Exploring the Temperature Dependent Magnetic Properties and Magnetoimpedance Effect in Fe-rich Microwires for Temperature Monitoring

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***Abstract*—In this work, we provide new experimental results on temperature dependence of hysteresis loops and the Giant MagnetoImpedance (GMI) effect of amorphous $Fe_{75}B_9Si_{12}C_4$ microwires. We observed a remarkable improvement of GMI ratio and modification of hysteresis loops from rectangular to inclined upon heating. The observed experimental results are discussed considering relaxation of internal stresses upon heating, Hopkinson effect and modification of the thermal expansion coefficients upon heating.**

Keywords- Magnetic microwires; Magnetic softness; Giant magnetoimpedance effect; Internal stresses; Magnetic anisotropy.

I. INTRODUCTION

Amorphous magnetic materials are commonly considered among the most promising magnetic materials because of their excellent magnetic and mechanical properties [1]-[5]. Such amorphous materials can be prepared with planar (ribbons) or cylindrical (wires) shapes.

Magnetic wires can have unique magnetic properties, such as magnetic bistability [6]-[8] and/or giant magnetoimpedance, GMI, effect [9]-[11], which are suitable for development of several technological applications [12]-[15]. Therefore, research on amorphous magnetic wires has attracted substantial attention since the 70-s [6]-[15].

Recently, substantial attention has been paid to development of amorphous materials with new functionalities, such as reduced dimensions, enhanced corrosion resistance or biocompatibility [11][13]. Therefore, great attention has been paid to development of alternative fabrication methods allowing preparation of biocompatible amorphous materials with reduced dimensionality [11][13].

Accordingly, studies of glass-coated microwires with reduced diameters (between 0.5 and 100 μm), covered with thin, insulating, biocompatible and flexible glass-coating prepared by the Taylor-Ulitovsky method have attracted great attention [11] [13]. Such microwires are covered with thin, insulating, biocompatible and flexible glass-coating allowing better corrosion resistance and biocompatibility. Additionally, such microwire can present excellent magnetic softness or magnetic bistability [11] [13]. Such features of glass-coated microwires allow development of new exciting applications in various magnetic sensors, as well as in smart composites with tunable magnetic permittivity [6][11][13]-[21]. One more advantage of glass-coated microwires is their excellent mechanical properties [4] [5].

One of the most promising applications of glass-coated microwires is the external stimuli (temperature, stress, magnetic field) monitoring [22]-[25]. As was previously demonstrated [22], the dispersion of the effective permittivity, ε_{ef}, of the composites with magnetic wire inclusions depends on the metallic wires geometry, as well as on the magnetic wires impedance. The utilization of ferromagnetic wires allows tuning of this dispersion through changing the wire magnetic structure by external stimuli (magnetic field, stress or temperature) [22]-[25].

For such applications, studies of temperature dependence of the GMI effect are essentially relevant. However, there are only very few studies on temperature dependence of GMI and most studies were performed in different amorphous materials (ribbons or thick magnetic wires without glass-coating) [26]-[29].

In this paper, we provide our recent experimental results on temperature dependence of the GMI effect and hysteresis loops for Fe-rich ($Fe_{75}B_9Si_{12}C_4$) microwires.

This paper is organized as follows. In Section 2, the experimental methods, as well as the microwires characteristics analyzed in this paper are provided. Section 3 presents the experimental results dealing with temperature dependence of hysteresis loops and GMI effect. Finally, we conclude the paper in Section 4.

II. EXPERIMENTAL SYSTEM DETAILS

Amorphous $Fe_{75}B_9Si_{12}C_4$ glass-coated microwires (metallic nucleus diameter, d= 15.2 µm, total diameter, D= 17.2 µm) with positive magnetostriction coefficient, λ_s, ($\lambda_s \approx 38x10^{-6}$), have been prepared using the Taylor-Ulitovsky method, previously described elsewhere [16] [18].

