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Influence of shear deformation on the normal force of magnetorheological elastomer

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ABSTRACT

The influence of shear deformation on the normal force of magnetorheological elastomer was investigated. In quasi-static shear, the normal force decreases with increasing shear strain at low magnetic field, while increases with increasing shear strain when the magnetic field exceeds 452 mT. In oscillatory shear, the normal force shows similar trend. However, it decreases sharply when the strain amplitude exceeds 7%. A microstructure based theory was proposed to investigate this phenomenon. Under shearing, the elastic modulus decreases while the magnetic torque increases, which lead to the different trends of normal force at different magnetic fields. This mechanism agrees well with the experimental results.

1. Introduction

Magnetorheological elastomer (MRE), analog of magnetorheological fluid (MRF), is a kind of composite consisting of micro-sized ferromagnetic particles embedded in nonmagnetic rubber or rubber-like matrix. Due to the controllable properties in the external magnetic field, MRE has been widely used in various applications [1–6].

In the past decade, most researches focused on the shear property of MRE [7,8]. However, with the gradually wider application of MRE, the normal property of MRE has attracted more and more attentions [8–10]. In most MRE based devices, the MRE often works in the shear-compression status [11,12]. Additionally, both the shear property and the normal force result from the interactions between the particles and the interactions between the particles and the matrix. The similar mechanism may lead to some links between the normal force and the shear property, which is necessary for the design of MRE based devices.

In this study, the influence of shear deformation on the normal force of MRE was investigated under both quasi-static shear and oscillatory shear. A theoretical model was proposed to explain the phenomenon qualitatively.

2. Materials and experiment

MRE fabrication: The MRE samples were fabricated with carbonyl iron particles (Type CN, with the average diameter of 6 μm, from BASF Co., Germany), HTV silicone rubber (Type: MVQ 110-2, from Dong Jue Fine Chemicals Nanjing Co. Ltd), vulcanizing agent (double methyl double benzoyl hexane, from Shenzhen Gujia Co.), and Di-(2-ethylhexyl) phthalate (from Shanghai resin factory Co. Ltd.). The MRE samples were cured under a magnetic field of 1.5 T parallel to the thickness direction of the samples. The mass ratio of the iron particles was 80% and the thickness of the sample was 1 mm.

Normal force test: A plate–plate magneto-rheometer (Physica MCR301, Anton Paar, Austria) was used to investigate the influence of shear deformation on the normal force of MRE. The sample size was 10 mm in radius and 1 mm in thickness. During the measurement, the sample was pre-compressed with a force of 20 N so as to prevent the slip between the sample and the shear plate when shearing. When the pre-compression force reached 20 N, the compressive strain was maintained constant. The accuracy of the normal force was 0.03 N during the experiment.

3. Results and discussion

The experimental results under quasi-static shear are shown in Fig. 1. Here, quasi-static shear means the shear rate is quite low, i.e. 10^{-4}/s. From Fig. 1(a), with increasing magnetic field, MRE becomes stiffer, which is commonly called magnetorheological effect. Besides, it is found that the normal force of MRE is influenced by the shear

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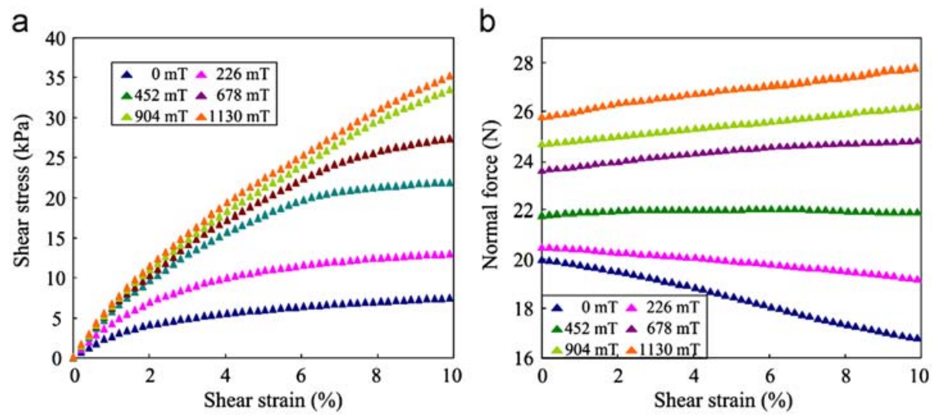

Fig. 1. Normal force of MRE under quasi-static shear; (a) shear stress vs. shear strain; and (b) normal force vs. shear strain.

