FERROMAGNETIC RESONANCE IN CAST MICROWIRES AND ITS APPLICATION FOR NONCONTACT DIAGNOSTICS

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(Received May 3, 2020)

DOI: 10.5281/zenodo.4118691 CZU:[537.226.4+537.311.22]:004.8

Abstract

Ferromagnetic resonance in glass-coated Fe-based cast amorphous microwires reveals large residual stresses appearing in the microwire core during casting. These stresses, together with magnetostriction, determine the magnetoelastic anisotropy. Ferromagnetic resonance frequency is affected, in addition to residual and internal stresses, by external stresses applied to the microwire or a composite containing it (so-called stress effect). The dependence of ferromagnetic resonance frequency on the deformation of microwires is proposed to be used in the distant diagnostics of dangerous deformations of critical infrastructure objects and in medical application.

Keywords: magnetic microwire, magnetostriction, ferromagnetic resonance, magnetoelastic anisotropy.

Rezumat

Rezonanța ferromagnetică în microfire amorfe pe bază de Fe, în inveliș de sticlă, manifestă tensiuni reziduale mari care apar în miezul microfirului în timpul turnării. Aceste tensiuni împreună cu magnetostricția, determină anisotropia magnetoelastică. Frecvența de rezonanță feromagnetică este influențată, atât de tensiunile interne și reziduale, cât și de tensiunile externe aplicate microfirului sau compozitului său (așa-numitul efect de stres). Dependența frecvenței de rezonanță feromagnetică de deformarea microfirelor este propusă a fi utilizată în diagnosticarea la distanță a deformațiilor periculoase ale obiectelor critice de infrastructură și în scopuri medicale.

Cuvinte cheie: microfir magnetic, magnetostricție, rezonanță feromagnetică, anisotropie magnetoelastică.

1. Introduction

Interest in magnetic microwires has greatly increased in the last few years mainly due to their technological applications. Glass-coated amorphous magnetic micro- and nanowires (GCAMNWs) are attracting particular attention because of their applicability for multifunctional radioabsorbing shielding.

Glass-coated microwires were first introduced in 1924 by Taylor [1]. Cast GCAMNWs are prepared by a modified Taylor–Ulitovsky process [2–4]. The preparation of microwires and studies of magnetic properties were reported in many publications by various research teams [2–21].

For Fe-rich GCAMNWs with positive magnetostriction, the easy magnetization direction lies along the wire axis, as determined by the maximal component of the stress tensor, that is, axial tensile stress [4, 6–8]. The microwires exhibit a unique domain structure characterised by axial domains.

The phenomenon of natural ferromagnetic resonance (NFMR) in CGCMMWs [4, 6–13] is of particular interest in view of using it for noncontact diagnostics of distant objects. The diagnostics become possible due to the stress effect on the NFMR, that is, the shift of the resonance frequency as a result of a deformation of the object (and, consequently, the magnetic microwires mechanically connected to the object). This frequency shift can be measured by irradiating the object with microwaves emitted by a radar at frequencies near the NFMR and detecting the reflected signal, thus revealing a deviation of the resonance frequency from the original value.

To assess the feasibility of implementing the method of monitoring the safety of the infrastructure facilities (as well as for other applications), we examine the correlation between the NFMR frequency in a range of 1–12 GHz (determined by the dispersion of the permeability when a microwave passes through a controlled object with embedded magnetic microwires) and the mechanical stress of the microwire cores (for example, during stretching and/or bending). The correlation between the mentioned frequency and the alloy composition in the microwire core (or magnetostriction in a range of 1–40 ppm) was also verified.

Theoretical studies performed simultaneously have shown that a significant percentage of absorption can be attributed to the geometric resonance effect, while the effect of the composition is expected for thin microwires when the core radius is comparable to the thickness of the skin layer.

The main specific feature of GCAMNWs is that they consist of an amorphous magnetic alloy core (a metallic conductor) with a diameter of 0.1–50 μm that is covered with a Pyrex-like coating with a thickness of 0.5–20 μm. In the aforementioned preparation process, the metallic core solidifies together with the glass coating. Therefore, strong residual stresses take place owing to the rapid quenching from the melt and the fairly different thermal expansion coefficients of the metallic alloy and the glass coating. These residual stresses strongly affect the magnetic properties and even the crystallization process of glass-coated microwires. More technological aspects of the Taylor–Ulitovsky method for the production of cast GCAMNWs, which can have various microstructures and compositions of the metallic core, are described in [2–4, 10, 11].

2. Theoretical Details

The glass coating of cast GCAMNWs protects the metallic core from corrosion and provides electrical insulation. In addition, it induces strong mechanical stresses in the core. The theory of residual stress is described in [4]. Mechanical stresses in the core determine the magnetoelastic anisotropy which is at the origin of a unique magnetic behavior.

