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Effect of magnetic nanoparticles on damping property of nature rubber

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Abstract A new kind of magnetic rubber was prepared by doping Fe_3O_4 nanoparticles into nature rubber matrix, which was characterized by the scanning electron microscopy and X-ray spectroscopy. They showed that the Fe_3O_4 nanoparticles were well dispersed in rubber matrix. Furthermore, the mechanical and magnetic properties of the magnetic rubber were investigated, indicating the improvement of tensile strength from 13.9 to 15.8 MPa and high saturation magnetization (16.7 emu/g) compared with the nature rubber. What' more, the loss factor of magnetic rubber treated by an external homogenous magnetic field (1.5 T) was improved from 0.07 to 0.15 compared with magnetic rubber without treating by the magnetic field. The result is attributed that after applying a magnetic field, magnetic nanoparticles on the rubber matrix are magnetized; meanwhile, magnetic dipole moments are induced, which causes magnetic field and can absorb shock energy.

Keywords Enhancement · Damping property · Nature rubber · Magnetic nanoparticles

Introduction

Vibration and noise often lead to undesirable consequences such as unpleasant noise, fatigue and failure of structures, decreased reliability and degraded performance [1]. Rubber is a commonly used material in controlling noise and vibration because of its high damping property. It should be noted that the loss factor (tanδ) can be used to evaluate damping properties of rubber. Generally, the

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loss factor is larger and the damping property is better. So the importance of vibration isolator's research on the loss factor of rubber to improve the damping properties has rapidly increased in recent years [2, 3]. To get large loss factor, the doping content of particle on the rubber matrix was increased [4]. However, the distance between particles was much smaller with the increment of particle content. The free volume that offers the space for mobility of the rubber chain decreased, resulting in the decrement of the loss factor. So, the loss factor is difficult to be improved by increasing doping content of particles [5]. Therefore, it is very important for finding a new method to enhance the loss factor of rubber, which is necessary to improve its damping properties.

Recently, the magnetic fluid was studied as a new kind of damper [6]. The generated magnetic field on the magnetic fluid can create a repulsive force that is proportional to outer vibration force; the moving magnet behaves like a viscous damper. For the same reason, the magnetic particles are doped into rubber matrix and the generated magnetic field on the magnetic rubber is expected to absorb the outer shock energy, resulting in improvement of the loss factor. However, although there were some studies reporting magnetic fluid dampers [6–9], there were few studies to investigate the damping property of magnetic rubber. In addition to this, the magnetic Fe_3O_4 particles have attracted particular interests for its strong magnetic properties, simple synthesis and its low cost [10, 11], which is fit to be as magnetic filler of magnetic rubber applied on rubber vibration isolators.

So here, the magnetic rubber has been prepared and the effect of Fe_3O_4 nanoparticles grafted with polymer on the damping properties of magnetic rubber was further investigated. The result is very value to study a new method of improving the damping property of rubber.

Experimental

Preparation of magnetic rubber containing Fe_3O_4 nanoparticles

Magnetic Fe_3O_4 nanoparticles grafted with PEG were prepared by the co-precipitation of $FeCl_3 \cdot 6H_2O$ and $FeSO_4 \cdot 7H_2O$ with NaOH in the presence of PEG-6000 according to the previous literature [12].

The Fe_3O_4 nanoparticles was further incorporated in nature rubber (NR) matrix, with adding appropriate amounts of ZnO, Stearic acid, Tetra Methyl Thiuram Disulphide (TMTD), Mercapto Benzo Thiazole Sulphide (MBTS) and Sulpher. The mixing was done in a Brabender Plasticorder (Torque Rheometer) model PL 3S. The doping content of Fe_3O_4 nanoparticles was controlled for 20 parts/100 g of rubber by weight (phr). Two types of magnetic rubber (MREs), isotropic magnetic rubber and structured magnetic rubber were prepared. The isotropic MREs were cured at 150 °C for 20 min under a pressure of approximately 15 MPa. The structured MREs were subjected to an external homogenous magnetic field of 1.5 T and then the samples were at 150 °C for 20 min under a pressure of approximately 15 MPa. The magnetic field for the pre-structured process was provided by a self-developed magnet heat couple device.

