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Influence of arrangement field on magnetostrictive and mechanical properties of magnetostrictive composites

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Abstract: Non-aligned and aligned polymer-bonded $Tb_{0.3}Dy_{0.7}Fe_2$ composites with 20% particle volume fraction were prepared under different arrangement fields (i.e. 0, 10 kA/m, 20 kA/m, 30 kA/m, 60 kA/m and 100 kA/m) during their gel process. Static magnetostriction, dynamic magnetostriction, elastic modulus and compressive strength of all specimens were tested and compared. Experimental results indicate that all the parameters are positively dependent on the arrangement field. The dependence is significant at low field levels, the critical value of which is 30 kA/m for the composites fabricated. No obvious improvement of the properties can be observed for a larger field. Such critical values are defined as the optimal arrangement field to manufacture magnetostrictive composites.

Key words: magnetostrictive composites; Terfenol-D; arrangement field; magnetostriction

1 Introduction

Magnetostrictive effect, the phenomenon of the change in elastic state exhibited by certain ferromagnetic materials subjected to changes in the magnetization state, was first observed by JOULE more than 150 years ago[1].

Early researchers studied magnetostriction of iron, nickel, and cobalt. With the discovery of the significant magnetostriction found in the rare earth materials in 1960s, a new era in magnetostrictive materials was begun. An excellent magnetostrictive material discovered by CLARK in 1970s was called Terfenol-D, a specially formulated compound of terbium, dysprosium, and iron, which has saturation magnetostriction more than 1×10^{-2} at room temperature and relatively small applied field. Therefore, it has been a commercially available magnetostrictive material for application in many fields[2]. However, the brittleness in tension and the development of eddy currents have limited its useful frequency range[3]. In response to these shortcomings, SANDLUND et al[4] combined Terfenol-D particles with a passive polymer matrix to form magnetostrictive particulate composites. The insulating layer created by the matrix between the particles eliminates eddy current losses at high frequencies. Moreover, the polymer matrix produces a relatively tough material that can better accommodate tensile and shear loading states[5−7].

Composites based on 1-3 architectures were produced by aligning Terfenol-D particles in the matrix with an applied magnetic field during the thermal cure process[8−10]. Previous studies proved that the 1-3 type magnetostrictive composites exhibit larger magnetostriction than those based on 0-3 architectures, which are fabricated by dispersing Terfenol-D particles randomly in a polymer matrix[11−13]. But surprisingly, studies have not agreed on the degree of influence of the arrangement field on the properties of the composites. For instance, in SANDLUND's experiment, the saturation magnetostriction of 1-3 composites was 40% higher than that of 0-3 ones, while in LIM's experiment, the promotion was 10%[12−13]. We conjecture the reason to the different arrangement fields applied, which needs to be verified by experiments. In addition, the effects of the arrangement fields on magnetomechanical

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coupling coefficient, elastic modulus and compressive strength need to be studied.

In this study, 0-3 type and 1-3 type magnetostrictive composites were prepared by dispersing Terfenol-D particles with 20% particle volume fraction in an unsaturated polyester resin matrix. Different arrangement magnetic fields (i.e. 0, 10 kA/m, 20 kA/m, 30 kA/m, 60 kA/m and 100 kA/m) were applied during the gel process to align the particles along the longitudinal direction of the mold. The static and dynamic magnetostrictive properties, magnetomechanical coupling coefficient, elastic modulus and compressive strength of the samples were tested.

2 Experimental

2.1 Materials

Terfenol-D powder was supplied by the Gansu Tianxing Rare Earth Functional Materials Co. Ltd., China. The particle shape is irregular (Fig.1) and the particles size is normally distributed in the range of 30−500 μm (Fig.2). A three-part unsaturated polyester resin with a low viscosity of 0.2 Pa·s(25 ℃) and a high elastic modulus of 3 GPa was used as polymer matrix. The gel time of the resin system was 30 min at room temperature.

