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Citation: Applied Physics Letters 107, 111901 (2015); doi: 10.1063/1.4931127
View online: http://dx.doi.org/10.1063/1.4931127
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/107/11?ver=pdfcov
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A high-damping magnetorheological elastomer with bi-directional magnetic-control modulus for potential application in seismology

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(Received 2 July 2015; accepted 6 September 2015; published online 16 September 2015)

A high-damping magnetorheological elastomer (MRE) with bi-directional magnetic-control modulus is developed. This MRE was synthesized by filling NdFeB particles into polyurethane (PU)/epoxy (EP) interpenetrating network (IPN) structure. The anisotropic samples were prepared in a permanent magnetic field and magnetized in an electromagnetic field of 1 T. Dynamic mechanical responses of the MRE to applied magnetic fields are investigated through magneto-rheometer, and morphology of MREs is observed via scanning electron microscope (SEM). Test result indicates that when the test field orientation is parallel to that of the sample’s magnetization, the shear modulus of sample increases. On the other hand, when the orientation is opposite to that of the sample’s magnetization, shear modulus decreases. In addition, this PU/EP IPN matrix based MRE has a high-damping property, with high loss factor and can be controlled by applying magnetic field. It is expected that the high damping property and the ability of bi-directional magnetic-control modulus of this MRE offer promising advantages in seismologic application. © 2015 AIP Publishing LLC.

In this paper, a high damping MRE with bi-directional changing modulus is prepared by incorporating hard magnetic particles (NdFeB) into polyurethane (PU)/epoxy (EP) interpenetrating network (IPN) matrix. Field dependences and time dependences of shear modulus and loss factor were investigated systematically under oscillatory shear mode. A possible physical mechanism was proposed to explain the phenomenon qualitatively.

The fabrication involves three basic steps: (1) dispersion of NdFeB particles into the liquid-state matrix, (2) adding plasticizer and curing agent into the suspension step by step, and (3) curing of the mixture under a steady magnetic field. In our previous research, we prepared MRE based on PU/EP IPN matrix with improved damping and mechanical properties. Details about the process and principle of reaction can be obtained from our recent work.

The necessary raw materials include PU matrix (Castor oil was purchased from Sinopharm Chemical Reagent Co., Ltd., China. MDI was purchased from Yantai Wanhua Polyurethanes Co., Ltd., China), Diglycidyl ether of bisphenol-A (DGEBA)-based EP was purchased from Baling Petrochemical Co., Ltd., Hunan, China, 2,4,6-Tri (dimethylaminomethyl)phenol (DMP-30) was purchased from Wuhan Hongda Co., Ltd., China, and it was used as curing agent. Di-butylphthalate (DBP) was purchased from Tianjin Bodi Chemical Holding Co., Ltd., China, it was used as plasticizer. NdFeB (with a wide size distribution (1–100 μm)) was provided by Guangzhou Nuode Transmission Parts Co., Ltd., China. The weight content of NdFeB particles in each sample is 80 wt. %.

In this paper, the samples were prepared in disc forms with 20 mm in diameter and 2 mm in thickness. A plate–plate

Earthquake is one of the most destructive natural disasters. With excellent magnetic control stiffness, magnetorheological elastomer (MRE) is a promising solution for complicated engineering challenges in seismologic field. In the past decade, many researchers developed various vibration isolator based on MRE in order to alleviate the vibration of buildings caused by earthquake. Generally, MRE based isolator needs to be extremely stiff to keep the buildings stable during earthquakes. But for the purpose of alleviating the vibration of earthquake, it is expected the stiffness of isolator can be reduced to obtain a large deformation when the quake hits. Conventional MRE are usually prepared by blending soft magnetic filler with polymer matrix, and its modulus increases with increasing magnetic field density. Therefore, researchers expected to prepare a novel MRE with negative magnetic-control modulus. Zhang et al. prepared a patterned body centered cubic (BCC) MRE, its modulus shows a trend of slightly decreasing with magnetic field. Unfortunately, the fabricated BCC MREs have limited applications because of its narrow range of modulus change. After many failed attempts, an alternative solution was proposed by Yang et al. They applied electromagnet and permanent magnets onto a multilayered MRE structure, and the stiffness of this isolation system can be decreased by increasing current to offset the permanent magnetic field. To sum up, it is obviously necessary to develop a negative magnetic-control modulus MRE for application in seismology. In addition, damping capacity is usually employed to judge a material’s ability to dissipate elastic strain energy. It is also critical for energy dissipation and shock absorption. A high damping magnetorheological material can be a suitable candidate for magneto-dampers and energy absorbers.
magneto-rheometer (Physica MCR301, Anton Paar, Austria) was used to investigate the influence of magnetic field and
time on the modulus and loss factor of MRE. The testing
magnetic field of MR devices was generated by an electro-
magnet. The range of magnetic flux density is 0–1.2 T,
adjusted by DC power supply.

