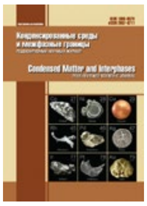

ISSN 1606-867X (Print)
ISSN 2687-0711 (Online)
Condensed Matter and Interphases
Kondensirovannye Sredy i Mezhfaznye Granitsy
https://journals.vsu.ru/kcmf/

Original articles

Brief review
https://doi.org/10.17308/kcmf.2023.25/11472

Natural ferromagnetic resonance in microwires and its applications. Brief review

S. A. Baranov[1,2]✉

[1]*Moldova State University, Institute of Applied Physics,*
5 Academiei st., Chisinau MD-2028, Republic of Moldova

[2]*Shevchenko Pridnestrov'e State University,*
128 25- Oktyabrya st., Tiraspol 33000, Pridnestrov'e, Republic of Moldova

Abstract

The paper analyzes technological aspects of the Taylor–Ulitovsky method used to produce microwires of various structures.

Natural ferromagnetic resonance (NFMR) in cast glass-coated amorphous magnetic micro- and nanowires was theoretically and experimentally studied. The NFMR phenomenon is due to the large residual stresses appearing in the core of the microwire during the casting process. These stresses, along with magnetostriction, determine magnetoelastic anisotropy. Besides residual stresses, the NFMR frequency is influenced by externally applied stresses on the microwire or the composite containing the so-called stress effect (SE).

The dependence of the NFMR frequency on the deformation of microwires and the external stresses on them is proposed to be used for remote diagnostics in medicine.

Keywords: Cast glass-coated amorphous magnetic micro- and nanowire, Magnetostriction, Natural ferromagnetic resonance

Funding: The study was supported by the Moldovan National Project and the project of Shevchenko Transnistria State University.

For citation: Baranov S. A. Natural ferromagnetic resonance in microwire and its application. Brief review. *Condensed Matter and Interphases*. 2023;25(4): 581–586. https://doi.org/10.17308/kcmf.2023.25/11472

Для цитирования: Баранов С. А. Естественный ферромагнитный резонанс в микропроводе и его применения. Краткий обзор. *Конденсированные среды и межфазные границы*. 2023;25(4): 581–586. https://doi.org/10.17308/kcmf.2023.25/11472

✉ Serghei A. Baranov, e-mail: sabaranov07@mail.ru

1. Introduction

The purpose of this work is to draw attention to the possibility of solving a number of technological problems associated with the application of micro- and nanowires.

One such problem may be related to increasing the mechanical toughness of windows in industrial and residential buildings. Another problem is associated with electromagnetic shielding. Both problems are related to protection against terrorist attacks, since terrorists use concentrated electromagnetic pulses to destroy computers or other electronic equipment.

These problems can be solved by manufacturing window glasses reinforced with cast glass-coated amorphous micro- and nanowires (GCAMNW) with a special composition and structure, which, on the one hand, increase their tensile strength during mechanical destruction, and on the other hand, are responsible for properties shielding them against electromagnetic radiation.

The proposed ideas are related to the technology of production of cast glass-coated amorphous micro- and nanowires. The technology for the production of cast glass-coated amorphous micro- and nanowires (GCAMNW) by the Taylor-Ulitovsky method is presented, for example, in [1–4] (see below). The phenomenon of natural ferromagnetic resonance (NFMR) for cast glass-coated micro- and nanowires with a magnetic core (GCAMNW) has been studied by many teams of researchers (the main results are presented in [3–7]).

Recently, the NFMR has attracted some interest in terms of using them for the remote contactless diagnostics of deformations [7]. This is possible due to the stress effect (SE) in the NFMR. SE leads to a change in the NFMR frequency during the deformation of the controlled object and, accordingly, the mechanically connected magnetic core in GCAMNW. The change in the NFMR frequency can be detected with a radar at frequencies near the NFMR which detects the reflected high-frequency signal and its deviations from the original value [7]. The remote testing proposed in this paper will allow monitoring these deformations and stresses.

