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Original Research Article

Magnetostriction of field-structural composite with Terfenol-D particles

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ARTICLE INFO

Article history:
Received 8 November 2013
Accepted 21 February 2015
Available online 20 March 2015

Keywords:
Smart materials
Active materials
GMM
SMART
Experimental mechanics

ABSTRACT

The paper describes the magnetomechanical properties of magnetostrictive composites containing a 70% volume fraction of Terfenol-D powder. Except for a reference specimen, composites were subjected to polarization during curing of the resin. The results of tests showed that polarization, its direction and type have an effect on the properties of the produced composites. The highest values of magnetostriction from the manufactured composite samples were obtained for the perpendicularly polarized specimen. For a pre-stress of 7 MPa the strain amounted to 720 ppm. The results indicate that the magnetostriction of the composite increases owing not only to the proper crystallographic orientation of the material, which is usually [1 1 2], but also to the proper preparation of the specimen in this case through polarization.

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1. Introduction and research goal

Giant magnetostrictive materials (GMMs) [1] can convert magnetic energy into mechanical energy (actuator-type action) and vice versa (sensor-type action). Terfenol-D, an alloy of rare earth elements terbium, dysprosium and iron, is particularly efficient in energy conversion. This material finds various applications in aircraft [2], car [3], ship [4] and civil engineering structures and is successfully used in medicine [5], the mining industry [6], acoustic equipment [3,4] and so on. A prospective application area for Terfenol-D, which is a typical representative of the GMM group, is (electric) energy harvesting from, for example, mechanical vibration systems [2,5]. Two drawbacks, i.e. low tensile strength and the occurrence of high eddy currents, detract from the numerous advantages of Terfenol-D. Attempts are made to eliminate the drawbacks through composite materials.

The main advantages of magnetostrictive composites based on a nonmagnetic polymer matrix and containing Terfenol-D powder particles are:

- reduction of bulk Terfenol-D's drawbacks (eddy currents at higher operating frequencies and its brittleness limiting its use under, e.g., tensile stress [1,6]), whereby its application range is significantly extended;

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http://dx.doi.org/10.1016/j.acme.2015.02.009

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- new potential applications in, e.g., the structural heath monitoring (SHM) of composite materials and structures (tagging [7]).

1.1. *Motivation and main problems to be solved*

The main objective of many academic and industrial research centres is to produce a composite characterized by optimum magnetostriction (and possibly also inverse magnetostriction). The task is challenging for many reasons. An analysis of the literature on polymer composites with added Terfenol-D particles and the present authors' experience indicate that the following aspects are key:

- the form (continuous fibres, particles [8]) of Terfenol-D in composites and its (ordered, randomly oriented) distribution in the polymer matrix;
- the crystallographic orientation of particles [8];
- the volume fraction of Terfenol-D in the matrix, the possibility of adding other ferromagnetic powders [9];
- the type of polymer [9];
- the polymer manufacture process parameters (temperature, time, deaeration, etc.) [8];
- the parameters of the magnetic field used to create the structure of the GMM composite, demagnetization [8] and magnetization [10];
- the preloading (prestressing or prestraining) of the sample [11];
- the geometric dimensions of the specimen (particularly, the ratio of length to lateral dimensions, i.e., the aspect ratio) [12];
- the correct technique of measuring the deformation (magnetostriction) of the specimen under a strong magnetic field [13].

Aspects relating to the modelling of magnetostriction for this class of composites [12] were intentionally not included above, since the present research has an experimental character.

Therefore, the main goal of this research was to investigate the magnetostriction of a field-structural composite with Terfenol-D particles. Presented composites supposed to replace the bulk Terfenol-D rods in industrial applications such as actuators or dampers. It was decided to closely examine the influence of the polarization direction and a pre-stress σ_0 on received values of magnetostriction for newly created composite samples. The results were compared with those obtained for bulk Terfenol-D sample with the same geometry as prepared composites.

It was also deemed critical to use such a strain measuring method which would eliminate the strong influence of the magnetic field on the result.

2. Material preparation

A magnetostrictive composite (further referred to as: the GMM composite (GMMc)), was made by combining epoxy resin and GMM powder with a particle size of 5–300 μm. The particle size distribution and the particle shape and size are shown in Fig. 1. One can clearly see that the powder particles vary in their size and shape and have sharp edges.

