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The performance of magnetorheological fluid in squeeze mode

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Abstract
In magnetorheological (MR) fluid, the rheological properties can be changed in a controlled way, the changes being reversible and dependent on the strength of the magnetic field. The fluids have potentially beneficial applications when placed in various geometrical arrangements. The squeeze mode is a geometrical arrangement where two flat parallel solid surfaces, facing each other, are pushed towards each other by an external force operating at right angles to the surfaces. The liquid initially in the gap between them is free to move away from this increasingly small gap, and it does so by flowing parallel to the surfaces, and collecting in a region where it is no longer in the gap between them. The performance of an MR fluid in compression (squeeze) mode has been studied with the magnetic field being generated by a coil carrying different magnitudes of DC electrical current. A test rig was designed to perform this operation with the flat surfaces being horizontal and being pushed together in a vertical direction and the liquid being forced to move in all directions in a horizontal plane. The rig operated by decreasing the size of the gap at a constant rate. For each trial the current in the coil was kept constant and the instantaneous compressive force was recorded. When plotting compressive stress against compressive strain for each trial, the slope of the curve was found to be larger in general when the current was larger. This was an expected result; however, the behaviour is more complicated than this. For a significant range of values of compressive strain, the slope falls to zero, so that the compressive stress shows no increase during this period while the compressive strain continues to increase. The details of this behaviour are strongly dependent on the initial size of the gap.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

A magnetorheological (MR) fluid is a suspension of micron-sized magnetically soft particles in a carrier liquid, which exhibits dramatic changes in rheological properties. The change from a free-flowing liquid state to a solid-like state is reversible and depends on the presence of a magnetic field. Under the influence of a magnetic field these particles arrange themselves to form very strong chains of 'fluxes' (Hagenbuchle and Liu 1997), with a pole of one particle being attracted to the opposite pole of another particle. Once aligned in this manner, the particles are restrained from moving away from their respective flux lines and act as a barrier preventing the flow of the carrier fluid.

Potential applications of MR fluids have been suggested, especially applications in the automotive industry where benefits could be achieved in parts such as clutches, brakes, dampers and actuators (Jolly *et al* 1999, Huang *et al* 2002, Yoo and Wereley 2002). Most of the researchers assume a geometrical arrangement referred to as shear mode in their design, but they found that the magnitudes of the stress in systems with shear mode geometry are too low to be of

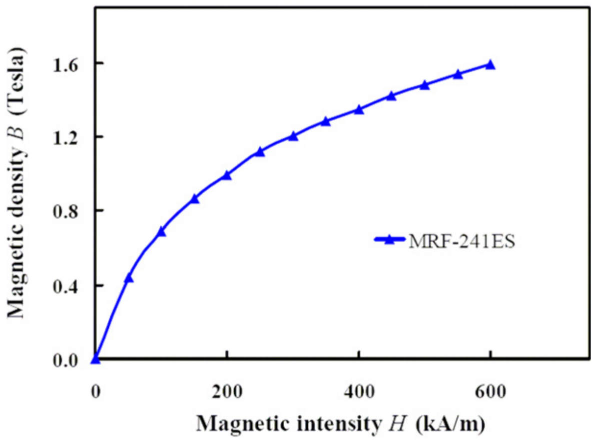


Figure 1. Magnetic induction curve for MRF-241ES.

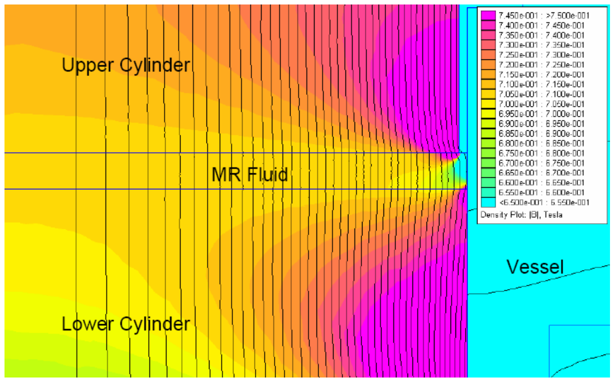


Figure 2. Flux density B taken from the middle half of the test rig (axial symmetric model), which was about 0.7 T on average, distributed evenly inside the MR fluid when 1.6 A of current flows through the coil, and the gap size was set to 2 mm. Two-dimensional flux lines seemed to penetrate the MR fluid and were aligned to the compression direction.