Figure 1 shows the microstructure of the NdFeB par-
ticles and MRE sample observed by a scanning electron
microscope (SEM, MIRA3 TESCAN). The image of the
NdFeB particles is presented in Figure 1(a). It can be seen
that NdFeB particles have a wide size distribution, about
1–100 μm as mentioned above. They also have various
shapes and dispersed individually. Because NdFeB particles
are non-magnetic before magnetization, they can be uni-
formly dispersed in the matrix as shown in Figure 1(b).

Hysteresis loops of NdFeB particles and MRE sample are
shown in Figure 2. It is obvious that remanence and coerciv-
ity of MRE decreased compared to those of the NdFeN par-
ticles. This phenomenon is caused by nonmagnetic of the
matrix MRE. It is well known that coercivity of the perma-
nent magnets strongly depends on their orientation; thus, this
situation could also be attributed to the particle rotation
within the elastic matrix.16

To study the influence of orientation and intensity of
external magnetic field on modulus of MRE, we selected a
periodically changing magnetic field and a transient
magnetic field. The tests were conducted at a frequency of
10 Hz and constant shear strain amplitude of 0.1%. We have
studied the influence of the rate of the magnetic field change
on field dependences of the modulus, and set 10 s and 1 s as
different measuring interval. Periodically changing magnetic
field dependences of the storage modulus (G' -10 s and
G' -1 s) are shown in Figure 3(a), and the loss modulus
(G'' -10 s and G'' -1 s) with the same hysteretic loop as storage
modulus, as shown in Figure 3(b). Here, we defined that the
negative value of magnetic field denotes the orientation of
test magnetic field when it is opposite to the magnetization,
and positive value denotes the orientation parallel to the
magnetization. One can see that curve-10 s and curve-1 s
have the same tendency at periodically changing magnetic
field. But G' -1 s and G'' -1 s are greater than G' -10 s and
G'' -10 s, respectively, at the same magnetic field density. It is
mainly because that sufficient time is needed for the turn of
magnetic domain, and increase of velocity of magnetic field
may lead to more remanence. As can be seen from Figure
3(a), application of magnetic field can induce both increase
and decrease of the G' of MRE depending on its orientation.
Initially, G' -10 s and G'' -10 s decreased with increasing
opposing field, G' -10 s decreased from 0.61 MPa to
0.12 MPa and G'' -10 s from 0.44 MPa to 0.06 MPa when
opposing field increases from 0 mT to 240 mT. The main rea-
on is that the magnetic particles interact and tend to build
chainlike structures within the polymer matrix to minimize
the magnetic field energy during previous magnetization.
When the orientations of external field are opposite to that of
the magnetization field, the external field causes disorienta-
tion of the particles and distortion of the internal chainlike
structures formed after sample magnetization. In particular,
magnetostatic interaction of the magnetic particles should be
proportional to the magnetization, and it leads to stronger
coupling with polymer matrix.17,18 The degaussing of par-
ticles can weaken the magnetostatic interaction. Thus, the
decreasing modulus can be also attributed to degaussing of
particles. In addition, G' -1 s and G'' -1 s have the same tend-
cency at the initial stage just like G' -10 s and G'' -10 s; how-
ever, the decrease of G' -1 s and G'' -1 s is smaller. G' -1 s
decreased from 0.61 MPa to 0.24 MPa and G'' -1 s from
0.32 MPa to 0.14 MPa. When the field is strong enough to
rearrange the particles when the orientation of the magnet-
ization changes, a new structure begins to form and the mod-
ulus starts to increase again.19 As a result, the values of G'

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**FIG. 1.** SEM image of (a) NdFeB par-
ticles and (b) MRE sample.

**FIG. 2.** Hysteresis loops magnetization (magnetic moment per unit mass)
versus magnetic field for NdFeB particle and MRE sample.
and $G''$ in curve-10 s and curve-1 s increased when opposing fields continue to increase. Due to the presence of magnetic remanence, the demagnetizing curve does not coincide with the initial curve. When the orientation of external field is parallel to that of the magnetization field, the variation trend of G' and G'' of samples is the same as that of the initial stage with opposing fields. They decreased with the increasing codirectional field at first. When the codirectional field continues to increase, the G' and G'' of samples increased with the increasing codirectional field sharply. The G'-10 s and G''-10 s increased from 0.12 MPa to 1.16 MPa and 0.07 MPa to 0.54 MPa, respectively, when co-directional fields increases from 240 mT to 860 mT. And G'-1 s and G''-1 s increased from 0.17 MPa to 1.23 MPa and from 0.1 MPa to 0.71 MPa, respectively. At last, each modulus decreased with decreasing co-directional field. Obviously, opposing field causes more decrease of modulus while codirectional field causes more increase.

