

# Identification of Magnetostrictive Composites at Low Frequencies of Magnetic Field Changes

**Jerzy Kaleta**

Professor  
Wroclaw University of Technology  
Faculty of Mechanical Engineering

**Daniel Lewandowski**

Assistant Professor  
Wroclaw University of Technology  
Faculty of Mechanical Engineering

**Rafal Mech**

Ph.D. Student  
Wroclaw University of Technology  
Faculty of Mechanical Engineering

*The role of Smart Magnetic Materials (SMM) is still increasing. One type of SMM are Giant Magnetostrictive Materials (GMM) which can be represented Terfenol-D. The biggest difficulty with mechanical application of GMM is its brittleness. On the other hand, increase of frequency generate meaningfully eddy currents. These disadvantages tend to search new solutions in a form of composite materials with giant magnetostriction (GMMC). This paper is focused on the investigations of several composites, with outstanding magnetostrictive properties. Composites with different preparation methodology (different directions of polarization) were subjected to cyclic magnetic field with various of frequencies. An influence of magnetic field changes and different frequencies on the response of the manufactured material were examined and the results were compared with solid Terfenol-D material. Investigated composite are promising magnetostrictive materials that enable to create a new type of actuators and magnetic field sensor.*

**Keywords:** magnetostriction, giant magnetostrictive materials (GMM), SMART, GMM composites, Terfenol-D, active materials.

## 1. INTRODUCTION

Among today's engineering materials used, increasing attention is attached to active materials, referred to most often in literature of the matter as SMART. The key meaning in description and making use of these materials have cross-fields. Smart Magnetic Materials (SMM) play a big part in this numerous group of materials, from which the chosen ones are the objects of investigations described hereafter. In SMM we include magnetorheological materials, materials with giant magnetostriction, materials with giant magnetoelasticity, magnetocaloric materials and others.

Giant magnetostrictive materials (GMMs) [1] can convert magnetic energy into mechanical energy (actuator-type action) and vice versa (sensor-type action). The monolithic RE-Fe giant magnetostrictive alloy, Terfenol-D, exhibits giant magnetostriction in a considerably low magnetic field at room temperature and is particularly efficient in energy conversion. This material finds various applications in aircraft [2,7], automotive [8], ship [2,8], and civil engineering structures and is successfully used in medicine [2] the mining industry [2,8], acoustic equipment [2,8], 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 [6,7,12]. However, its usage was restricted due to eddy current loss at high frequency. In addition, it has a shortcoming such as

intrinsic brittleness accompanied by maximizing the fraction of the brittle, Laves phase. The magnetostrictive composite materials have been developed as an alternative way to overcome both eddy current loss and intrinsic brittleness since 1990 [10].

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

- reduction of solid Terfenol-D's drawbacks (eddy currents at higher operating frequencies and its brittleness limiting its use under, e.g., tensile stress [2,11], whereby its application range is significantly extended,
- new potential applications in, e.g., the structural health monitoring (SHM) of composite materials and structures (tagging) [3,9].

Therefore, the main goal of this research was to investigate the magnetostriction of a field-structural composite with Terfenol-D particles. The composite was to replace the solid Terfenol-D rods in an actuator and a damper. It was decided to closely examine the effect of the (perpendicular, parallel, without polarization) direction of composite polarization and different frequencies of magnetic field stimulation. The results were to be compared with those obtained for solid Terfenol-D samples with the same geometry.

## 2. MATERIAL

In this study, the magnetostrictive composite (also referred to as GMMc) was used. It was made by combining the epoxy resin and the GMM material (Terfenol-D) powder. At first, the epoxy resin Epolam 2015 (from Axons Technologies company) was mixed with the curing agent. Next, the appropriate amount of Terfenol-D powder (Gansu Tianxing Rare Earth

---

Received: March 2012, Accepted: April 2012.

Correspondence to:

Instytut Materialoznawstwa i Mechaniki Technicznej,  
Smoluchowskiego 25 str Wroclaw, 50-370, Poland  
E-mail: Jerzy.Kaleta@pwr.wroc.pl

Functional Materials Co., Ltd.) was added, with particle size of about 5-300 $\mu\text{m}$ . The grain-size distribution is shown in Figure 1 and in Figure 2 is shown the shape and size of the particles. It is clearly visible that the particles have varying shape and size and their edges are sharp.