Characterizations

The morphologies of MRE were observed using a XL30 ESEM at an accelerating voltage of 10 kV. The sample was coated with a thin layer of gold before SEM observations.

The phase structural identification of the MRE was characterized by the X-ray diffraction (XRD) with CuK$_\alpha$ radiation ($\lambda = 1.54$) at a scan rate of 4°/min.

Tensile tests were performed on an Universal Testing Machine with a crosshead speed of 50 mm/min at 25 °C. The average of five tests is reported here.

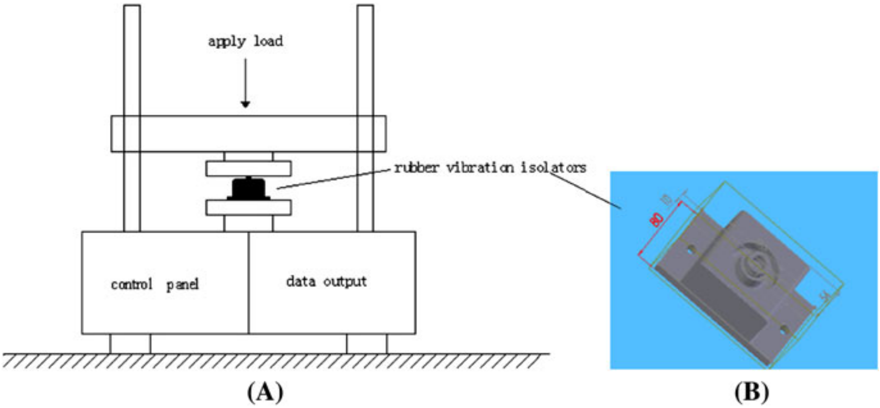
The compression set was tested according to the ASTM D 395-03. The testing environment was 70 °C; dimensions of the standard specimens were $\varphi 29.0 \times 12.5 \pm 0.5$ mm.

The magnetic property of MRE was measured at room temperature using a HH-15 vibrating sample magnetometer (VSM, $I_{\max} = 50$ Å, $P \leq 6$ kW, $H_{\max} = 15{,}000$ Oe, sensibility between 4 and 5×10^{-5}), made by Nanjing University Instrument Plant.

The damping property of magnetic rubber was obtained by using a dynamic mechanical analyzer (DMA Q800 TA, made by Instruments-Waters LLC) (Scheme 1). And the structure of rubber sample is shown in Scheme 1, too. To measure the preload and vibration amplitude, a displacement transducer with a range of −0.15–0.15 mm was used. Then it was tested under specified load 1200 N at a frequency of 30 Hz. And the measurements were recorded on a personal computer through a Sony DAT measurement system.

Results and discussion

The magnetic rubber was prepared by general approach of mixture [13]. Sun et al. [13] have investigated the preparation of magnetic rubber and stated that the



Scheme 1 **a** The representation of experiment equipment and **b** the structure of experiment sample for damping property

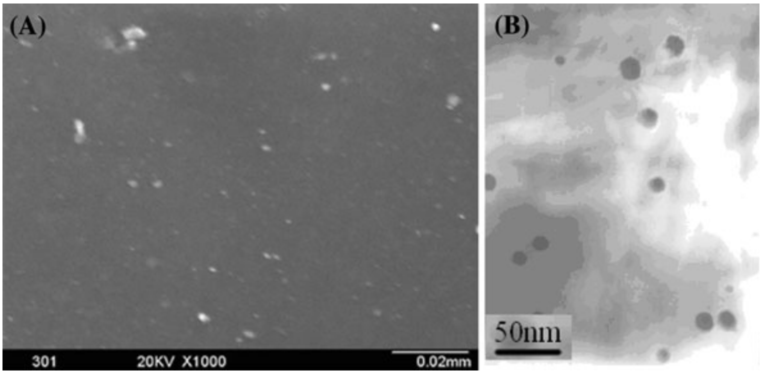


Fig. 1 **a** SEM image of magnetic rubber containing Fe_3O_4 nanoparticles and **b** TEM image of Fe_3O_4 nanoparticles