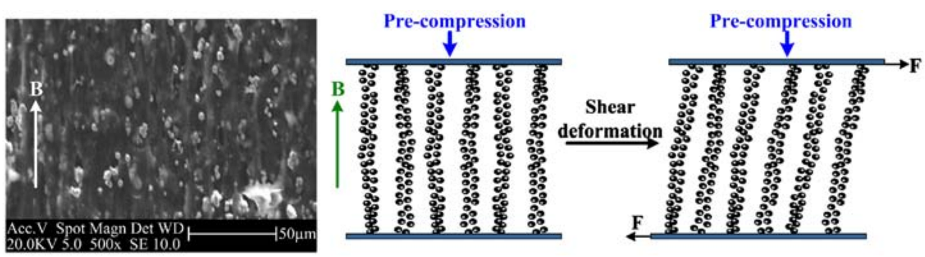

Fig. 2. SEM image of MRE (a) and shear deformation of chainlike structures (b).

deformation (Fig. 1(b)). It is important to note that due to the pre-compression, the initial normal force is 20 N when the magnetic field is 0 mT. With increasing magnetic field, the initial normal force increases, which is resulted from the magnetic-field-induced normal force and has been discussed in the reported literature [8]. In this study, the concerned phenomenon is the shear-deformation-related normal force. From Fig. 1(b), it is interesting to find that there are two different trends of the normal force with increasing shear strain. At low magnetic field, the normal force decreases with increasing shear strain, while increases with increasing shear strain when the magnetic field exceeds 452 mT. Fig. 2(a) shows the microstructure of the MRE sample observed by a scanning electron microscope (model XL-30 ESEM, Philips). Obvious chainlike structures of iron particles can be observed. Therefore, a chainlike structure based theory was proposed to explain the phenomenon in Fig. 1(b).

Inside MRE, the iron particles form chainlike structures. When exposed to magnetic field, there are strong magnetic interactions among the iron particles in a chain structure. Therefore, MRE can be regarded as a fiber reinforced composite (Fig. 2(b)). Each chainlike structure represents a fiber, which is parallel to the external magnetic field. When shearing, the chainlike structure tilts. Therefore, the elastic modulus in the pre-compression direction E_x can be represented as [13]

$$\frac{1}{E_x} = \frac{1}{E_1}\cos^4\theta + \left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1}\right)\sin^2\theta\cos^2\theta + \frac{1}{E_2}\sin^4\theta \tag{1}$$

where E_1 and E_2 are the elastic modulus parallel to the fiber direction and perpendicular to the fiber direction respectively, G_{12} is the shear modulus, ν_{12} is Poisson's ratio, and θ is the tilt angle of the fiber direction respect to the pre-compression direction. The relationship between E_x and the tilt angle is shown in Fig. 3, where G_{12} is calculated from Fig. 1(a), E_1 and E_2 are obtained from the reported literature [8] or calculated from the pre-compression, and ν_{12} equals 0.5. From Fig. 3, the elastic modulus E_x in the pre-compression direction decreases with increasing shear strain and this decreasing trend slows with increasing magnetic field. In the measuring of normal force, the compressive strain is fixed. Therefore, decreasing elastic modulus leads to the decreasing normal force, which may be the reason why the normal force decreases with increasing shear strain in Fig. 1.

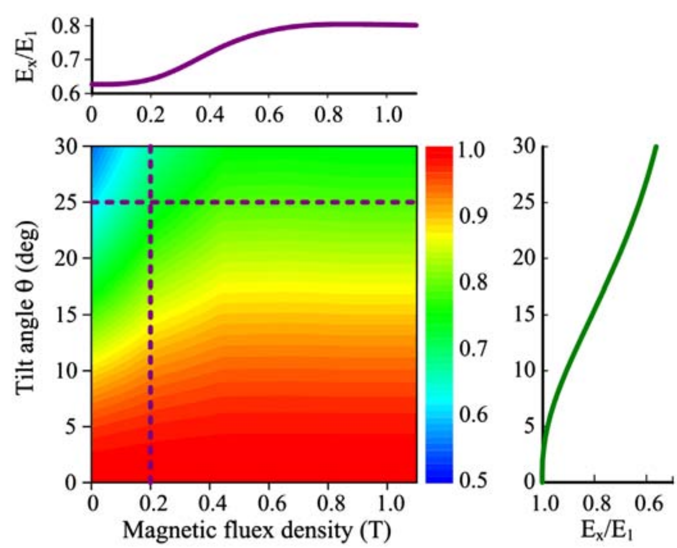

Fig. 3. Elastic modulus in the pre-compression direction.

