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The energy dissipation behaviors of magneto-sensitive polymer gel under cyclic shear loading

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ABSTRACT

The energy dissipation behaviors of a typical magneto-sensitive polymer gel, named as magnetorheological plastomer (MRP), under two types (linear and sinusoidal strains) of cyclic loading was studied. The energy dissipation capability is evaluated by the dissipated energy density which is calculated from the stable stress–strain curve within a cycle. It was found that the dissipated energy changes with the variation of magnetic field and particle content, the anisotropic MRP dissipates more energy than the isotropic one. The type of actuating strain can also decide the value of dissipated energy density, but the energy dissipation mechanism of MRP cannot be changed by it. These results give valuable guidance to the potential application of MRP on dampers or absorbers, as well as to further understand its energy dissipation mechanism.

1. Introduction

Magnetorheological plastomer (MRP) is a kind of novel magneto-sensitive polymer gels. Normally, it is prepared by mixing micrometer sized soft magnetic particles with plastic polymer matrix [1]. In the absence of magnetic field, MRP behaves like plasticine, so it is easily to be changed into various shapes. Due to the plasticity of polymer matrix, MRP overcomes the particle sedimentation problem in conventional MR fluids [2], while inherits the moveable characteristics of magnetic particles in the presence of magnetic field. When an external magnetic field is applied, the magnetic particles in MRP will be magnetized and the magnetized particles can move to form chain-like microstructures along with the field's direction, making MRP change from isotropic to anisotropic. The particle chains will reorient once the field's direction varies. After the magnetic field is removed, the chain-like microstructures will still retain in the matrix, which is analogous to the characteristic of MR elastomers [3,4] whose particle chains can be 'frozen' in the polymer matrix. These unique characteristics enable MRP has great application potential in absorber and damper [5–7].

When MRP works in absorber or damper, it can absorb or attenuate the energy from external vibration or impact, then the damage of equipment can be weaken or avoided. Therefore, the energy dissipation capability within a loading period is an important factor to evaluate its damping performance. The damping property of MRP can be easily adjusted by an external magnetic field [1], which indicates that the control of energy dissipation is promising to be achieved. So far, the energy dissipation mechanism of MRP has not been clarified, though it is a principal problem needed to be solved before designing an intelligent magneto-controllable absorber or damper. So far, we have obtained some scattered results about the energy dissipation property of MRP under cyclic shear loading [6,8], but it lacks systematically discussion on the energy dissipation mechanism aiming at magneto-sensitive polymer gels, and this is the motivation of this work.

In this study, the energy dissipation behaviors of MRP under cyclic shear loading were experimentally investigated. To do this, two types of cyclic shear loading, i.e. linear and sinusoidal, were respectively applied to the MRP. Then the relationships between dissipated energy and related influence factors (including particle distribution, magnetic field, and particle content) were discussed. Meanwhile, the energy dissipation mechanism was qualitatively analyzed according to the related experimental results, hoping this work can provide a valuable reference to the practical application of MRP.

2. Material and method

The MRP is prepared by mixing carbonyl iron particles (Type

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CN, provided by BASF in Germany with an average radius of 6 μm) with a polyurethane matrix evenly without adequately cross-linking. The polyurethane is synthetized through three reaction stages: polymerization reaction, chain-extending reaction, and cross-linking reaction. The synthesis detail can be found in our previous work [1]. In this work, five different MRP samples with 40%, 50%, 60%, 70%, and 80% weight fraction of iron particles were prepared, and were named as MRP-40, MRP-50, MRP-60, MRP-70, and MRP-80, respectively.

A parallel-plate rheometer (Physica MCR 301, Anton Paar Co., Austria) is used to investigate the rheological behaviors of MRP under different cyclic shear loadings. A Rheoplus LAOS module can read the original stress–strain hysteresis loop under an oscillatory cycle when a sinusoidal actuating strain is applied to the sample, from which the dissipated energy can be calculated. If the sample was actuated by the cyclic linear strain with low strain rate (lower than 0.1 s^{-1}), the quasi-static stress–strain hysteresis loop can be measured directly.

