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Structure and magnetic properties of magnetostrictive $Td_{0.3}Dy_{0.7}Fe_{1.9}$ / polyurethane composite materials

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Materials

ABSTRACT

Purpose: The aim of this work is to obtain polyurethane matrix composite materials reinforced by $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles and to observe changes of magnetic properties and magnetostriction of samples with different particle size distributions of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder.
Design/methodology/approach: Polyurethane matrix composite materials reinforced by $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ magnetostrictive particles fabricating method were developed during the investigations, making possible to obtain materials with good physical properties. The influence of the concentration and powder particles size of the $Td_{0.3}Dy_{0.7}Fe_{1.9}$ on magnetic and magnetostrictive properties were estimated. Metallographic examination of powders morphology and the structure observations of composite materials were made.
Findings: Composite materials consisting of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ particles can extend the possibilities of application the magnetostrictive materials and reduce the cost of their manufacturing. The obtained materials show regular distribution of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder in polyurethane matrix.
Research limitations/implications: The advantage of polyurethane matrix magnetostrictive composite materials are their simple technology and lowering manufacturing cost in comparison to monolithic $Td_{0.3}Dy_{0.7}Fe_{1.9}$. These efforts can be considered as very up-to-date from the scientific point of view.
Originality/value: The originality of this investigations is the statement that increasing the size of the $Td_{0.3}Dy_{0.7}Fe_{1.9}$ particles cause increasing the strain response and this is due to the demagnetization effects.
Keywords: Smart materials; Magnetostrictive composites materials; $Td_{0.3}Dy_{0.7}Fe_{1.9}$; Magnetic properties

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1. Introduction

$Td_{0.3}Dy_{0.7}Fe_{1.9}$, commercialy called as Terfenol-D, has been known for its magnetostrictive properties and represents a very interesting class of smart materials. Magnetostrictive materials are useful for motion control applications and as elements of sensing systems for nondestructive damage evaluation [1-3]. Much of the work on developing the optimum properties of the $Td_{0.3}Dy_{0.7}Fe_{1.9}$ was carried out by Wu at al. and Palit at al. [4-6]. On the other hand, the limited applications of the $Td_{0.3}Dy_{0.7}Fe_{1.9}$ monolithic material arises from the intrinsic brittleness, high price, large magnetic fields required to induce strain and development of eddy currents in high frequency range. Potential solutions are $Td_{0.3}Dy_{0.7}Fe_{1.9}$ based composite materials, which have been examined since it was noticed that $Td_{0.3}Dy_{0.7}Fe_{1.9}$ disadvantages could be overcome by combining $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder with polymer matrix. The polymer creates an insulating layer between $Td_{0.3}Dy_{0.7}Fe_{1.9}$ particles and eliminates eddy current losses at high frequencies. The brittleness will decrease also, allows tensile loading [7-10].

Interaction between magnetic particles and bonding material are the keys to the overall properties of the composite [11,12], so for several years there have been made attempts to develop and produce $Td_{0.3}Dy_{0.7}Fe_{1.9}$ / polymer composite materials [13,14]. In some works epoxy, phenol type and vinyl-ester resin have been used as binders for $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder with satisfactory results [15-19].

The aim of this work is investigation of the magnetic properties, microstructures characterization of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder and structure of the composite materials with polyurethane matrix, as well as evaluation of the influence of particle size and volume fraction on the magnetostrictive response.

2. Experimental procedure

2.1. Material

The examined composite materials with 1.5% and 15% $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder by volume were prepared by distributing magnetostrictive fraction in polyurethane resin matrix. The $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder was obtained from Etrema Products Inc., USA and was varying in particles size of 38-106 µm, 106-212 µm and 212-300 µm. The two-part polyurethane resin (Smooth-cast 325) used as the binding material was supplied by KauPoSil and has ultra low viscosity.

In order to obtain composite material, the particles and resin were homogenously mixed together and the resulting slurry was contained in the mould. For each particle-size range, two rectangular samples with different volume fraction of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder were prepared. The dimensions of sample were 2x4x6 mm.

2.2. Investigation

Research have been conducted to evaluate the magnetostriction of composite materials as a function of magnetization as well as particle size and volume fraction of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$.

