Energy dissipation characteristics of magnetosensitive elastomer under impact loading

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Abstract: Magnetosensitive (MS) elastomers are a class of material that ferro-magnetic particles dispersed in rubber or elastomer whose mechanical properties change with the external magnetic fields. To investigate energy dissipation properties of MS elastomers, experimental method is adopted. Firstly, this paper presents a new fabrication method of a magnetosensitive elastomers with particles in millimeter scale distributed in ideal isotropic or in chain. Then, a drop hammer testing setup is developed to measure the energy dissipation and study the impact behaviour of magnetosensitive elastomers (MSEs). For the same volume fraction and size of particle, the dissipated energy per unit length of MSEs increases with the magnetic field increasing, and chain-like structured MSEs dissipate more energy than homogenous MSEs under the same external magnetic field.

1. Introduction
Magnetosensitive elastomer, also referred to as magnetorheological elastomer in the literature, is a class of smart material that consists of non-colloidal, magnetically-polarizable particles dispersed in a non-magnetic polymer medium, typically containing carbonyl iron particles of diameter in several microns [1]. The stiffness of MS elastomers can change rapidly and reversely in the external magnetic stimulus [2-4], which may be useful in impact protection for passenger safety. For instance, some automobile parts such as bumper, headrest, instrument panel and other interior decorations, are required to change stiffness and absorb impact energy adaptively in terms of the variations in mass and velocity of passengers or pedestrians in crash accidents [5]. In order to utilize magnetosensitive elastomers in adaptive energy absorber for car collision protection, it is necessary to understand their energy dissipation properties under impact loading.

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This study investigates the energy dissipation capacity of MS elastomers under two possible influential factors: particle arrangement and magnetic field strength. A new method to fabricate MSE with ideal isotropic and chain-like of macro-particles is introduced. The macro particles (diameter in millimeter) are arranged in elastomers manually, which can greatly avoid the agglomeration of particles. A special drop hammer experimental system is developed that can measure the energy dissipation of MSE under various magnetic fields and impact loadings.

2. Experimental setup

2.1 MSE sample preparation

The sample’s ingredients are iron particles, silicone rubber SE901A, and silicone rubber SE901B. The particles are spheres with an average diameter of 8 mm, obtained from Yongda Steel ball Factory (Guangzhou Province, China). The silicone rubber SE901A and B are Kenseer SE900 series from Huitian rubber Corporation, China. Their properties are listed in Table 1.

| Type        | Density (g cm$^{-3}$) | Hardness (Shore A) | Tensile strength (MPa) | Elongation (%) |
|-------------|-----------------------|--------------------|------------------------|---------------|
| SE901A/B    | 0.98                  | 20                 | 0.5                    | 90            |

Firstly, silicone rubber SE901A and SE901B are simultaneously poured into a container with 1:1, and then they are mixed by using a stirred bar for five minutes at room temperature. After two ingredients are evenly mixed, the silicon rubber mixture is put into a vacuum to eliminate air bubbles for one hour before it is cured in the mold.

The typical processing method in preparation of MSEs with micro-particles (the particles and elastomers are directly mixed) is not effective for preparing MSEs with macro-particle because the particle in millimeter size will sink in the silicon rubber immediately, therefore the ideal homogenous MSEs or chain-like MSEs would be unable to obtain. Hence, it is necessary to design a new method for processing MS elastomer with macro-particles.

![Figure 1. Schematic image of the steel mould.](image-url)
In this study, a steel mold is designed and manufactured as shown in Figure 1, which is used to prepare the macro-particle MSE composite materials. It includes locating plate, bolt, base, constraint plate and steel sheet. The size and position of the circular holes in locating plate determines the arrangement of macro-particle in MSEs.

Firstly, the base is laid on the desk, and the bolts are used to fasten the constraint plate in L-shape cross section. The first layer of steel sheet is placed to the side of two vertical constraint plates with dual adhesive tape. Secondly, the silicon rubber mixture is poured into the mould until its height reaches the top surface of the steel sheet, being cured for 20 h at room temperature. Thirdly, the locating plate is laid on the top surface of steel sheet. The iron particles are placed on the position of the circular hole in the locating plate, and then the silicone rubber precursor is cured for another 20 h. At this time, the viscosity of silicon rubber mixture can keep the particle not sink. Fourthly, the locating plate is removed, and the second layer of steel sheet is fasten to the constrain plate. The above-mentioned procedure is repeated until the MSE specimen is produced.