The hysteresis loops have been measured using MicroSense EV9 Vibration Sample Magnetometer (VSM), as well as using fluxmetric methods. The latter was previously successfully employed for characterization of magnetically soft microwires at room temperature [30], while utilization of VSM magnetometry allowed to measure the hysteresis loops of 5 mm long samples from room temperature up to 300 °C, as described elsewhere [31]. The hysteresis loops were represented as the dependence of normalized magnetization, M/M_0 (where M is the magnetic moment at a given magnetic field and M_0 is the magnetic moment of the sample at the maximum magnetic field amplitude measured at room temperature) versus magnetic field, H.

Specially designed experimental set-up allows to measure sample impedance and evaluate $\Delta Z/Z$-ratio in the temperature, T, range from room up to T= 300 °C at frequencies, f, up to 110 MHz [32].

We used the GMI ratio, $\Delta Z/Z$, determined as:

$$\Delta Z/Z = [Z\,(H) - Z\,(H_{max})]\;/\;Z\,(H_{max}), \qquad (1)$$

where Z is impedance of the wire, H and H_{max} are the applied and maximum DC magnetic fields.

III. EXPERIMENTAL RESULTS AND DISCUSSION

As shown in Figure 1, a rectangular hysteresis loop is observed for as-prepared $Fe_{75}B_9Si_{12}C_4$ glass-coated microwire, as expected for Fe-rich microwire with positive λ_s [18].

A remarkable change in hysteresis loop is observed upon heating: the hysteresis loops of studied sample becomes essentially non-rectangular (see Figure 2a). The substantial effect of heating can be better appreciated from Figure 2b, where the change in the low field hysteresis loop upon heating is shown. Rectangular hysteresis loop transforms into inclined upon heating (see Figure 2b).

The observed changes in hysteresis loops upon heating are almost completely reversible: as shown in Figure 3, the hysteresis loop measured after heating up to 300 °C and cooling back to room temperature becomes again rectangular.

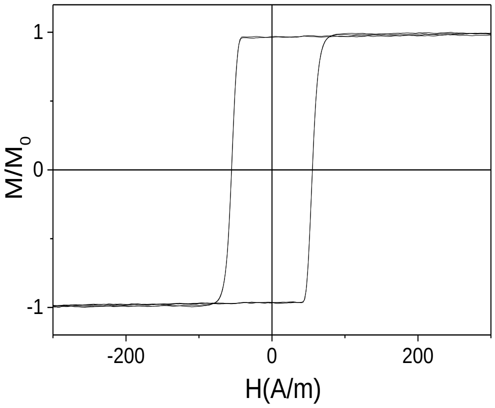

Figure 1. Hysteresis loops of as-prepared sample.

The aforementioned GMI effect is successfully explained in terms of skin effect of magnetically soft conductors. The origin of the GMI effect is related to the effect of a magnetic field, H, on the penetration depth, δ, of an electrical current flowing through the magnetically soft conductor [9]-[11]. The relationship between δ and the circumferential magnetic permeability, μ_ϕ, for the case of magnetic wires is given by:

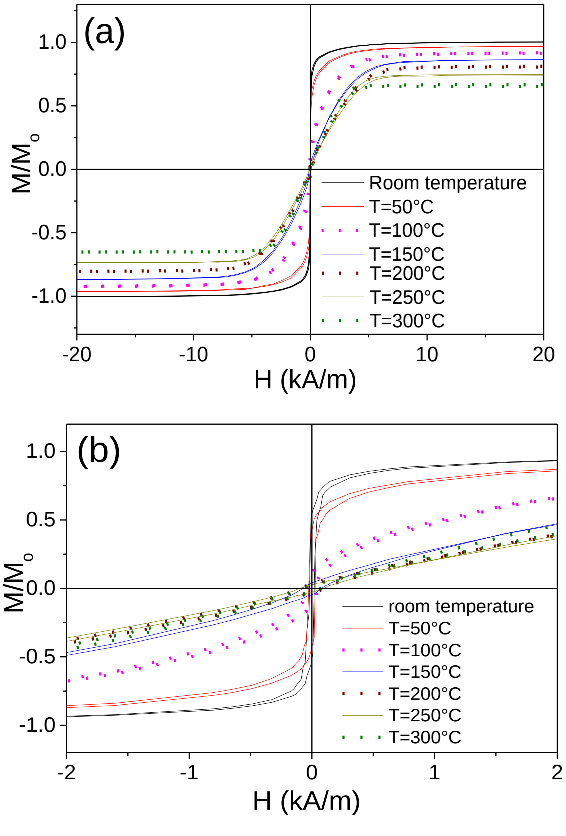

Figure 2. Hysteresis loops of studied sample, measured at different T (a). Low field hysteresis loops (b) measured at the same T.

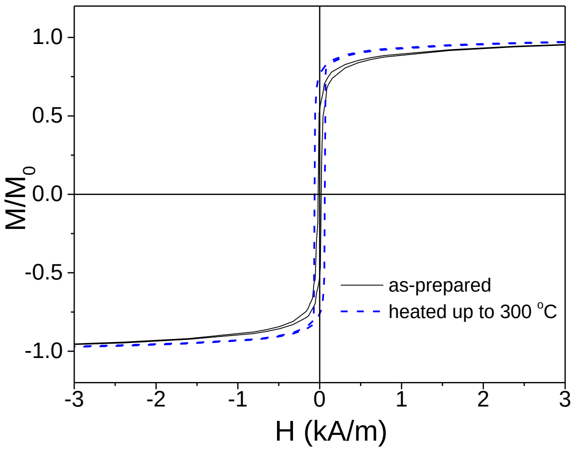

Figure 3. Hysteresis loops of studied sample, measured before and after heating up to 300 °C.

$$\delta = \sqrt{\pi \sigma \mu_{\phi} f} \quad (2)$$

where σ is the electrical conductivity and f the frequency of the current along the sample.

Accordingly, high $\Delta Z/Z$-ratio values are usually observed in magnetic wires with high μ_{ϕ}- values, typically observed in amorphous wires with low transversal magnetic anisotropy [9]-[11][23].

As reported elsewhere [11], for magnetic wires with rectangular hysteresis loops, the $\Delta Z/Z$-ratio values are usually rather low. However, the observed influence of heating on the shape of the hysteresis loops suggests a modification of the GMI effect. Figure 4 shows the results of the temperature dependence of the GMI effect of studied microwire. Indeed, evidenced from Figure 4, a remarkable increase in $\Delta Z/Z$-ratio is observed for the studied sample upon heating (see Figure 4). Temperature dependencies of maximum GMI ratio, $\Delta Z/Z_{max}$, for 50 and 100 MHz are summarized in Figure 4c.

The origin of the rectangular hysteresis loop of Fe-rich microwires is commonly attributed to the peculiar domain structure of as-prepared Fe-rich microwires consisting of axially magnetized inner single domain and outer domain shell with radial magnetization [6] [7] [33]. Axial magnetic anisotropy of as-prepared Fe-rich microwires (λ_s >0) is commonly explained considering preferentially axial character of the internal stresses arising during the fabrication process consisting of simultaneous rapid solidification of metallic nucleus surrounded by glass-coating with rather different thermal expansion coefficients [18] [34] [35]. The main origin of such stresses is the difference in thermal expansion coefficients of the glass-coating and the metallic nucleus. Accordingly, the heating effect on hysteresis loops shape must be attributed to a decrease in internal stresses upon heating.