In [7], we assumed that the controlled objects can include infrastructure facilities, namely: bridges, dams, levees, wind generator towers, high-rise buildings, pipes of thermal power stations, embankments, etc. The diagnostics can also be applied to moving objects: automobiles, airplanes, drones, missiles, etc., which can be at risk of destruction caused by natural, man-made, or technological disasters (including repeated or long-term effects of stresses and deformations). We have conducted a number of detailed studies dedicated to this topic, namely, the possibility of implementing the proposed control method. For example, SEs have been analyzed in terms of their practical application (according to [7]) in medicine. The changes in the frequency of natural ferromagnetic resonance (NFMR) have also been studied. They were detected with a radar by changes in the absorption of an electromagnetic wave by an object with GCAMNW. These effects were due to applied external mechanical stresses. The absorption of composite materials in the form of screens with built-in segments of GCAMNW have been experimentally investigated. Theoretical studies have also been carried out, which have shown that a significant proportion of the absorption can also be due to geometric resonance [3, 4, 7–10]. The greatest effect is expected for nanowires with a core radius comparable with the thickness of the skin layer.

Scientific literature presents the results of simultaneous research of the use of giant magnetic impedance (GMI) to measure such SEs (see, for example [8]). However, the use of the GMI effect does not seem to be technological (this issue has already been covered in [7]) and will not be considered in this paper. It should be noted that the influence of SEs on GMI has also been studied in [9].

The method proposed in this article is valuable due to its simplicity (see below). The microwire, if used to diagnose stresses within the skeletal system, must be placed inside the tested object. Microwave scanning and signal analysis of the receiving device (radar) will allow detecting the stresses and deformations of a skeletal object. To avoid exposing the entire body to microwave radiation, GCAMNW can be used in radio-absorbing materials which shield the rest of the body.

2. Technology of microwave production

It is known that GCAMNW is produced by a modified Taylor–Ulitovsky method (see [1–4]). In other words, to manufacture GCAMNW, a metal alloy (in the form of a thin bar) is placed in a glass tube. Due to the fact that it is heated in a high-frequency inductor to the glass melting and then metal melting temperatures (see Fig. 1), the part of the glass tube adjacent to the molten metal softens and envelops the metal droplet. The capillary, which is filled with a liquid alloy metal, is drawn out of the droplet. The metal forms the core of the microwire, and the walls of the capillary, made of silicate glass, form its glass coating (which often serves as insulation). Depending on the composition of the metal droplet (which is in the molten state and is located in a silicate glass microbath) and on the GCAMNW casting speed, the structure of the micro- and nanowire core can be mono- or polycrystalline, amorphous, or nanocrystalline (importantly, these structures can be combined in the core).

In [3], a formula was derived for the radius of the microwire, R_s (the outer radius of the glass coating), which was determined by the formula:

$$R_c \sim A\eta^{2-k}V_d^k\sigma_s^{1-k}, \quad (1)$$

where k is a parameter which depends on the casting speed ($0 < k < 1$); $A \sim 1/\rho$, ρ is the average density of the microwire; V_d is the casting speed; σ_s is the surface tension; and η is the dynamic viscosity of the glass:

$$\eta \sim \eta_0 \exp\{\Delta H/RT + c[\exp(\varepsilon/RT) - 1]\},$$

where $\varepsilon \sim 2$–10 kJ/mol, $\Delta H \sim 10^2$ kJ/mol, R is the universal gas constant, η_0 is the initial glass viscosity, and c ($c \sim 0.4$–0.9) is material constants.

Formula (1) is characterized by the following asymptotic behavior.

1. If the value of the speed of pulling the microwire is extremely small, the value R_c is large, therefore, the formula:

$$R_c \sim \eta^{5/3}V_d^{1/3}\sigma_s^{2/3}, \quad (1a)$$

where $k = 1/3$.

2. If the casting speed is high enough, R_c is:

$$R_c \sim \eta V_d \quad (1c)$$

where $k = 2/3$.