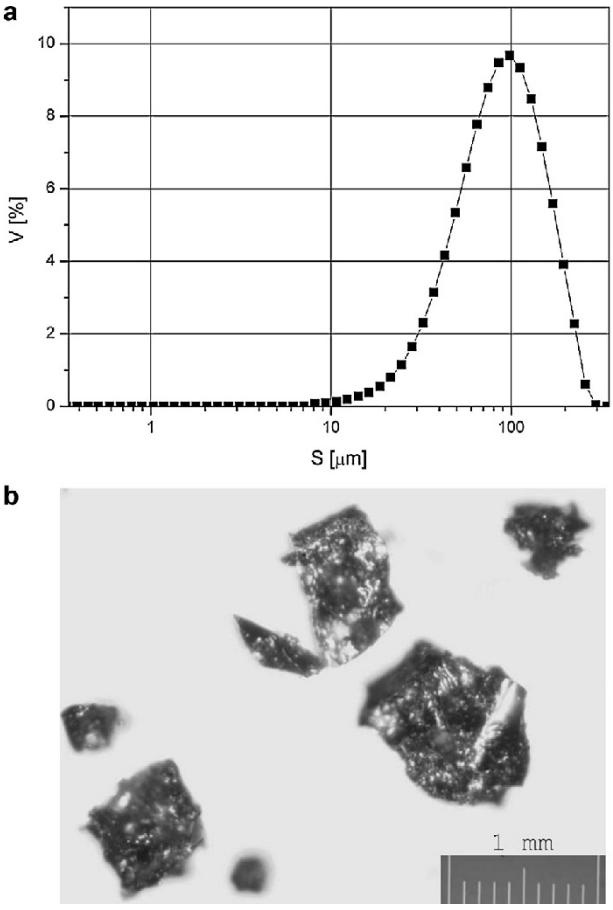

Fig. 1 – Particle size distribution and microscopic image of Terfenol-D powder.

The manufacturing procedure is shown in Fig. 2. First (stage A) a measured volume of hardener was added to epoxy resin Epolam 2015 (Axons Technologies). The ratio of hardener to the resin was 30/100. Next, to the prepared mixture, a Terfenol-D powder was introduced (D). The amount of Terfenol-D powder corresponded to 46% of volume fraction of the whole volume of mixture. Subsequently, the whole mixture was intensively stirred until all the components were homogenized (F). After proper stirring, the mixture was placed inside the vacuum chamber (G), where had place a deaeration process. Thus, the resin had a relatively low viscosity, the process allowed to get rid of unnecessary air introduced into the mixture during the sintering process. In the next step after deaeration the mixture was poured into previously prepared cylindrical containers (H). Then the containers with the mixture were subjected to polarization process together with additional deaerated. This additional deaeration process should allow to get rid of the air, which might had been introduced to the mixture during pouring process.

Finally (Fig. 2(J)), the prepared specimens were subjected to polarization.

