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Intelligent epoxy matrix composite materials consisting of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ magnetostrictive particulates

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ABSTRACT

Purpose: This paper presents the acceptable technology to fabricate epoxy-bonded $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ composites in an effort to produce $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ bulks with good magnetostrictive properties through the optimization of some fabrication parameters.

Design/methodology/approach: Intelligent polymer matrix composite materials consisting of magnetostrictive particulates was obtained by homogenously mixing low viscosity epoxy resin and $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder with grains from 38 to 106 μm. The relationships among the manufacturing technology of these materials, their microstructure, as well as their magnetostriction were evaluated. Materialographic examination of powders morphology and the structure of composite materials were also made.

Findings: Composite materials consisting of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles can extend the possibilities of application the magnetostrictive materials and reduce the cost of their manufacturing. The obtained materials show regular distribution of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder in epoxy matrix.

Research limitations/implications: The advantages of the bonded magnetostrictive composite materials are their simple technology, possibility of forming their properties and lowering manufacturing costs. It is expected that the magnetostrictive properties of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ composites presented in this work can be further improved by amelioratethe fabrication parameters.

Originality/value: Manufacturing processes of intelligent epoxy matrix composite materials consisting of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ magnetostrictive particulates.

Keywords: Magnetic properties; $Tb_{0.3}Dy_{0.7}Fe_{1.9}$; Magnetostrictive composite materials; Polymer matrix

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PROPERTIES

1. Introduction

A magnetostrictive material is a material whose shape changes as a function of applied magnetic field. Magnetostriction λ is measured as the $\Delta l/l_0$, where l_0 is the length of the material in its un-magnetized state, along a given direction, and Δl the resulting strain.

The monolithic alloy of terbium, dysprosium and iron, commonly referred to as $Td_{0.3}Dy_{0.7}Fe_{1.9}$ (Terfenol-D) exhibits giant magnetostriction (800-1200 ppm) in a considerably low magnetic field (50-200 kA/m) at room temperature. The physical properties of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ are listed in Table 1.

Table 1.
$Tb_{0.3}Dy_{0.7}Fe_{1.9}$ properties [12]

Thermal properties	
Coefficient of thermal expansion	12 ppm/ºC
Thermal conductivity	13.5 W/m·K
Electrical properties	
Resistivity	58 x 10^{-8} Ω·m
Curie temperature	380 ºC
Magnetostrictive properties	
Strain (estimated linear)	800-1200 ppm
Energy density	14-25 kJ/m^3
Magnetomechanical properties	
Relative permeability	3-10
Coupling factor	0.75

$Td_{0.3}Dy_{0.7}Fe_{1.9}$ has attracted a great attention for many technological applications, such as actuation and sensing. However, many factors have limited its use [1-5]:

- development of eddy currents that limit useful frequency range (due to low electrical resistivity);
- brittleness in tension (causes difficulties in machining and device fabrication);
- large magnetic fields required to induce strain;
- high price.

For potential applications in technological devices, such as sensors and actuators, it is desirable to form a composite system by combining magnetostrictive phases with matrix, in order to have giant magnetostrictive effect and, at the same time, to reduce disadvantages of monolithic material [6-9].

The magnetostrictive composite materials have been developed as an alternative way to overcome each of mentioned above concerns. In particularly throughout [1,10,11]:

- reducing intrinsic brittleness;
- improve toughness and allows tensile loading;
- ameliorate manufacturability;
- decrease weight (with a much lower density).

Connection non-magnetic matrix with the magnetostrictive powder can significantly reduce the field strength necessary for large strains and improves the fracture resistance of the material; a non-metallic binder creates insulating layers between the particles, increasing resistivity, lowering eddy current losses and thereby increasing operating frequency. Additional benefits of using magnetostrictive particulate composites based on $Td_{0.3}Dy_{0.7}Fe_{1.9}$ particles and a passive polymer binder are their tailorable properties and cost-effectiveness [9,13,14].

Magnetostrictive composites are fabricated in an effort to produce materials with good magnetostrictive properties through the optimization of the many fabrication parameters. In recent years this area of designing composites attracts many investigations. Extensive studies have been conducted to evaluate magnetomechanical properties, in particular the magnetostriction as a function of drive field/magnetization, stress bias, temperature, elastic modulus of matrix, as well as particle size and volume fraction of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ [13-16]. Chen et al. [13] examined magnetostrictive composites with various kinds of matrices and concluded that the modulus of the matrix has a significant influence on effective magnetostriction. Duenas and Carman [14,17] conducted a series of experiments and studied the magnetostrictive response of the composite with resin and $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles. Hudson et al. [15] evaluated the dynamic properties of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ composites.