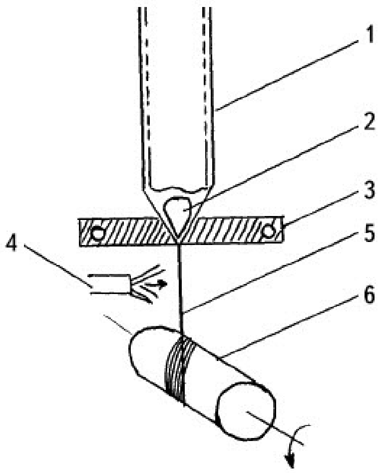

Fig. 1. The process of microwire casting: *1* – glass tube; *2* – metal droplet; *3* – inductor; *4* – water; *5* – glass-coated microwire; *6* – rotating receiver coil

2. Within limits of extremely high casting speed, at $k \to 1$, we obtain:

$$R_c \sim \eta V_d \quad (1c)$$

These formulas have been confirmed by experiment.

Here is the simplest solution to the problem of calculating residual stresses (on the surface between silicate glass and metal) for GCAMNW, which has already been considered, for example, in [3]. The formulas for the radial $\sigma_{r(0)}$, tangential $\sigma_{\varphi(0)}$, and axial $\sigma_{z(0)}$ stress components have the form of [3]:

$$\sigma_{r(0)} = \sigma_{\varphi(0)} = P = \sigma_m \frac{kx}{\left(\frac{k}{3}+1\right)x + \frac{4}{3}},$$

$$\sigma_{z(0)} = P\frac{(k+1)x+2}{kx+1}, \quad (2)$$

$$x = \left(\frac{RA}{Rm}\right)^2 - 1,$$

$\sigma_m = \varepsilon E_1$, $\varepsilon = (\alpha_1 - \alpha_2)(T^* - T) \approx 5\cdot 10^{-3}$, α_i is thermal expansion coefficients (TEC) of metal ($i = 1$) and glass ($i = 2$); T^* is the solidification temperature of the composite in the metal/glass contact region ($T^* \sim 800$–1000 K); T is temperature at which the experiment is carried out; R_m is radius of the metal core of the microwire ($d_m = 2R_m$); and R_c is the outer radius of the glass coating of the microwire *($D_c = 2R_c$)*:

$$k = \frac{E_2}{E_1} \sim (0.3 \div 0.5),$$

E_i is Young's moduli (metal ($i = 1$) and glass ($i = 2$)).

To simplify the above formulas, Poisson's ratios for glass and metal are taken ~ 1/3. According to (1), the highest stress is the longitudinal stress:

$\sigma_{z(0)} \sim (2 \div 3)P$,

i.e.:

$\sigma_{z(0)} > \sigma_{r,\varphi(0)}$,

and the maximum value of P is defined as:

$P \to 0.5\sigma_m \sim 10^9$ Pa.

With additional longitudinal strain, that occurs when the microwire is embedded in a solid matrix, which also deforms under external influence, the following term is added to the expression for residual axial tension in the metal core:

$$\sigma_{ez} = \frac{P_0}{S_m(k\,x + 1)}, \qquad (2,a)$$

where P_0 is the force applied to the composite and, accordingly, to the core of the microwire; $S_m = \pi R_m^2$ is the cross-sectional area of the core of the microwire; k is the ratio of the Young's modulus of the coating to the Young's modulus of the microwire; and x is the ratio of the area of the coating to the area of the microwire (see (1).

We also give the formulas for stresses inside the metal (they are presented in [3]):

$$\sigma_r \approx P_1'\left(1 - \frac{b_1^2}{r^2}\right), \qquad \sigma_\varphi \approx P_1'\left(1 + \frac{b_1^2}{r^2}\right), \qquad (2b)$$

where $P_1' \approx \dfrac{P_1}{1 - (b_1 / R_m)^2} \approx P_1 \approx P.$

These formulas have been confirmed experimentally.