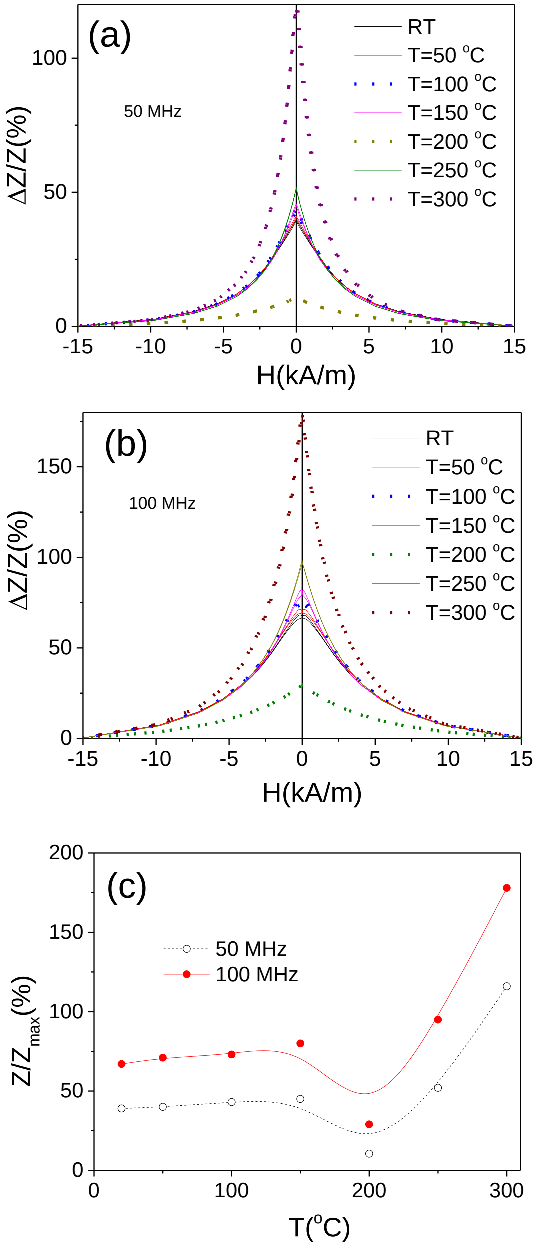

Figure 4. $\Delta Z/Z(H)$ dependencies of studied sample measured at 50 (a) and 100 MHz (b) at various temperatures and $\Delta Z/Z_{max}$ (T) dependencies evaluated for 50 and 100 MHz (c).

The transformation of the hysteresis loops from rectangular to inclined must be the main reason of remarkable GMI effect improvement.

Upon samples heating, several processes are expected: the reduction of internal stresses originated by the rapid solidification of a composite microwire with a different thermal expansion coefficient of the metal nucleus and glass coating and relaxation of internal stresses (as in any amorphous materials). Additionally, the origin of the substantial GMI effect improvement at T= 300 °C can be related to the Hopkinson effect. The Hopkinson effect is manifested as a sharp magnetic permeability maximum at temperatures slightly below the Curie temperature, T_c, [36][37]. The origin of such effect is commonly associated with a faster decrease of magnetic anisotropy constant with temperature as compared to the magnetization.

A comparison of the hysteresis loops measured at different T (see Figure 5a) shows that, indeed, higher magnetic permeability is observed at T= 300 °C, as compared to the hysteresis loops measured at T= 200 °C and 250 °C (see Figure 5 a).

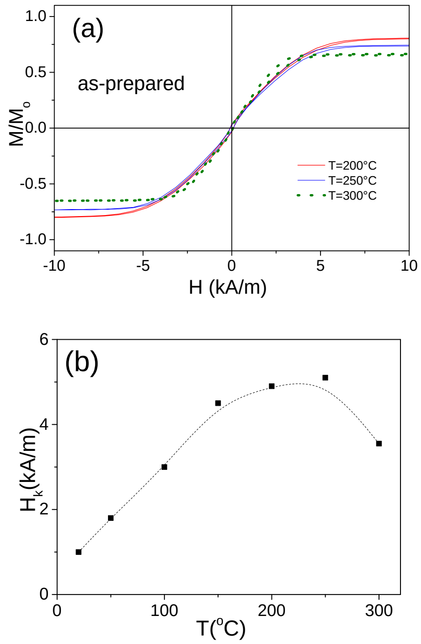

Figure 5. Change in the hysteresis of studied samples upon heating (a) and H_k(T) dependencies evaluated from hysteresis loops (c).