Observations of morphology of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder 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 10 and 20 kV accelerating voltage.

The magnetic behaviour of composite materials was characterized by the hysteresis loop measurements using vibrating-sample magnetometer (MagLab 1.2 T, Oxford Instruments, Ltd.) in room temperature and in a maximum field up to 1 T.

The magnetostriction was measured at room temperature either parallels or perpendicularly to the applied field using a three terminal capacitance technique with a maximum applied magnetic field of 1 T. The detailed measuring procedure has been described in details in the previous works [20,21].

3. Results and discussion

3.1. Structure

Morphology of the $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder, observed on the scanning electron microscope is shown in Fig. 1. Examinations of the chemical composition on the particles made by the X-ray energy dispersive spectrometer (EDS) confirms presence of iron, dysprosium and terbium in the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$, confirmed that the chemical composition of the powder is in good correlation with Etrema Products Inc. date [19].

Figures 2, 3 compares polyurethane matrix - $Td_{0.3}Dy_{0.7}Fe_{1.9}$ particle interfaces found in the obtained composite materials. Based on this investigation, the polymer-matrix bond appears to be of good quality. However, insignificant interfacial damage occurred in the composite with 1.5% volume ratio of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder and the particle size distribution of 212-300 µm (Fig. 2c). The observed material damage is likely due to the very low tensile strength of $Td_{0.3}Dy_{0.7}Fe_{1.9.}$ and high surface defect population of the ground particles.

Based on the scanning electron microscope examinations it was found out that with the higher content of the $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder, its particles are homogenously distributed in the entire polyurethane matrix. Examinations show that few voids in the specimens could be found.

3.2. Magnetic properties

The obtained composite materials are characteristic of remanence (B_r) and induction coercive force (H_c). Results of the magnetic properties study of the $Td_{0.3}Dy_{0.7}Fe_{1.9}$ / polyurethane composite materials are presented in Figs. 4 and 5.

The examination carried out indicate on difference of the magnetic properties of the composite materials depending on the particle size and concentration of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ fraction (Table 1). Tests revealed that the highest magnetic saturation (B_s = 0.120 T) was characteristic for the composite with 15% volume ratio of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder and the particle size distribution of 38-106 µm. Magnetic saturation values decrease along with increasing the particle size of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ (B_s = 0.006 T for the composite with 1.5% volume ratio of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder and the particle size distribution of 212-300 μm).

It was estimated that remanence (B_r) value increase with the addition of the magnetic part in the composites, while coercive force (H_c) is not influenced.

a)

b)

c)

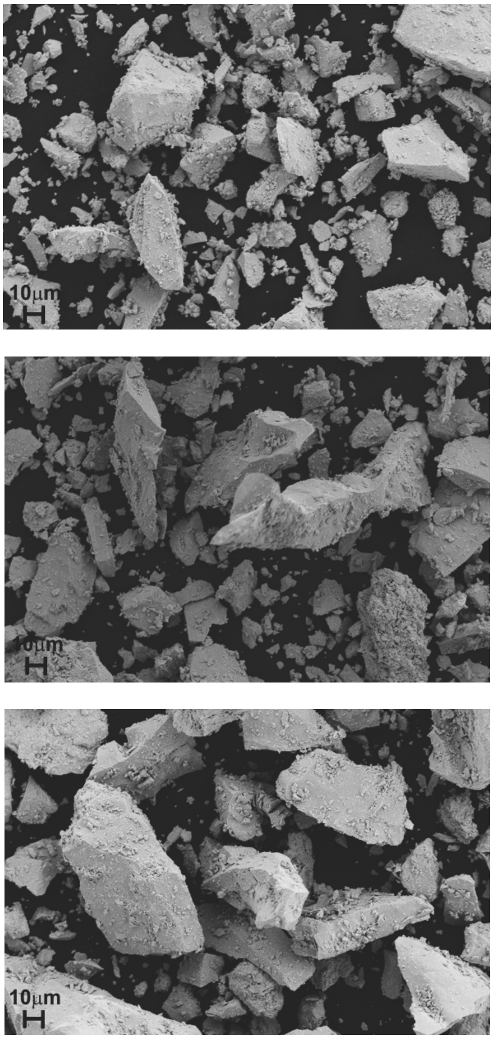

Fig. 1. Morphology of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder with the average size of: a) 38-106 μm, b) 106-212 μm and c) 212-300 μm; SEM

