behaviour under the magnetic field, we will employ linear viscoelasticity. This will be used because, in general, there is less ambiguity when compared to directly measuring the shear yield stress, which often requires interpretation of the flow curves - however, useful information on the solid-like nature of the material can be obtained. Indeed, it is worth pointing out that linear viscoelastic measurements have been successfully used by other workers to characterize the solid-like nature of magneto-rheological materials under a field - in particular the dramatic change in the storage modulus G' upon application of the field points to this variable's usefulness as a descriptor of the system's state (e.g. Chin *et al.*, 2001; Rankin *et al.*, 1999; See, 2003). Consequently, in this paper, we will chiefly focus on the storage modulus G', and will use this to monitor the rheological changes in the MRS before and after compression.

This paper will be structured as follows. In the next section we will describe the materials and apparatus used. This will be followed by a description of the results and discussion. Concluding remarks will be presented in the final section.

2. Experimental

2.1. Materials

The magneto-rheological sample consisted of particles of carbonyl-iron powder (average particle size 4 μm, ISP Corp, grade S3700) dispersed in a 0.1 Pas silicone oil (Dow Corning) with a volume fraction of 30%. The samples were inspected at the conclusion of each test, and no significant clumping or sedimentation of the particulate was observed. This is our standard volume fraction for testing, as a clear difference in flow properties can be observed between the field-on and field-off states.

2.2. Apparatus

An Anton Paar Physica MCR300 rheometer was used, in its controlled strain mode. The measuring geometry comprised of stainless steel, parallel plates of diameter 20 mm. The MRS sample was sandwiched between the plates and the upper plate was brought down towards the bottom plate to compress the sample. In all tests, the initial gap used was 1.0 mm. During the compression, no torsional motion was applied to the sample.

To apply the magnetic field to the sample, a magneto-rheological test cell was attached to the rheometer (Physica TEK 70-MR). This cell consisted of a unit under the bottom plate, which housed the lower half of a magnetic circuit constructed from iron elements. This contained a coil of 495 windings through which a dc electric current was passed to generate the magnetic field. On the upper side, there was a removable cylindrical block which sat on the

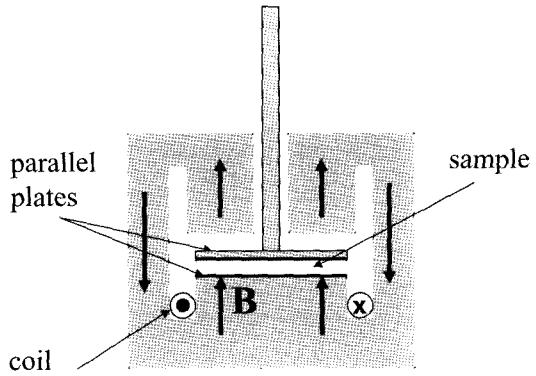

Fig. 1. Schematic cross section of the magneto-rheological test cell.

bottom stage and completely enclosed the two plates, with a central hole to pass the rheometer shaft. This block was also made up of iron elements and constituted the upper half of the magnetic circuit, thus enabling a uniform magnetic field to be applied perpendicularly across the plates (see the schematic in Fig. 1). The magnetic flux density across the plates was controlled by the rheometer software which adjusted the electric current through the coil, taking into account the air gap immediately above the upper plate, and the characteristic permeabilities and dimensions of the other elements comprising the magnetic circuit. The maximum magnetic flux density across the plates achievable with this system was 0.54 T. It should be noted that there is actually a lack of magnetic field immediately below the shaft, but this effect is not considered to be large since the shaft diameter is only 4 mm. In these tests the following three magnetic flux densities were used: 0.057 T, 0.27 T, 0.54 T. All experiments were conducted at room temperature (25°C).