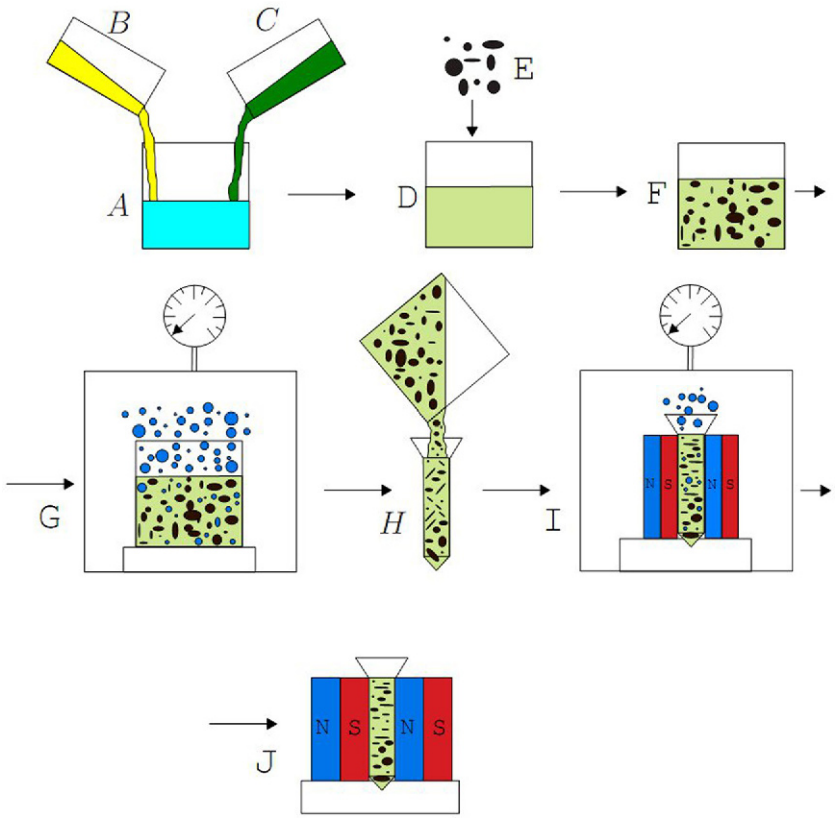

Fig. 2 – Scheme of specimen preparation procedure: mixing (A) epoxy resin (B) with hardener (C), preparation of resin mixture (D), addition of Terfenol-D powder (E) to resin mixture (F), deaeration (G), purring into container (H), additional deaeration (I), final polarization (J).

One of the samples was polarized perpendicularly and second parallel to the principal specimen axis. In order to obtain proper direction of polarization, the specimens were inserted between permanent magnets (perpendicular polarization) and into the coil (parallel polarization) as it was shown in Fig. 3(a and b). The value of magnetic field used for the preliminary magnetization was 150 kA/m. Immediately after inserting containers with the mixture in a magnetic field the specimens together with magnetic field sources were placed in the MTS testing machine. The testing machine was used in order to reduce the amount of the epoxy resin in the mixture. The resin was squeezed out with the use of specially prepared rods, with filters. The filters assured that the Terfenol-D particles stayed inside the containers. As a result, a material with an increased volume fraction of Terfenol-D powder was obtained. The specimens were left in the MTS testing machine for 4 h for preliminary cure of the resin. Next, they were placed in a furnace at a temperature of 80 °C for 24 h until the matrix fully cured. The GMMs produced in this way contained 70% volume fraction of Terfenol-D powder. The final dimensions of the specimens were as follows: the diameter – 10 mm and the length – 50 mm (the length/diameter ratio – 5/1).

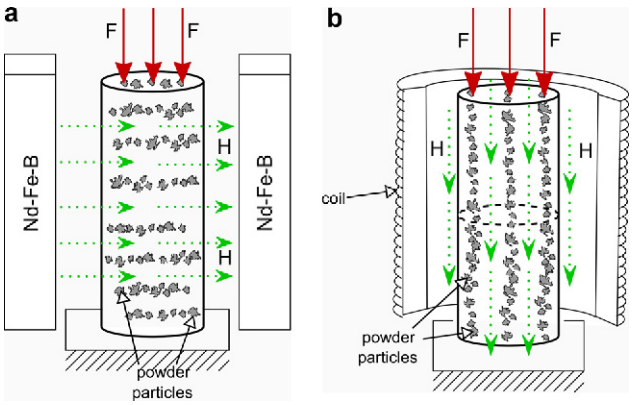

Fig. 3 – Scheme of introducing polarization into the samples.

3. Test methodology

The magnetostriction of the produced GMMc was investigated and compared with that of bulk Terfenol-D. The measurements were performed at room temperature (22 °C). The scheme of measuring system and a view of the test rig are shown in Fig. 4(a and b). Pre-stress σ_0, which is an external load applied to the magnetostrictive material, was precisely applied and maintained with use of MTS testing machine. Application of a pre-stress should increase a value of magnetostriction obtained for the same magnetic field applied to the material.

