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Fabrication and characterisation of patterned magnetorheological elastomers

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Keywords

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Fabrication and Characterisation of Patterned Magnetorheological Elastomers

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Abstract. Magnetorheological elastomers (MREs) are composites that highly elastic polymer matrices are filled with magnetic particles. These materials exhibit unique characteristics that their modului can be controlled by an external magnetic field. This paper presents analysis, fabrication and characterization of novel patterned MREs. By taking into account the local magnetic field in MREs and particles' interaction magnetic energy, the magnetic field-dependent mechanical properties of MREs with lattice and BCC structures were theoretically analyzed and numerically simulated. Soft magnetic particles were assembled in polydimethylsioxane matrix to fabricate new MREs with uniformly lattice and BCC structures, which were observed by microscope. The field-dependent modulus of the new MREs was characterized by a parallel-plate rheometer. The experimental results agreed well with numerical simulations.

Keywords: magnetorheological elastomers, field-dependent modulus, microstructures.
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INTRODUCTION

Magnetorheological (MR) materials, including MR fluids, MR foams and MR elastomers, are an important branch of smart materials [1]. For the past two decades, MR fluids have obtained considerable attractions and a variety of applications have been reported [2-5]. MREs are composites that highly elastic polymer matrices are filled with magnetic particles. MREs and MR fluids have similar field response properties; however, there are some distinct differences in operating these two classes of materials. The most noteworthy is that MREs operate within the pre-yield regime while MR fluids typically operate in a post-yield continuous shear or flow regime. In other words, the 'strength' of MR fluids is characteristised by the yield stress while MREs are characterized by field dependent modulus. In the view of applications, MREs devices are used to adjust the nature frequency of a structure, which is dominated by the equivalent stiffness; while MR fluids devices provide damping function, which is the process of dissipating energy. Therefore, these two materials are complementary rather than competitive. Recently, MREs have found a lot of applications, such as vibration absorbers, engine mounts, and variable impedance surfaces [6, 7].

In literature, both anisotropic [8, 9] and isotropic [10,11] MREs were fabricated and their mechanical properties have been investigated analytically and experimentally. In analyzing the field-dependent modulus of MREs, a number of models were proposed based on the analysis of the dipole model for particle energy interaction. Jolly *et al.* [12] presented a point-dipole model, where the MR effect was studied as a function of particle magnetization. This model was borrowed from the previous studies on MR fluids. Davis [13] calculated the shear increment by using finite element analysis, which was for isolated single chains of periodically spaced dipoles. Shen *et al.* [14] fabricated MREs with polyurethane and natural rubber matrix and presented a mathematical model to represent the stress–strain relationship of MRE. This model takes into account all the dipole interactions in a chain. Zhang *et al.* [15] proposed a model considering the local field. It is noted that these modeling studies are based on the assumption that MREs only have simple chain structure, where all particles are located within chains. There are very few reports in discussing the influence of other chains and in predicting the field-dependent properties with other complex structures. It may be due to the fact that it is difficult to find an effective fabrication technique in developing MREs with precisely controlled structures. Also, the modeling approach on the field-dependent properties of MREs with complex structures is very rare.

This paper consists of two major parts. The first is to theoretically analyze the field-dependent properties of MREs with a pre-designed structure. The second part is to fabricate MREs with pre-designed structures by using micro technology and to characterize their field-dependent mechanical properties.

THE SIMULATION ANALYSIS OF PATTERNED MRE

A lattice structure based MRE consisting m layers is proposed to introduce the simulation approach in figure 1. In each layer the distances of particles in three directions are *dx*, *dy* and *dz*, respectively. The local magnetic field was firstly calculated, which is induced by the external magnetic field as well as the dipole fields from all the magnetized particles. Then the interaction energy of a particle with all others particles in the structure was represented.