Confirmatory tests were also performed in which the direction of current through the coils was reversed, thereby switching the direction of the magnetic field. It was found that the magnetorheological behaviour did not depend on the direction of the field, which was expected since ideally the magnetostatic interparticle forces depend on the magnitude of the polarisation and not explicitly on the field polarity. Further, tests were also carried out on magnetically inert silicone oils to confirm that the application of the magnetic field did not affect the rheometer's torque measurement system.

2.3. Rheological measurements

The samples were initially sheared without a magnetic field at a shear rate of 100 s^{-1} for 1 min to ensure good dispersion. The shearing was then stopped and for 10 minutes the magnetic field was applied across the plates with the sample subject to no deformation (no compression or shearing). This period was to allow the aggregates to form in the sample.

After the magnetic field had been applied for 10 min, the compressions and rheological tests commenced. The magnetic field continued to be applied to the sample through all these tests. As mentioned previously, the sample was characterised via measurement of the storage modulus, using an oscillatory shear strain at a frequency of 20 Hz and a strain amplitude within the linear viscoelastic limit (detailed in the following section). These measurements were carried out before and after the compression tests, which will now be described.

To compress the sample, the upper plate was lowered to the required gap value. The following types of compression were carried out:

(a) One-step compression test - The gap was reduced with one movement of the rheometer plate, typically over 2~3 seconds.

(b) Slow compression test - Here the upper plate was lowered very gradually. For example, the plate was lowered 0.01 mm from an initial gap of 1.0 mm to a gap of 0.99 mm. The upper plate was then held at this position for 60s. It was then lowered further to 0.98 mm, and the process repeated, until the plate eventually reached the final target gap of, say, 0.9 mm. The viscoelastic measurement was carried out at this final gap. In addition, during some of these movements, linear viscoelastic measurements were performed at intermediate heights to monitor any variations during the compression process.

To describe the compressive deformation, a characteristic strain is used, defined as d/h_0 where h_0 is the initial gap value (1 mm) and d is the displacement of the upper plate from its initial position. At this point, some comments are warranted on the magnitude of the compressions applied - we chose 5% as the maximum compression. Displacements larger than this would have caused substantial change in the wetted area of the plates, and indeed, could possibly have lead to overflow of the sample. Further, as pointed out earlier, Tao and co-workers in their papers (Tang *et al.*, 2000; Tao, 2001) did not state the compressive strain their samples were subjected to, making it impossible to facilitate a direct comparison based on the strain magnitudes. However, the micrographs of the structures (e.g. Fig. 16 in Tao, 2001) seem to suggest that the displacements applied were not very large, so 5% would appear to be a reasonable value.

In addition, it should be pointed out that, strictly speaking, a reduction in the gap is accompanied by a small change in the magnetic field strength since the magnetic resistance associated with the gap is altered, while the magnetomotive force in the magnetic circuit produced by the electric current through the coils is kept constant. This effect could be estimated by considering an approximate magnetic circuit, and it was found that the change in flux intensity was less than 10% even for the largest compressive strains considered in this study.

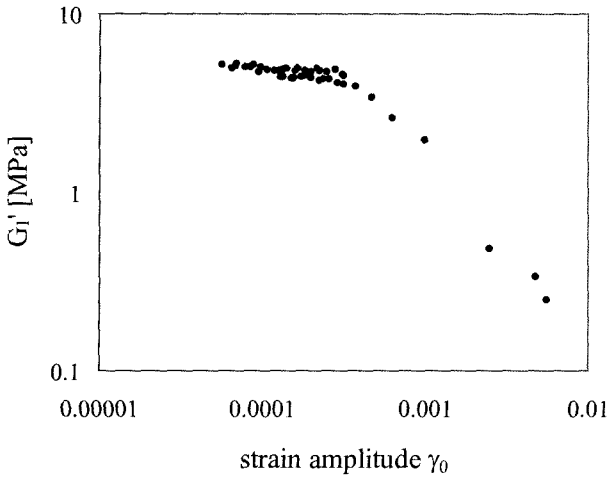

Fig. 2. Results of the tests on linear viscoelasticity, under a field of 0.54 T and gap of 1 mm. The in-phase component (fundamental) G_1' of the stress signal is plotted against strain amplitude γ_0. G_1' equals the conventional storage modulus G' when the response is in the linear viscoelastic regime.

