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Properties of the magnetostrictive composite materials with the polyurethane matrix reinforced with Terfenol-D particles

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Properties

ABSTRACT

Purpose: The aim of this work is to obtain functional composite materials and to observe changes of magnetic properties of samples with different particle size distributions of magnetostrictive Terfenol-D ($Tb_{0.3}Dy_{0.7}Fe_{1.9}$) powder. The influence of the concentration and particles size of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ on magnetic properties were investigated as function of applied magnetic field intensity, temperature and frequency.
Design/methodology/approach: The investigated samples were obtained by casting of the composite materials with the polyurethane matrix reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles. Magnetizations versus applied field curves were registered using the Oxford Instruments Ltd. vibrating sample magnetometer (VSM). Volume magnetic susceptibility was determined as temperature function on the Cahn RG automatic electrobalance (Ventron Instrumens, USA). Testing of the magnetic permeability in function of frequency was made using the Maxwell-Wien bridge system and the electrical properties were made by the resistivity measurements.
Findings: Analysis establishes a direct connection between physical properties and structural characteristics of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder size: the increases of particle size distribution of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder in composite materials amplify the magnetic responses and - at the same time - causing growth of resistivity values also. Moreover, in the investigated frequency range, no effect was observed of frequency on the susceptibility value for the particular material, which suggests possibility of using these materials in the high-frequency magnetic fields.
Practical implications: The polyurethane matrix in investigated composite materials causes growth of resistivity, limiting these way losses for eddy currents at the high operating frequency of the transducers.
Originality/value: The obtained results show the possibility of manufacturing the magnetostrictive composite materials based on the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles, with desired physical properties (including electrical one) in cost effective way in comparison to conventional giant magnetostrictive materials (GMM).
Keywords: Magnetostriction; Terfenol-D; Giant magnetostrictive materials; Composite materials

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1. Introduction

The development of - so-called - Giant Magnetostrictive Materials began with tests using terbium - and later also samarium or gallium - with dysprosium compounds [1-3]. The materials with composition developed during the initial period presented high magnetostriction, but only in magnetic fields of very high strength and/or in cryogenic temperature. The introduction of the RFe_2 phase (where R is rare earth metal) enabled the shift of the Curie temperature of such materials above ambient temperature, while the magnetic field required for the magnetostrictive deformation was reduced by the appropriate selection of proportions between the concentration of terbium and dysprosium - elements with opposite magnetocrystalline anisotropy, which caused the compensation of the alloy effective anisotropy value close to zero in ambient temperature [4,5]. The discovery was the start of research on alloys defined by the general formula: $Tb_xDy_{1-x}Fe_y$ ($x = 0.27$-0.3; $y = 1.9$-2), the wide group thereof was called „terfenols" (after the abbreviation of the elements composing them and the name of laboratory in which the discovery was made: TER-FE-Naval Ordnance Laboratory, USA).

The $Tb_xDy_{1-x}Fe_y$ alloys are intermetallic phases with Laves C15 phase structure, very fragile in ambient temperature. Reaching a giant magnetostriction in magnetic fields of low strength for low strength polycrystals is only possible when the grains are *[111]* oriented (i.e. in the direction of easy magnetization), at the same time - this is the direction along which measurements are made, which is due to giant anisotropy of magnetostriction ($\lambda_{[111]} >> \lambda_{[100]}$). This is one of the factors causing that $Tb_xDy_{1-x}Fe_y$ type alloys are usually produced by hard-to-perform methods of directional crystallization, which increases material costs. Furthermore, the production irregular form of materials is complicated and requires the application of precise machining at the final stage [6,7].

The advantages of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ include most of all the high value of the linear magnetostriction, being 0.2%, the ability of non-contact carrying of loads from 500 to 600 MPa with very short signal response time (~1μs in ambient temperature and <150 kA/m in low fields) - compared to the conventional materials. Moreover, these alloys are characterized with high reliability, large deformation energy density (~20 kJ/m^3), low sound speed and high magnetomechanical coupling coefficient [8-10].

