Key Engineering Materials Vol. 495 (2012) pp 285-288
Online available since 2011/Nov/15 at www.scientific.net

doi:10.4028/www.scientific.net/KEM.495.285

An Experimental Investigation of Magnetorheological (MR) Fluids under Quasi-Static Loadings

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Keywords: Test Equipment, Magnetic Simulation, Magnetorheological Fluids, Squeeze Mode

Abstract. In our earlier work, test equipment has been designed, simulated and fabricated to perform experiment on MR fluids in squeeze mode. Preliminary results were gathered and presented for the purpose of validating the test equipment. Therefore, in this paper, a further systematic investigation of MR fluids in squeeze mode has been carried out. As a result, MR fluids experienced rheological changes in three stages during compression and tension. Fluid-particles separation phenomenon was the main caused for the unique behaviour of MR fluids. Particle chains depended on the structure transformation in which the carrier fluid movement can be controlled by changing the magnetic field strength.

Introduction

Magnetorheological (MR) fluids in squeeze mode are capable to produce the highest stresses among other working modes; shear and flow. There are many type of applications that can be developed for utilizing the advantages of low amplitudes and high stresses [1]. Comparable with electrorheological (ER) fluid, Stanway et al. have employed the squeeze mode in their work and discovered that the stress produced under squeeze was much higher than shear stress [2]. The finding was supported by Monkman in his research about ER effect under compressive stress [3]. Consequently, the interest of MR fluids in squeeze mode with accredited to ER fluids need to be performed.

Farjoud et al. conducted modelling and testing MR fluids in squeeze mode in order to enhance the idea for designing MR devices [4]. They managed to construct rheometer that useful for testing MR fluids behaviour with different parameters. The results indicated that during the squeezing process of MR fluid, a clumping effect was observed in which depended on magnetic field strength. Our previous experimental study, which was involved design, simulation and testing led to preliminary results of MR fluids behaviour in squeeze mode under quasi-static loadings [5]. Accordingly, a thorough and systematic investigation has to be performed in order to obtain more reliable data. Therefore, this paper presents an extending work with more establish results and discussions on some of the factors that influenced the behaviour of MR fluids.

Experimental Procedures

In this paper, methodological aspect of the experiment such as designing test equipment, magnetic simulation, MR fluids selection and test procedures were referred to our previous work [5]. The main parts of the design consisted of upper, lower and support cylinders as shown in Fig. 1. A type of magnetic material (AISI 1020 low carbon steel) was utilized to make the upper and lower cylinders, while combination of magnetic and non-magnetic materials (AISI 304 stainless steel) were utilized to make the support cylinder. An electromagnetic coil was made from 22SWG copper wire with 2750 turns. Magnetic simulation was carried out on test equipment using finite element method magnetics (FEMM) that depended on the input data such as materials selection, type of coil, number of coil turns and current values. MR fluids that used in this study were MRF-241ES, MRF-132DG and MRF-122-2ED. Compression and tension tests were done on each MR fluid with three process parameters such as initial gap distance, upper cylinder's speeds and currents.