In cylindrical coordinates, the residual tension is characterized by axial σ_z, radial σ_r, and tangential σ_φ, components, which are independent of the radial coordinate. The value of these stresses depends on ratio x:

$$x = \left(\frac{R_c}{R_m}\right)^2 - 1, \quad (1)$$

where R_m is radius of the metallic core and R_c is the total microwire radius [4].

A formula for stresses in the metallic core of cast GCAMNWs was derived in [4]:

$$\sigma_r = \sigma_\phi \equiv P_\nu, \quad (2)$$

$$P_\nu = \varepsilon E_1 \frac{kx}{[k(1-2\nu)+1]x + 2(1-\nu)}, \quad (3)$$

where $\varepsilon E_1 = \sigma_0 \sim 2$ GPa is the maximum stress in the metallic core; ε is the difference between the thermal expansion of the metallic core and that of the glass coating with expansion coefficients α_1 and α_2: $\varepsilon = (\alpha_1 - \alpha_2)(T^* - T)$; E_1 is the Young modulus of the metallic core, T^* is the solidification temperature of the composite in the metal/glass contact region ($T^* \sim 800$–1000 K), and T is the room temperature. The technological parameter k is the ratio between Young's moduli of the glass and the metal: $k = E_2/E_1 \sim 0.3$–0.6, ν is the Poisson ratio.

Let us consider the case where all the Poisson ratios are $\nu = 1/3$ in order to obtain

$$P = \varepsilon E_1 \frac{kx}{(k/3+1)x + 4/3}, \quad (4)$$

$$\sigma_z = P\frac{(k+1)x+2}{kx+1}. \quad (5)$$

The general theory of residual tension is described in [4], where other calculations of residual tension are criticized. Here, we will analyze the case where the depth of the skin layer is smaller than the core radius r. In this case, Eqs. (1)–(5) provide a good description of the experiment (see below).

For materials with a positive magnetostriction, the orientation of the microwire magnetization is parallel to the maximal component of the stress tensor, which is directed along the microwire axis. Therefore, cast Fe-based microwires with a positive magnetostriction show a rectangular hysteresis loop with a single large Barkhausen jump between two stable magnetization states and exhibit the NFMR phenomenon. Equations (1)–(5) provide an adequate interpretation of the experiments concerning FMR and NFMR (see below).

We proposed a model in which residual stresses σ_r and σ_z in a GCAMNW monotonically decrease towards the wire axis. This model differs from the models of the standard theory (see [5]).

With an additional longitudinal strain, which occurs when the microwire is embedded in a solid matrix that is deformed under an external impact, the following term is added to the expression for the residual axial tension:

$$\sigma_{ez} = \frac{P_o}{S_m(k\ x\ +1)}, \tag{6}$$

where P_o is the force applied to the composite; S_m is the microwire cross-sectional area; k is the ratio of the Young modulus of the coating to that of the microwire; x is the ratio of the cross-sectional area of the coating to that of the microwire.

3. Experimental Results

The theory of NFMR is described in [6–8]. A cast GCAMNW was considered to be a ferromagnetic cylinder with a small radius R_m. We introduce the depth of the skin layer δ:

$$\delta \sim [\omega(\mu\mu_0)_{eff}\Sigma_2]^{-1/2} \sim \delta_0(\mu)_{eff}^{-1/2}, \tag{7}$$

where $(\mu\mu_0)_{eff}$ is the effective magnetic permeability, and Σ_2 is the electrical conductivity of the microwire. In the case of our magnetic microwires, with the relative permeability $\mu \sim 10^3$ (see below) and ω ~ 9–10) GHz, while δ varies in a range of 1–2 μm.

It is known (see [6–13]) that for $R_m > \delta$, the general expression for the FMR frequency ω is as follows:

$$(\omega/\gamma)^2 = (H_k + 4\pi M_s)\cdot H_k, \tag{8}$$

where M_s is the saturation magnetization and $\gamma/2\pi \sim 3$ MHz/Oe is the effective gyromagnetic ratio. The anisotropy field is given by $H_k \sim 3\lambda\sigma/M_s$, where λ is the magnetostriction constant, and σ denotes the mechanical stress originated during preparation (see Eqs. (1)–(6)).

The NFMR frequency can be written as

$$\omega(GHz) \approx \omega_o\left(\frac{0.4x}{0.4x+1} + \frac{\sigma_{ez}}{\sigma_o}\right)^{1/2}, \tag{9}$$

where

$$\omega_o(GHz) \approx 1{,}5(10^6\lambda)^{1/2}.$$

Near the NFMR frequency, the dispersion of permeability μ is given by

$$\mu(\omega) = \mu'(\omega) + i\mu''(\omega), \tag{10}$$

with μ'' exhibiting a peak and μ' passing through zero at resonance (see [4, 6–8]).