In spite of indubitable advantages of giant magnetostrictive materials (GMM), making them an important active module of executive devices, using them in industrial scale is limited by some factors [11-13]. The optimization of magnetostrictive alloys' properties was made through synthesizing the materials with the strength of the specific elements. The tests proved that, in spite of the ability to combine high magnetostriction with low anisotropy in these materials, the alloys hold defects characteristic for metal materials, including the induction of eddy currents, caused by the low resistivity of the material. Such factors restrict and sometimes even impede the application of the materials in transducers operating in power frequency magnetic fields [14-16].

It seems that an effective solution of the above issues is the production of a composite material with end properties requiring transmission of the specific effect from strain hardening to the matrix, which can be obtained through mechanical, electrical, optical, magnetic, thermal and/or chemical coupling between the components [17]. Polymer materials - thanks to their insulation properties and good adherence to the fiber or particle surface - provide the correct transmission of load onto the reinforcing phase in the composite materials and enable the formation of practically any shapes of the material. Furthermore, the polymer matrix produces non-conductive layers between the magnetostrictive particles, thus eliminating, thanks to increased resistivity, the losses for eddy currents in high frequencies of the transducer's operation. The matrix also makes the resultant material more elastic and in consequence better adapted to operation in complex load conditions [18,19].

The first literature reports about the magnetostrictive composite materials with the polymer matrix appeared in 1994 [20] and in 1996 [21]. Since then there have been conducted intensive studies concerning to magnetostrictive composite materials with various polymer matrix [8,10,22].

The aim of this work is to investigate of magnetic and electrical properties of the newly-developed magnetostrictive composite material with polyurethane matrix.

2. Materials and methodology

2.1. Materials

Examinations were made on Terfenol-D (i.e. $Tb_{0.3}Dy_{0.7}Fe_{1.9}$) powder (Etrema Co, USA), demonstrating the giant magnetostriction, as well as on samples of the composite material reinforced with them. The size of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles were denoted by their manufacturer as: 38-106 μm, 106-212 μm and 212-300 μm. The Smooth-cast 325 (Smooth-on Inc., USA) two-component polyurethane resin with low viscosity was used as the matrix in order to ensure sufficient particle wetting.

Composite materials with cylindrical shape were made by casting and for the particles sedimentation reasons, moving the mould continuously was required until the matrix gelation was completed. After cross-linking process finished, specimens were placed in an oven at 338 K for 5 h to ensure full cure of the resin. In this work, specimens containing particles volume fraction given in the Table 1 were made.

Table 1.
Concentration of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder in obtained samples

Volume fraction of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$, %	Mass fraction of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$, %
10	48.7±0.5
15	60.1±0.5
20	68.1±0.5

2.2. Methodology

Magnetizations versus applied field curves were registered using the Oxford Instruments Ltd. vibrating sample magnetometer (VSM) and on the basis of these relationships the hysteresis loop curves were drawn and afterwards - the remanance B_r, permeability μ_{rmax}, as well as coercive field H_c quantities of powder and composites samples were determined.

Volume magnetic susceptibility χ_v, as value specifying ability of given substance to change its magnetization, was determined as temperature function for composite materials and $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powders on the Cahn RG automatic electrobalance (Ventron Instrumens, USA) with sensitivity of 10^{-7} cm^3/g and with Faraday's method in the constant magnetic field $H_0 \sim 17$ kA/m, as well as in temperature range 50-350 K. For measurements taken in temperature range above ambient temperature the oven or for temperature range below 273 K - liquid helium flow cryostat were used. Moreover, magnetic susceptibility versus frequency dependence for $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powders and composite samples were registered using the Lake Shore 7225 AC susceptometer/DC magnetometer in the range up to 10 kHz.

Testing of the magnetic permeability in function of frequency was made using the measurement system whose main element was the alternating current Maxwell-Wien bridge (Agilent E498A Precision LCR Meter). During investigation the inductance, as well as resistance values of the induction coil with 31 turns were measured. Inside this coil the samples with cylindrical shape with diameter of 8.7 mm and the length of 40 mm has been placed. The measurement was taken for two cases: the first one when current intensity has variable values in the range 0.5-100 mA (for frequency equals to 1 kHz) and the second one - when current intensity has constant value equals to 50 mA and frequency was changed from 20 Hz up to 2 MHz. The measurements were carried out on the samples locating inside the coil with shackle, and the effective magnetic permeability were estimated based on the following relation:

$$\mu_{ef} = \frac{Ll}{\mu_0 Z^2 A} \quad (1)$$

where:
- L - the inductance of the coil, H;
- l - the length, m;
- μ_0 - the magnetic permeability of vacuum;
- Z - the number of turns in the induction coil;
- A - the cross-section area of transverse section of the rod, m^2.