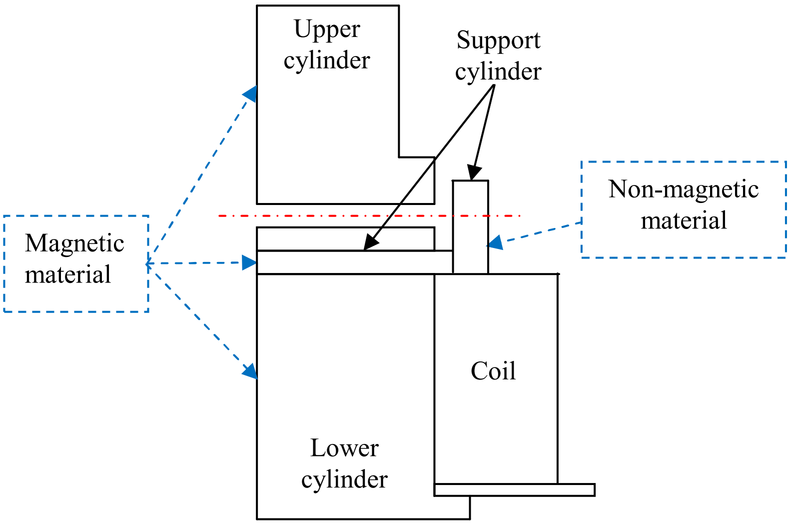


***Fig. 1**. Sketch of middle half of test equipment configuration.*

Results and Discussions

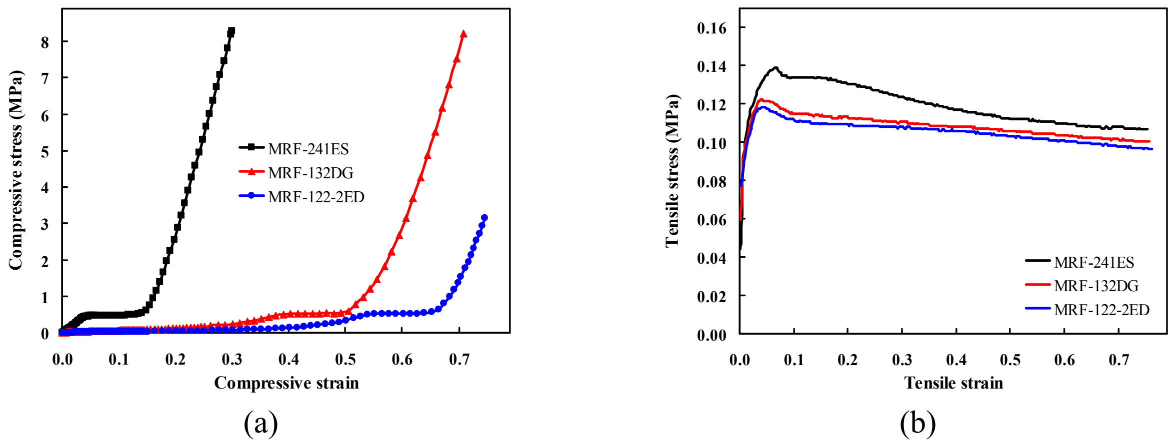
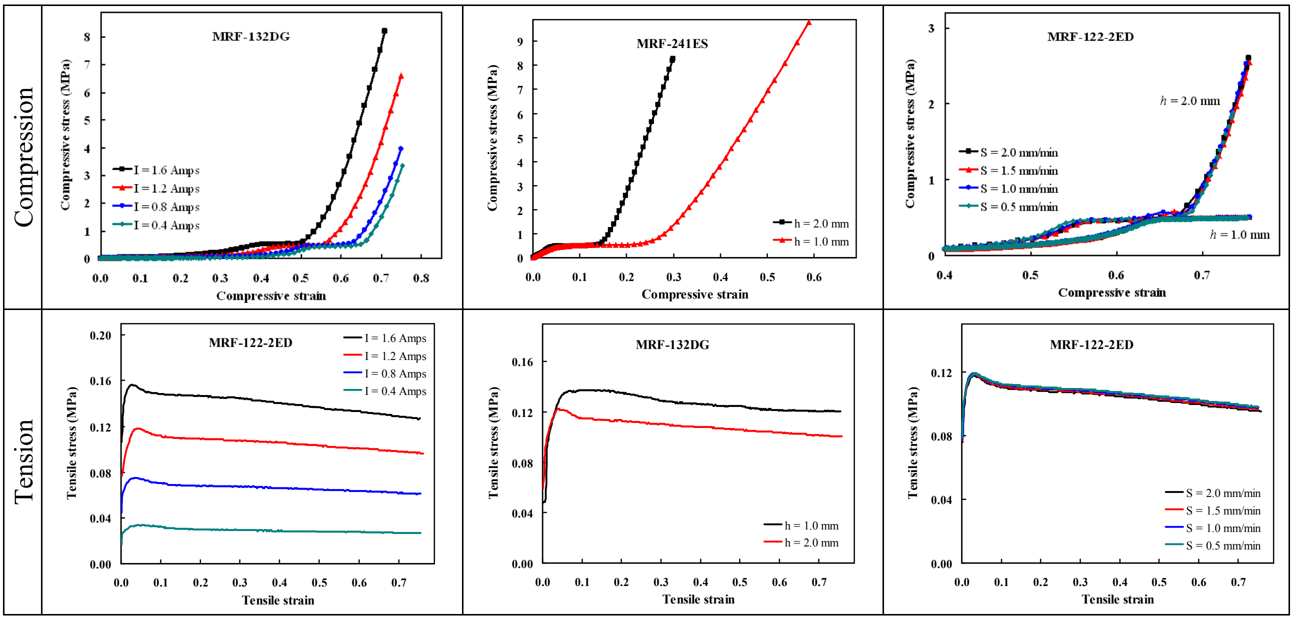


***Fig 2**. Stress-strain relationships of MR fluids under (a) compression [6] and (b) tension [8].*

MR fluids behaviour under compression. Fig. 2(a) shows stress-strain relationships that been obtained from compression test equipment for MR fluids. The compressive stresses at the initial compression were increased with increasing compressive strains. Then the stresses tended to stabilize for certain values of strains. Later, the stresses increased again with higher values of stresses and strains. Basically three steps of compression were involved in the process [6]. At the first step, magnetic particles and carrier fluid inside the MR fluids were acted together as one material like alloy or composite. Therefore the curves obtained were quite similar to any solid material under compression. Then at the second step, the combination of magnetic particles and carrier fluid started to separate [7], where the carrier fluid moved out and left the particles inside the compression area. The curves at this step resembled the whole process between the interaction of both materials to withstand the forces and at the same time, the movement of carrier fluid. After that, a new structure contained of particles have a better resistance to the compression forces in which represented the curves at the third step.