The evolution of average magnetic anisotropy field, H_k, upon heating is provided in Figure 5b. Such H_k –values were evaluated from the hysteresis loops, as previously described [38].

In order to separate the effect of heating from the effect of the internal stresses relaxation, the comparison of the *ΔZ/Z(H)* dependencies measured at room temperature before and after heating up to 300 °C is provided in Figure 6.

A comparison of the *ΔZ/Z(H)* dependences (see Figure 6 a,b) clearly shows some $\Delta Z/Z_{\max}$ improvement after heating to 300 °C. This increase in $\Delta Z/Z_{\max}$ must be related to the relaxation of internal stresses. However, the main contribution to the increase in $\Delta Z/Z_{\max}$ is related to the heating itself.

The observed experimentally results on substantial temperature dependence of the GMI effect and magnetic properties of Fe-rich microwires can be useful for temperature monitoring. However, the effect of heating must be separated from the internal stresses relaxation upon heating.

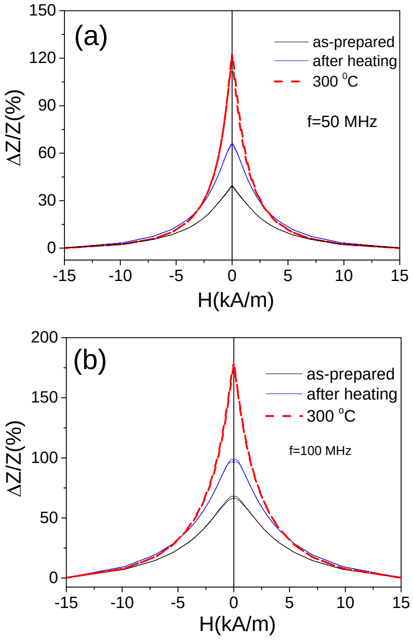

Figure 6. *ΔZ/Z(H)* dependencies measured at 50 MHz (a) and 100 MHz (b) at room temperature before and after heating and at T=300 °C

IV. CONCLUSIONS

The temperature dependence of the magnetic properties and the GMI effect of amorphous FeSiBC microwires have been thoroughly analyzed using both hysteresis loops and GMI measurements. A substantial change in hysteresis loops shape and GMI effect upon heating is observed. We observed a remarkable improvement of the GMI ratio and modification of hysteresis loops from rectangular to inclined upon heating of FeSiBC microwire. The observed experimental results are discussed considering relaxation of internal stresses upon heating, Hopkinson effect and modification of the thermal expansion coefficients upon heating.

The observed significant effect of temperature on the hysteresis loop shape and the GMI effect of FeSiBC microwires coated by insulating, flexible and biocompatible glass-coating opens up the possibility of using such Fe-rich microwires for temperature sensors and for temperature monitoring in composites with magnetic microwire inclusions.

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REFERENCES

[1] F. Fiorillo, G. Bertotti, C. Appino, and M. Pasquale, Soft Magnetic Materials (Ed. J. Webster), Wiley Encyclopedia of Electrical and Electronics Engineering, 1999, John Wiley & Sons, Inc., p. 42. doi:10.1002/047134608X.W4504.pub2.

[2] J. Durand, "Magnetic Properties of Metallic Glasses" in Topics in Applied Physics, Vol. 53, Glassy Metals II. Atomic Structure and Dynamics, Electronic Structure, Magnetic Properties, H. Beck and H.-J. Giintherodt Eds., Springer-Verlag, Berlin Heidelberg New York Tokyo, pp. 343-386, 1983.

[3] D. C. Jiles, "Recent advances and future directions in magnetic materials", Acta Mater., vol. 51, pp- 5907-5939, 2003.

[4] T. Goto, M. Nagano, and N. Wehara, "Mechanical properties of amorphous $Fe_{80}P_{16}C_3B_1$ filament produced by glass-coated melt spinning", Trans. JIM, vol. 18, pp. 759–764, 1977.