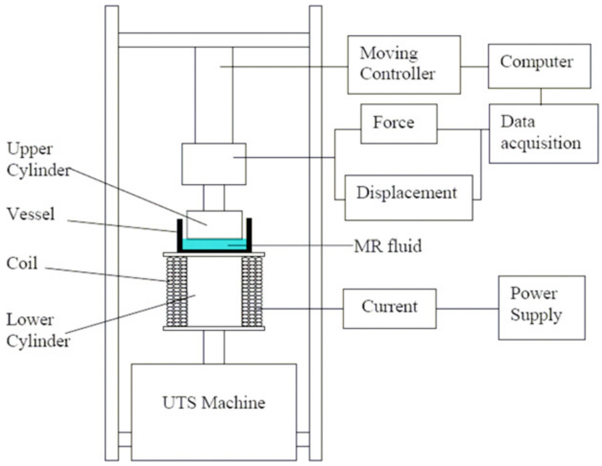


Figure 3. The bottom of the upper cylinder and the bottom of the vessel containing the MR fluid are two parallel surfaces. A measured amount of fluid was sandwiched between these two parallel surfaces, so that the fluid was compressed in a direction normal to these surfaces when the upper cylinder moved towards the bottom of the vessel containing the fluid. All experiments were performed in a displacement control mode.

value in the potential applications listed above. However, the geometrical arrangement designated the squeeze mode can produce compression and tensile stresses which are much higher, and this has generated new interest in this approach. The values of compressive stress are similar to those reported in experimental studies using electrorheological (ER) fluids (Lukkarinen and Kaski 1998, Monkman 1995, Tian *et al* 2002a). Tian *et al* (2002b) have investigated the stepwise compression of fluids containing zeolites and silicones in squeeze mode. They also studied compression starting with different initial gap sizes and under different applied electrical potentials (Tian *et al* 2003).

Despite the fact that MR fluids have been investigated repeatedly in the squeeze mode geometry, many of the studies dealt with controlling vibration for rotor systems. Forte *et al* (2004), Ahn *et al* (2004) and Carmignani *et al* (2006) developed an MR squeeze film damper system for rotor applications. Wang *et al* (2005) investigated the dynamic performance of this system and subsequently (Wang *et al* 2006) analysed the mechanical properties of the film and the unbalanced response characteristics of the MR squeeze film in the damper–rigid rotor system. However, a thorough study of the stress–strain characteristics in compression of MR fluids in squeeze mode is still not complete. This paper presents an experimental investigation of the performance of an MR fluid in squeeze mode under different applied currents and starting with different gap sizes.

2. Design of the magnetic circuit

The main objective of the magnetic circuit design is to produce the correct magnetic flux density across the MR fluid. A length of copper wire with a resistance of 29 Ω was wound around a cylinder, forming 2750 turns, in order to generate a magnetic field. The magnetic behaviour of the equipment was analysed using a finite element method magnetics (FEMM) software package (Meeker 2006). The magnetic properties of the non-magnetic materials were assumed to be linear whereas the properties of magnetic materials such as low carbon steel were assumed to follow the B–H curves given in the software package. An MR fluid of type MRF-241ES (water-based) produced by the Lord Corporation was tested in these experiments (Lord 2007). The typical magnetic properties for this material are shown in figure 1.

An axial symmetric model was selected in the FEMM software package. The magnetic flux density distribution within the fluid is shown in figure 2. The following parameters were used to specify the geometry of the coil: inner diameter = 60 mm, outer diameter = 92 mm, and width = 100 mm. These parameters limit the area in which the copper wire can be wound. The current density was limited to 4 A mm^{-2} in connection with the appropriate wire diameter.

3. Experiment

A schematic diagram of the experimental set-up, similar to that used for studying ER fluid by Tian *et al* (2003), is as shown in figure 3. The diameter of the vessel used to contain