3.3. Magnetostrictive results

Magnetostriction is attributed to change shape the crystals of ferromagnetic materials when they are placed in a magnetic field. The increase in length (longitudinal strain) or the contraction of diameter (lateral strain) is roughly proportional to the applied magnetic field.

a)

b)

c)

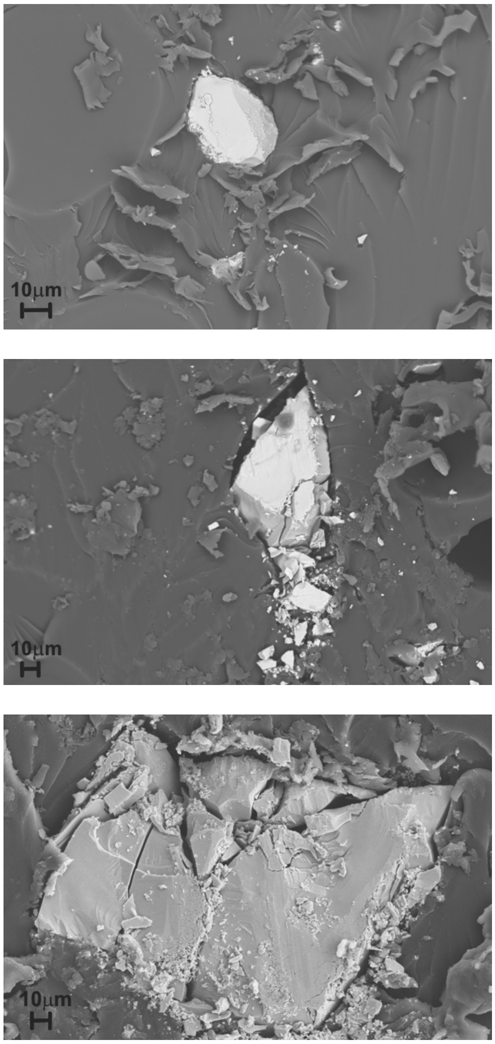

Fig. 2. Structures of the composite materials with the polyurethane matrix reinforced with the 1.5% volume ratio of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder. The particle size distribution of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ are: a) 38-106 μm, b) 106-212 μm and c) 212-300 μm; SEM

Table 1.
Magnetic properties of the composite materials with the polyurethane matrix reinforced with the $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder

$Tb_{0.3}Dy_{0.7}Fe_{1.9}$, vol. %	Grain size, μm	H_{max}, kA/m	H_c, kA/m	B_S, T	B_r, T
1.5	38-106	1218	0.71	0.016	0.00018
	106-212	1213	0.73	0.010	0.00014
	212-300	1213	0.73	0.006	0.00004
15	38-106	1215	0.71	0.120	0.0013
	106-212	1212	0.73	0.105	0.001
	212-300	1216	0.74	0.08	0.0007

a)

b)

c)