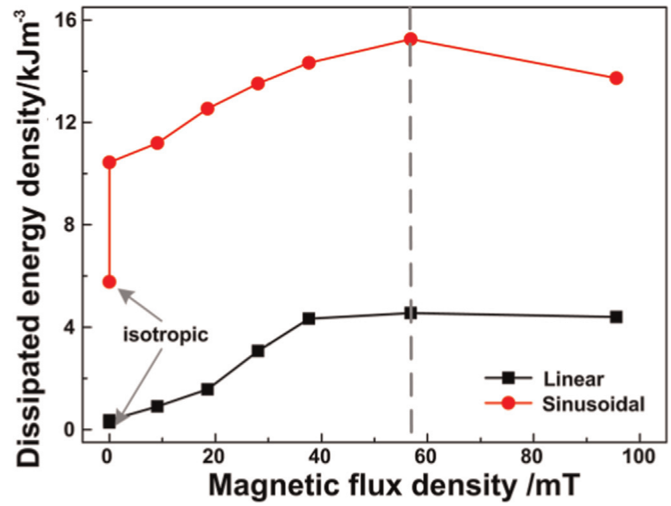

Fig. 2. The dissipated energy density of MRP-70 varies with different magnetic fields actuated by cyclic sinusoidal and linear strain, respectively. The MRP-70 is anisotropic except for the isotropic ones (marked as 'isotropic' in the figure).

3. Results and discussion

Normally, two kinds of particle distribution can exist in MRP in the absence of magnetic field: random or structured, which were also defined as isotropic and anisotropic, respectively. The MRP with randomly dispersed particles is not a stable state in the presence of magnetic field, as the randomly distributed particles will rearrange to form chain-like structure. Thus the energy dissipation properties of MRP with different particle distributions should be compared without external magnetic field. The area enclosed by the stress–strain curve actually represents the dissipated energy density within an oscillatory cycle. The larger the stress–strain curve, the stronger the energy dissipated ability of MRP [5]. Given this, the energy dissipation can be quantitatively compared. In Fig. 1, it is found that the area of stress–strain curves of anisotropic MRP is larger than that of isotropic MRP, no matter which type of loading is. The related dissipated energy density is shown in Fig. 2, and the result is coincident with our intuitionistic recognition. As have been mentioned before [1], the energy dissipation mainly originates from the inner friction of molecular chains of matrix and the interfacial slipping between the particles and the matrix. When an actuating strain is applied, the microstructure of MRP will change to some extent. The destruction of particle chains in anisotropic MRP induces an extra energy dissipation comparing to the isotropic MRP. The energy from interfacial slipping between polymer matrix and particles will also be dissipated more for the MRP with the chain-like microstructure. In other words, the energy dissipation induced by the structured difference can be easily distinguished under cyclic shear loading.

Fig. 1 also shows that the shape of stress–strain curves is determined by the type of actuating strain. Fig. 1a presents a typical linear viscoelastic property of MRP under a cyclic sinusoidal strain (dynamic mechanical behavior). Meanwhile, the instantaneous elasticity and plastic flow phenomenon can be found in Fig. 1b (quasi-static mechanical behavior). These results demonstrate that different rheological properties of MRP will present by different types of actuating strain. The discrepancy can be also quantitatively compared by the dissipated energy density, 5.78 kJ/m^3 for sinusoidal loading and 0.27 kJ/m^3 for linear loading (Fig. 2, the isotropic MRP). With the same amplitude of actuating strain (i.e. 0.2%) in the absence of magnetic field, more energy will be dissipated in case the actuating strain is sinusoidal. Therefore, the type of actuating strain is an important factor when considering the response behavior of MRP under cyclic loading.

Except for the type of actuating signal, the on–off state of magnetic field will also affect the energy dissipation of anisotropic MRP, as Fig. 1 shows. The interaction between particles will generate under magnetic field, making the particle chains more rigid and more difficult to be destroyed. Thus it will take more energy to destroy the particle chains when an external magnetic field is