Testing of electrical properties was made on stand consisting of the stabilized DC power unit, slide rheostat, ammeter, voltmeter, and sample holder. To ensure precise contact of the sample surface with electrodes, to ensure the homogeneous distribution of electrical charge, and to minimize the effect of load of electrodes on the measured current value, samples were prepared for testing with 3 mm thick copper disks mounted at the ends. The resistivity values were estimated by using Ohm principle based on the following relation:

$$\delta = \frac{U}{I} \cdot \frac{A}{l} \quad (2)$$

where:
- δ - the resistivity, Ω·m;
- l - the length of the sample, m;
- A - the cross-section area of transverse section of the rod, m^2;
- U - the voltage, V;
- I - the current intensity, A.

3. Results and discussion

Basing on taken measurements of magnetic susceptibility χ as function of temperature, volume magnetic susceptibility χ_v as function of frequency in the range up to 10 kHz, magnetic permeability μ_{ef} in function of frequency in the range of 20 Hz-2 MHz as well as magnetization versus applied field curves, the magnetic properties of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powders and the newly - elaborated composite materials has been assigned.

Based on the magnetisation curves in the function of magnetic field intensities for $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powders and composite materials reinforced with them (Table 2), it has been found that - in case of composites - along with reduced ration of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ fraction in the matrix, the magnetisation changes and the saturation magnetisation M_s assumes values approximate for the particular ratios of the reinforcement materials, changing in direct proportion to them: for composite materials with 10% $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ ratio its value is from 0.077 T to 0.094 T, while for samples reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles with 15% and 20% ratios, it is ~0.13 T and ~0.2 T, respectively. The highest magnetisation saturation value (being 0.981 T) was obtained for $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder of particle size from the range 38-106 µm.

Table 2.
Magnetic properties of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powders and the composite materials reinforced with them

$Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powders grain size range, µm	Volume fraction of powder, %	M_s, T	H_{max}, kA/m	H_c, kA/m	B_r, T	B_s, T
38-106	10%	0.094	1230.03	3.67	0.007	1.626
	15%	0.136	1228.48	4.60	0.009	1.664
	20%	0.199	1224.59	5.39	0.013	1.723
	100%	0.981	1213.73	8.25	0.077	2.492
106-212	10%	0.079	1225.37	1.79	0.003	1.603
	15%	0.134	1224.59	2.44	0.006	1.659
	20%	0.196	1226.53	2.91	0.008	1.721
	100%	0.980	1224.59	4.61	0.029	2.509
212-300	10%	0.077	1226.92	2.55	0.005	1.602
	15%	0.131	1226.92	3.22	0.008	1.659
	20%	0.209	1226.92	3.71	0.011	1.738
	100%	0.910	1213.73	5.11	0.028	2.422