3. Prerequisites to using high-frequency properties of the microwire

The theory of NFMR is presented in [3–7]. For a ferromagnetic metal cylinder (with a small radius R_m) located in GCAMNW, the depth of the skin layer is determined by:

$$\delta \sim [\omega(\mu\mu_0)_e \Sigma_2]^{-1/2} \sim \delta_0(\mu)_e^{-1/2}, \qquad (3)$$

where $(\mu\mu_0)_e$ is the effective high-frequency magnetic permeability, and Σ_2 is the electrical conductivity of the microwire, and ω is microwave frequency.

In the case of GCAMNW, the relative high-frequency magnetic permeability can reach a value of ~ 10^3 in the frequency range of ~ 9–10 GHz; in this case, the depth of the skin layer decreases to 1–2 μm.

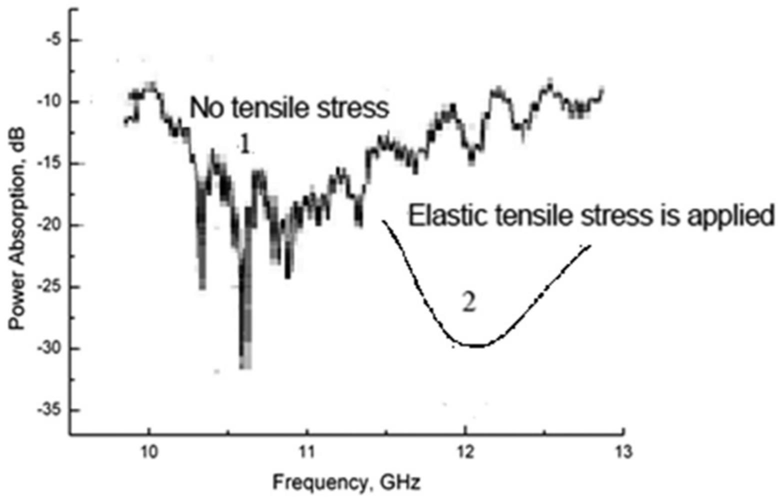

Fig. 2. *1* – average absorption characteristics of a shielding containing a microwire exhibiting NFMR at microwave frequencies ranging from 10–12 GHz for $Fe_{68}C_4B_{16}Si_{10}Mn_2$ (R_m ~ 5 μm, x ~ 5) microwires; *2* – hypothetical absorption curve in case of external pressure

It is known (see [3–5]) that if $R_m > \delta$, the general expression for the frequency of ferromagnetic resonance (FMR or NFMR) ω is:

$$(\omega/\gamma)^2 = (Hk + 4\pi M_s)\cdot Hk, \tag{3a}$$

where M_s is the saturation magnetization and γ is the gyromagnetic ratio [3, 7]. The value of anisotropy is determined as $Hk \sim 3\,\lambda\sigma/M_s$, where λ is the magnetostriction constant and σ is the effective mechanical stress in the GCAMNW metal core.

For the FMR and NFMR frequencies, the following can be obtained:

$$\omega(\text{GHz}) \approx \omega_0\left(\frac{0.4x}{0.4x+1}+\frac{\sigma_{ez}}{\sigma_0}\right)^{1/2}, \tag{4}$$

where $\omega_0(\text{GHz}) \approx 1.5(10^6\lambda)^{1/2}$.

Therefore, a change in the geometric parameters of GCAMNW, the applied external stress and, most importantly, due to magnetostriction, makes it possible to overlap the frequency range from 1 to 12 GHz, which creates prerequisites for using GCAMNW for the purposes proposed above.

4. Conclusions

The article presents the main results of the theory and the experiment related to the production of cast glass-coated microwires. The method of continuous casting of glass-coated microwires (Taylor–Ulitovsky method) has some limitations determined by the physical properties of metal and glass. The range of casting operating temperatures is specific for a given metal alloy composition and a certain type of glass, i.e. for each pair, metal alloy – glass.

We presented simple analytical expressions for residual stresses in the metal core of the microwire, which clearly show their dependence on the ratio of the radius of the microwire to the radius of the metal core and on the ratio of Young's moduli of glass and metal (see formulas (1) and (2)). Theoretical modeling based on the theory of thermoelastic relaxation shows that the residual stresses increase from the axis of the microwire to the surface of its metal core, which is in accordance with the previously obtained experimental data. Therefore, when cast microwires are manufactured by the Taylor–Ulitovsky method, the residual stresses reach the maximum values on the surface of the metal core.