3. Results and discussion

Fig. 2 shows the results of the test for linear viscoelasticity, under a magnetic flux density of 0.54 T. The compression of data points at the lower strain amplitudes arises from the use of the logarithmic strain axis for clarity (during the tests the strain amplitudes were actually ramped up linearly) - nevertheless, the trend of the curve is clear. Results for other flux densities showed similar trends. Note that no compression had been applied to the sample. It is seen that the material showed linear viscoelastic behaviour up to a shear strain amplitude ~ 0.0003. At strain amplitudes larger than this, the aggregates became increasingly broken up, leading to a reduction in the modulus. Therefore, to ensure we were measuring in the linear viscoelastic regime, the shear strain amplitude was maintained at 0.0001 in all subsequent oscillatory shear flow tests. Note that this limiting strain value for the linear viscoelastic regime in an iron-based MRS agrees with that reported by Chin *et al.* (2001).

The effects of compression speed are illustrated in Fig. 3, for the case of a 0.54 T magnetic flux density. The final compressive strain here was 0.05. There appeared to be little difference between the one-step compression and the slow compression, as evidenced by the similarity of the G' values measured at the final compressive strain of 0.05. This result is not unexpected, since the typical timescale for re-arrangement of individual particle configurations in the aggregates is usually very short (of the order of ms), and so even under the faster compression there was more than adequate time for the structural re-arrangements to take place.

In addition, Fig. 3 makes clear the following important

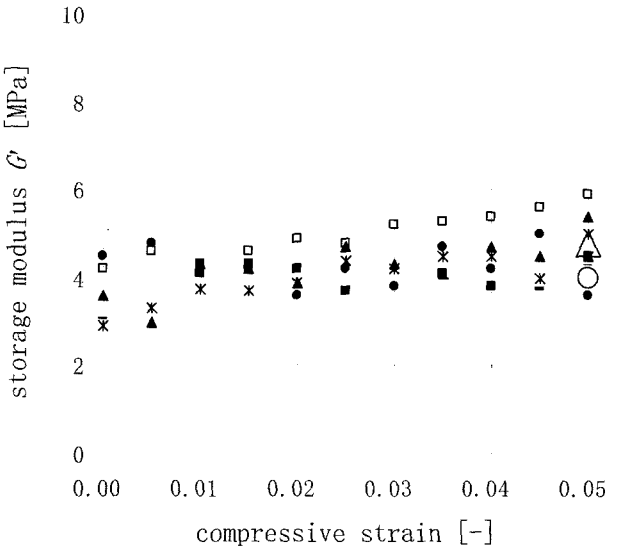

Fig. 3. Effects of compression and compression speed on the storage modulus G', under a constant magnetic flux density 0.54 T. The final value of compressive strain is 0.05 in these tests. The values of G' measured during the slow compression are indicated at the intermediate strains. The triangle above 0.05 is a measurement made in a separate test after a slow compression, with no measurements of G' performed at the intermediate positions (*i.e.* removing the effects arising from intermediate measurements). The circle above 0.05 is the average G' value obtained after a one-step compression. Note that results from several different tests have been plotted on the same graph, to indicate the reproducibility (each test corresponding to the one of the symbols: *, □, ■, ●, ▲).

result: there seemed to be no significant enhancement of G' as the sample underwent compression. This is in contrast to the results of Tao and Tang (Tang *et al.*, 2000; Tao, 2001) using their wedge device, where dramatic increases in the solid-like nature of the MRS were observed as a result of compression.