The chain of ferrous particles along the external magnetic field is shown in Figure 2. Denoting the radius of particles by \( R \) (4 mm), and the gap between the adjacent particles is \( 2w \). Their relationship can be written as [6],

\[
\frac{w}{R} = 0.05
\]  

\( \text{(1)} \)

\( \text{Figure 2. The chain of ferrous particle in MSE.} \)

\( \text{Figure 3. (a) The homogenous MSEs and (b) the chain-like MSEs.} \)

Hence, \( w \) is 0.2 mm. The volume fraction of particles is 27%, which is considered as the optimum volume fraction of MSEs [6]. It is also assumed that the arrangement of particles is 3*3*3, in total twenty-seven particles. The specimen of MSE with homogenous (30 mm in length, 30 mm in width, 30 mm in thickness) or chain-like (35 mm in length, 35 mm in width, 25 mm in thickness) particles are manufactured, as shown in Figure 3(a) and 3(b), respectively.

2.2 Special drop hammer system

The special drop-hammer impact system is developed, as illustrated in Figure 4. The rectangular line in Figure 4 (d) shows the magnetic circuit, which is generated by the electromagnet system. The magnetic intensity is controlled by the electrical current intensity in the coil and measured by a Tesla
gauge (model: WT10A, Wei Te magnetoelectric engineering Corp, China). The induced magnetic field is imposed in the direction of particle chains in MSE.

![Schematic image of the performance testing setup](image)

**Figure 4.** (a) Schematic image of the performance testing setup; (b) the detailed view of upper testing setup; (c) the detailed view of lower testing setup; (d) the detailed view of magnetic route of upper testing setup: (1) base; (2) support rod; (3) cross beam; (4) adjusting plate; (5) cross-shaped shaft; (6) nut; (7) guide bars; (8) hammer; (9) MSEs specimen; (10) T shape iron coin; (11) bolt; (12) L shape iron coin; (13) upper slab; and (14) coil.

The cross-shaped shaft and adjusting plate is used to modify the position of the guide bars, in order to make sure the hammer can pass through the holes in the upper slab smoothly to impact the specimen. The acceleration sensor (model: YJ9A, made by Beijing Oriental Vibration and Noise Institute in China) is laid on the top surface of the hammer with thread connection. The hammer is raised along the guide bars, and its height determines the impact velocity.
3. Experimental results and discussion

For homogenous and chain-like MSEs, the impact behavior is studied at different magnetic intensity from \( B = 0 \text{ mT} \) to \( B = 240 \text{ mT} \), with the height of initial position of hammer being 10 mm. At each experimental condition, three identical specimens are conducted, and the final result is an average of these three sets of data. The relationship between acceleration of hammer and time is shown in Figure 5.

![Figure 5. The acceleration-time history of impacting elastomers.](image)

From Figure 5, it can be seen that the hammer rebounds after it impacts the specimen. This rebounding process repeats until the hammer keeps steadily. The amplitude of the acceleration, \( a_{max} \), reduces. Here, only the first impact process is studied.

To analyze the dynamics of the impact system, the impact structure which includes a hammer and MSE can be considered as the single-degree-of-freedom system, as Figure 6 shows.

![Figure 6. Model of an impact system.](image)

The motion of the hammer is described by the following equations,

\[
m \ddot{x} = F_{R1}(\dot{x}) + F_{R2}(x) - mg
\]

with the initial conditions,
where \( m \) is the mass of the hammer, \( F_{R1} \) and \( F_{R2} \) are the damping force and elastic force produced by MSE.

\[
F_{R1}(\dot{x}) = c \dot{x} \tag{4}
\]

\[
F_{R2}(x) = kx \tag{5}
\]

where \( c \) is the damping coefficient of MSE, and \( k \) is the stiffness of MSE. \( v_0 \) is the initial impact velocity of hammer,

\[
v_0 = \sqrt{2gh} \tag{6}
\]

where \( h \) is the height of initial position of the hammer, 10 mm. \( g \) is the gravity acceleration. Therefore, the initial velocity is 0.447 m/s.

The hammer mass moves along the \( x \) direction with decreasing velocity until it reaches zero. Combining the equation (4) and (5) into equation (2),

\[
m\ddot{x} = c\dot{x} + kx - mg \tag{7}
\]

When the hammer drops down to the maximum displacement, \( x_{\text{max}} \), its acceleration also reaches maximum, \( a_{\text{max}} \), while the velocity is zero. At this time, the equation (7) can be written as,

\[
m\ddot{x}_{\text{max}} = kx_{\text{max}} - mg \tag{8}
\]

As the hammer mass is a constant, the maximum acceleration in the first impact process, can directly reflect the stiffness of MSE specimen.

The relationship of acceleration and time for homogenous and chain-like MSEs are shown in Figure 7 and Figure 8, respectively.

\[\text{Figure 7. The acceleration-time history of pure elastomer and homogenous MSEs}\]
Figure 8. The relationship of acceleration and time of pure elastomer and chain-like MSEs.