These cast microwires are characterized by the presence of residual stresses which appear because of the difference in the thermal expansion coefficients of the metal alloy and the glass coating. This feature is the main factor determining the physical properties of such microwires, in particular, their magnetic properties.

For GCAMNW, the NFMR frequency depends on residual stresses and applied external mechanical stresses. The NFMR phenomenon, which we discovered in GCAMNW [3, 7], allows creating new materials that work in the microwave region with a wide frequency range. NFMR in GCAMNW is characterized by an important property, stress effect (SE). This SE can be used for the remote contactless diagnostics of deformations in objects. These objects can be periodically scanned with a floating-frequency radar to determine the deviation of the initial NFMR frequency. In this way, it is possible to track potentially dangerous deformations and stresses in any studied object.

We also considered the application of microwires in composites to improve their absorption characteristics of shielding.

Conflict of interests

The author declares that they has no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

1. Taylor G. F. A method of drawing metallic filaments and a discussion of their properties and uses. *Physical Review*. 1924;23(5): 655–660. https://doi.org/10.1103/physrev.23.655

2. Vazquez M. Soft magnetic wires. *Physica B: Condensed Matter*. 2001;299(3-4): 302–313. https://doi.org/10.1016/S0921-4526(01)00482-3

3. Baranov S. A., Larin V. S., Torcunov A. V. Technology, preparation and properties of the cast glass-coated magnetic microwires. *Crystals*. 2017;7(6): 1–12. https://doi.org/10.3390/cryst7060136

4. Peng H. X., Qin F. X., Phan M. H. *Ferromagnetic microwires composites: from sensors to microwave applications*. Springler: 2016. 245 p. https://10.1007/978-3-319-29276-2

5. Starostenko S. N., Rozanov K. N., Osipov A. V. Microwave properties of composites with glass coated

amorphous magnetic microwires. *Journal of Magnetism and Magnetic Materials.*2006; 298 (1): 56–64. https://doi.org/10.1016/j.jmmm.2005.03.004

6. Yıldız F., Rameev B. Z., Tarapov S. I., Tagirov L. R.,Aktaş B. High-frequency magnetoresonance absorption in amorphous magnetic microwires. *Journal of Magnetism and Magnetic Materials*. 2002;247(2): 222–229. https://doi.org/10.1016/s0304-8853(02)00187-7

7. Adar E., Yosher A. M., Baranov S. A. Natural ferromagnetic resonance in cast microwires and its application to the safety control of infrastructures. *International Journal of Physics Research and Applications*. 2020;3(1): 118–122. https://doi.org/10.29328/journal.ijpra.1001028

8. Nematov M. G., Adam A. M., Panina L.V., … Qin F.X. Magnetic anisotropy and stress-magnetoimpedance (S-MI) in current-annealed Co-rich glass-coated microwires with positive magnetostriction. *Journal of Magnetism and Magnetic Materials.* 2019;474: 296–302. https://doi.org/10.1016/j.jmmm.2018.11.042

9. Buznikov N. A., Kim C. O. Modeling of torsion stress giant magnetoimpedance in amorphous wires with negative magnetostriction. *Journal of Magnetism and Magnetic Materials.* 2007;315(2): 89–94. https://doi.org/10.1016/j.jmmm.2007.03.186

Information about the authors

Serghei A. Baranov, Dr. Sci. (Phys.-Math.), Senior Researcher of the Moldova State University, Institute of Applied Physics, Laboratory of Electrical and Electrochemical Treatment of Materials (Chisinau, Republic of Moldova); Associate Professor of the Shevchenko Pridnestrov'e State University (Tiraspol, Pridnestrov'e, Republic of Moldova).

sabaranov07@mail.ru

Received 28.09.2023; approved after reviewing 10.10.2023; accepted for publication 16.10.2023; published online 25.12.2023.

Translated by Irina Charychanskaya