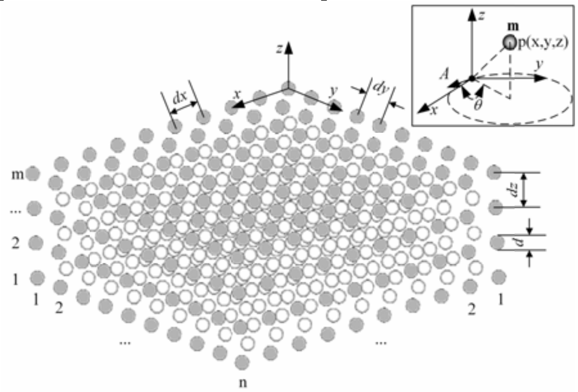

FIGURE 1. Schematic of the MREs with a lattice structure and the magnetic field induced by a dipole.

Local Magnetic Field And Magnetic Dipole

When a magnetic field H_0 is applied, the magnetic dipole moment induced on a particle is:

$$\mathbf{m}_i = 3\frac{\mu_p-\mu_m}{\mu_p+2\mu_m}V_p H_{loc} \quad (1)$$

where μ_p and μ_m are the relative permeabilities of particles and medium, respectively; V_p is the volume of particle. The local magnetic field H_{loc} is given by

$$H_{loc} = H_0 + H_p \quad (2)$$

where H_0 is initial magnetic field and H_p is magnetic field caused by dipole moment of all particles.

Suppose that in figure 1 magnetic field is applied in the direction of Z axis and all the magnetizable particles have been magnetized as dipoles. A magnetic vector potential A at the zero point induced by the magnetic dipole moment $\mathbf{m}$ at the position P (x, y, z) can be expressed as:

$$A_x = A\sin\theta = \frac{\mu_0}{4\pi}\cdot\frac{y}{(x^2+y^2+z^2)^{3/2}}|\mathbf{m}|$$
$$A_y = -A\cos\theta = \frac{\mu_0}{4\pi}\cdot\frac{-x}{(x^2+y^2+z^2)^{3/2}}|\mathbf{m}|$$
$$A_z = 0 \quad (3)$$

Where $\sin\theta = y/\sqrt{x^2+y^2}$, $\cos\theta = x/\sqrt{x^2+y^2}$.

For $B = \nabla\times A$

$$B_x = \frac{\mu_0}{4\pi}\cdot\frac{-3xy}{(x^2+y^2+z^2)^{5/2}}|\mathbf{m}|$$
$$B_y = \frac{\mu_0}{4\pi}\cdot\frac{-3yz}{(x^2+y^2+z^2)^{5/2}}|\mathbf{m}|$$
$$B_z = \frac{\mu_0}{4\pi}\cdot\frac{x^2+y^2+2z^2}{(x^2+y^2+z^2)^{5/2}}|\mathbf{m}|$$
$$(4)$$

$B=B_x i+ B_y j + B_z k$ and $H_p = \sum_{i=1}^{\infty}\frac{B_i}{\mu_0}D\mathbf{m}$ where B_i is the magnetic flux density induced by the dipole i. D is the influence factor calculated with the simulation.

The magnetic dipole moment on a particle is

$$\mathbf{m}_i = \frac{3\beta V_p}{1-3D\beta V_p}H_0 \quad (5)$$

where $\beta=(\mu_p-\mu_m)/(\mu_p+2\mu_m)$.

Interaction Energy Of Particles And Field-Dependent Modulus

The interaction energy of two dipoles $\mathbf{m}_1$ and $\mathbf{m}_2$ can be expressed as:

$$E_{12} = \frac{\mu_0\mu_m}{4\pi}\left(\frac{\mathbf{m_1}\cdot\mathbf{m_2}}{r^3} - \frac{3}{r^5}(\mathbf{m_1}\cdot\mathbf{r})(\mathbf{m_2}\cdot\mathbf{r})\right) \quad (6)$$

Assuming one dipole is located at the zero point, and the other dipole is located at the position (x, y, z), the interaction energy of the two dipoles with equal strength $\mathbf{m}$ and direction is

$$E_{12} = \frac{\mu_0\mu_m|\mathbf{m}|^2}{4\pi}\left(\frac{1-3\cos^2\varphi}{|r|^3}\right) = \frac{|\mathbf{m}|^2(1-3\frac{z^2}{x^2+y^2+z^2})}{4\pi\mu_0\mu_m(x^2+y^2+z^2)^{3/2}} \quad (7)$$

