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Fabrication of $Tb_{0.3}Dy_{0.7}Fe_2$/epoxy composites: Enhanced uniform magnetostrictive and mechanical properties using a dry process

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ABSTRACT

To improve the uniformity of the magnetostrictive properties of Terfenol-D composites along the field direction, a dry method is developed in the present study. We examined the compaction pressure, particle volume fraction, particle size and composite configuration as factors that affected the magnetostrictive properties of the composites. The experimental results indicated that the magnetostrictive properties were improved with the increase of compaction pressure and particle volume fraction. In addition, larger average particle size was shown to result in more pronounced magnetostrictive properties. The particle alignment due to the orientation field is beneficial for the promotion of the magnetostrictive properties. The largest saturation magnetostriction and the maximum piezo-magnetic coefficient in the absence of a mechanical preload was obtained at 1005 ppm and 4.08 nm/A, respectively, for the aligned composite including a particle volume fraction of 77% and an average particle size of 210 μm.

1. Introduction

Magnetostrictive materials generally refer to the materials whose shape changes as a function of the applied magnetic field [1]. Terfenol-D, an alloy composed of terbium, dysprosium and iron, represents a giant magnetostrictive material with huge commercial values, which have been adopted in a number of fields [2,3]. However, its more widespread applications may be limited by several factors such as the development of eddy currents with increasing frequency, the brittleness in tension, as well as the high cost [4–7].

To overcome the shortcomings of the monolithic Terfenol-D, a composite system (i.e. magnetostrictive composites) was developed by combining Terfenol-D particles with a polymer matrix. Compared with the conventional monolithic materials, magnetostrictive composites can offer several particular advantages in terms of reduced eddy currents losses, improved toughness, lower density and lower cost [8–10].

Traditionally, magnetostrictive composites were fabricated using a wet method. Since the settlement of the particles in the liquid polymers frequently occurred, the properties of the composites were inhomogeneous. Applying a magnetic field or reversing the mold during the fabrication is expected to overcome the disadvantages to some extent. In this study, a dry process was proposed to the solution of the problems as aforementioned, and the influencing factors were studied experimentally.

2. Experimental

2.1. Magnetostrictive composites samples preparation

Polycrystalline $Tb_{0.3}Dy_{0.7}Fe_2$ powder (Gansu Tianxing Rare Earth Functional Materials Co., Ltd., China) was used as the active particles to prepare magnetostrictive composites. The shape of the particles was irregular [11]. The particles were sieved into two groups with size distribution in the range 30–150 μm (average particle size of 102 μm) and 150–300 μm (average particle size of 210 μm). Epoxy resin in solid state, particle form, supplied by China Iron & Steel Research Institute Group, was used as the polymer matrix.

The $Tb_{0.3}Dy_{0.7}Fe_2$ particles were dispersed in an acetic acid solution for a few minutes to etch off a layer of surface, and then washed several times using distilled water. Epoxy resin particles were dissolved in an acetone solution. The washed $Tb_{0.3}Dy_{0.7}Fe_2$ particles were then dispersed in the solution. To ensure that all the particles were coated with the resin uniformly, an ultrasonic wave of 50 kHz was applied until all the acetone was volatilized. The treated $Tb_{0.3}Dy_{0.7}Fe_2$ particles were obtained.

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Then the coated particles were put into molds to form rod (for 0–3 composites) or cubic (for 1–3 composites) materials under a compaction pressure ranging from 600 to 1000 MPa. For the 1–3 composites, 20 kA/m orientation field was applied perpendicularly in the compressive direction before applying the compaction pressure. The compression process was carried out at room temperature. After being removed from the mold the samples were cured at 100 °C for 2 h.

Different magnetostrictive composites were fabricated to investigate the effects of the compressive pressure, the particle volume fraction, the particle size and the composites configuration on properties of the composites (Table 1).

2.2. Properties testing

The response of static magnetostriction λ to applied field H in the absence of an externally applied mechanical preload was evaluated directly by strain gauges. To test whether the distribution of the particles in the polymer matrix is uniform, three small strain gauges (1×1 mm^2) were glued at different positions along the length direction of the specimen No. 1 (Fig. 1).