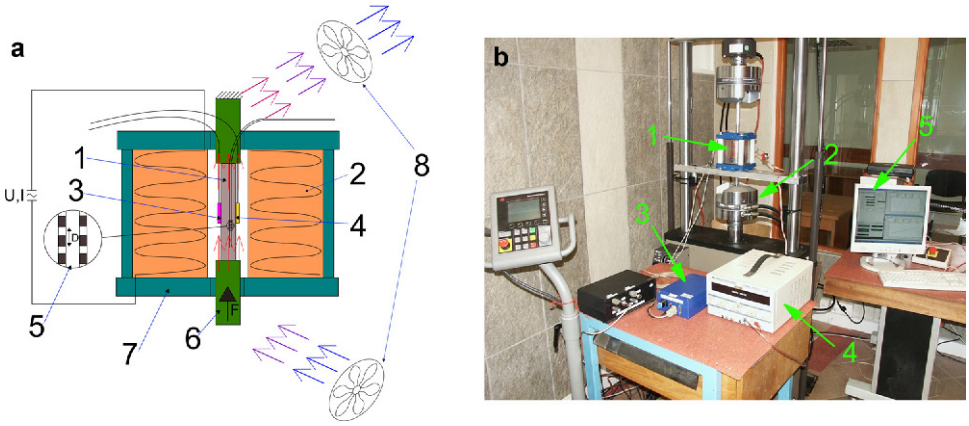

Fig. 4 – (a) Scheme of measuring system (1 – GMMc specimen, 2 – coil, 3 – temperature sensor, 4 – Hall probe, 5 – strain sensor (FBG), 6 – MTS, 7 – steel casing, 8 – cooling unit). (b) View of test rig (1 – coil with sample, 2 – MTS, 3 – FBG measurement unit, 4 – power pack, 5 – PC with data acquisition).

During the tests the strength of magnetic field was adjusted by adjusting the intensity of the current flowing in the coil winding. For this purpose, an adjustable (adjustment range of 0–30 V, 20 A) power supply was used. The range of magnetic field, dependent on the magnetic circuit parameters, was 0–168 kA/m. In order to check whether there is a parity effect, the measurement was made for both positive and negative values of magnetic field strength H. The value of magnetic field was measured using a Hall probe placed inside the coil, next to the sample.

The strain $\Delta\lambda$ of the samples was measured using optical fibre sensors (fibre Bragg grating (FBG)) shown in Fig. 5. In this way the influence (directly proportional to the change in the length of Bragg wave) of the electromagnetic field on the magnitude of the measured physical quantity (strain) was eliminated [14]. FBG sensors of the bare fibre type, were installed directly on the surface of the sample along its principal axis, as it is shown in Fig. 5(b). The sensors operated in the first telecommunication window (~840 nm). An IPHT (Jena) measuring system was used as the signal processing unit (SPU). The strain change was measured with a sampling rate of up to 5 Hz (quasi-static measurement). The FBG based measuring method is described in more detail in [15]. In addition, the temperature inside the coil was measured during the test. All the parameters were recorded automatically. The test rig is described in detail in [13].

4. Results

In order to determine the magnetomechanical properties of the GMMc, the values of magnetostriction $\Delta\lambda_{max}$ obtained for maximum magnetic field strength $H = 168$ kA/m were compared. A comparison of the test results for the composite materials and bulk Terfenol-D, under a pre-stress of 1 MPa is shown in Fig. 6 and it appears that the best results of magnetostriction for prepared composite samples were obtained for the specimen with perpendicular polarization. The magnetostriction of this GMMc is lower by 280 ppm (which amounts to 30 %) than that of the bulk material.

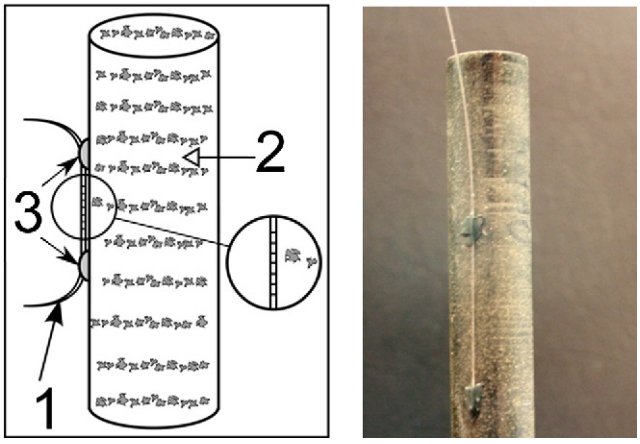

Fig. 5 – Strain measurement by means of FBG. Placement of sensor on composite specimen: 1 – Fibre Bragg Grating sensor, 2 – specimen, 3 – glue.