[5] V. Zhukova et al., "Correlation between magnetic and mechanical properties of devitrified glass-coated $Fe_{71.8}Cu_1Nb_{3.1}Si_{15}B_{9.1}$ microwires", J. Magn. Magn. Mater., vol. 249, pp. 79–84, 2002.

[6] M. Vázquez and D.-X. Chen, "The magnetization reversal process in amorphous wires", IEEE Trans. Magn., vol. 31, no. 2, pp. 1229-1239, 1995.

[7] K. Mohri, F.B. Humphrey, K. Kawashima, K. Kimura, and M. Muzutani, "Large Barkhausen and Matteucci effects in FeCoSiB, FeCrSiB, and FeNiSiB amorphous wires", IEEE Trans.Magn., vol. 26, no. 5, pp. 1789- 1781, 1990.

[8] A. Zhukov et al., "Frequency dependence of coercivity in rapidly quenched amorphous materials, J. Mat. Sci. Eng. A vol. 226-228, pp. 753-756, 1997.

[9] K. Mohri, T. Uchiyama, L. P. Shen, C. M. Cai, and L. V. Panina, "Amorphous wire and CMOS IC-based sensitive micro-magnetic sensors (MI sensor and SI sensor) for intelligent measurements and controls", J. Magn. Magn. Mater., vol. 249, pp. 351-356, 2001.

[10] A. Zhukov et al., Giant magnetoimpedance in rapidly quenched materials", J. Alloys Compound., vol. 814, pp. 152225, 2020.

[11] M. Knobel, M. Vazquez, and L. Kraus, Giant magnetoimpedance, Handbook Magn. Mater., vol. 15, pp. 497- 563, 2003.

[12] V. Zhukova et al., "Electronic Surveillance and Security Applications of Magnetic Microwires", Chemosensors, vol. 9, p. 100, 2021.

[13] T. Uchiyama, K. Mohri, and Sh. Nakayama, "Measurement of Spontaneous Oscillatory Magnetic Field of Guinea-Pig Smooth Muscle Preparation Using Pico-Tesla Resolution Amorphous Wire Magneto-Impedance Sensor", IEEE Trans. Magn., vol. 47, pp. 3070-3073, 2011.

[14] Y. Honkura, "Development of amorphous wire type MI sensors for automobile use", J. Magn. Magn. Mater., vol. 249, pp. 375-381, 2002.

[15] A. Zhukov et al., "Magnetoelastic sensor of level of the liquid based on magnetoelastic properties of Co-rich microwires", Sens. Actuat. A Phys., vol. 81, no. 1-3, pp.129-133, 2000.

[16] V. Zhukova et al., "Development of Magnetically Soft Amorphous Microwires for Technological Applications", Chemosensors, vol. 10, p. 26, 2022.

[17] D. Kozejova et.al., "Biomedical applications of glass-coated microwires", J. Magn. Magn. Mater., vol. 470, pp. 2-5, 2019.

[18] A. Zhukov et al., "Advanced functional magnetic microwires for technological applications", J. Phys. D: Appl. Phys., vol. 55 p. 253003, 2022, doi:10.1088/1361-6463/ac4fd7.

[19] L. Ding, S. Saez, C. Dolabdjian, L. G. C. Melo, A. Yelon, and D. Ménard, "Development of a high sensitivity Giant Magneto-Impedance magnetometer: comparison with a commercial Flux-Gate", IEEE Sensors, vol. 9 (2), pp. 159-168, 2009.

[20] D. Makhnovskiy, N Fry, and A. Zhukov, "On different tag reader architectures for bistable microwires", Sens. Actuat. A Phys., vol. 166, pp. 133-140, 2011.

[21] S. Gudoshnikov et al., "Evaluation of use of magnetically bistable microwires for magnetic labels", Phys. Stat. Sol. (a), vol. 208, no. 3, pp. 526–529, 2011.