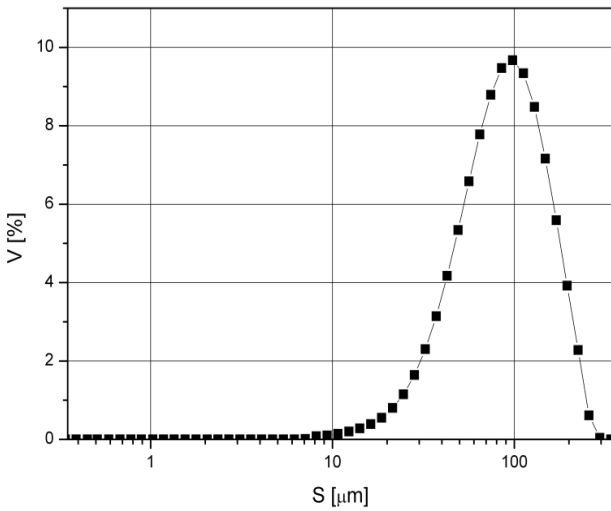


Figure 1. Terfenol-D powder particles size distribution.

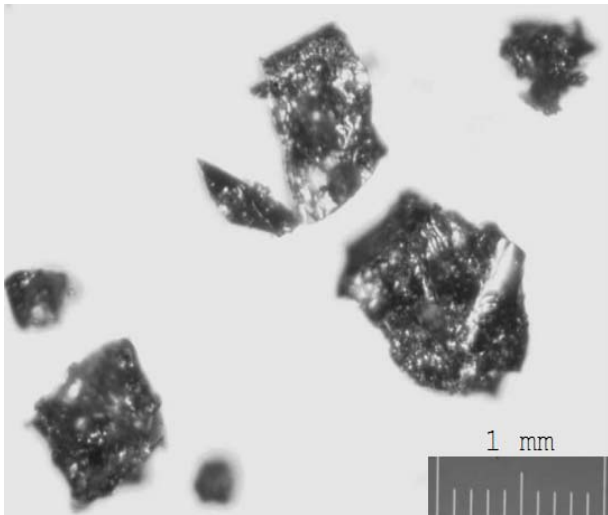


Figure 2. Shape and size of Terfenol-D powder particles.

Specimens presented in this work contain 70 % of Terfenol-D particle volume fractions and have different polarization directions. For each case the particles and resin were homogeneously mixed together and deaerated. Moreover, one of the samples was polarized perpendicular, and others were polarized parallel to the main axis of specimen. This effect was obtained by using respectively permanent magnets and coil during composites curing process.

The Container with mixture was placed between two magnets or inside coil and after that placed on MTS hydraulic pulsator, where samples were pressed with force of 10 [kN] through 4 hours up to the preliminary resin binding. This process allowed to reduce excess of epoxy resin from samples and to obtain high volume fraction of Terfenol-D particles. Schemes of these processes are shown in Figures 3a and 3b) respectively, for perpendicular and parallel polarized specimens. Additionally, one of the specimen was cured without any source of magnetic field.

After 24 hours preliminary cured specimens were placed in an oven at 70 [°C] for another 24h to ensure full cure of the epoxy resin. Samples produced in this way contain small portion of pores, which confirms the good connection of powders with resin. Polymer material provides a good magnetic insulation of the Terfenol-D powder grains and prevents its oxidation.

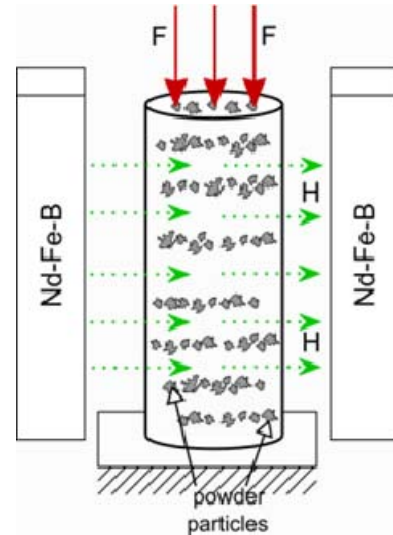


Figure 3a. Schema of perpendicular polarization to the main axis of the sample during curing process. F - direction of force during curing process, H - direction of magnetic field during curing process.