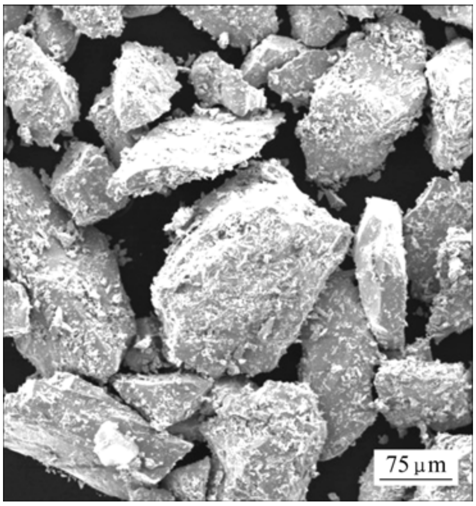

Fig.1 Irregular shape of Terfenol-D particles

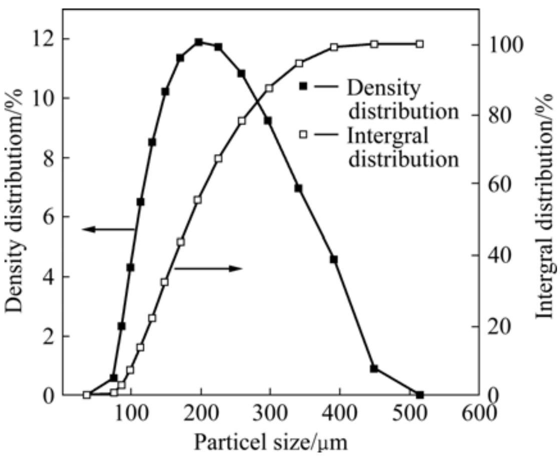

Fig.2 Particle size distribution

2.2 Specimen fabrication

All the ingredients were mixed by using a stirrer bar for about 5 min at room temperature. After all ingredients were evenly mixed, the mixture was put into a duralium mold with a cavity of *d*10 mm×25 mm. Then the mold was placed in a vacuum for degassing. Three minutes later, the mold was sealed and placed in an arrangement field (i.e. 0, 10 kA/m, 20 kA/m, 30 kA/m, 60 kA/m and 100 kA/m) which was generated by a PEM−1022LS magnetic field system. Twenty-two minutes later, the resin became gel and the mixture system was supposed to be stable. Then, the mold was placed in an oven and cured at 80 ℃ for 2 h. Finally, specimens were obtained by removing from the mold. To minimize the end effects, very small bi-directional strain gauges (1 mm×1 mm) located at the center of the length direction of the composite samples were used to measure magnetostriction, as shown in Fig.3.

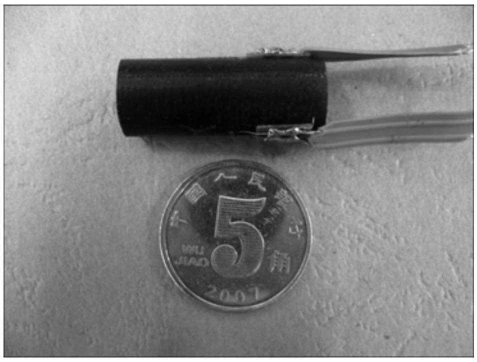

Fig.3 Photo of specimen

2.3 Apparatus and procedures

The magnetic field was generated by a PEM−1022LS magnetic field system, the intensity of which was adjusted in the range of 0−796 kA/m by tuning the electric current intensity. A Hall probe connected with a CST-Ⅱ magnetometer was used to measure the magnetic field. A YE2537 strain measuring instrument was used to measure the magnetostriction.

Under constant external preload, dynamic magnetostriction d_{33} is obtained from

$$d_{33}=\left(\frac{\partial\lambda}{\partial H}\right)_{\sigma} \tag{1}$$

where λ is the magnetostriction and H is the applied field. To obtain d_{33} behavior with the applied field, a three-parameter sigmoidal function was fitted to λ vs H plots. The pointwise slopes of the fitting curves correspond to

d_{33}, which can be achieved by differentiating the curves.