[22] D. Makhnovskiy, A. Zhukov, V. Zhukova, and J. Gonzalez, "Tunable and self-sensing microwave composite materials incorporating ferromagnetic microwires", Advances in Science and Technology, vol. 54, pp 201-210, 2008.

[23] F. Qin and H. X. Peng, "Ferromagnetic microwires enabled multifunctional composite materials", Prog. Mater. Sci., vol. 58 (2), pp. 183-259, 2013.

[24] M. Churyukanova et al., "Non-contact method for stress monitoring based on stress dependence of magnetic properties of Fe-based microwires", J. Alloys Compd., vol. 748(5), pp. 199-205, 2018.

[25] A. Allue et al., "Smart composites with embedded magnetic microwire inclusions allowing non-contact stresses and temperature monitoring", Compos. Part A Appl., vol. 120, pp. 12-20, 2019, doi: 10.1016/j.compositesa.2019.02.014

[26] J. Nabias, A. Asfour, and J. Yonnet, "Temperature Dependence of Giant Magnetoimpedance in Amorphous Microwires for Sensor Application", IEEE Trans. Magn., vol. 53(4), p. 4001005, 2017. DOI:10.1109/TMAG.2016.2625841.

[27] J. D. Santos, R. Varga, B. Hernando, and A. Zhukov, "Enhancement of GMI effect in magnetic microwires through the relative temperature dependence of magnetization and anisotropy", J. Magn. Magn. Mater., vol. 321, pp. 3875–3877, 2009.

[28] M. Kurniawan et al., "Temperature Dependent Giant Magnetoimpedance Effect in Amorphous Soft Magnets", J. Electron. Mater., vol. 43, pp. 4576–4581, 2014.

[29] P. Corte –Leon et al., "Effect of temperature on magnetic properties and magnetoimpedance effect in Fe -rich microwires", J. Alloys Compound. vol. 946, p. 169419, 2023.

[30] L. Gonzalez-Legarreta et al., "Optimization of magnetic properties and GMI effect of Thin Co-rich Microwires for GMI Microsensors", Sensors, vol. 20, p.1558, 2020.

[31] B. Kunca et al., "Soft magnetic performance of ultra-rapidly annealed high-Bs Fe-(Co)-B nanocrystalline alloys at elevated temperatures", J. Alloys Compd., vol. 911, p. 165033, 2022, DOI: 10.1016/j.jallcom.2022.165033.

[32] F. Andrejka, "Influence of thermal treatment in external magnetic field on microstructure and magnetic properties of selected rapidly quenched alloys" (Doctoral dissertation), Technical University, Kosice, Slovakia, 2018.

[33] V. Zhukova, J. M. Blanco, A. Chizhik, M. Ipatov, and A. Zhukov, "AC-current-induced magnetization switching in amorphous microwires", Front. Phys. vol. 13, no. 2, p. 137501, 2018. https://doi.org/10.1007/s11467-017-0722-6

[34] S. A. Baranov, V. S. Larin, and A. V. Torcunov, "Technology, Preparation and Properties of the Cast Glass-Coated Magnetic Microwires", Crystals, vol. 7, p. 136, 2017.

[35] H. Chiriac and T. A. Óvári, "Amorphous glass-covered magnetic wires: preparation, properties, applications", Progr. Mater. Sci., vol. 40, no. 5, pp. 333-407, 1996.

[36] K. He, H. Xu, Z. Wang, and L. Cheng", Hopkinson effect in soft magnetic materials", J. Mater. Sci. Technol., vol. 16, pp 145-147, 2000.

[37] V. Zhukova, M. Ipatov, A. Talaat, and A. Zhukov, "Hopkinson effect in Co-rich glass-coated microwires", Phys. Status Solidi C, vol. 11, no. 5–6, pp. 1130–1132, 2014. doi:10.1002/pssc.201300715.

[38] A. Zhukov et al., "Induced Magnetic Anisotropy in Co-Mn-Si-B Amorphous Microwires", J. Appl. Phys., vol. 87, pp. 1402-1408, 2000. doi:10.1063/1.372063