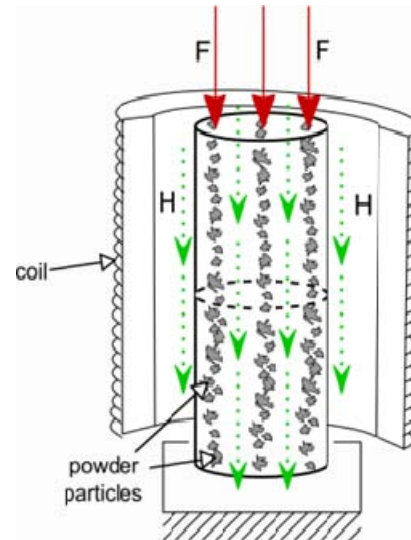


Figure 3b. Schema of parallel polarization to the main axis of the sample during curing process. F - direction of force during curing process, H - direction of magnetic field during curing process.

Moreover, to find out, if polarization applied during the curing process to manufactured composites had made any changes in magnetization of specimens, made magnetic scans of their surfaces were made (Figures 4a and 4b). Scans were obtained thanks to using the innovative system of MagScanner, which was described in [4]. It is evident that there is a difference between manufactured specimens with different types of polarization. The magnetization layout along its main axis for parallel polarized specimen is even as evident in (Figure 4a), as contrasted with parallel polarized specimen (Figure 4b). This confirms that the samples

that have been polarized preserved direction of the desired magnetization.

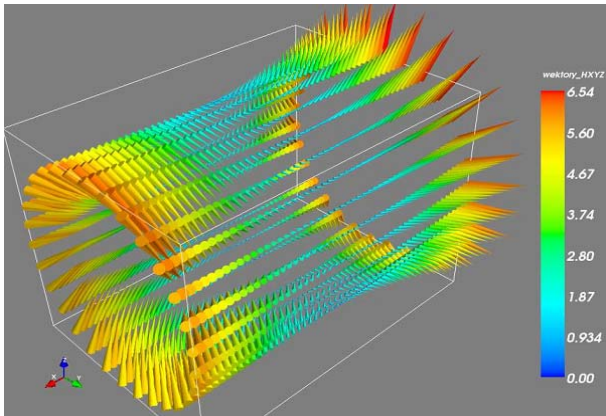


Figure 4a. 3D magnetic vectors fields around perpendicular premagnetized Terfenol-D composites.

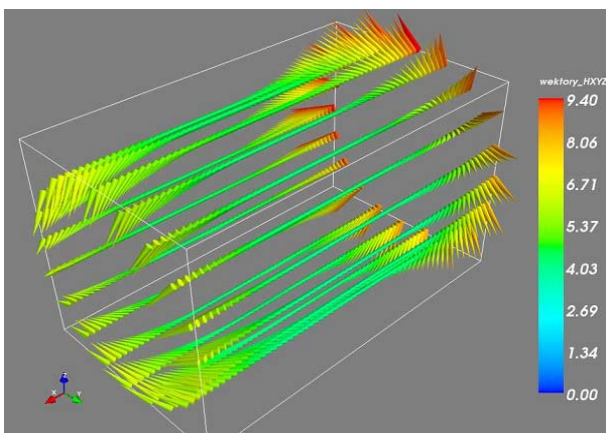


Figure 4b. 3D magnetic vectors fields around parallel premagnetized Terfenol-D composites.

### 3. MEASURING METHODOLOGY

In this section the experiments methodology involving quasi-static measurements of magnetostriction of produced composites and the measurements made for different magnetic field frequencies, was shown.