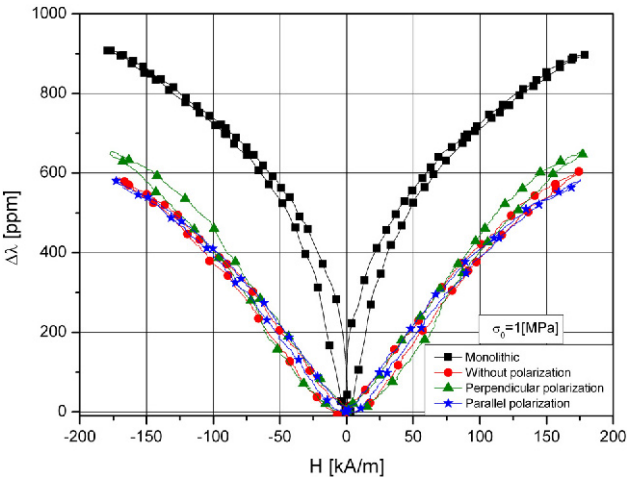

Fig. 6 – Magnetostriction at magnetic field strength H and pre-stress of 1 MPa for bulk Terfenol-D and GMM composites.

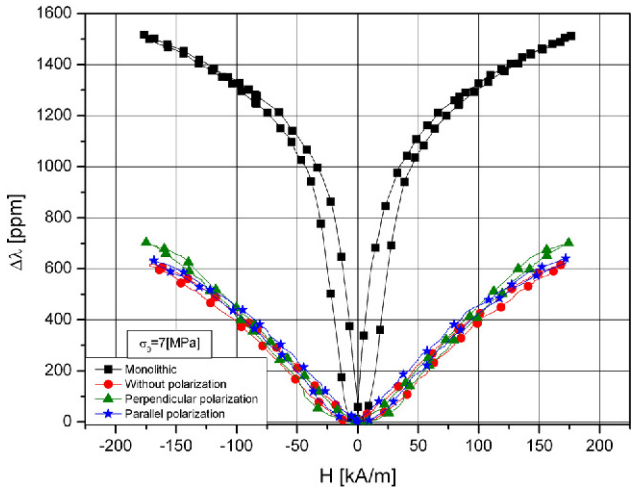

Fig. 7 – Magnetostriction at magnetic field strength *H* and pre-stress of 7 MPa for bulk Terfenol-D and GMM composites.

Fig. 7 shows a comparison of the test results for the GMM composites and bulk Terfenol-D at higher pre-stress (7 MPa). In comparison with the previous diagram, one can notice that the magnetostriction of the GMMc increases with increase of the pre-stress, but much less than in the case of bulk Terfenol-D. The magnetostriction for the composite with perpendicular polarization at 7 MPa is lower by 700 ppm (which amounts to 45%) than that of the bulk material.

The influence of pre-stress σ_0 for the GMMs and bulk Terfenol-D is shown in Fig. 8(a). It is possible to observe, that for the prepared composites, the received magnetostriction tends to be rising, up to the pre-stress value of 9 MPa. A similar trend was observed for bulk Terfenol-D, but the influence of a pre-stress on the value of magnetostriction is shifted to the higher values. The results obtained for the GMM composites indicate a much weaker influence of σ_0 on magnetostriction than in the case of the monolithic material, which is shown in Fig. 8(b).

Also the influence of pre-stress on hysteresis loop area ΔW was compared. The latter was defined as follows:

$$\Delta W = \frac{|W_1| + |W_2|}{2},$$

where $|W_1|$ – the absolute value of the magnetomechanical hysteresis loop area for the negative values of magnetic field in coordinate system $\lambda - H$ (marked green in Fig. 9), $|W_2|$ – the absolute value of the magnetomechanical hysteresis loop area for the positive values of magnetic field in coordinate system $\lambda - H$ (marked yellow in Fig. 9).