For the particle at the coordinate origin, its interaction energy with all the particles is

$$E = \sum_{i=1}^{\infty}\frac{\mu_0\mu_m|\mathbf{m}|^2(1-3\frac{{z_i}^2}{{x_i}^2+{y_i}^2+{z_i}^2})}{4\pi({x_i}^2+{y_i}^2+{z_i}^2)^{3/2}} \quad (8)$$

When the particles are moved in the X-Y plane (The magnetic field direction is along with Z axis), the interaction energy can be written as

$$E = \sum_{i=1}\frac{\mu_0\mu_m|\mathbf{m}|^2((x_i+\Delta x_i)^2+(y_i+\Delta y_i)^2-2{z_i}^2)}{4\pi((x_i+\Delta x_i)^2+(y_i+\Delta y_i)^2+{z_i}^2)^{5/2}} \quad (9)$$

In this paper, only the simple shear in x direction has been deduced, because the deduction of a 3D shear is too complex in this case. However, for an isotropic structure, the x, y axis shears have the same behaviors. The shear force in any other direction is the combination of the one direction shears in x, y axis. By defining the scalar shear strain of the particle chain as $\varepsilon = \Delta x/z$, i.e. the shear direction is in the x axis, the modulus induced by the application of a magnetic field can be computed by taking the derivative of inter-particle energy density with respect to the scalar shear strain and divided by the shear strain.

$$\Delta G = \sum_{i=1}^{\infty}\frac{3\mu_0\mu_m|\mathbf{m}|^2 z(x_i+\varepsilon z_i)(4z^2-{x_i}^2-2x_i\varepsilon z_i-\varepsilon^2{z_i}^2-{y_i}^2)}{4\pi\varepsilon({x_i}^2+2x_i\varepsilon z_i+\varepsilon^2{z_i}^2+{y_i}^2+z^2)^{7/2}V_{unit}}$$
$$(10)$$

where V_{unit} is the unit volume of the structure with one particle. For example, the lattice structure has the $V_{unit} = dx \cdot dy \cdot dz$, as shown in figure 1.

The Fabrication Of Patterned MREs

In this work, polydimethylsiloxane (PDMS) (Dow corning 184) material and pure iron balls (Shenzhen Universal Ball Manufacturing Co. China) were used as a matrix and dispersed particles, respectively.

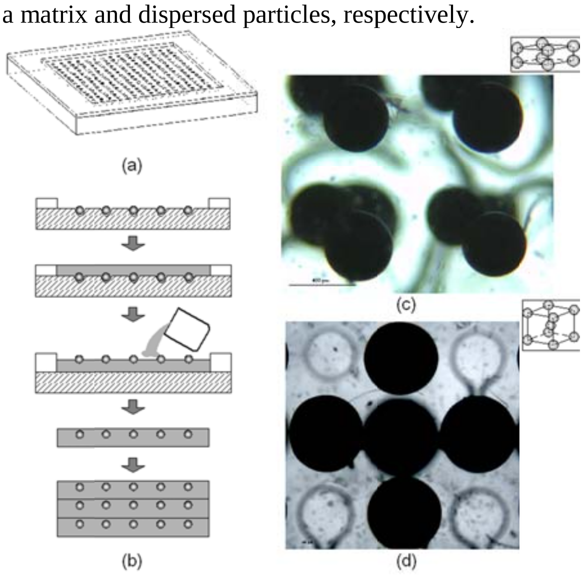

FIGURE 2. The fabrication process and structures of patterned MREs. (a) patterned mould; (b) fabrication steps; (c) lattice structure; (d) BCC structure.

A patterned mould was prepared at first (figure 2a), which is a methyl-methacrylate board with regular holes etched by laser. Pure iron balls were filled into holes and then a thin layer of PDMS was located on the mould's top surface to fix particles position. After PDMS is cured, the thin layer embedded with patterned magnetic iron particles was taken off from mould. Then several layers were overlapped according to designed position and thickness, and fill the gap with PDMS and remove air bubbles in a vacuum. Finally patterned MRE was cured in constant temperature oven (figure 2b). By using different moulds and overlapping positions, different structures of MREs can be obtained, such as lattice chain, Body Center Cubic (BCC).