Three magnetostriction–field (λ–H) curves obtained by measuring the strain response at different positions are illustrated in Fig. 2. There is a slight difference among the three curves indicating the distribution of the particles in the specimen is uniform. On the contrary, the magnetostriction–field curves measured at different positions for the composites prepared by traditional wet process were significantly different due to the non-uniform distribution of the particles in the matrix [12]. The uniformity of its properties is an inherent advantage of the composite prepared by the dry process. Therefore, the strain response measured by the strain gauge at the middle position was taken as the magnetostriction for the other specimens.

Under constant external mechanical preload, quasi static piezo-magnetic coefficient d_{33} was obtained from the λ–H plots via

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

A frequency domain method was employed by an impedance analyzer (SI1260) and two solenoids (a DC solenoid and an AC solenoid) to measure Young's modulus in the longitudinal direction at room temperature and with zero stress bias. This process involved application of a swept sinusoidal excitation of constant amplitude to the composite over the frequency in the range 50–90 kHz. The elastic modulus defined as the change in stress divided by the change in strain at constant magnetic field strength is related to the magnetic resonance (f_y) frequency, as observed from the spectrum by

$$E_{33}^{H} = 4l^2 f_r^2 \rho \tag{2}$$

where l and ρ are the length and density of the composite.

The density of the composites was tested according to Archimedes's principle. The electrical resistivity ρ_e of magnetostrictive composites is related to their characteristic frequencies, which was calculated by

$$\rho_e = R\frac{S}{l} \tag{3}$$

where R and S are the resistance and cross-sectional area of the specimens.

Scanning electron microscope (SEM, JSM-5600LV) was used to identify the morphological microstructure of the specimens.

3. Results and discussion

The static magnetostriction–field (λ–H) curves and the piezomagnetic coefficient-field ($d_{33}-H$) curves of all specimens are

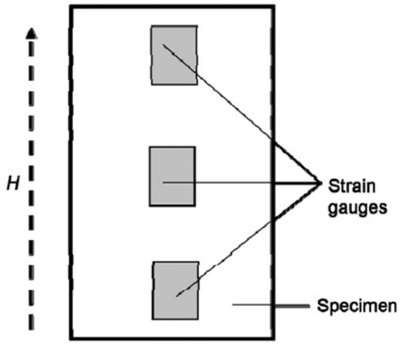

Fig. 1. Distribution of strain gauges on specimen No. 1.

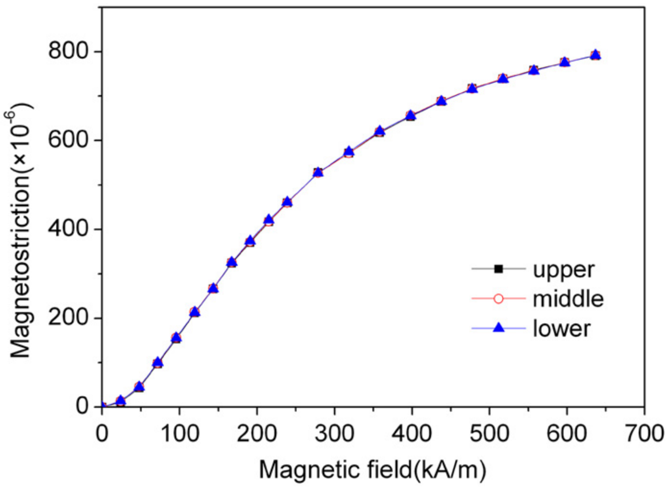

Fig. 2. Magnetostriction–field curves measured by the strain gauges at different positions along the length direction of the specimen No. 1.

Table 1
Design scheme of magnetostrictive composites specimens.

Specimens.	Compaction pressure (MPa)	Particle volume fraction (%)	Average particle size of $Tb_{0.3}Dy_{0.7}Fe_2$ (μm)	Composites configuration
No. 1	1000	77	102	0–3
No. 2	800	77	102	0–3
No. 3	600	77	102	0–3
No. 4	1000	77	210	0–3
No. 5	1000	62	210	0–3
No. 6	1000	52	210	0–3
No. 7	1000	77	210	1–3