In order to measure the dynamic magnetomechanical properties of the composites in the longitudinal direction at room temperature with zero stress bias, specimens were placed inside two solenoids: an inner solenoid for generating an AC magnetic drive field, and an outer solenoid for providing a DC magnetic bias field. The drive solenoid was made by winding a layer of 80-turn magnetic wire, connected electrically parallel to each other, on a 60 mm-long, 12 mm-inner diameter Teflon bobbin. The bias solenoid had a length of 60 mm, an inner diameter of 18 mm, with a multi-layer of 830 turns. A pair of steel rods, situated at both ends of the sample, homogenized the magnetic flux distribution at or near the ends[14]. An impedance analyzer (SI 1260) was used to generate a swept sinusoidal voltage of constant amplitude at a prescribed frequency range. The output impedance frequency spectra at different bias field levels were recorded. The magnetomechanical coupling coefficient (k_{33}) was calculated as

$$k_{33}=\sqrt{\frac{\pi^2}{8}\left(1-\frac{f_r^2}{f_a^2}\right)} \qquad (2)$$

where f_r and f_a are the resonance and anti-resonance frequencies, respectively.

To test the mechanical properties including the elastic modulus and the compressive strength under zero magnetic field bias, the samples were mechanically loaded using an MTS system. All the compression tests reported were conducted in load control mode. The YE2537 strain measuring instrument was used to measure the strain.

3 Results and discussion

3.1 Effects of arrangement field on static magnetostriction

Fig.4 shows the relationship between the static magnetostriction and the applied field of the specimens. The magnetostriction is a function of the applied field. Under the same applied field, the strain of the specimens prepared under larger arrangement field is larger than that under smaller field. Fig.5 presents the relationship between saturation magnetostriction and arrangement field. It is indicated that the saturation magnetostriction increases fast with increasing the arrangement field at low field levels (i.e. 0−30 kA/m), while it becomes slower at high levels (30−100 kA/m). The specimen prepared under 10 kA/m arrangement magnetic field presents a saturation magnetostriction 32% larger than that of non-aligned one, while the specimen prepared under a 30 kA/m magnetic field presents a 61% larger saturation magnetostriction. However, the promotion of

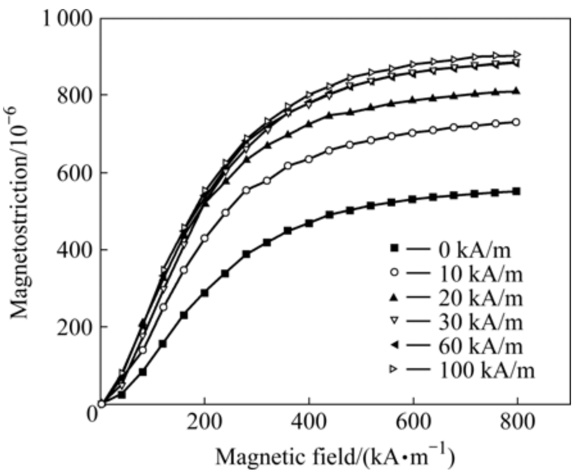

Fig.4 Relationship between static magnetostriction and applied field for specimen prepared under different arrangement fields

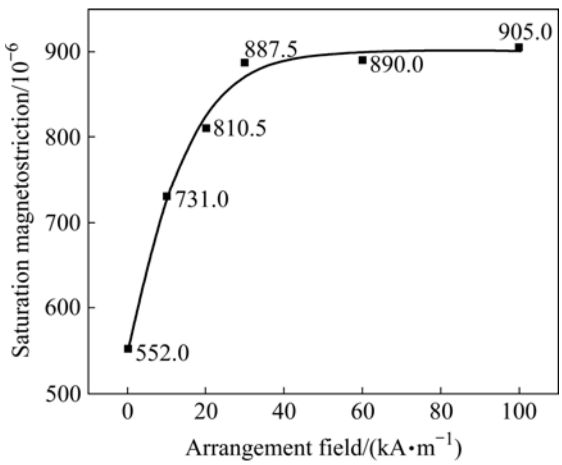

Fig.5 Relationship between saturation magnetostriction and arrangement field

static magnetostrictive property becomes insignificant by applying an arrangement field larger than 30 kA/m.

The reason for this phenomenon is possibly that more particles are rotated in their easiest magnetic direction along the field direction with increasing the arrangement field. When the field reaches a certain value, nearly all the particles have been fully rotated, and no obvious increase of magnetostriction can be observed with a larger field.