First of all, quasi-static magnetomechanical properties of the composite samples were examined. The monolithic Terfenol-D material was also investigated to compare the results. The tests were conducted at the room temperature, for the specific and constant value of the initial stress which was applied by the testing machine. The machine had the task of keeping the constant load acting on each specimen. Next, the strain was measured. Such strain appeared as a result of the magnetic field with a time-varying strength acting along the main axis of the examined samples.

The magnetic field strength acting on the magnetostrictive composite was dependent on the strength of the current in the coil. The magnetic field was generated by the adjustable power supply unit (0 - 30 V, 20 A). The magnetic field strength range was limited by the magnetic circuit and amounted to 0 ÷ 168 kA/m. The measurement was conducted with the use of the Hall effect sensor (placed in the coil), for both positive and negative H values to check the evenness of the phenomenon in the composite samples. The sample

displacement  $\Delta L$  was measured using the innovative method of fiber Bragg grating (FBG) sensors. In this way the influence of the electromagnetic field on the results was eliminated. The FBG method is described in more detail in [13]. The strain sensors were placed directly on the specimens, as shown in Figure 5. One of the sensors was placed along the main axis of the specimen while the second sensor was put on the sample circumference. The aim of such sensor arrangement was to check whether the volumetric magnetostriction occurs in the material, apart from the linear magnetostriction.

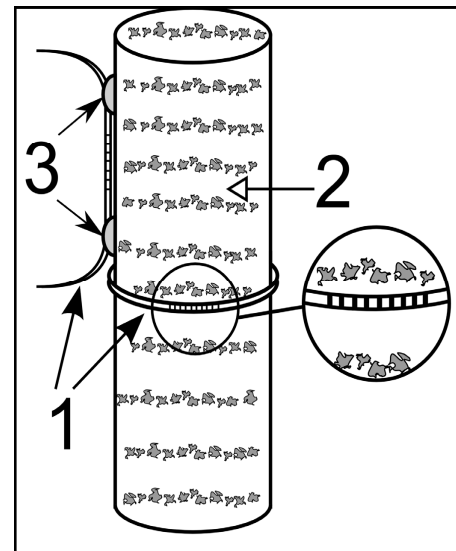


Figure 5. Arrangement of the strain sensors on a sample: 1 – sensors, 2 – specimen, 3 – glue [5].

Additionally, during the tests the temperature inside the coil was measured. All of the parameters were saved using automatic measurement system, which is shown in Figure 6. The detailed description of the test stand can be found in [5].

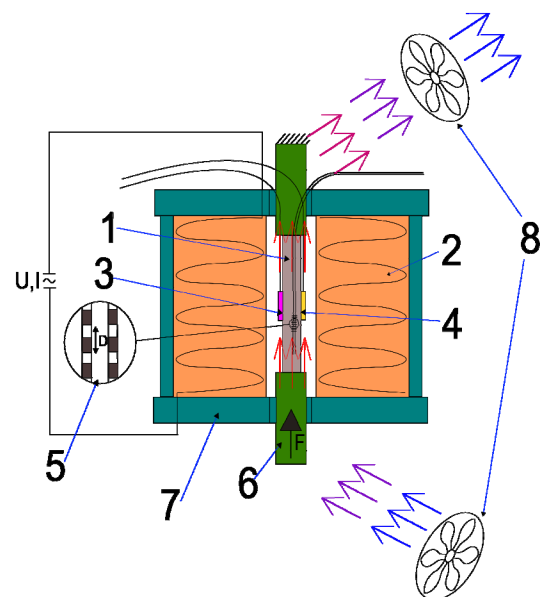
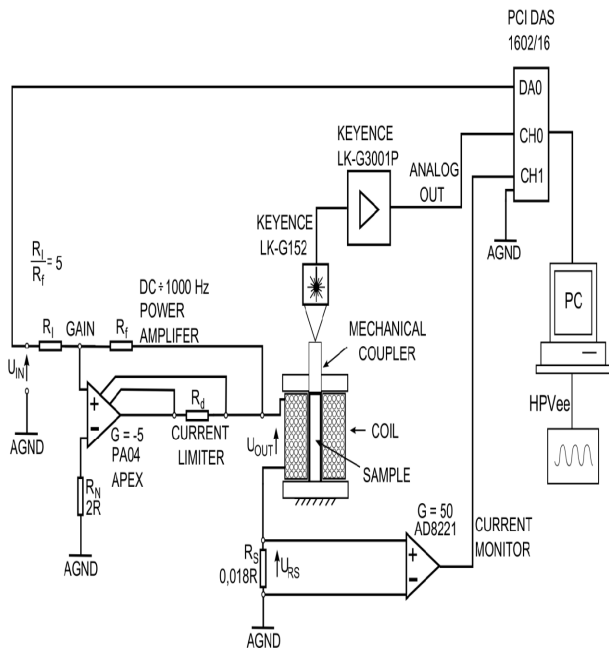