From Figure 7 and 8, it can be illustrated that the acceleration amplitude of MS elastomers is greater than that of pure elastomers, and the $a_{max}$ of the MSEs increases with the external magnetic field intensity increasing. It is because that the stiffness of MSE is greater than that of matrix, and the stiffness of MSEs increases with the magnetic field intensity increasing, which is consistent with the results from the published paper [7]. The maximum acceleration of the specimen is listed in Table 2.

Table 2. The maximum acceleration of the specimen in different magnetic field strength.

| Type         | Magnetic field intensity (mT) | Maximum acceleration (m s$^{-2}$) |
|--------------|------------------------------|-----------------------------------|
| Elastomer    | 0                            | 55.08                             |
| Homogenous   | 0                            | 82.55                             |
|              | 120                          | 91.09                             |
|              | 240                          | 207.06                            |
| Chain-like   | 0                            | 112.46                            |
|              | 120                          | 319.82                            |
|              | 240                          | 478.21                            |

From Table 2, it can be seen that the maximum acceleration in the first impact process of chain-like MSEs is greater than homogenous MSEs. It is because that the stiffness of chain structure is more dependent on magnetic field.
At the time of the maximum acceleration, in Figure 7 and 8, the velocity of hammer drops to zero. Hence, the kinetic energy of the hammer, $E$, is all dissipated by the specimen.

$$ E = \frac{1}{2} m v_0^2 $$ (9)

MSEs dissipate energy in two ways [8]: (1) eliminate or absorb the energy due to its viscosity, $E_c$; (2) store energy due to its elastic properties, $E_k$.

$$ E_c = \int_0^{x_{max}} F_{R1}(x) dx $$ (10)

$$ E_k = \int_0^{x_{max}} F_{R2}(x) dx $$ (11)

Hence, the energy equilibrium can be written as,

$$ E = E_c + E_k $$ (12)

Combining equation (4) and (5) into equation (9) to (12),

$$ \frac{1}{2} m v_0^2 = \int_0^{x_{max}} c \dot{x} dx + \frac{1}{2} k x_{max}^2 $$ (13)

As the hammer mass and the initial dropping height are ensured, the input energy of the impact system is a constant, $Q$. Therefore, the equation (13) can be illustrated, as Figure 9 shows.

**Figure 9.** The energy equilibrium curves.

With the stiffness of the specimen increasing, its maximum deformation reduces. The energy dissipation per unit length of specimen is measured as,

$$ \bar{E} = \frac{E}{x_{max}} $$ (14)
Hence, the greater the stiffness of MSE specimen is, the greater $\overline{E}$ is. The maximum deformation and energy dissipation per unit length of specimen are shown in Table 3.

### Table 3. The energy dissipation characteristic of specimen.

| Type            | Magnetic field intensity (mT) | $\delta_{\text{max}}$ (mm) | $\overline{E}$ (J/m) |
|-----------------|-------------------------------|----------------------------|----------------------|
| Elastomer       | 0                            | 10.7                       | 9.89                 |
| Homogenous      | 0                            | 6.67                       | 18.8                 |
|                 | 120                           | 5.39                       | 22.37                |
|                 | 240                           | 4.71                       | 22.48                |
| Chain-like      | 0                            | 4.76                       | 22.24                |
|                 | 120                           | 4.15                       | 25.50                |
|                 | 240                           | 3.89                       | 27.22                |

From Table 3, it can be seen that the dissipated energy per unit length of chain-like MSEs is greater than that of homogenous MSEs, and both of them increase with the external applied magnetic field.

### 4. Conclusion

In this research, a new method to fabricate MSE with macro-particle (size in millimeter) is proposed. By using this method, ideal isotropic and chain-like structured MSEs can be prepared manually. A drop hammer testing setup is developed to investigate the energy dissipation characteristics of MSE elastomers under impact loadings and various magnetic fields. It is concluded that, for the same particle volume fraction, particle size and applied magnetic field, the impact acceleration amplitude of chain-like MSEs are greater than homogenous MSEs, and the dissipated energy per unit length of chain-like MSEs is greater than that of homogenous MSEs. The energy dissipation per unit length of MSEs with different particle arrangement both increase with the external applied magnetic field intensity.

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### References

[1] Carlson J D and Jolly M R 2000 Mechantronics **10** 555
[2] Varga Z, Filipcsei G and M Zrinyi 2006 Polymer **47** 227
[3] Zhou G Y 2003 Smart Mater. Struct. **12** 139
[4] Bellan C and Bossis G 2002 *Int. J. Mod. Phys. B* **16** 2447

[5] Deshmukh S S and Mechinley G H 2007 *Smart Mater. Struct.* **1** 106

[6] Davis L C 1999 *J. Appl. Phys.* **86** 3348

[7] Kallio M 2005 *The elastic and damping properties of magnetorheological elastomers* VIT publications **4** 92

[8] Wereley N M 2011 *J. Intell. Mater. Syst. Struct.* **22** 515