Figure 1 shows the resonance frequency of 9.5 GHz for a $Fe_{68}C_4B_{16}Si_{10}Mn_2$ microwire.

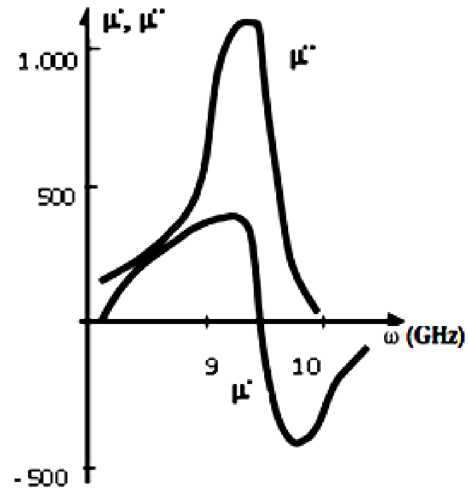

Fig. 1. Frequency dispersion of the real and imaginary parts of the relative permeability around the NFMR frequency for a $Fe_{68}C_4B_{16}Si_{10}Mn_2$ microwire (R_m ~ 5 μm, x ~ 5).

In the vicinity of the resonance μ" is described by (see [6–8]):

$$\mu''/\mu_{dc} \sim \Gamma\Omega/[(\Omega - \omega)^2 + \Gamma^2], \tag{11}$$

where μ_{dc} is the static magnetic permeability and Γ is the width of the resonant curve.

Modulating the microwire diameter and the magnetostriction through the microwire composition makes it possible to prepare microwires with a tailorable permeability dispersion for radio-absorption applications (see [6–8]): (i) determining the resonant frequency in a range of 9–12 GHz and (ii) controlling the maximum of the imaginary part of magnetic permeability.

Pieces of microwires were embedded in planar polymeric matrices to form composite shielding for radio-absorption protection. Experiments were performed employing a commercial polymeric rubber with a thickness of 1–3 mm. The microwires were spatially randomly distributed within the matrix prior to the matrix solidification. The concentration was maintained below 8–10 g of microwire dipoles (1–3 mm long) per 100 g of rubber [4, 6–8].

A typical result obtained in an anechoic chamber is shown in Fig. 2 for radio-absorbing shielding with embedded $Fe_{68}C_4B_{16}Si_{10}Mn_2$ microwires. It is evident that an absorption level of at least 10 dB is obtained in a frequency range of 8–12 GHz with a maximum attenuation peak of 30 dB at about 10 GHz. In general, optimum absorption is obtained for microwires with metallic cores with a diameter of $2R_m$ ~ 10 μm (x ~ 5) and a length of L = 1–2 mm. These microwire pieces can be treated as dipoles whose length L is comparable to one half of the effective wavelengths $\Lambda_{eff}/2$ of the absorbed field in the composite material (i.e., in connection to a geometric resonance). A similar result was obtained for radio-absorbing shielding with a different GCAMNW (see [4, 6–8]).

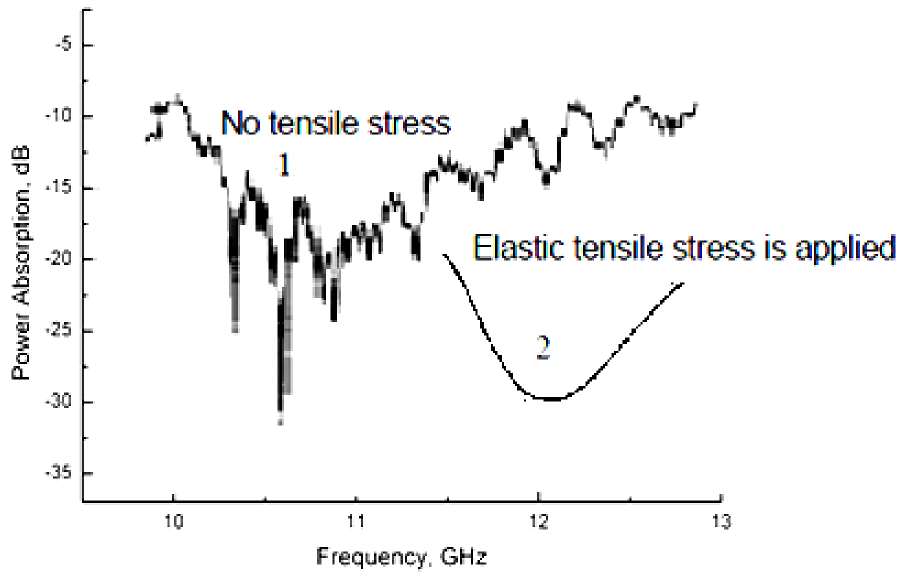

Fig. 2. (*1*) Average absorption characteristics of a shielding containing a microwire composite exhibiting NFMR at microwave frequencies in a range of 10–12 GHz for $Fe_{68}C_4B_{16}Si_{10}Mn_2$ microwires (R_m ~ 5 µm, x ~ 5) and (*2*) a hypothetical absorption curve in the case of an external pressure.