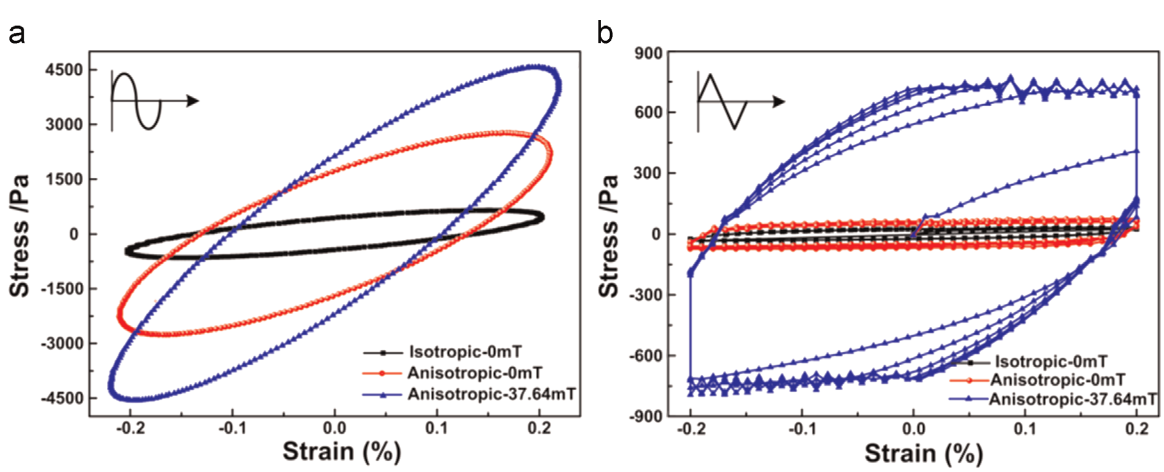

Fig. 1. The strain–stress hysteretic curves of MRP-70 under three different states (isotropic MRP without magnetic field, anisotropic MRP without magnetic field, and anisotropic MRP under a 37.64 mT magnetic field) actuated by cyclic sinusoidal (a) and linear (b) strain, respectively.

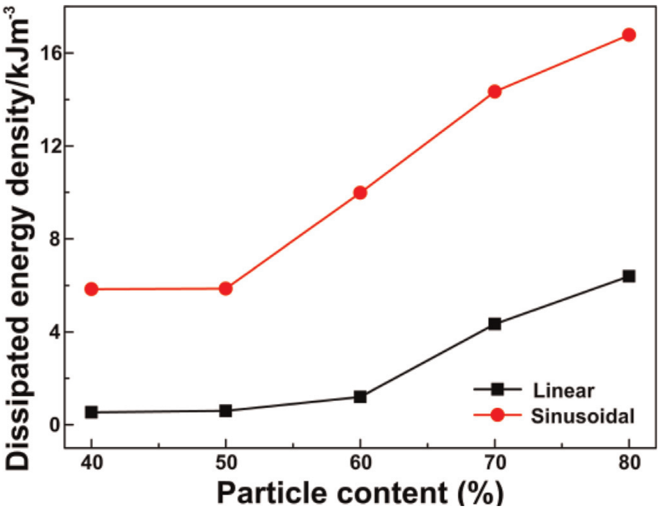

Fig. 3. The dissipated energy density of anisotropic MRP with different particle content actuated by cyclic sinusoidal and linear strain, respectively. A 57 mT magnetic field is applied during the test.

applied. The interaction between particles is determined by the external magnetic field, so the dissipated energy is sensitive to the magnetic field strength (as shown in Fig. 2). However, the dissipated energy not always increases with the increasing of magnetic flux density. When the magnetic flux density exceeds 57 mT, the dissipated energy will decreases slightly with the increasing of magnetic flux density. This interesting phenomenon indicates that the part of dissipated energy may be restrained under magnetic field. Considering the origin of the energy dissipation, we speculate that the movement of polymer matrix may be restricted by the particle chains when the magnetic field is applied, and this restriction effect will be strengthened with the increasing of magnetic flux density. When the magnetic flux density increases to around 60 mT, the restrained dissipated energy from polymer matrix exceeds the dissipated energy from the destruction of particle chains, so a peak value appears with the increasing of magnetic flux density. It is needed to note that the dissipating mechanism is ubiquitous in MRP and not decided by the type of actuating signal.

The discrepancy of dissipated energy density actuated by sinusoidal and linear strain can also be confirmed in Fig. 3. Here, we concentrate on the influence of particle content on the dissipated energy. Fig. 3 demonstrates that the dissipated energy can also be influenced by the particle content. In the testing region, the adjusting range of dissipated energy by particle content (10.95 kJ/m^3, from MRP-40 to MRP-80) is even wider than magnetic field (4.81 kJ/m^3, from 0 mT to 57 mT). In the presence of magnetic field, the destruction of particle chains (resistance to magnetic interaction and the interface slipping between particles) is the dominating energy dissipating mechanism. Obviously, more chains will generate in the MRP with high particle content under the same magnetic field, thus more energy will be dissipated for the MRP with high particle content when actuated by the same strain signal.

4. Conclusion

Although the magnitude of dissipated energy and the shape of hysteresis loop are highly dependent on the type of actuating strain, the ubiquitous energy dissipating mechanism in MRP will not change by it. No matter which form of actuating strain is, the anisotropic MRP will dissipate more energy than the isotropic one, the dissipated energy is sensitive to the magnetic field and particle content. In particular, there is a peak value for dissipated energy with the increasing of magnetic flux density, demonstrating that the restriction effect to the movement of molecular chains will weaken the energy dissipation from the polymer matrix and the restriction effect will be strengthened with the increasing of magnetic flux density. Based on the experimental results, a theoretical analysis is needed to further reveal the mechanism of magneto-sensitive energy dissipation in the future.

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