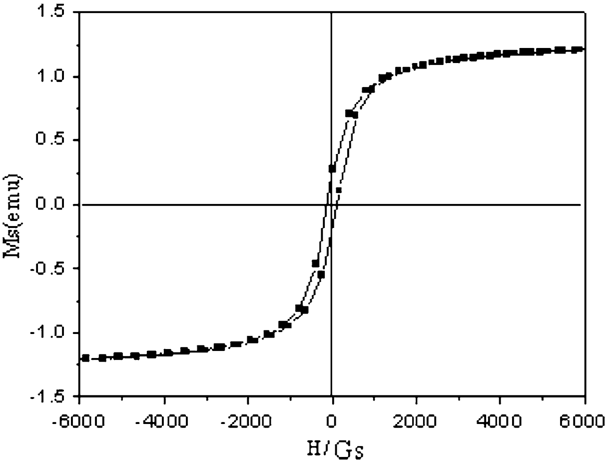


Fig. 2 The hysteresis loop of the magnetic rubber

preparation process could be carried out in a controlled manner. So, here we did not study the preparation of magnetic rubber in detail. The structure of the magnetic rubber was verified by the SEM image as shown in Fig. 1a. It shows that few particles aggregate. Furthermore, the gaps between Fe_3O_4 nanoparticles and nature rubber are not also seen. Here, the good dispersion is attributed to the strong adhesion between Fe_3O_4 nanoparticles and rubber matrix. In addition to this, the dimension of fillers is almost same with pure Fe_3O_4 nanoparticles (as shown in Fig. 1b), further suggesting that the Fe_3O_4 nanoparticles are good dispersion in nature rubber. These characterizations are very important to study the damping property of magnetic rubber.

Figure 2 shows the hysteresis loops of the magnetic rubber. It records 16.7 emu/g saturation magnetization and 152.0 Gs coercive force. The result indicates that the Fe_3O_4 nanoparticles is easy to be magnetized, meanwhile, magnetic dipole moments

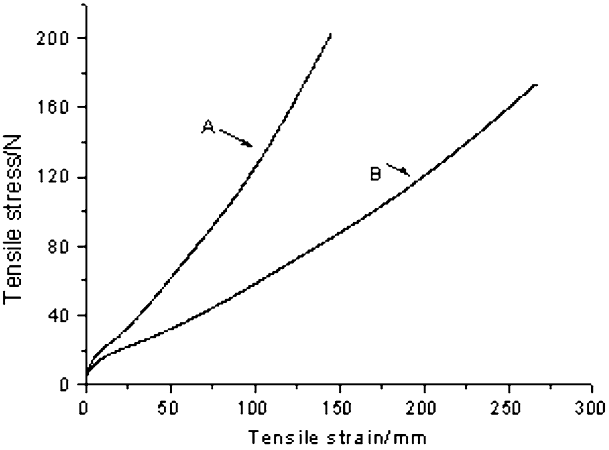


Fig. 3 The stress–strain curve of the (*a*) structure magnetic rubber and (*b*) nature rubber

are easy to be induced, which causes the formation of magnetic field inside the magnetic rubber. It provides an opportunity to study the effect of magnetic field on the damping property of rubber.

The tensile strength of the magnetic rubber was further investigated by the tensile test. Figure 3 shows the typical tensile stress–strain curves of the nature rubber and magnetic rubber with a loading of 20 phr Fe_3O_4 nanoparticles. It shows that the tensile strength of nature rubber increases from 13.9 to 15.8 MPa after filling with Fe_3O_4 nanoparticles. The result was different from the previous works [14, 15], in which the tensile strength of magnetic rubber decreased with increasing in doping content of magnetic particles. Here, the improvement of tensile strength further suggests that the magnetic nanoparticles grafted with polymer are well dispersed in rubber matrix, which is necessary to the application of magnetic rubber on the vibration isolators.

The compression test of magnetic rubber was carried out as shown in Fig. 4. It shows the variation of the percentage of compression set against time for the two types of magnetic rubber. From this Fig. 4, it is clear that the percentage of compression set increases with increasing in time. It is interesting that the percentage of compression set of structure magnetic rubber is relatively lower compared with isotropic magnetic rubber. This is due to that the magnetic field on the structure magnetic rubber can create a repulsive force, which restricts the compression. In addition to this, the smaller distance between nanoparticles on the structure magnetic rubber reduces mobility of the rubber chains, which also restricts this compression [14]. Generally, it is lower for the compression set, and it is better for using in the damping material.