Figure 6. A scheme of the measuring stand: 1 – examined magnetostrictive composite sample, 2 – coil, 3 – magnetic field sensor (Hall-effect device), 4 – temperature sensor DS18B20, 5 – strain sensor (fiber Bragg grating; about 850 nm covered with ORMOCER), 6 – MTS machine, 7 – steel housing, 8 – cooling system [14].

The experimental setup for measurements of influences of magnetic field frequencies changes on specimens magnetostriction is shown in Figure 7. It consists: of the original steel casing with a coil, which was responsible for applying magnetic field to specimens, frequency generator and high power amplifier PA04 APEX, which were respectively responsible for changes in the frequency of actuator work and value of magnetic field generated by coil.

Moreover, the setup consists of the signal amplifier to gather data from power amplifier to pc, laser displacement measurement head KEYENCE LK-G152 to measure displacement generated by specimens and also PC for acquisition of all data, subsequently treated using the program HPVee.

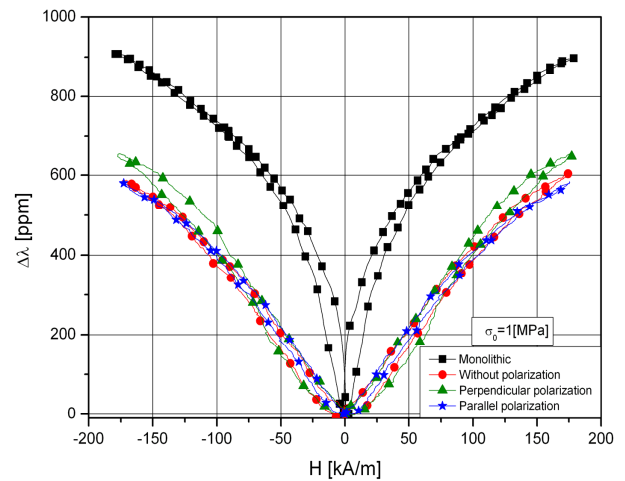


**Figure 7. Schema of actuation experimental setup for dynamic investigation of magnetomechanical properties of magnetostrictive composites.**

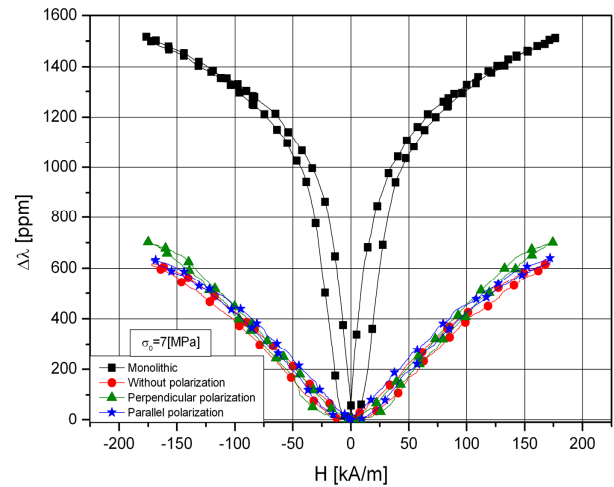
Investigation was based on the measurements of influence of a variety of frequencies and intensity of magnetic field on dynamic properties of composite materials, and monolithic Terfenol-D. During the experiment, prepared samples were placed inside the coil, where spring assured compressive loading. Next, with the use of frequency generator and high power amplifier parameters of this setup were changing. In this way the properties and actuating possibilities of composite materials, and monolithic Terfenol-D were compared. These studies were designed to determine the basic dynamic characteristics of composite materials at low frequencies of excitation  $f = 1 - 5$  [Hz].