Although described above $Td_{0.3}Dy_{0.7}Fe_{1.9}$ composites have many advantages, there has been reported [11,17-19] significantly reduced magnetization and magnetostriction in that materials as compared to monolithic $Td_{0.3}Dy_{0.7}Fe_{1.9}$. Some experiments [20-22] have established that the magnetostriction would be improved when the particulate are magnetically aligned in the one direction (1-3 type composite). The field aligns the particles such that the mechanical behavior is similar to that exhibited by a continuous fiber composite. When a magnetic field is further applied, an effective magnetostriction has been observed due to the particle's magnetostriction and the magnetic interaction force between particles [22].

The main objective of this work concerns the research on the structure and magnetostriction of composite materials with the epoxy matrix reinforced by the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder.

2. Experimental

2.1. Material and technology

The magnetostrictive composites were prepared using $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder (Etrema Products Inc., USA) and a two-part epoxy resin as the binding material. The particles were of varying shape of 38-106 µm. The epoxy resin was supplied by Polysciences and has low viscosity of 60 cps, in order to permit sufficient particle wetting.

For this study, specimens containing particle volume fractions of 70, 75, 80 and 90 % were produced. For each case the particles and resin were homogenously mixed together. The resulting slurry was contained in rectangular aluminium mould of size 60x36x10 mm. Then the mixture was placed in an oven at 70°C for 10h to ensure full cure of the epoxy. After cooling, a specimen has been removed from mould, and it was grinding using abrasive paper (400 and 800 grade). The nominal shape of the composites were rectangular with dimensions 2x3x4 mm.

2.2. Measurements

Magnetostriction (λ) was measured by using a three terminal capacitance technique with a maximum applied magnetic field of 1 T. The design of the capacitance cell follows closely Tsuya's construction [23]. The cell was made up of a fixed electrode and movable one, which can move due to magnetostriction in both directions depending on the changes in length of a specimen. Any change in the dimension of the sample caused by the magnetostriction is observed as a variation in capacitance across the two electrodes [24,25]:

$$\Delta l = \frac{\varepsilon\varepsilon_0 S\Delta C}{(C - C_0)^2} \tag{1}$$

where:
ε – permittivity of free space,
ε_0 – dielectric constant of the environment,
S – area of the electrodes,
C_0 – a stray capacity (does not depend on the distance between the electrodes),
$\Delta C = C - C_1$ and

$$C = \frac{\varepsilon\varepsilon_0 S}{d} + C_0 \tag{2}$$

where:
d – the distance between electrodes.

All the measurements were performed at room temperature.

Observations of morphology of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder particles and resulting composite materials were made on the DSM 940 OPTON scanning electron microscope at the maximum magnification of 1000× using the secondary electron detection at the 15 and 20 kV accelerating voltage.

3. Results and discussion

3.1. Structure

The polymer matrix composite materials were reinforced with the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ magnetostrictive particles, which morphology, observed on the scanning electron microscope is shown in Figure 1.

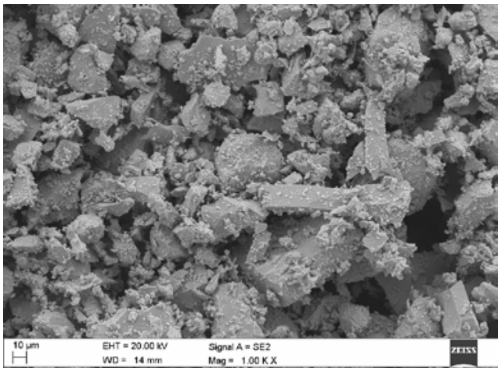

Fig. 1. Morphology of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder particles with the average size of 38-106 µm observed by SEM