In Fig. 1(b), when the magnetic field exceeds 452 mT, the normal force exhibits increasing trend with increasing shear strain, which is opposite to the explanation in Fig. 3. To solve the problem, the magnetic torque should be considered. Martin [14] and De Vicente [15] found that the tilt iron chain would generate a magnetic torque when exposed to external magnetic field. Therefore, a vertical resistance force along the direction of the magnetic field would be generated. It can be expressed as:

$$F_{vertical} = \frac{3}{4}\pi a^2 \mu_0 \mu_{fr} \beta^2 H^2 \sin 2\theta \sin\theta \tag{2}$$

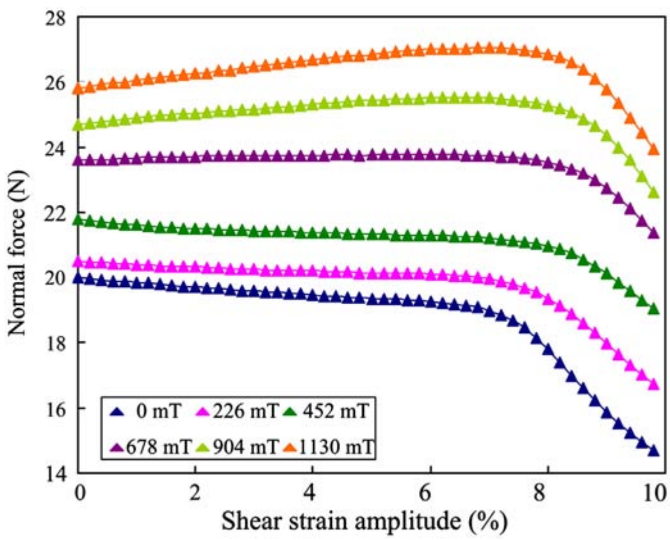

Fig. 4. Normal force of MRE under oscillatory shear at 1 Hz.

where a is the particle radius, μ_0 is the permeability of vacuum, μ_{fr} is the permeability of the matrix, β is the magnetic constant, H is the external magnetic field strength and θ is the tilt angle of the chain. Obviously, the vertical resistance force increases with increasing magnetic field and increasing tilt angle, i.e. increasing shear strain. Therefore, the magnetic torque may be the reason why the normal force of MRE increases with increasing shear strain when the magnetic field exceeds 452 mT.

In summary, there are two factors which would influence the normal force of MRE under shear deformation. One is the elastic modulus in the pre-compression direction and the other is the magnetic torque. The two factors have opposite effect on the normal force of MRE under shear deformation. When the magnetic field is low, the decreasing normal force resulted from the decreasing elastic modulus in the pre-compression direction is bigger than the increasing normal force resulted from the magnetic torque. Therefore, a decreasing trend of the total normal force can be seen in Fig. 1(b). However, when the magnetic field increases, the decreasing trend of the elastic modulus in the pre-compression direction slows and the magnetic torque increases. When the magnetic field exceeds 452 mT, the increasing normal force resulted from the magnetic torque becomes bigger than the decreasing normal force resulted from the elastic modulus in the pre-compression direction. Therefore, an increasing trend of the total normal force can be seen in Fig. 1(b).

Beside the quasi-static shear, another shear mode is oscillatory shear. In this case, the shear strain oscillates sinusoidally. The experimental results are shown in Fig. 4. Comparing Fig. 1 and Fig. 4, the trend of the normal force under oscillatory shear is similar to the normal force under quasi-static shear when the strain amplitude is smaller than 7%. However, different from the quasi-static shear, the normal force decreases sharply when the strain amplitude exceeds 7% under oscillatory shear. Under oscillatory shear, the chainlike structures of MRE are easier to be changed than that under quasi-static shear. When the strain amplitude exceeds 7%, the chainlike structures begin to break, which weakens the magnetic torque and the elastic modulus in the pre-compression direction. Therefore, a sharp decreasing of the normal force is observed in Fig. 4.

4. Conclusions

The influence of shear deformation on the normal force of MRE was investigated. Under quasi-static shear, the normal force decreases with increasing shear strain at low magnetic field while increases with increasing shear strain when the magnetic field exceeds 452 mT. To characterize the property of MRE, a microstructure based theory was proposed. Under oscillatory shear, the normal force is similar to the one in quasi-static shear. However, it decreases sharply when the shear strain amplitude exceeds 7%, which is due to the break of the chainlike structures of the iron particles.

Acknowledgments

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