#### 4. RESULTS

First of all, one can find a short description of results obtained for quasi-static properties of the manufactured materials. Response of strain magnetostriction in the function of magnetic field intensity of each of composite specimens produced, and of monolithic Terfenol-D rod were compared and results are shown in (Figure 8a, and 8b).



**Figure 8a. Magnetostrictive dependence from magnetic field intensity H for value of pre-stresses 1 MPa for monolithic Terfenol-D, and manufactured composites.**



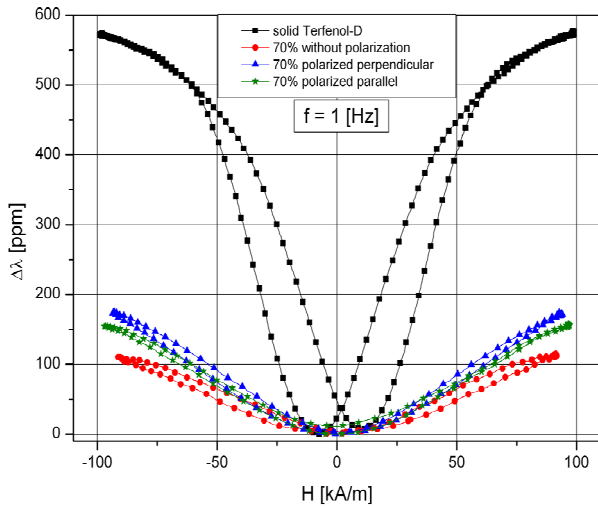
**Figure 8b. Magnetostrictive dependence from magnetic field intensity H for value of pre-stresses 7 MPa for monolithic Terfenol-D, and manufactured composites.**

Magnetostriction of each specimen was measured parallel to the applied magnetic field, and it occurred that produced specimens didn't show clearly magnetic saturation as it was in the case of monolithic Terfenol-D material. The saturation is represented by the shape of hysteresis loop, for monolithic material, with increasing of magnetic field intensity changes in magnetostriction are decreasing of up to the saturation point. Nevertheless, in specimens the shape of plot remains linear and changes are not clearly visible. More details on quasi-static measurements can be found in [5].

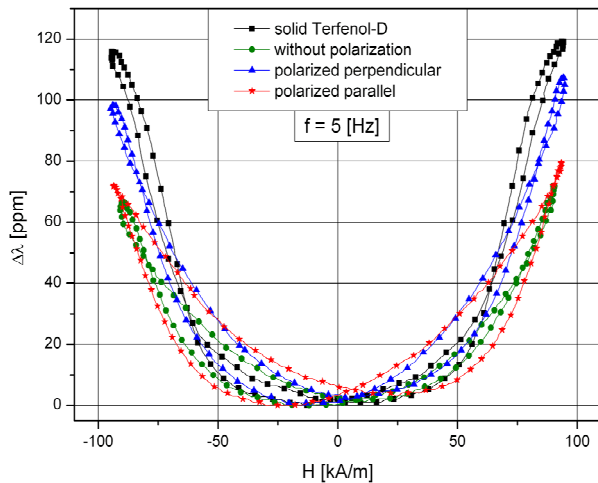
Below are shown the results obtained for the dynamic tests of composite materials and solid material of Terfenol-D, as cores of the actuator. Tests were carried out for low-frequency magnetic field changes, being in the range of 1 - 5 [Hz]. Figure 9 and Figure 10 show the summary results for the samples made of composite material and solid Terfenol-D.