MR fluids behaviour under tension. Fig. 2(b) shows stress-strain relationships that obtained for MR fluids under tension loadings. Three steps of curves pattern were involved in the process [8]. The tensile stresses at the initial tension process were increased with the increased of strains until the curves reached peak points. Then the stresses decreased rapidly at the second step before further decreased slowly at the third step. Movement between the particles and carrier fluid played an important role to the stress-strain relationships of MR fluids. At the first step, magnetic particles and carrier fluid inside the MR fluids were acted together as described in the compression process. During the process, the MR fluids acted as solid materials and their behaviour were mostly like solid materials. Then at the second step, the same situation as in compression occurred, where the carrier fluid flew out. The curves at this step decreased because of the broken chains between the particles and carrier fluid. After that, a new structure contained of particles behaved like ductile materials under tension.



(a) (b) (c)

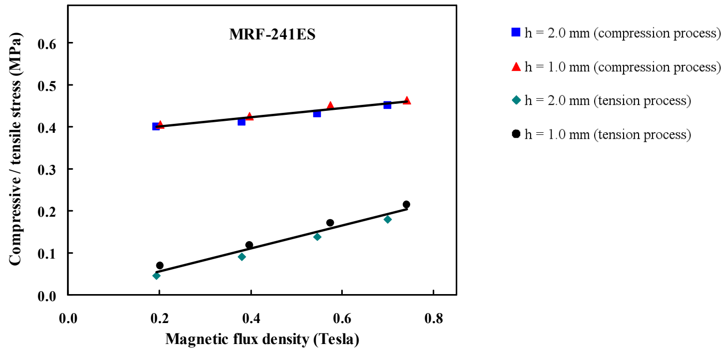
Fig. 3. *Effects of the (a) applied currents, (b) initial gap distances and (c) comprssive/tensile speeds on the MR fluids.*

Effects of various factors on the MR fluids. Fig. 3 shows the best effects of applied current, initial gap distances and speeds on selected MR fluids. Higher values of applied current have generated higher magnitude of magnetic field strengths [6,9]. Therefore, higher stresses were needed during the compression/tension processes with stronger magnetic fields as shown in Fig. 3(a). Higher stresses were also obtained from the bigger initial gap distance as shown in Fig. 3(b). More MR fluids could be filled at bigger initial gap distances in which resulting more volume fraction of particles at that area. Thus, the effect of initial gap distance became more obvious when the particles were left alone at the third step of compression/tension. Contrary to the effects of applied current and initial gap distance, compressive/tensile speeds produced a little impact on MR fluids. Consequently, both compression and tension processes have showed the same effects, where stresses were depended on higher values of applied current and bigger values of initial gap distances in terms of stress-strain relationships. However, the effect of compressive and tensile speeds on MR fluids were very small.

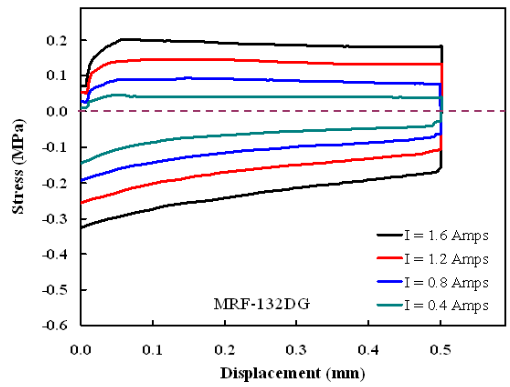
Comparison between compressive and tensile stresses of the MR fluids. The relationships between the stresses and the magnetic flux density at the first step as shown in Fig. 4(a) were described a general linear equation as follow

$$\sigma_y = kB + \sigma_{min} \tag{1}$$

where σ_y is the maximum value of compressive or tensile stress at the first step (MPa), k is the constant value (MPa/Tesla), B is the magnetic flux density (Tesla) and σ_{min} is the value of the compressive or tensile stress at zero magnetic flux density. The compressive stress was much higher than tensile stress at the first step because of the interaction between the particles and carrier fluid was higher during the compression. However, the combination of compressive and tensile stresses with referred to the same magnitude of dispacement (Fig. 4(b)), was likely a dynamic stress-strain pattern. This result showed that investigation on quasi-static loading could produce more details result as compared with dynamic loading.



(a)



(b)

***Fig. 4**. (a) Compressive and tensile stresses versus magnetic flux density of MRF-241ES and (b) combination of compressive and tensile stresses of MRF-132DG.*

Conclusion

Magnetorheological (MR) fluids have a unique characteristic in which its rheological properties can be changed and controlled by adjusting magnetic field strength. In conjunction with its special characteristic, a systematic investigation on MR fluids under quasi-static loadings was carried out. The stress-strain pattern of MR fluids was involved three steps of either compression or tension, where the increament on the volume fraction of particles contributed to the each step. Various parameters have been given to the MR fluids in order to obtain optimum stresses. However, two of the parameters; applied current and initial gap distances, have showed significant effects to the MR fluids. While compressive/tensile speed was apparently not influenced the MR fluids characteristic. Finally, both compression and tension processes were compared at the first step, and matched the stresses from quasi-static loadings to dynamic loadings.

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