The damping property of magnetic rubber was further characterized by using a dynamic mechanical analyzer as shown in Fig. 5. The dynamic stiffness, static stiffness and loss factor are concluded in Table 1. As observed from this table, comparing with isotropic magnetic rubber, the dynamic and static stiffness of structure magnetic rubber increase from 2619.0 and 2624.4 N mm^{-1} to 3371.0 and 3126.3 N mm^{-1}, respectively. The result is attributed to repulsive force of magnetic

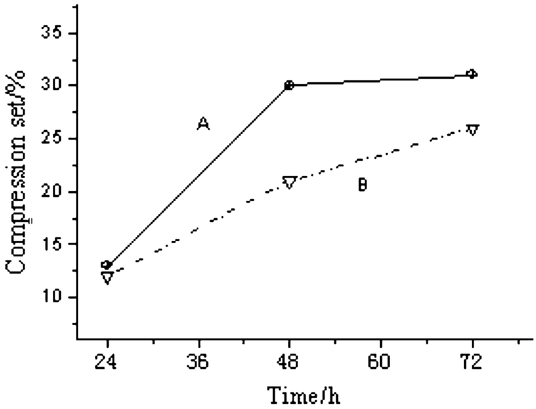


Fig. 4 The percentage of compression set of (*a*) isotropic magnetic rubber and (*b*) structure magnetic rubber in various times

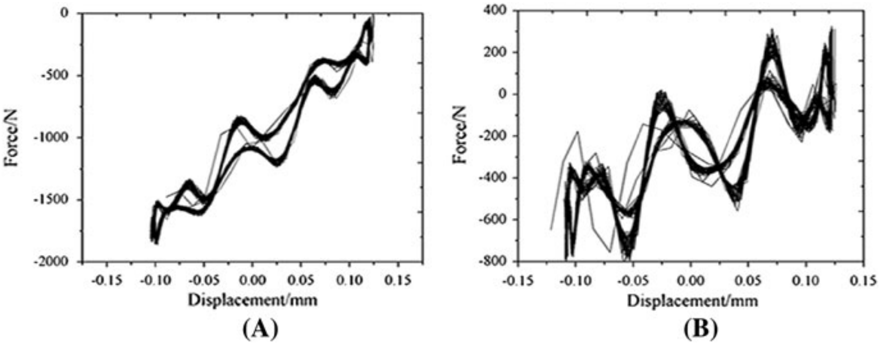


Fig. 5 Dynamic stiffness graphs of **a** structure magnetic rubber and **b** isotropic magnetic rubber in various times

Table 1 Damping properties of magnetic rubber vibration isolator

	Dynamic stiffness/N mm^{-1}	Static stiffness/N mm^{-1}	Loss factor
IMRE	2638.0	2624.4	0.007
SMRE	3371.0	3126.3	0.15

field inside the rubber and the decrease in the distance between nanoparticles, consequently, induce the improvement of stiffness of the structure magnetic rubber. The result is consistent with the result of Fig. 3. Moreover, the loss factor of structure magnetic rubber is also improved from 0.07 to 0.15 compared with isotropic magnetic rubber. The result was different with the previous work [14], in which the loss factor of structure MREs decreased when the free volume became smaller due to that the distance between the particles was much closer than that of isotropic MREs at the same particle content. Here, the observed larger loss factor is attributed that the effect of repulsive force of magnetic field on the loss factor is larger than that of decrease in free volume. The properties are in agreement with the results for magnetic fluid damper [6].

Conclusions

The magnetic rubber was prepared and their mechanical and damping property were further investigated. The tensile strength of MERs was improved from 13.9 to 15.8 MPa compared with nature rubber. Moreover, the loss factor of structure magnetic rubber increased from 0.07 to 0.15 compared with isotropic magnetic rubber. Therefore, it was shown that the magnetic Fe_3O_4 nanoparticles were a kind of effective fillers for enhancing mechanical properties and loss factor of rubber. Furthermore, it was also shown that the stiffness and loss factor of the magnetic rubber could be controlled by an external homogenous magnetic field, which is expected to apply on smart materials. The detailed future studies are needed to study the effect of external homogenous magnetic field on the damping property of magnetic rubber.

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