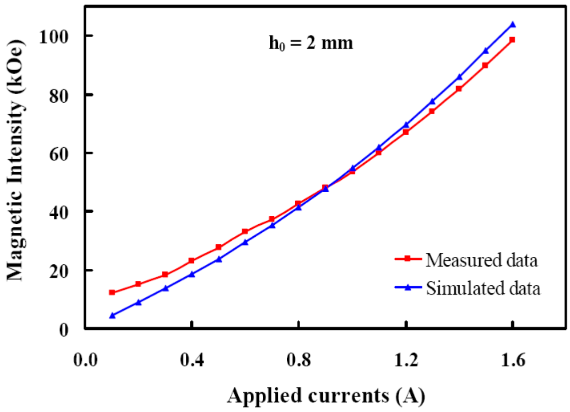
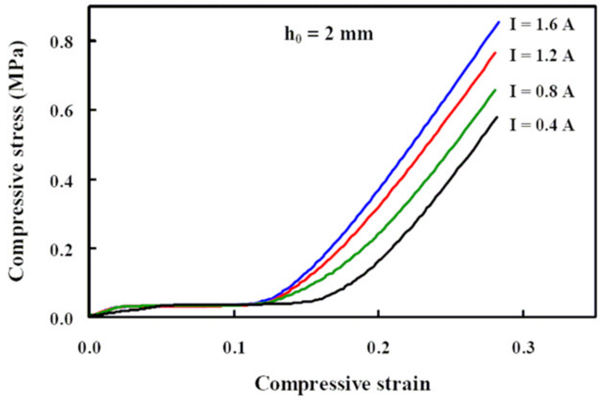
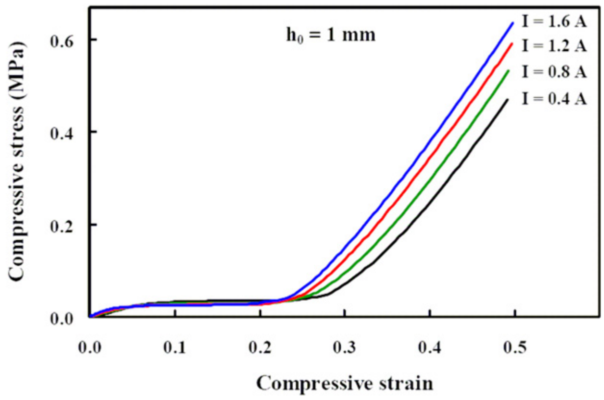


Figure 4. Values of the magnetic field strength obtained by direct measurement and simulation were in good agreement. The magnetic field strength increased when the applied current increased.



(*a*)



(*b*)

Figure 5. Compressive stress versus compressive strain under different applied currents for (a) 2 mm of the initial gap size and (b) 1 mm of the initial gap size.

the MR fluid is a little larger than the diameter of the upper cylinder, so that the gap region remains flooded by the MR fluid throughout the compression. The compression of the MR fluid was carried out by lowering the upper cylinder towards the bottom of the vessel containing the fluid using a computer-controlled movement. Two sets of experimental trials have been carried out. In the first set, the gap size was set initially to 2 mm and different current values (0.4, 0.8, 1.2 and 1.6 A) were maintained throughout the compression trial. Then, the upper cylinder was lowered at a speed of 0.5 mm min^{-1}, which can be considered as quasi-static loading, and the load was recorded continuously. The same procedure was carried out in the second set of experimental trials, except that the initial gap size between the upper cylinder and the bottom of the vessel was set to 1 mm.

A DC magnetometer (gauss-meter) supplied by AlphaLab Inc. was used to validate the results of the FEMM software package for the magnetic field strength generated by the coil. Figure 4 shows the magnitude of the magnetic field strength (oersted) for both the measured and the simulated results at an initial gap size of 2 mm.

4. Results and discussion

The relationship between the compressive stress and the compressive strain under different applied currents is depicted in figures 5(a) and (b). The compressive stress increases with increasing compressive strain.

Applying Kirchhoff's law for magnetic circuits, the number of turns N (in a coil) and the applied current I determine the magnitude of the magnetic field strength H.

$$NI = \oint H\,\mathrm{d}l. \tag{1}$$

In this equation, length l refers to the total length of the whole magnetic circuit and must include not only the length of the lower cylinder around which the coil is wound but also the rest of the magnetic circuit, and most of the flux lines pass through the MR fluid. Therefore, l is also larger if the gap size is large. For the same number of turns, a higher electrical current or a small gap size will result in a greater magnetic field strength.

In view of this one might have expected that a higher compressive stress would occur where the applied magnetic field strength is greatest, but in fact higher values of compressive stresses are required when the initial gap size is set to 2 mm in comparison to the situation when the initial gap size of 1 mm has been set as shown in figure 6. This result emphasizes that the compressive stress of MR fluid is strongly affected by the initial gap size which is similar to that reported by Tian *et al* (2003).

In another observation, for a constant compressive speed of 0.5 mm min^{-1}, the value of the compressive stress increases as the gap closes (figure 7). The curves show greater values of compressive stress as the gap between the two cylinders becomes smaller. However, all the curves show the same values of compressive stress at the beginning of compression until the instantaneous gap size has reached nearly 1.8 mm. Then, the curves show a variation according to the current.