The powder is also characterised with coercion intensity H_c equal to 8.25 kA/m, saturation induction B_s = 2.492 T and remanence B_r = 0.077 T. The composite materials with polyurethane matrix, reinforced with this type of powder are distinguished by coercion field equal to 3.67 kA/m (with the powder volumetric ratio 10%) to 5.39 kA/m (with 20% volumetric ratio) and saturation induction equal to 1.626 T and 1.723 T, respectively. The increase of the size of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder particles causes the decrease of the coercion intensity - the lowest value recorded is 1.79 kA/m (for the composite material reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder with 106-212 µm granulation and 10% of its volumetric share in the matrix) and decrease of saturation induction B_s to the minimum value recorded for the materials tested - equal to 1.603 T (for the composites reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder with 106-212 µm, as well as 212-300 µm granulation and 10% of its volumetric share in the matrix). The measurements made enabled finding that the composite materials reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles with finer granulation, i.e. 38-106 µm powder show lower magnetic properties. The saturation induction of materials in which the particles of such granulation represent 20% of the volumetric ratio is 1.723 T, with 0.013 T magnetic residue and 5.39 kA/m coercion. However, the composite materials of identical ratio of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles with 106-212 µm granulation are characterised with coercion intensity equal to 2.91 kA/m, saturation induction equals 1.721 T and remanence of 0.008 T. In case of composite materials reinforced with powder within the particle size range from 212 to 300 µm, coercion intensity is in the ranges from 2.55 kA/m (composite materials of 10% $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder volumetric ratio) to 3.71 kA/m (with 20% reinforcement ratio volumetrically), while saturation induction is on the level 1.602 T and 1.738 T, respectively. The maximum intensities of magnetic field H_{max} reach a slight diversification of values in the range from 1213.73 kA/m for powders of particle size of the range 38-106 µm and 212-300 µm to 1230.03 kA/m for composite material reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles with 38-106 µm granulation and 10% volumetric ratio. The values of this level for composite materials reinforces with powders of particle size 212-300 µm are constant and are 1226.92 kA/m, while for the composite materials reinforced with powders of particle size from 38 to 106 µm, H_{max} decreases along with the increase of the ratio of reinforcement material in the matrix, reaching the lowest - i.e. 1213.73 kA/m - value for the powder of this granulation.

Based on susceptibility versus temperature relationship curves the effect was analyzed of temperature on magnetic properties of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powders and of the magnetostrictive composite materials. These characteristics (Fig. 1) have the non-linear character with the maximum susceptibility values obtained at the temperature of about 200 K. With the further temperature rise, magnetic susceptibility turn in lower values and at the ambient temperature (i.e. about 300 K), change of the susceptibility versus temperature relationship occurs: one can see that in the plot as the slightly ascending line segments. Introducing various concentrations of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ magnetic particles into polymer matrix changes the flow of curve and character of the temperature relationship only slightly. Regardless of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder particles size, along with lowering of the volume concentration of powders in the composite material, shifting of the curve is observed to the lower susceptibility values in the entire examination temperature range. This behaviour is mainly affected by the magnetic fraction concentration in the particular material.

It was found based on the volume magnetic susceptibility versus frequency measurements made (Fig. 2), that susceptibility of the composite materials is proportional to the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ fraction concentration in polymer matrix and reaches highest values for materials reinforced with powder with particle size range 38-106 µm. The obtained results are being complementary to magnetic permeability dependence of frequency in the range 20 kHz to 2 MHz (Fig. 3).

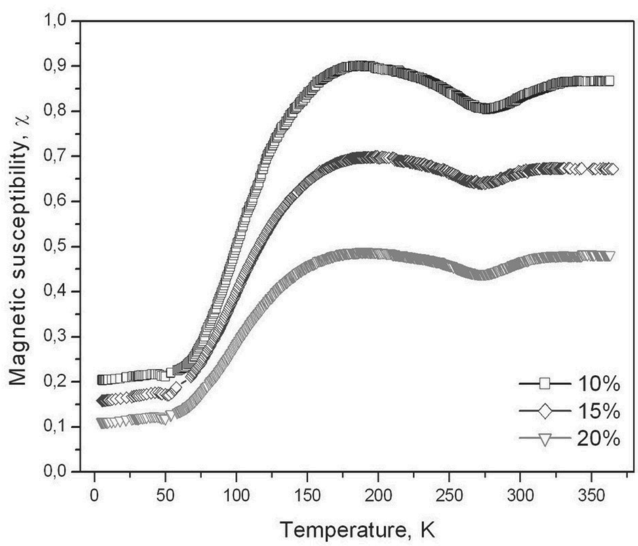

Fig. 1. Susceptibility versus temperature relationship curve for composite materials reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder with granulation from 38 to 106 µm