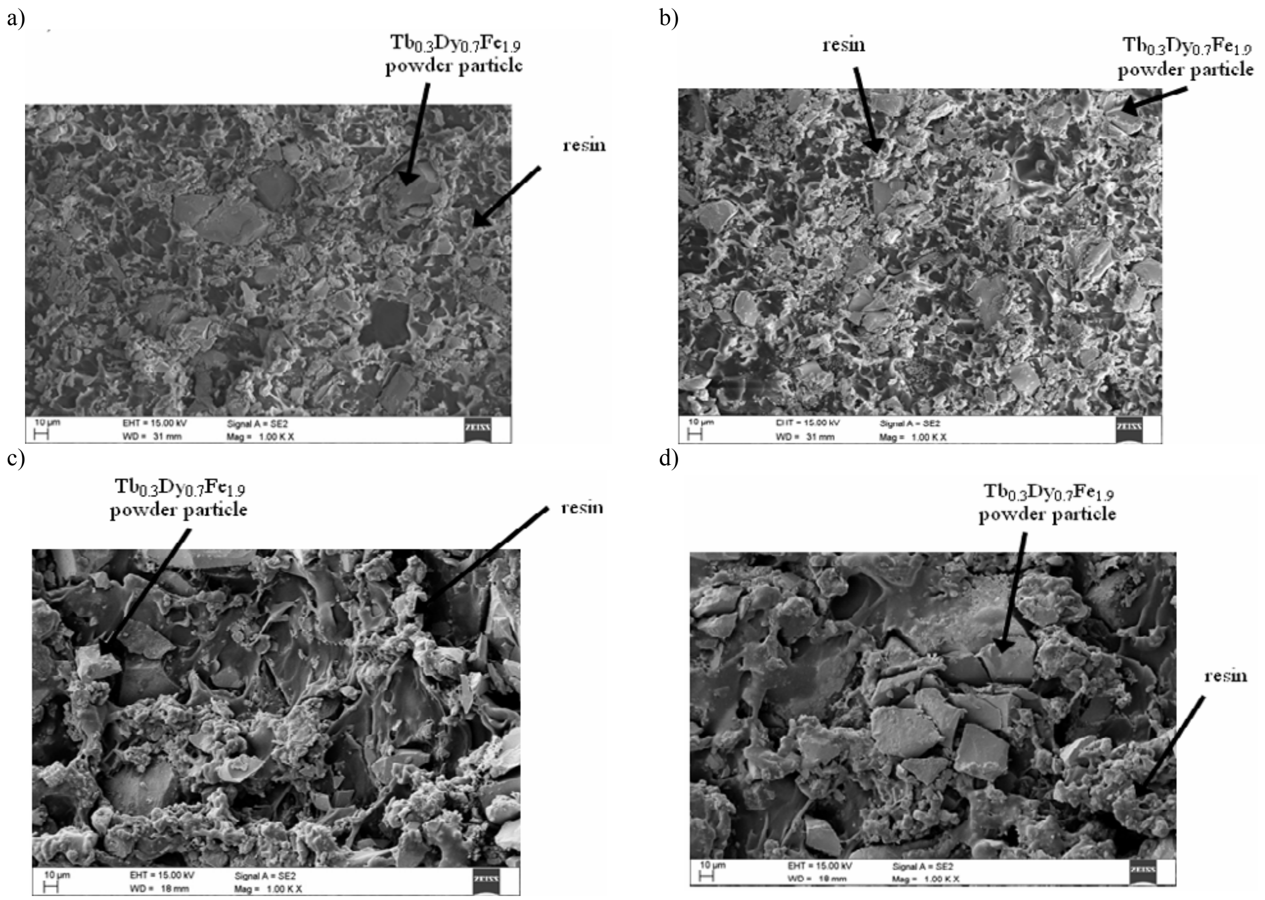

Fig. 2. SEM micrograph of a cross section of composite with 70 % (a), 75 % (b), 80 % (c) and 90 % (d) volume fraction of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$

Figure 2 shows structure of fabricated composite consisting $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particulates observed in scanning electron microscopy. Small portion of pores was notice, which confirm the good connection of powders with resin.

The high density of the composite materials was caused by the homogeneous distribution of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder in the matrix. Polymer material provides a good magnetic insulation of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder grains and restricts its oxidation.

3.2. EDS analysis

Examinations of the chemical composition on the particles made by the X-ray energy dispersive spectrometer (EDS) (Figure 3) confirms presence of iron, dysprosium and terbium in the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ magnetostrictive composites. Information about the weight and atomic ratios of the particular elements is given in the Table 2.

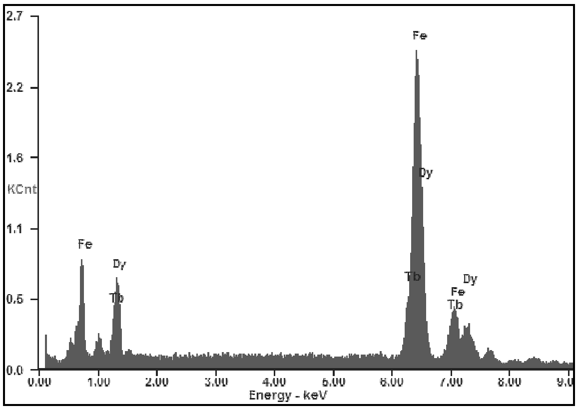

Fig. 3. EDS analysis of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder

Table 2.
Chemical composition of powders investigated in the present study (EDS)

Element	Concentration of element	
	wt. %	at. %
Tb	17.19	09.75
Fe	41.79	67.48
Dy	41.02	22.76

The obtained results confirmed that the chemical composition of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder is in good correlation with Etrema Products Inc. date.