Two categories of structures were fabricated in this study, as the lattice structure sample and BCC structure sample (figure 2c & 2d). The photos taken by Leica DFC280 Microscope show that the particles are dispersed on the layer regularly. The diameter of the iron ball in sample one is 400 um, the distances between particles in plane and that in thickness direction are 800 um and 480 um, respectively. Three layers are prepared in the thickness direction. The parameters in sample two are 800 um, 1000 um and 1000 um, respectively.

RESULTS AND DISCUSSIONS

The MR effect of patterned MRE was evaluated by measuring the shear modulus with and without an applied magnetic field using a Rheometer (MRD 180, Anton Paar Companies, Germany), equipped with an electromagnet kit. The rubber segments were sandwiched between a rotary disk and a base.

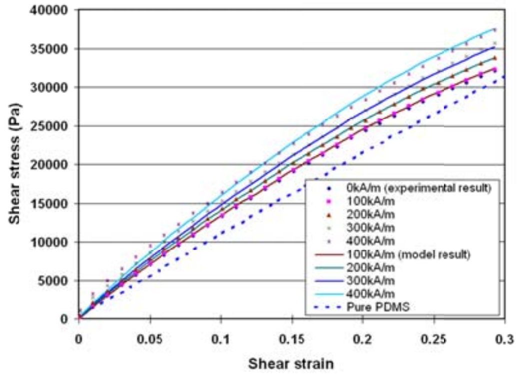

FIGURE 3. The strain stress curve of lattice structural MRE at different magnetic field: simulation and experimental results.

The Quasi-Static shear mode was employed to evaluate the shear modulus of MRE. Figure 3 shows the strain-stress curves of the lattice structural MRE sample at 5 different magnetic field intensities of 0, 100, 200, 300 and 400kA/m, respectively. The modulus of MREs shows an increasing trend with magnetic fields. The shear stress in the figures is looked as the combination of elastic stress and field induced stress of MRE. The simulation result is obtained by the program and the parameters of the sample. Obviously, the model prediction agreed well with experimental results.

For a chainlike structure based MRE, the optimum volume fraction of iron particles was predicted to be 27% and the relative change in modulus due to a large magnetic field was 50% [7]. However, our sample has a relatively low modulus increment of 18% in a magnetic field of 400 kA/m. This is mainly due to the fact that the sample has a low particle volume fraction of 11%. To improve the field induced modulus, the volume fraction of particle must be increased.

The field-dependent modulus change of BCC based MRE was calculated by Eqn (10). In contract to the lattice structure MRE, the BCC based MRE shows a decreasing trend with magnetic field (figure 4). For example, the modulus change at 300 kA/m is about two orders higher than that at 100 kA/m. This finding is very interesting as it may provide a concept to develop "negative" MREs, which are expected to wide potential applications of MREs in special conditions. Also, the field-dependent modulus change increases steadily with the rise of particle volume fraction. To verify the simulation analysis, steady shear experiments were conducted and the results were shown in figure 5, where modulus shows a slightly decreasing trend with a magnetic field. It should be noted that the modulus change is not very notable, the reason of which are due to the low particle volume fraction and the high matrix modulus. It is noted that the fabricated BCC MREs have limited applications because of it narrow modulus changes. However, these results might provide concepts to develop other new MREs with controllable mechanical properties by designing special patterned structures.