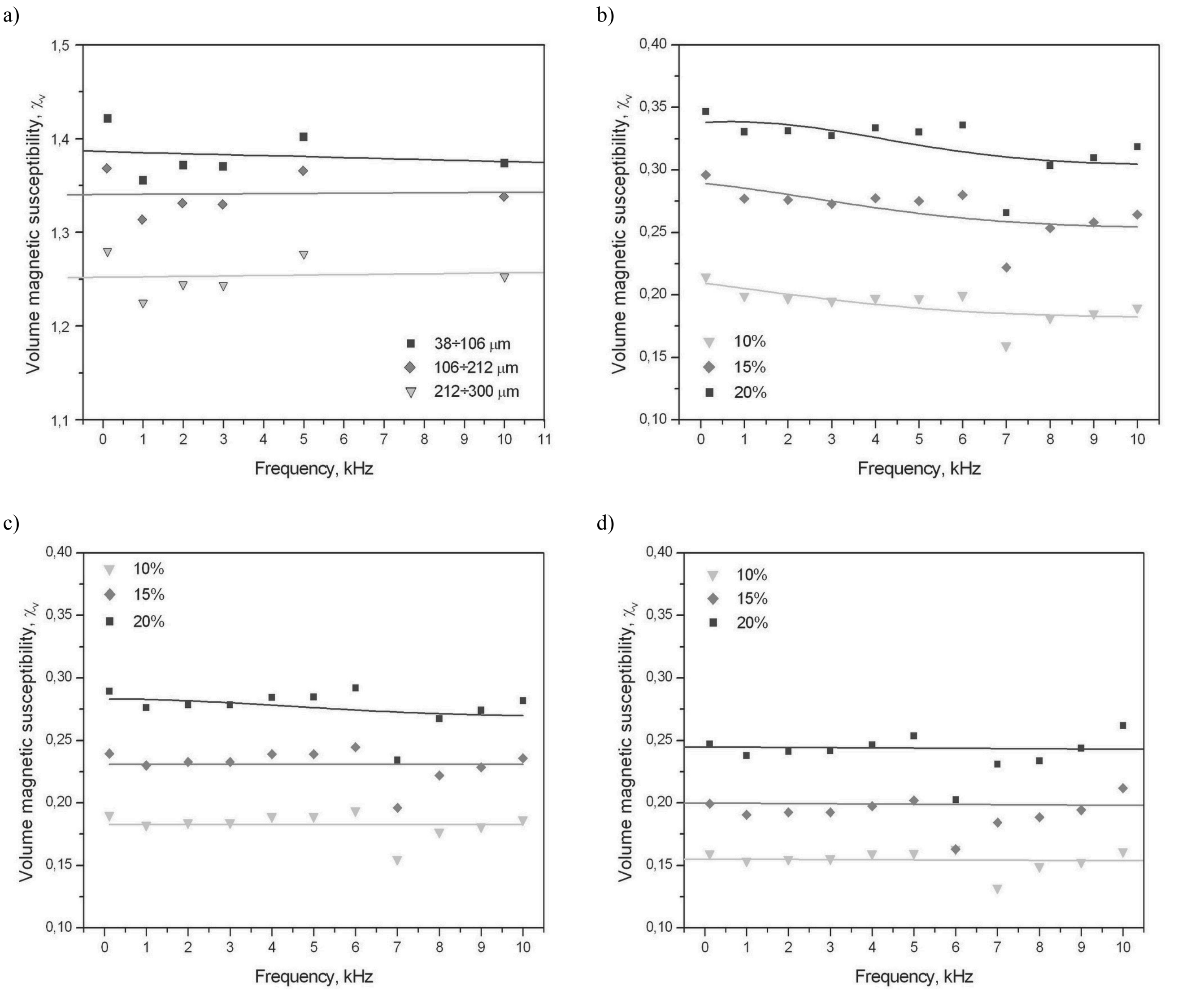

Fig. 2. Susceptibility - frequency relationship for the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powders (a) and the magnetostrictive composite materials reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powders with particle size: 38-106 μm (b), 106-212 μm (c), 212-300 μm (d)

The results of examination of the magnetic permeability dependence of frequency confirmed that permeability of the composite materials increase if the particle size decreases. The permeability value of composite materials with 20% volume fraction of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder with particle size range 38-106 μm at frequency 50 Hz is equal to 1.24, whereas for composite materials with the same volume fraction of the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder, but with particle size range 212-300 μm, the effective permeability is equal to 1.16. It was also noticed that - in the investigated frequency range - no effect was observed of frequency on the permeability value for the particular material.