3.3. Magnetostrictive results

In this section magnetostrictive strain response as a function of magnetic field is described.

Dependence of longitudinal magnetostriction on the induction of applied magnetic field B for samples of the composite with different volume fraction is shown on the Figure 4.

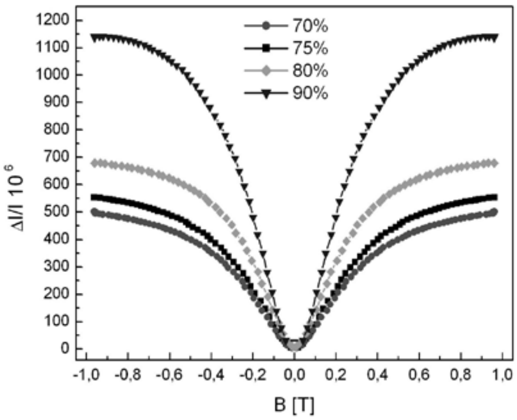

Fig. 4. Effective magnetostriction in the direction of magnetic field vs. applied magnetic field for composites with different volume fraction of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$

The value of λ measured at magnetic saturation is called the saturation magnetostriction λ_S. The saturation magnetostriction values measured parallel to the applied field are listed in Table 3. The composites reaches a saturation strain at most of 1050 ppm as compared to the monolithic $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ material saturation of 800-1200 ppm. This behaviour may be a result of the manufacturing process [9,10] for these composites.

For the sample having 90 % volume fraction, in the magnetic field with the induction of 0.59 T, the obtained value of the magnetostriction was 1050 ppm. It was the highest value of magnetostriction of all the samples analyzed. In the magnetic field with the induction of 0.49 T, the lowest value of the magnetostriction (397.94 ppm) was observed for the sample having 70 % volume fraction of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$.

Table 3.
Magnetostriction values for TD composites

TD, wt. %	Field, T	λ_S, ppm
70	0.49	397.94
75	0.63	498.54
80	0.53	600
90	0.59	1050

In order to see whether the magnetostrictive properties depend on the volume fraction, the results for λ for each type of specimens are shown in Figure 5. It is seen that the magnitude of λ is increased substantially by the volume fraction.

As the volume fraction of particulate increases, more domains are oriented parallel to the applied field and yields the highest magnetostrictive response at the same time. The 90 % and 80 % volume fraction specimens produced magnetostriction of 1050 and 600 ppm, respectively.

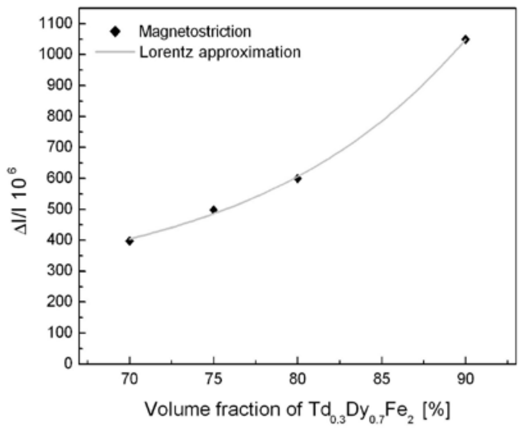

Fig. 5. Measured results for magnetostriction of composites with different volume fractions of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$. Measurements were made at B = 0.48 T

4. Conclusions

In this work, magnetostrictive properties of epoxy-bonded $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ composites have been investigated. By evaluating the effects of volume fraction, it was found that the composites with 90% volume fraction exhibit a great saturation magnetostriction value, reaching ~ 1050 ppm.

The epoxy resin used for the particle binder possesses a very low room temperature viscosity that is necessary for a quality composite, but also provides to decrease of magnetostriction in relate to the monolithic $Tb_{0.3}Dy_{0.7}Fe_{1.9}$.

Some researches conducted investigation to evaluate magnetostrictive properties of epoxy matrix composite materials consisting of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particulates, but any of them apply to $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder with grains from 38 to 106 μm

It is expected that magnetostriction of the intelligent polymer matrix composite materials achieved in this work can be further improved by more accurate fabrication parameters. There is some way for ameliorate magnetostriction of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ composite materials, which might be achieved for example by conducting particles alignment in the magnetic field before curing of epoxy. This procedure lead to obtain a more anisotropic composition. Secondly, use of different binders could show if the behaviour of matrix – powder particles connection will have influence on the properties these materials [20,22,26].

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