Figure 9 shows the results for a frequency equal  $f = 1$  [Hz] and Figure 10 for a frequency equal  $f = 5$  [Hz]. It is clear that in the case of frequency  $f = 1$  [Hz], the response of solid material is much higher than is the case of composite materials, and the hysteresis loop of this material is higher than in the case of composite materials. However, at higher frequencies, the

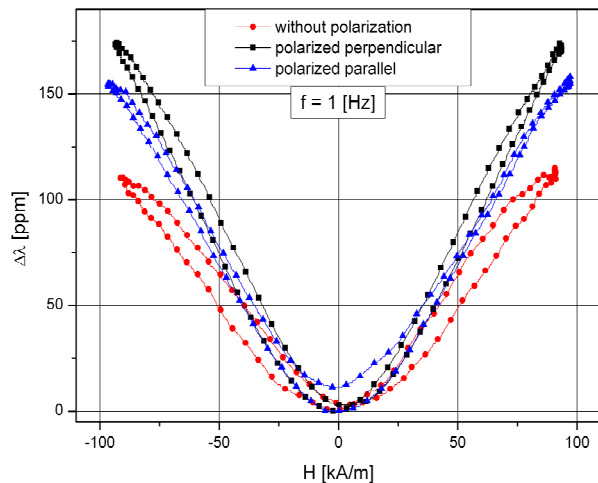
differences in responses between the material and produced solid composite samples have been severely reduced, which can be seen in Figure 9. This shows that the composite material can behave much better at higher frequencies.



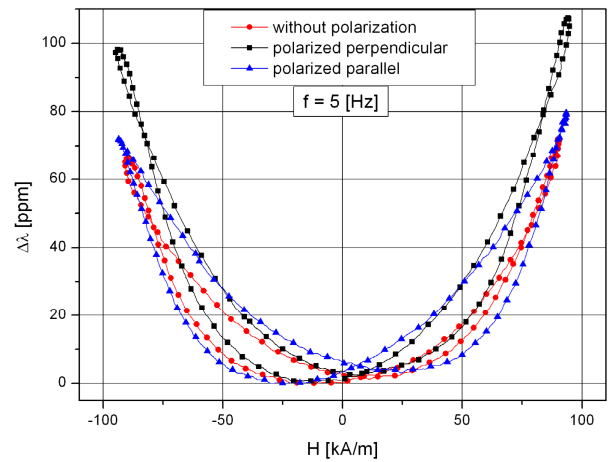
**Figure 9. Comparison of magnetostrictive dependence from magnetic field intensity H at frequency  $f = 1$  [Hz], for composite specimens and solid Terfenol-D.**



**Figure 10. Comparison of magnetostrictive dependence from magnetic field intensity H at frequency  $f = 5$  [Hz], for composite specimens and solid Terfenol-D.**



**Figure 11. Comparison of magnetostrictive dependence from magnetic field intensity H at frequency  $f = 1$  [Hz], for composite specimens.**



**Figure 12. Comparison of magnetostrictive dependence from magnetic field intensity H at frequency  $f = 5$  [Hz], for composite specimens.**

In addition, the graphs 11 and 12 compare the results only for composite materials, also for the frequency values ranging between 1 and 5 [Hz] respectively. It is clear that both the frequency 1 [Hz] and 5 [Hz], the largest value of response in the magnetostriction (strain of the material) was obtained for the specimen, which was polarized perpendicular to its main axis during the production process, while the lowest result was obtained in specimen without polarization. On the basis of these results one can find that applying initial polarization in the production of the material has a significant influence on subsequent magnetomechanical properties.

## 5. CONCLUSIONS

In this work, dynamic properties of epoxy-bonded Terfenol-D composites have been investigated. By evaluating the effects of polarization direction, it was found that the composites with perpendicular polarization show highest magnetostriction value, in comparison to the others, such as parallel polarized and without polarization in the entire frequency range. What is more at higher values of frequencies response of composite material was comparable with monolithic Terfenol-D, and this is why it can be suggested that composite material provides the basis for applying it in actuating devices.

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 decrease of magnetostriction in relation to the monolithic Terfenol-D material. Magnetostriction of the GMM composites achieved in this work can be further improved by more accurate fabrication parameters, especially by investigation over polarization and differences in the volume fraction of particles. Moreover, researches over different matrixes as binders could show if the behavior of matrix-powder connection will have influence on the properties of these materials.