3.2 Effects of arrangement field on dynamic magnetostriction

Fig.6 presents plots of d_{33} as a function of the applied field for all specimens gelled under different arrangement fields. It is shown that, for all the composites, d_{33} increases initially up to a certain peak and then decreases with increasing the applied field. As the arrangement field increases, the maximum dynamic magnetostriction increases, as shown in Fig.7. With the

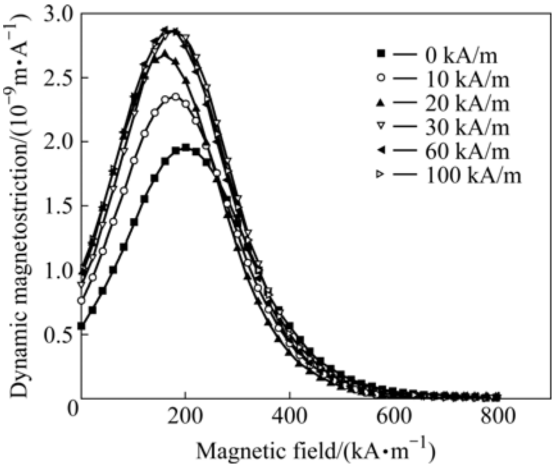

Fig.6 Relationship between dynamic magnetostriction and applied field

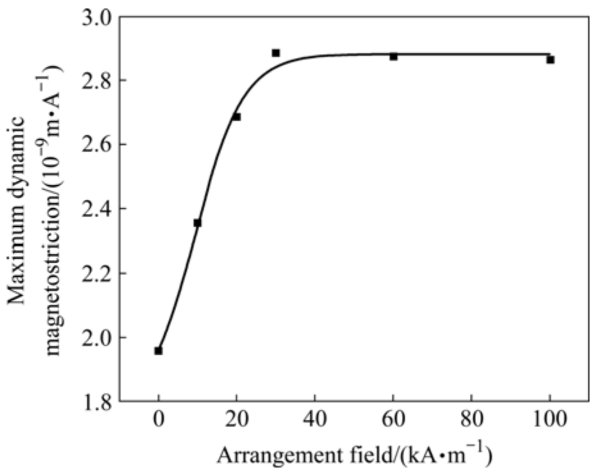

Fig.7 Relationship between maximum dynamic magnetostriction and arrangement field

same reason of variation of the static magnetostriction, the tendency becomes insignificant when the arrangement field is larger than 30 kA/m.

3.3 Effects of arrangement field on magnetomechanical coupling coefficient

The magnetomechanical coupling coefficients under different bias fields (i.e. 14 kA/m, 28 kA/m, 42 kA/m and 50 kA/m) for all specimens are obtained by substituting their resonance and anti-resonance frequencies into Eq.(2). The dependence of k_{33} on magnetic bias field for all specimens is similar, as shown in Fig.8. k_{33} reaches its maximum value when the bias field approximates 40 kA/m, then decreases with increasing the bias field, although the data at high magnetic bias field levels are not given due to the limit of the DC current source. In the same magnetic bias field level, specimens prepared at high arrangement field levels present a larger magnetomechanical coupling coefficient than those prepared at low levels. In Fig.9 the relationship between k_{33} and the arrangement field at a 42 kA/m bias field is plotted. The improvement of k_{33} with increasing the arrangement field is significant at low field levels (i.e. 0−30 kA/m), while it becomes less obvious at high levels (i.e. 30−100 kA/m).

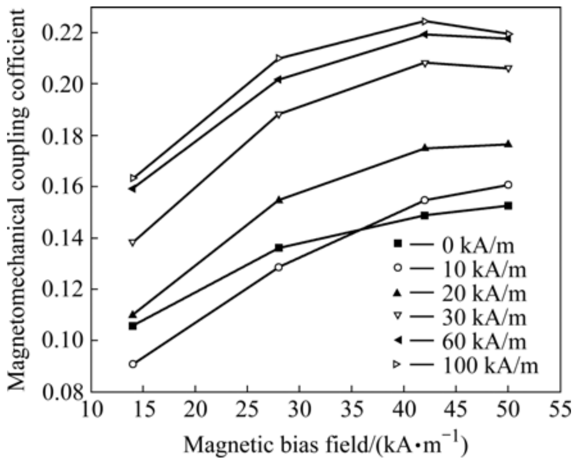

Fig.8 Relationship between magnetomechanical coupling coefficient and magnetic bias field