The composite materials tested are characterised with high resistivity depending on the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder volumetric ratio in the matrix and the size of such particles. The resistivity of the newly developed materials with U = 200 V voltage fits within the range from 1 kΩ·m (for composite materials reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder with particle size 212-300 μm and volumetric ratio of 20%) to 30.5 kΩ·m (for 38-106 μm size $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ and volumetric ratio 10%) (Fig. 4). Based on the recorded current-voltage characteristics it has been found that their course is typical for dielectric materials. With the increasing ratio of matrix in the composite materials, the weak contact between the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles causes high resistivity, while for composite materials with 20% ratio, the resistivity decreases due to the conducting properties of the reinforcement material. The resistivity values correspond to the losses on eddy currents of the composite materials produced. Compared to its value for monolithic $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ (i.e. $58 \cdot 10^{-8}$ Ω·m) causes that the materials developed represent an attractive alternative for them, which is of particular importance in the context of their application in magnetic fields of high frequency of magnetisation.

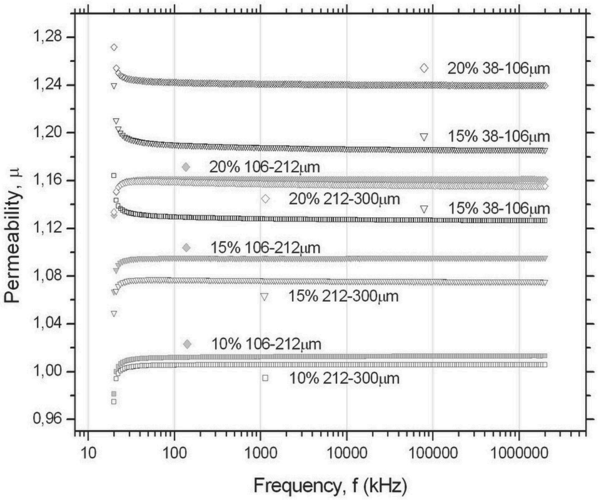

Fig. 3. Permeability dependence of frequency for the magnetostrictive composite materials

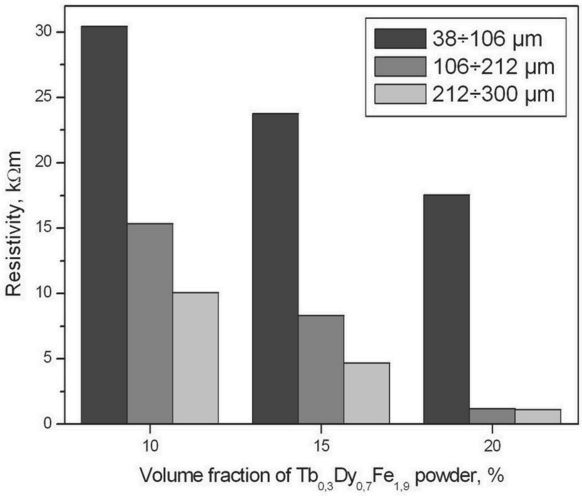

Fig. 4. Relation between the $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder volume fraction in the composite materials and the resistivity (for U = 200V)

4. Conclusions

An important factor - especially from a point of view of newly elaborated composite materials as an final control elements for example in active intelligent systems - is necessity of taking into consideration an influence of frequency and temperature on their properties in operating conditions. Higher temperature indispensably accompanies changeable magnetic field, and high frequencies in particular - as a result eddy currents causing energy losses are being induced in conductive materials also. In order to verify chosen selection of materials with regards for application, complementary research has been made regarding magnetization versus applied field curves, susceptibility in a function of temperature as well as susceptibility and permeability in function of frequency.