## ACKNOWLEDGMENT

The research was supported by Wrocław 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] Engdhal, G.: *Handbook of Giant Magnetostrictive Materials*, Academic Press, 2000.
- [2] Hedrick, J. B.: Rare Earths in Selected U.S. Defense Applications, 40th Forum on the Geology of Industrial Minerals, 2004.
- [3] Hommema, J.: *Magnetomechanical Behavior of Terfenol-D Particulate Composite*, Master’s Thesis, University of Illinois, 1999.
- [4] Kaleta, J. and Wiewiórski, P.: Wireless 3D Magnetic Field Digitizer for inspection of parts constructed using Smart Magnetic Materials, in: *Proceedings of the IV Eccomas Thematic Conference on Smart Structures and Materials*, pp. 363-364, 2009.
- [5] Kaleta J., Lewandowski D., Mech R. and Zajac, P.: *Smart Magnetic Composites (SMC)*, Composite Materials / Book 2, John Cuppoleti (Ed.), InTech, 2011.
- [6] Monaco, E., Franco, F., Iadevaia, M. and Lecce, L.: Interior active noise control in turbofan aircraft: Numerical simulation and experimental validation for optimal actuators positioning, 19th International Congress on Acoustics, 2007.
- [7] Monaco, E., Lecce, L., Natale, C., Pirozzi, S. and May, C.: Active noise control in turbofan aircrafts: theory and experiments, *Acoustics 08*, pp. 4629-4634, 2008.
- [8] Pinkham M.: High Tech Materials, the Authoritative Monthly Newsletter on Rare Earth, Speciality Metals and Applied Technology, Vol. 2, Issue 12 December, 2001.
- [9] Quattrone, R., Berman, J., Trovillion, J., Feickert, C., Kamphaus, J., White, S., Giurgiutiu, V. and Cohen, G.: Investigation of Terfenol-D for Magnetostrictive Tagging of Fiber-Reinforced Polymer Composites, Engineering, research and Development Center, 2000.
- [10] Sandlund L.: Magnetostriction, elasticmoduli, and coupling factors o composite Terfenol-D, *Journal of Applied Physics*, Vol. 75, pp. 5656–5658, 1994.
- [11] Verhoeven, J. D., Gibson, E. D., McMasters, O. D. and Ostenson, J. E.: Directional Solidification and Heat Treatment of Terfenol-D Magnetostrictive Materials, *Metallurgical Transactions A*, 21, 2249-2255, 1990.
- [12] Wang, L.: *Vibration Energy Harvesting by Magnetostrictive Material for Powering Wireless Sensors*, PhD thesis, North Carolina State University, 2007.
- [13] Blazejewski, W., Gasior, P. and Kaleta, J.: *Application of Optical Fibre Sensors to Measuring the Mechanical Properties of Composite Materials and Structures*, Advances in Composite Materials - Ecodesign and Analysis, InTech, 2011.
- [14] Mech R.: *Examining the Magnetomechanical Properties of Composites on the Basis of Powders of Giant Magnetostrictive Materials*, Master Thesis, Wroclaw University of Technology, 2008, (in Polish).

---

## ИДЕНТИФИКАЦИЈА МАГНЕТОСТРИКТИВНИХ КОМПОЗИТА НА НИСКИМ ФРЕКВЕЦНИЈАМА ПРИ ПРОМЕНАМА МАГНЕТНОГ ПОЉА

**Јиржи Калета, Даниел Левандовски, Рафал Мек**

Улога паметних магнетних материјала (СММ) се повећава. Један од типова СММ су и велики магнетостриктивни материјали (ГММ) који су представљени Терфенолом Д. Велики проблем који се јавља код примене овог материјала је крост. Такође, са повећањем фреквенције долази и до појаве ЕДИ струја. Ови недостаци захтевају да се врше истраживања у области композитних материјала тачније материјалима са (ГММЦ). Овај рад проучава неколико типова композитних материјала са посебним магнетостриктивним карактеристикама. Композити направљени различитим методама (различитим правцима поларизације) изложени су променљивом магнетном пољу различитих фреквенција. Утицај магнетног поља и различите фреквенције на произведене композите су анализирани и упоређени са чврстим Терфенолом Д. Анализирани композити показују добре карактеристике магнетостриктивних материјала који се могу користити при конструкцији нових актуатора и магнетних сензора.