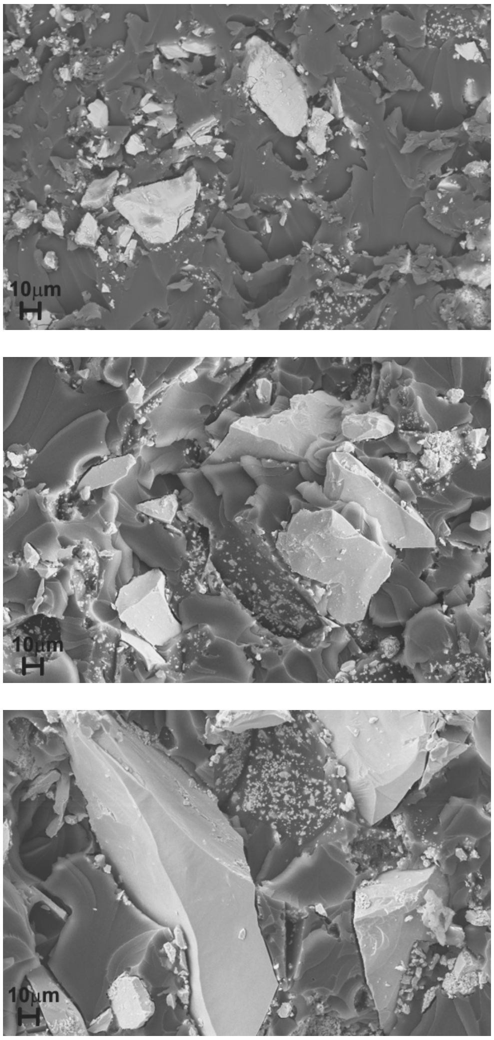

Fig. 3. Structures of the composite materials with the polyurethane matrix reinforced with the 15% volume ratio of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder. The particle size distribution of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ are: a) 38-106 µm, b) 106-212 µm and c) 212-300 µm; SEM

The magnetic-field dependence of magnetostriction for composites is shown in Figs. 6, 7. The results are from the samples with different binder contents and different particle size distribution in obtained composite materials. It can be seen that magnetostriction values increase with increasing the applied magnetic field (Table 2) and reach a highes value of 481 ppm at 0.946 T for the composite with 15% volume ratio of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder and the particle size distribution of 212-300 µm.

It is evident that for the composite with 1.5% volume ratio of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder, the saturation magnetization becomes small. Te relatively low magnetostriction may be due to the poor contact of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles combined with a too little amount of the magnetostrictive powder. The decrease in the magnetostrictive property with increasing the binder content can be explained by the dilution of the nonmagnetic binder.

The results have revealed a strong dependence of composite properties on different particle size distribution in the polyurethane matrix. For a given particle volume fraction of $Td_{0.3}Dy_{0.7}Fe_{1.9}$, increasing particles size, mainly increase the magnetostrictive response. This is due to the demagnetization effects associated with particle size and reduce the magnetic field a single particle experiences and thus reduce the strain responses.

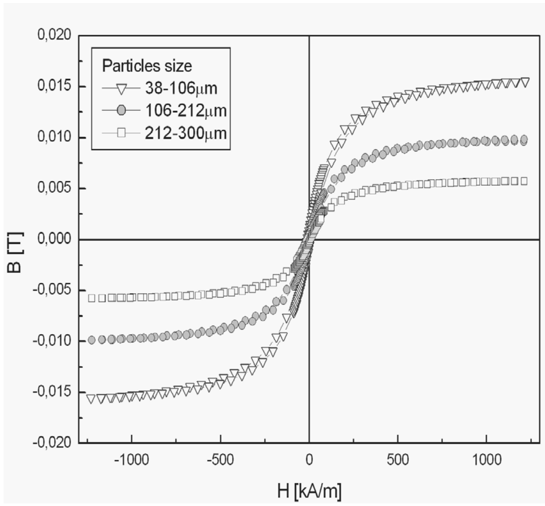

Fig. 4. Hysteresis loops of the $Td_{0.3}Dy_{0.7}Fe_{1.9}$ / polyurethane composite materials with different particles size for 1.5% volume fraction of $Td_{0.3}Dy_{0.7}Fe_{1.9}$

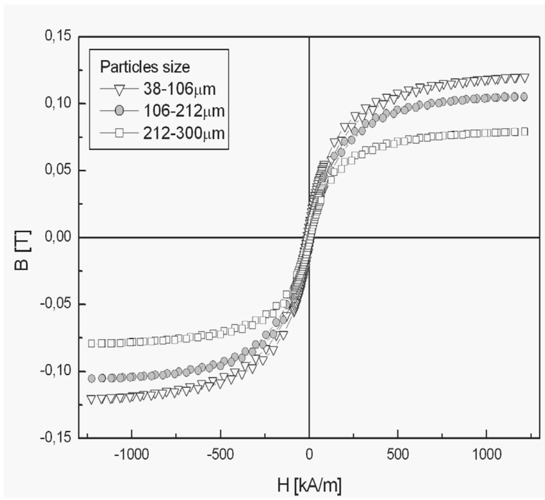

Fig. 5. Hysteresis loops of the $Td_{0.3}Dy_{0.7}Fe_{1.9}$ / polyurethane composite materials with different particles size for 15% volume fraction of $Td_{0.3}Dy_{0.7}Fe_{1.9}$