The process of compression of the MR fluid always shows the same three regions. All the curves of compressive stress versus compressive strain show similar characteristics despite the fact that the applied current ranged between 0.4 and 1.6 A and the initial gap size varied between 1 and 2 mm. Figure 8 shows the results for the process of compression at a larger scale. In the first region, the compressive stress increased

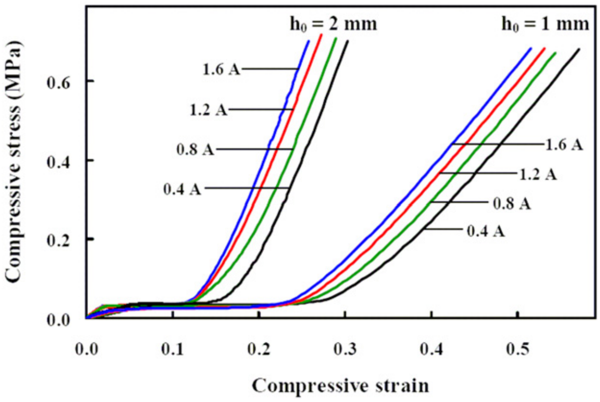


Figure 6. Comparison between two different initial gap sizes (1 and 2 mm) under various applied currents during the process of compression.

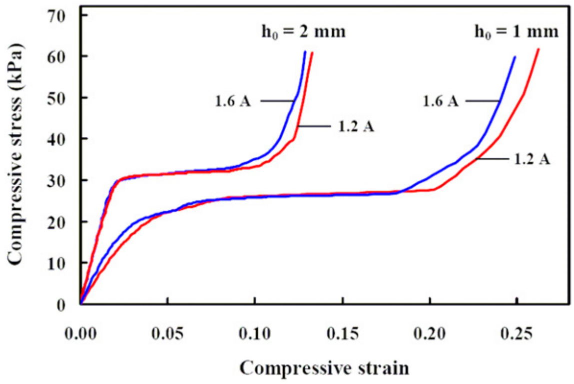


Figure 8. A larger scale of compressive stress versus compressive strain; the applied current and initial gap size were set to 1.2 and 1.6 A, and 1 and 2 mm, respectively.

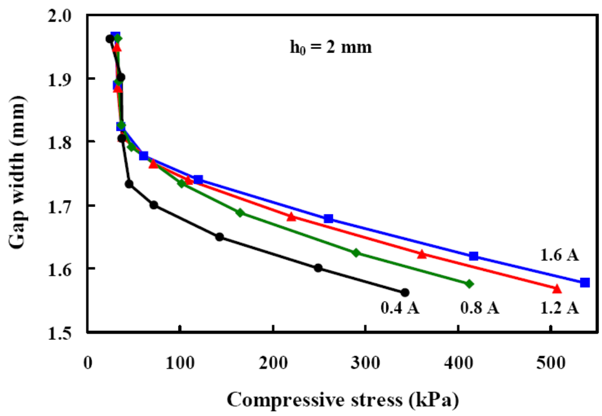


Figure 7. Gap width distances as a function of compressive stress at different applied currents ranging from 0.4 to 1.6 A.

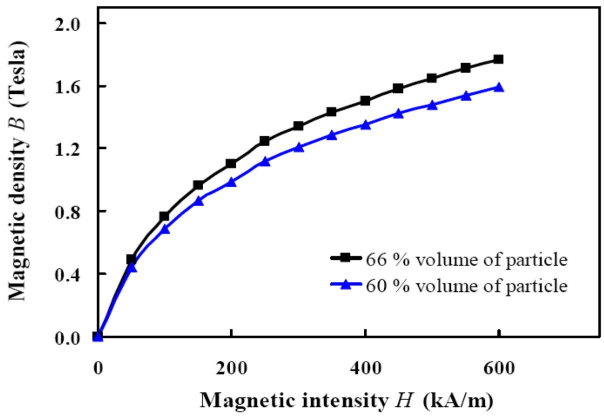


Figure 9. Magnetic induction curves of MR fluid for two different values of iron volume per cent.

gradually with the increase of the compressive strain until it reached nearly 25 kPa and 31 kPa for initial gap sizes of 1 and 2 mm, respectively. Then there is a plateau with the compressive stress remaining constant while the strain increased to values of about 16% ($h_0 = 1$ mm) and 8% ($h_0 = 2$ mm). This phenomenon has not been reported by any previous researchers. In the final region, the compressive stress began to increase again with further increased values of the compressive strain.

Some aspects of these regions can be explained by assuming that there is relative movement between the particles and the carrier liquid in the MR fluid. During the compression, while the liquid is being expelled, the solid particles, being magnetic, are assumed to be able to resist this expulsion to some extent. Therefore the volume fraction of the particle is assumed to increase because only the carrier liquid is being expelled. Now if this is true, the magnetic properties of the MR fluid will change as a result of this change in composition.