By considering the magnetic permeability μ_{ef} in dependence of frequency, it can be assumed that in lower frequency permeability of fine $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles (i.e. from the range 38-106 μm) attains higher values then for the coarse ones (i.e. for particle size in the range 106-212 μm and 212-300 μm). Although this tendency is confirmed in literature reports , there is no unequivocal explanation this phenomena. In that cases - according to data from literature [23,24] - the natural resonance frequency of composite materials reinforced with fine particles is lower than for the coarse ones. One can suppose that this phenomena is connected with dispersion of permeability, which may originated from [23,25]:

- the domain walls resonance (vibrating Bloch's walls due to the force acting on walls in the presence of high frequency external ac magnetic field),
- the natural ferromagnetic resonance (the forced precession of magnetization vectors in domains due to the presence of effective magnetic anisotropy),
- the relaxation of magnetization.

Moreover, it was also noticed that the values of permeability for particular composite materials is nearly constant in investigated frequency range. Increasing of extorting signal frequency up to 2 MHz causing that magnetic permeability for composite materials decrease of about 0.01 %, which suggest possibility of using newly-developed composite materials as intelligent actuators and sensors working in the high-frequency magnetic fields. In such cases, one of the indispensible factor accompanying to fast-changing magnetic field is raised temperature - its influence onto magnetic properties of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powders, as well as magnetostrictive composite materials have been analyzed on the base of magnetic susceptibility versus temperature curves. These curves have the non-linear character with the maximum susceptibility values obtained at the temperature of about 200 K. With the further temperature rise up to 273 K, these curves reach local minimum responding to anisotropy compensation. In the temperature range near 300 K, the change of the susceptibility versus temperature relationship occurs: one can see that in the plot as the slightly ascending line segments. Taking into account that thermal vibration accompanying to rising of temperature cause destroying of ordered spin magnetic moments, which leads to decay of magnetic domains , one may suppose that at the Curie point (i.e., 653K) which is the ferromagnetic/paramagnet phase transition temperature, the susceptibility value would either rapidly decrease by several orders of magnitude or this transition will be broadened within the temperature range. It was also noticed that decreasing of volume fraction of reinforced powders in matrix - irrespective of their size - causing lowering of magnetic susceptibility-temperature curve.

Results show that - thanks to the fact that the magnetically indifferent material has been used as the matrix - the magnetic properties of those composites depend on volume fraction of reinforcement and - to a lesser extend - on $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ particles size. The best results (i. e. H_c = 2.91 kA/m, B_r = 0.008 T and B_s = 1.721 T) were obtained for the composite materials reinforced with 20 % volume fraction of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ powder with particle size range from 106 to 212 μm.

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References

[1] A.E. Clark, H.S. Belson, N. Tamagawa, Magnetostriction anisotropy in cubic rare earth-Fe2 compounds, Proceeding of the American Institute of Physics Conference 10 (1973) 749-753.

[2] G. Engdahl, Handbook of giant magnetostrictive materials, Academic Press, San Diego, 2000.

[3] J.W. Xie, D. Fort, J.S. Abell, The preparation, microstructures and magnetostrictive properties of Samfenol-D, Journal of Alloys and Compounds 366 (2004) 241-247.

[4] J.R. Cullen, A.E. Clark, Magnetostriction and structural distortion in rare-earth intermetallics, Physical Review B 15 (1977) 4511-4515.

[5] M. Palit, J.A. Chelvane, S. Pandian, N. Das, V. Chandrasekaran, Effect of solidification rate on the microstructural features and magnetostriction of directionally solidified $Tb_{0.3}Dy_{0.7}Fe_{1.95}$, Scripta Materialia 58 (2008) 819-821.

[6] B.W. Wang, L. Weng, S.Y Li, S.Z. Zhou, X.X. Gao, Dynamic characteristic of Tb-Dy-Fe polycrystals with <110> axial alignment, Materials Science Forum 475-479 (2005) 2251-2254.

[7] J.C. Yan, S.X. Lü, X.Q. Xie, Z.G. Zhou, S.Q. Yang, S.Y. He, An alignment evaluation method for polycrystalline Terfenol-D based on magnetostriction effect, Journal of Magnetism and Magnetic Materials 234 (2001) 431- 436.

[8] L.A. Dobrzański, A. Tomiczek, A. Nabiałek, Z. Stokłosa, Magnetic properties of composite materials with giant magnetostriction, Archives of Materials Science and Engineering 51/2 (2011) 97-102.