Fig. 4 shows the effect of different magnetic flux densities on G' after one-step compressions up to the strain values indicated. In general, we observe that there was a significant increase in G' under the stronger magnetic flux densities, which confirms that the sample did indeed respond as a typical MRS. As before, we observe that, for all flux densities, there seemed to be no significant change in G' as the MRS was compressed.

Therefore, from Figs. 3 and 4, it would seem that the compressions we applied in these tests (up to strains of 0.05) did not have a significant effect on the solid-like nature of the MRS, as measured through the storage modulus. This is in contrast to the conclusions reached by Tao and Tang (Tang *et al.*, 2000; Tao, 2001). One reason for this discrepancy could be that, as mentioned previously, the group of Tao and Tang used a wedge device (12° angle) to

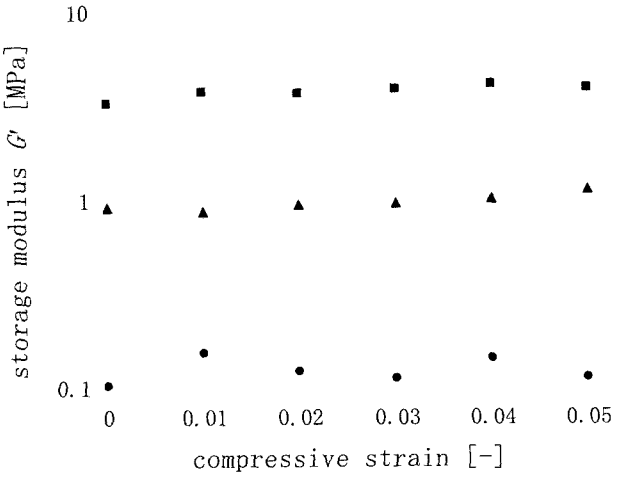

Fig. 4. The effect of different magnetic field strengths on storage modulus G' after one-step compression to the strain values indicated. The magnitudes of the magnetic flux densities are, from top: 0.54 T, 0.27 T and 0.057 T.

compress the MRS, which would impart considerable shearing across the entire sample during the motion. This combination of significant shearing and compression may provide enough disruption and lateral movement of the field-induced aggregates to promote the formation of thicker clusters (as observed in the micrographs obtained by Tao and Tang). Finally, it should also be noted that the volume fraction used (30%) tested was smaller than that of Tao, Tang and co-workers (46-50%), but it would be expected that enhancement effects would still manifest themselves at 30%, particularly since the response under compression is essentially governed by the behaviour of gap-spanning structures which would occur at both concentrations.

4. Conclusions

Up to now, most studies of the rheological behaviour of magneto-rheological suspensions have focussed on the response under shearing deformations. However, in many of the engineering applications being developed for this technology, the flow fields are considerably more complex than simple shear, and hence there is a need to characterise the response under a range of deformation geometries. This paper has focussed on the behaviour under a combination of compression in the field direction followed by small shear strains, using a parallel plate rheometer. It was found that the compression, up to compressive strains of 0.05, does not have a significant effect on the solid-like nature of the material (as characterised by the storage modulus). This behaviour is in contrast to recent reports in the literature (Tang *et al.*, 2000; Tao, 2001) which describe dramatic enhancements after compression of the material, measured in a sliding wedge apparatus. The difference could be attributed to the fact that the wedge apparatus imparts considerable shearing deformation to the sample, in addition to the compression. This combined motion in the experiments of Tao and Tang may have assisted in the formation of thicker particle aggregates, leading in turn to enhanced solid-like behaviour under the constant magnetic field.

This study has made clear that the rheological response of MRS clearly depends on not only the current deformation of the sample, but also on the geometry and magnitude of the preceding deformations. The development of a general constitutive framework for these materials thus presents major challenges, but such models would find use in the design of magneto-rheological engineering devices. Experimental studies such these will be complemented by particle-level computer simulations of the formation and break-up of the aggregates under imposed flow fields - these results will reported in the near future.

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