In Figure 4, we present the time dependences of modulus measured in bi-directional magnetic field with different intensity. We set the measuring interval to be 10 s and selected 0 mT, 150 mT, 400 mT, and 800 mT as four different stages of magnetization strength. One can see that G'-0 mT and G''-0 mT remain unchanged in zero magnetic fields. The sample becomes rigid in coedirectional field and soft in opposing field. Compared with G'-0 mT, G'-150 mT and G'-400 mT are smaller and G'-800 mT is greater in opposing field. It is interesting that G'-150 mT and G''-150 mT were slightly reduced at 0–400 s, because 150 mT was not strong enough to rearrange the particles. Instead, G'-400 mT and G'-800 mT increased at 0–400 s. G'-800 mT and G''-800 mT increased from 0.71 MPa to 1.69 MPa and 0.34 MPa to 0.72 MPa, respectively, when field orientations changed from negative to positive. In addition, the response time of sample in higher field is shorter than that in lower field. It may be explained by the fact that magnetic domain can turn more easily in higher field.

Damping is an important property of viscoelastic materials, and damping capacity is usually employed to judge a material’s ability to dissipate elastic strain energy. A high damping capacity is beneficial to energy dissipation and shock absorption in potential application of seismology. In Figure 5, we demonstrate field and time dependences of loss factor (tan $\delta$). There are several peaks in the curves of Figure 5(a) which demonstrate field dependences of the loss factor. Compared with curves of Figure 3, these peaks located at the field strength where modulus changes sharply. It is mainly because of the turn of magnetic domain which caused a lot of relative movement between matrix and particles leading to more energy dissipation. In particular, tan $\delta$-1 s is mostly greater than tan $\delta$-10 s in test magnetic field. It is possibly because that faster changing magnetic field can lead to more magnetic hysteresis loss. Another interesting phenomenon is found in Figure 5(b), a simultaneous jump of loss factor takes place at the moment of field switching (400 s and 1200 s). The loss factor increased significantly when magnetic field was 150 mT and 400 mT. It is caused by a fast growth of the loss modulus due to increasing energy dissipation in particle rotation when the field orientation is opposite to that of the particles’ magnetization. However, when magnetic field was 800 mT, the loss factor increased slightly and soon decreased when the time was at 400 s and 1200 s. It is mainly because that the response time of sample in higher field is shorter, and coupling effect between neighboring...
particles and matrix is stronger. Loss factor is calculated by \( \tan \delta = G''/G' \). As a consequence, \( G' \)-800 mT increases faster than \( G' \)-150 mT and \( G' \)-400 mT, the increase of storage modulus is larger than the loss modulus which leads to slightly jump of \( \tan \delta \)-800 mT. Compared with \( \tan \delta \)-0 mT, \( \tan \delta \)-150 mT and \( \tan \delta \)-400 mT, the increase of storage modulus is larger than the loss modulus which leads to slightly jump of \( \tan \delta \)-800 mT. Compared with \( \tan \delta \)-0 mT, \( \tan \delta \)-150 mT and \( \tan \delta \)-400 mT are greater and \( \tan \delta \)-800 mT is smaller. Loss factor ranges from 0.4–0.85, and it can be as high as 0.85 by controlling applied magnetic field. The loss factor of conventional MRE is usually lower than 0.3.\(^{21–23}\) Compared with conventional ones, this MRE has a higher loss factor.

In summary, a high-damping MRE with bi-directional changing modulus is developed by blending NdFeB particles with PU/EP IPN matrix. Superiority of this MRE as compared to conventional ones is demonstrated by experimental, the result which shows that the modulus can be bi-directionally controlled by external magnetic field. In addition, analysis of damping property indicated that this MRE has a higher loss factor than conventional ones. These advantages make it a promising candidate for application in seismology.

This work was supported by the National Natural Science Foundation of China (Grant No. 61203098) and the Fundamental Research Funds for the Central Universities (Grant Nos. CDJXY120004 and CDJZR120018). The authors are grateful for the supports.


**FIG. 5.** (a) Field dependences of the loss factor for MRE. (b) Time dependences of loss factor for MRE in different magnetic field.