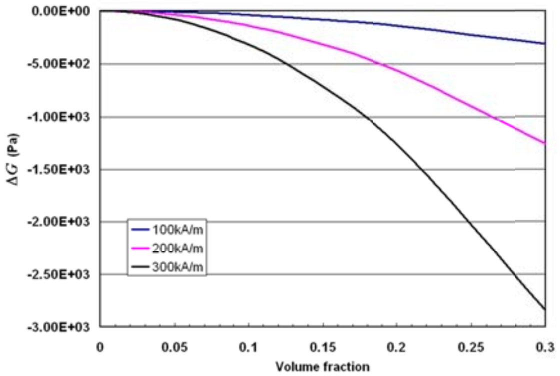

FIGURE 4. The relationship between the field-reduced modulus and particle's volume fraction in BCC MR elastomer

CONCLUSIONS

In this paper, two new MR elastomers, with a lattice structure and a BCC structure, were fabricated by precisely positioning iron particles in PDMS matrix. Both the MRE samples consist of three layers. The layer thickness is 480μm, the particle distances in each layer are 800μm. The particle volume fraction of the MRE samples is about 11%.

The field-dependent mechanical properties of the patterned MRE were investigated both numerically and experimentally. In numerical analysis, a quasi-static model that examines the effects of magnetic field was presented. This model takes into account the dipole interactions caused by all the dipoles, including the local field induced by all the particles and the interaction energy of all the particles. In experimental approach, the field-dependent modulus was measured under steady shear by a parallel-plate rheometer. For the MRE sample with lattice structure, the relative modulus increment is about 18% at a magnetic field of 400 kA/m. The comparison between experimental results and model-predictions indicates that the model could precisely predict material performances. For the MRE sample with a BCC structure, the field-induced modulus shows a decreasing trend with magnetic field, which was never been reported. This study is expected to design and develop novel field controlled MREs with pre-designed structures.

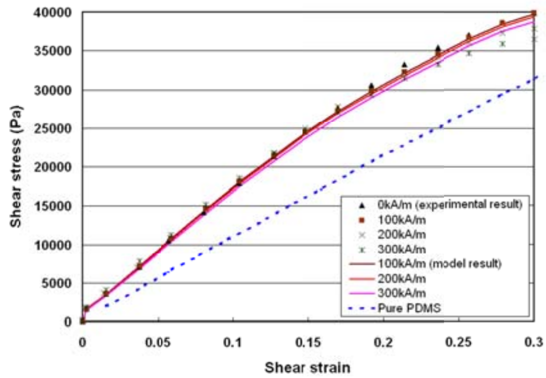

FIGURE 5. The relationship between the shear stress and strain in BCC MR elastomer

REFERENCES

1. J. D. Carlson and M. R. Jolly, *Mechatronics*, **10**, 555–569 (2000).
2. Q. Nguyen *et al.*, *Smart Mater. Struct.*, **16**, 2242-2252 (2007).
3. W. H. Li *et al.*, *Smart Mater. Struct.* **9**, 95-102 (2000).
4. B. Liu *et al.*, *Smart Mater. Struct.*, **15**, 1960-1966 (2006).
5. Q. Nguyen, S. Choi and N. M. Wereley, *Smart Mater. Struct.*, **17**, 025024 (2008).
6. D. York, X. Wang and F. Gordaninejad, *J. Int. Mat. Syst. Str.*, **18**, 1221-1225 (2007).
7. H. Deng, X. Gong and L. Wang, *Smart Mater. Struct.,* **15**, 111–116 (2006).
8. C. Bellan and G. Bossis, *Int. J. Mod. Phys. B*, **16**, 2447–2453 (2002).
9. G. Y. Zhou, *Smart Mater. Struct.* **12**, 139-146, (2003).
10. M. Lokander and B. Stenberg, *Polym. Test.*, **22**, 677–680 (2003).
11. X. L. Gong, X. Z. Zhang and P. Q. Zhang, *Polym. Test.*, **24**, 669-676 (2005).
12. M. R. Jolly, J. D. Carlson and B. C. Munoz, *Smart Mater. Struct.,* **5**, 607-614 (1996).
13. L. C. Davis, *J. Appl. Phys.*, **85**, 3348-3351 (1999).
14. Y. Shen, M. F. Golnaraghi and G. R. Heppler, *J. Intel. Mat. Syst. Str.*, **15**, 27-35 (2004).
15. X. Z. Zhang *et al. J. Appl. Phys.*, **96**, 2359-2364 (2004).