Table 2.
Saturation magnetostriction values for the composite materials with the polyurethane matrix reinforced with the $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder

$Tb_{0.3}Dy_{0.7}Fe_{1.9}$, vol. %, vol. %	Drain size, µm	Applied field, T	λ_S, ppm
1.5	38-106	0.952	26.1
	106-212	0.950	34.1
	212-300	0.962	39.2
15	38-106	0.951	332
	106-212	0.958	433
	212-300	0.946	481

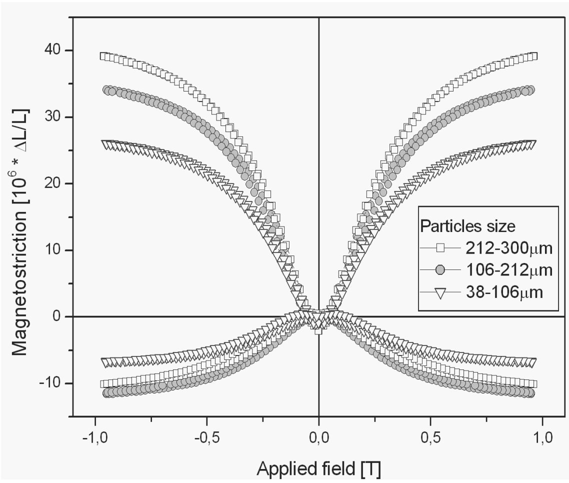

Fig. 6. Magnetic-field dependence of magnetostriction with the external applied field longitudinal and transverse to the internal bias field for $Td_{0.3}Dy_{0.7}Fe_{1.9}$ / polyurethane composite materials with different particles size for 1.5% volume fraction of $Td_{0.3}Dy_{0.7}Fe_{1.9}$

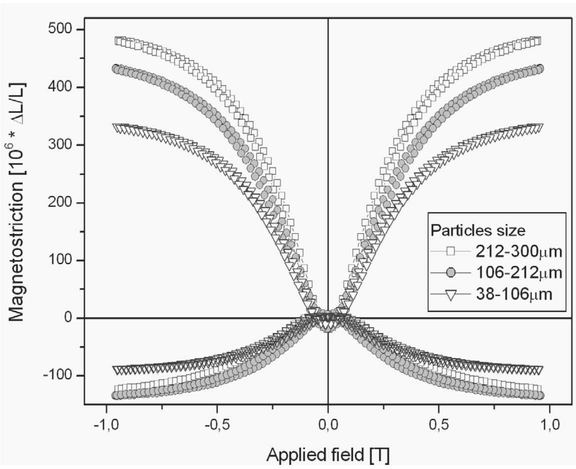

Fig. 7. Magnetic-field dependence of magnetostriction with the external applied field longitudinal and transverse to the internal bias field for $Td_{0.3}Dy_{0.7}Fe_{1.9}$ / polyurethane composite materials with different particles size for 15% volume fraction of $Td_{0.3}Dy_{0.7}Fe_{1.9}$

4. Conclusions

Basing on the investigation of the $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder and magnetostrictive $Td_{0.3}Dy_{0.7}Fe_{1.9}$ / polyurethane composite materials, the following statements can be derived:

- Scanning electron microscopy images reveal that the shape and size of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder particles is irregular;
- The higher $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder content, the more homogeneously distribute in the entire polyurethane matrix its particles are;
- Magnetic properties of composite materials varying with the particles size and concentration of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ fraction;
- The highest magnetic saturation (B_s = 0.120 T) was characteristic for the composite with 15% volume ratio of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder and the particle size distribution of 38-106 µm;
- Saturation magnetostriction of the composite materials increased with increased volume fraction of the magnetostrictive phase;
- The increase of particle size distribution of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder in composite materials amplify the magnetostrictive response (481 ppm at applied field of 0.946 T for the composite with 15% volume ratio of $Td_{0.3}Dy_{0.7}Fe_{1.9}$ powder and the particle size distribution of 212-300 µm).

These conclusions can be considered as very up-to-date from the scientific point of view and are very attractive for further investigation.

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