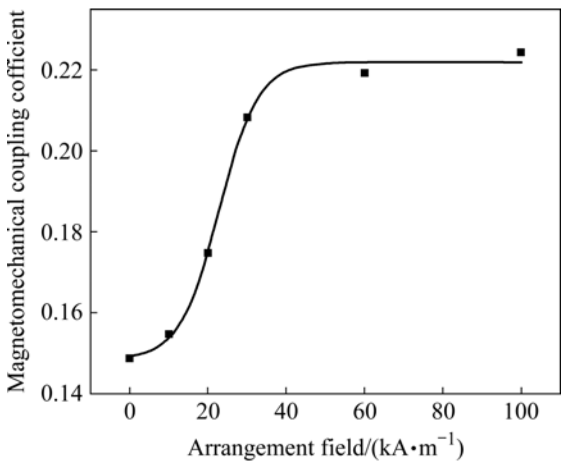

Fig.9 Relationship between magnetomechanical coupling coefficient and arrangement field at 42 kA/m bias field

3.4 Effects of arrangement field on mechanical properties

Fig.10 shows the relationship between the elastic modulus at zero bias field and the arrangement field. It is indicated that the elastic modulus dramatically increases with increasing the arrangement field at low field levels. By applying an arrangement field larger than 30 kA/m, the promotion of the elastic modulus becomes slight. The specimens prepared under the arrangement field of 10 kA/m and 30 kA/m present elastic modulus 8.6% and 15.6% larger than non-aligned specimen, respectively. The phenomenon is consistent with the indication of the rule-of-mixtures approach. With the increase of arrangement field, the modulus values are closer to the theoretical upper bound, suggesting that the composites are closer to a 1-3 configuration rather than 0-3 type [15].

The dependence of compressive strength on arrangement field is similar to that of the elastic modulus, as shown in Fig.11. The specimens prepared under the arrangement field of 10 kA/m and 30 kA/m present 13.9% and 15.1% larger compressive strength than non-aligned specimen, respectively.

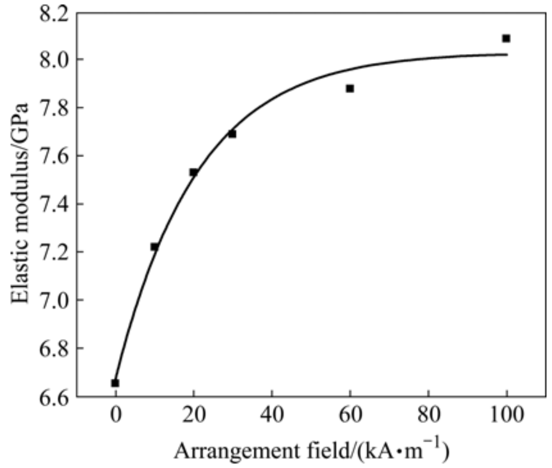

Fig.10 Relationship between elastic modulus and arrangement field

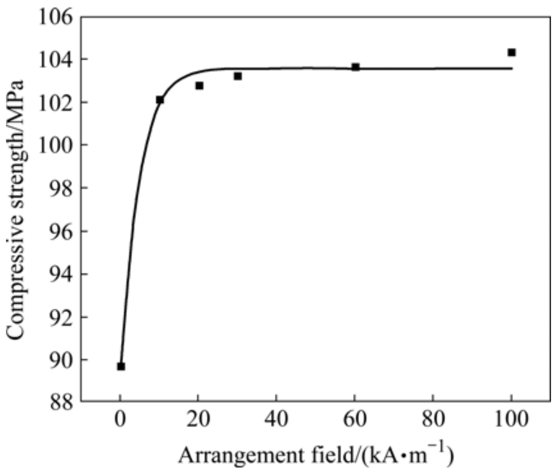

Fig.11 Relationship between compressive strength and arrangement field

4 Conclusions

1) Magnetostrictive properties of aligned magnetostrictive composites are larger than those of non-aligned ones.

2) The saturation magnetostriction and peak dynamic magnetostriction increase with increasing the arrangement field.

3) At the same bias field level, the magneto-mechanical coupling coefficient increases with increasing the arrangement field.

4) The elastic modulus and the compressive strength at zero bias fields positively depend on arrangement field.

5) An optimal arrangement field exists at 30 kA/m for no obvious improvement of the properties could be expected for a field larger than the optimal value.

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