An assumption has been made by other researchers concerning this change in magnetic properties. It is that the magnetic permeability is directly proportional to the volume fraction of the magnetic particles in the fluid (Simon *et al* 2001, Jolly *et al* 1999). The volume fraction can be calculated as follows:

$$\%\ \text{Volume of particles} = \frac{[w/\rho]_{\text{particles}}}{[w/\rho]_{\text{water}} + [w/\rho]_{\text{particles}}} \times 100 \tag{2}$$

where w is the weight per cent and ρ is the density of the two fractions, the particles and the carrier fluid. The carrier fluid is assumed to have the same density as water (1 g cm^{-3}) and the density of the particles is given as 3.86 g cm^{-3} (Lord 2007).

Initially the weight per cent of the particles and the carrier fluid were 85% and 15%, respectively, and therefore the volume per cent of the particles can be calculated to have been 59.48%. Now if the initial gap size is 2 mm, after the gap has decreased by 0.2 mm there will be a change in the volume of the MR fluid of 10%. If it is assumed that this change in volume is due to the expulsion of carrier fluid alone, and that there is no change in the volume of the particles, the new value of the volume fraction of the particles can be calculated. It is 66.09%.

Using the same assumption that other researchers have made, namely that the magnetic permeability is proportional to the volume fraction of particles, values for the flux density for different values of the magnetic field strength can now be calculated. This is illustrated in figure 9 where the example is given of a change in volume fraction from 60% to 66%.

(The magnetic field strength will, itself, be increasing as the gap decreases, as explained in an earlier section of this discussion.)

It may also be assumed that the greater the flux density, the greater the tendency will be for the magnetic particles to arrange themselves along the lines of magnetic flux, and to form greater resistance to the movement of the carrier fluid. As a result, a greater compressive stress will be required to maintain the constant compressive strain rate. This mechanism therefore helps to explain why the compressive stress increases so sharply in the third region of the stress–strain relationship.

It is equally true, of course, that as the volume fraction of particles increases, there will be an increase in the fluid's viscosity. For a concentrated suspension of solids, empirical data suggest the relationship (Shook 1993):

$$\frac{\mu_{\text{suspension}}}{\mu_{\text{pure-liquid}}} = \frac{1}{(1-\phi)^{\frac{5}{2}}} \tag{3}$$

where ϕ is the volume fraction of particles.

This formula predicts that the viscosity will increase 1.561 times when the volume fraction increases from 59.48% to 66.09%. Because of this higher viscosity, there will be an increase in the fluid's resistance to flow. It would suggest that much higher forces are needed to cause the liquid to flow as the volume fraction increases, and, in turn, this helps to explain why the compressive stress increases so sharply in the third region of the stress–strain relationship.

Other workers have also postulated that at very high volume fractions, as the value approaches the maximum packing density of the solids, there may be a tendency for the particles to agglomerate, trapping some of the carrier fluid and reducing the effective volume for the movement of the 'free' carrier fluid. If this occurs, the result would be further resistance to the flow, and even higher compressive stress would be required to overcome this resistance, which has to occur in the system where a constant strain rate is maintained.

All of these mechanisms help to explain why in the third region there is a very steep slope in the compressive stress versus the compressive strain relationship. They also help to explain why the slope is even steeper when the magnetic field strength is high, because the volume fraction is likely to increase more rapidly under these conditions.

5. Conclusion

Stress–strain relationships were obtained for a water-based MR fluid in squeeze mode using compression test equipment. The results are presented starting with different gap sizes and using different electrical currents to generate magnetic fields. They reveal that high values of compressive stress occur where the compressive strain is high, and that even higher values are obtained when the electrical current is high. Furthermore, the magnitude of the compressive stress, for a given compressive strain, depends on the initial gap size. Curves showing the relationship between compressive stress and compressive strain were constructed for two different initial gap sizes, and it can be seen that for the larger initial gap size there are larger compressive stress values. The curves can be divided into three different regions, because distinct characteristics of the relationship between stress and strain change as the process is carried out. Whereas in the first and third regions the compressive stress increases as the compressive strain increases, in the second region the compressive stress remains almost constant as the compressive strain increases. In the first two regions the compressive stress seems to be almost independent of the size of the electrical current generating the magnetic field, but in the third region higher values of compressive stress occurred when the electrical currents were highest. The sizes of the three regions depend on the initial gap sizes. Some aspects of the phenomenon can be explained by assuming that when the squeeze mode operates to cause the fluid to move, the liquid carrier moves to a greater extent than the solid particles, which are restricted from movement by the magnetic field.

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