[9] J.D. Snodgrass, O.D. McMasters, Optimized TERFENOL-D manufacturing processes, Journal of Alloys and Compounds 258 (1997) 24-29.

[10] A. Tomiczek, Magnetostrictive composite materials with the polymer matrix reinforced with $Tb_{0.3}Dy_{0.7}Fe_{1.95}$ particles, Ph.D. Thesis - unpublished, Main Library of the Silesian University of Technology, Gliwice, 2012 (in Polish).

[11] T.A. Duenas, G.P. Carman, Particle distribution study for low-volume fraction magnetostrictive composites, Journal of Applied Physics 90/5 (2001) 2433-2439.

[12] C. Rodríguez, M. Rodriguez, I. Orue, J.L. Vilas, J.M. Barandiarán, M.L.F. Gubieda, L.M. León, New elastomer - Terfenol-D magnetostrictive composite, Sensors and Actuators A 149 (2009) 252-254.

[13] J. Tian, Z. Zuo, D. Pan, S. Zhang, Bonded Terfenol-D composites with low eddy current loss and high magnetostriction, Rare Metals 29/6 (2010) 579-582.

[14] W. Bodnar, P. Stoch, J. Chmist, J. Pszczoła, P. Zachariasz, J. Suwalski, Electrical resistivity and Mössbauer effect investigations on Tb0.27Dy0.73(Mn1-xFex)2 intermetallics, Journal of Alloys and Compounds 505 (2010) 393-399.

[15] J. Liu, W. Ren, D. Li, N. Sun, X. Zhao, J. Li, Z. Zhang, Magnetic transitions and magnetostrictive properties of TbxDy1-x(Fe0.8Co0.2)2 (0.20≤x≤0.40), Physical Rewiev B 75 (2007) 064429.

[16] X. Zheng, P. Zhang, F. Li, Z. Cheng, B. Shen, A magnetic, magnetostrictive and Mössbauer study of Tb0.3Dy0.7-xPrx(Fe0.9Al0.1)1.95 alloys, Journal of Magnetism and Magnetic Materials 321/23 (2009) 3842-3846.

[17] A. Boczkowska, J. Kapuściński, Z. Lindemann, D. Witemberg-Perzyk, S. Wojciechowski, The composites, Publication of Warsaw University of Technology, Warsaw 2003 (in Polish).

[18] M. Bilewicz, J.C. Viana, L.A. Dobrzański, Development of microstructure affected by in-mould manipulation in polymer composites and nanocomposite, Journal of Achievements in Materials and Manufacturing Engineering 31 (2008) 71-76.

[19] K. Srinivasan, Composite materials, Production, properties, testing and application, Alpha Science International Ltd., Oxford, 2009.

[20] L. Sandlund, M. Fahlander, T. Cedell, A.E. Clark, J.B. Restrorff, M. Wun-Fogle, Magnetostriction, elastic moduli, and coupling factors of composite Terfenol-D, Journal of Applied Physics 75 (1994) 5656-5658.

[21] L. Ruiz de Angulo, J.S. Abell, I.R. Harris, Magnetostrictive properties of polymer-bonded Terfenol-D composites, Journal of Magnetism and Magnetic Materials 157/158 (1996) 508-509.

[22] J. Kaleta, D. Lewandowski, R. Mech, P. Gąsior, Magnetomechanical properties of Terfenol-D powder composites, Solid State Phenomena 154 (2009) 35-40.

[23] R. Dosoudil, M. Ušáková, J. Franek, A. Grusková, J. Sláma, Dispersion of complex permeability and EM-wave absorbing characteristics of polymer-based composites with dual ferrite filler, Journal of Magnetism and Magnetic Materials 320 (2008) 849-852.

[24] R. Dosoudil, M. Ušáková, J. Franek, J. Sláma, A. Grusková, Particle size and concentration effect on permeability and EM-wave absorption properties of hybrid ferrite polymer composites, IEEE Transactions on Magnetics 46 (2010) 436-439.

[25] T. Tsutaoka, Frequency dispersion of complex permeability in Mn-Zn and Ni-Zn spinel ferrites and their composite materials, Journal of Applied Physics 93 (2003) 2789-2796.