Hence area ΔW is a measure of a material's magnetomechanical damping, i.e., the energy losses arising as a result of the stimulation of the material with a magnetic field. Owing to this one can gain information about the efficiency of energy conversion. The results of the investigations are shown in Fig. 9. It is possible to notice that for pre-stress σ_0 of 5 MPa and higher values, hysteresis loop area ΔW stabilizes.

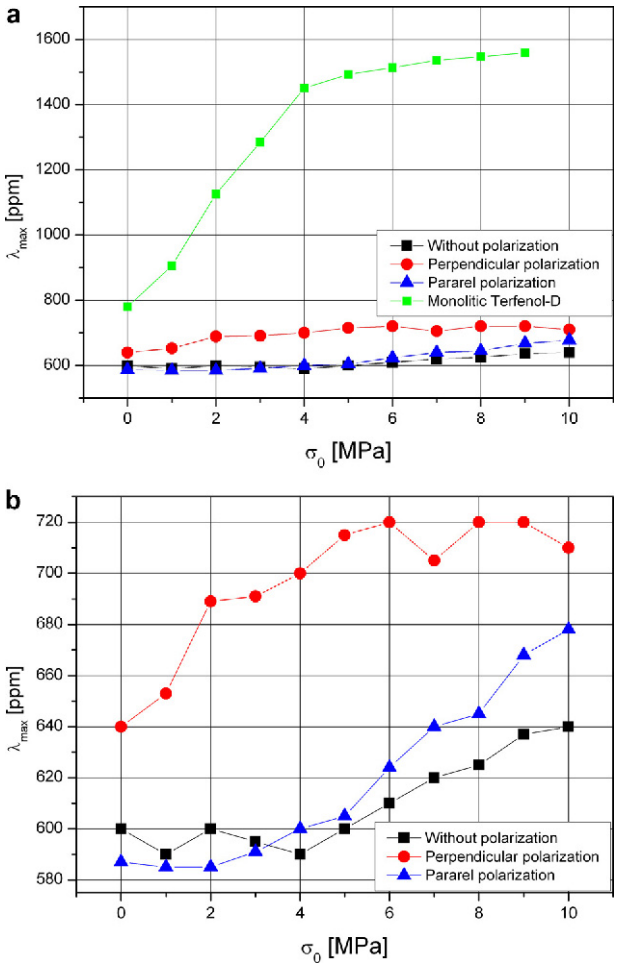

Fig. 8 – Maximum magnetostriction versus pre-stress: (a) GMM composites and bulk Terfenol-D and (b) manufactured composites.

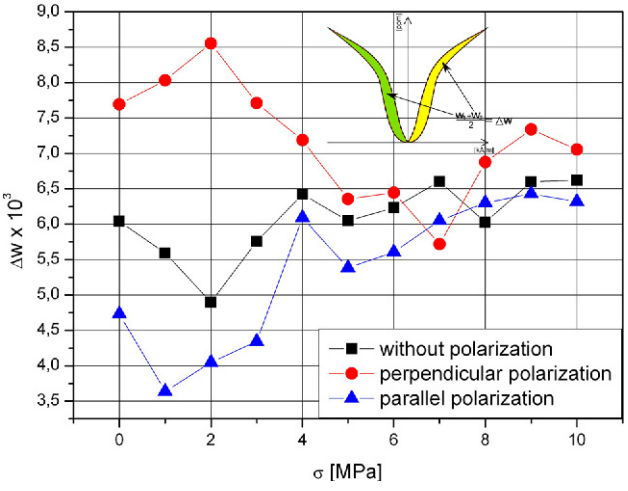

Fig. 9 – Hysteresis loop area ΔW versus pre-stress σ_0 for GMM composites.

5. Conclusions

A method of producing magnetostrictive composites containing powdered Terfenol-D (70 % volume fraction) and epoxy resin (the matrix), has been developed. The GMM composites with introduced magnetic polarization were produced and in order to determine their magnetostriction, subjected to the tests,. The results were compared with those obtained for the bulk Terfenol-D.

Polarization (applied during the curing of the matrix) has been found to have an influence on the magnetostriction of manufactured composites. Terfenol-D powder with varied particle size was used. The highest magnetostriction values were obtained for the composite with perpendicular polarization.

The influence of pre-stress σ_0 on the value of magnetostriction was also examined. In the case of the GMM composite, this influence is much lower than for bulk Terfenol-D. The optimum value of σ_0 for the tested GMMc was found to be 9 MPa. The maximum value of magnetostriction obtained for the GMMc amounted to 720 ppm (at $\sigma_0 = 9$ MPa) and was by 45% lower than that for solid Terfenol-D.

It should be noted that presented in this work composites containing 70% volume fraction of Terfenol-D particles have higher magnetostriction in comparison with the ones reported in [16] for composites containing 80% volume fraction of Terfenol-D powder. It means that the created GMM composites have magnetostriction on the level comparable with materials with a higher volume fraction of Terfenol-D powder.

In the authors' opinion, research on increasing the volume fraction of Terfenol-D powder in the GMM composite and on the effect of polarization on the value of magnetostriction should be continued.

Acknowledgments

The research was supported by Wroclaw Research Centre EIT+ within the project ''The Application of Nanotechnology in Advanced Materials'' – NanoMat (POIG.01.01.02-02-002/08) financed by the European Regional Development Fund (Innovative Economy Operational Programme, 1.1.2).

REFERENCES

[1] G. Engdhal, Handbook of Giant Magnetostrictive Materials, Academic Press, San Diego, 2000.
[2] E. Monaco, L. Lecce, C. Natale, S. Pirozzi, C. May, Active noise control in turbofan aircrafts: theory and experiments, Acoustics 08 (2008) 4629–4634.
[3] The authoritative monthly newsletter on rare earths, specialty metals and applied technology, December 2001.
[4] G. Altin, K.K. Ho, C.P. Henry, G.P. Carman, Crystallographically aligned Terfenol-D polymer composites for a hybrid sonar device, Integrated Ferroelectrics 83 (2006).
[5] P. Pouponneau, L. Yahia, Y. Merhi, L.M. Epure, S. Martel, Biocompatibility of candidate materials for the realization of medical microdevices, in: Proceedings of the 28th IEEE EMBS Annual International Conference, 2006.
[6] J.B. Hedrick, Rare earths in selected U.S. defense applications, in: 40th Forum on the Geology of Industrial Minerals, 2004.
[7] R.F. Quattrone, J.B. Berman, J.C. Trovillion, C.A. Feickert, J.M. Kamphaus, S.R. White, V. Giurgiutiu, G.L. Cohen, Tech. Rep., US Army Corps of Engineers and Engineer Research and Development Centre, 2000.
[8] C.Y. Lo, S.W. Or, H.L.W. Chan, Large magnetostriction in epoxy-bonded Terfenol-D continuous-fiber composite with [1 1 2] crystallographic orientation, IEEE Transactions on Magnetics 42 (2006).
[9] T.A. Duenas, G.P. Carman, Large magnetostrictive response of Terfenol-D resin composites (invited), Journal of Applied Physics 87 (2000).
[10] D.L. Huber, J.E. Martin, R.A. Anderson, D.H. Read, B.L. Frankamp, Magnetostriction of field structured magnetoelastomers, Tech. Rep., Sandia National Laboratories, 2005.
[11] G. Altin, K.K. Ho, C.P. Henry, G.P. Carman, Static properties of crystallographically aligned Terfenol-D polymer composites, Journal of Applied Physics 101 (2007).
[12] W.D. Armstrong, Nonlinear behavior of magnetostrictive particle actuated composite materials, Journal of Applied Physics 87 (2000).
[13] J. Kaleta, D. Lewandowski, R. Mech, P. Gasior, Magnetomechanical properties of Terfenol-D powder composites, Solid State Phenomena 154 (2009) 35–40.
[14] F.T.S. Yu, S. Yin (Eds.), Fiber Optic Sensors, Marcel Dekker Inc., 2002.
[15] J. Kaleta, W. Blazejewski, P. Gasior, M. Rybaczuk, Optimisation of the IV generation tanks for hydrogen storage applied in vehicles, modelling and experiment, in: 18th World Hydrogen Energy Conference, 2010.
[16] L. Dobrzaski, A. Wydrzyska, O. Iesenchuk, Intelligent epoxy matrix composite materials consisting of Tb0.3Dy0.7Fe1.9 magnetostrictive particulates, Archives of Materials Science and Engineering 35 (2009).