The experimental results can be interpreted using the theory described in [6–8, 20, 21]. Although the design of the absorption shielding can be based on disposing the dipolar pieces in a stochastic way, we consider, for simplicity, a theoretical analysis for a diffraction grating with a spacing between wires of $Q < \Lambda$ (Λ is the wavelength of the absorbed field). The propagation of an electromagnetic wave through an absorbing shielding with microwire-based elements is characterized by transmittance $|T|$ and reflectance $|R_r|$ coefficients given by [6–8]

$$|T| = (\alpha^2 + \beta^2)/[(1 + \alpha)^2 + \beta^2]; \quad (12)$$

$$|R_r| = 1/[(1 + \alpha)^2 + \beta^2], \quad (13)$$

where $\alpha = 2X_r/Z_0$, $\beta = 2Y/Z_0$ with $Z_0 = 120\pi/Q$, and the complex impedance $Z = X_r + iY$.

Absorption function G is correlated with the generalized high-frequency complex conductivity Σ (or high-frequency impedance Z). Here, we use an analogy between the case of a conductor in a waveguide and that of a diffraction grating. The absorption function, which is given by [6–8]

$$|G| = 1 - |T|^2 - |R_r|^2 = 2\alpha/[(1 + \alpha)^2 + \beta^2], \quad (14)$$

has a maximum of $|G_m| = 0.5 \geq |G|$ for $\alpha = 1$ and $\beta = 0$ simultaneously, for which $|T|^2 = |R_r|^2 = 0.25$. The minimum $|G| = 0$ occurs at $\alpha = 0$.

Theoretical estimations, taking into account only the active resistance of microwires, result in an attenuation in a range of 5–15 dB, being much lower than the experimental results, which, for a spacing of microwires of $Q = 10^{-2}$ m, range between 18 and 15 dB, while for a spacing of $Q = 10^{-3}$ m it increases to 20–40 dB. Thus, it becomes clear that the shielding exhibits anomalously high absorption factors, which cannot be attributed solely to the resistive properties of the microwires.

Let us consider the effective absorption function (as in Eq. (14)):

$$|G_{\mathrm{eff}}| \sim \Gamma_{\mathrm{eff}}\Omega_{\mathrm{eff}}/[(\Omega_{\mathrm{eff}} - \Omega)^2 + \Gamma_{\mathrm{eff}}^2], \quad (15)$$

where $\Gamma_{\mathrm{eff}} \geq \Gamma$ and $\Omega \sim \Omega_{\mathrm{eff}} = 2\pi c/\Lambda$.

A microwave antenna will resonate when the antenna length L satisfies the condition

$$L \sim \Lambda/[2(\mu_{\mathrm{eff}})^{1/2}]. \quad (16)$$

The NFMR in a single $Fe_{68}C_4B_{16}Si_{10}Mn_2$ microwire (see Fig. 1) occurs at $\Omega_{\mathrm{eff}} \sim 9.5$ GHz, and the absorption curve in Fig. 2 from $Fe_{68}C_4B_{16}Si_{10}Mn_2$ microwire pieces exhibits a maximum at $\Omega_{\mathrm{eff}} \sim 10$ GHz ($\Lambda \sim 3$ cm) and $\mu_{\mathrm{eff}} \sim 10^3$.

This corresponds to

$$L \sim 1\text{–}3 \text{ mm}, \quad (17)$$

where the concentration of microwires ($X_2 < 0.2$ according Eq. (15)) is significantly below the percolation threshold. A higher concentration of dipoles increases both the absorption $|G_{\mathrm{eff}}|$ and the reflectance $|R_{r1}|$, which can be simply determined (see [8, 20]):

$$|R_{r1}| \sim 1 - 2\sqrt{[\Omega/(2\pi\Sigma_m)]}, \quad (18)$$

where $\Omega/2\pi \sim 10^{10}$ Hz. Equation (18) is applicable, if the reflection factor $|R_{r1}|$ is small. (We consider $\Sigma_m \sim 10^{11}$ Hz (see [8]).

It is also worth mentioning that there is another principle of detecting the mechanical strain, which is examined in [21]. This principle is based on a giant magnetoimpedance (GMI) effect (see Fig. 3), so that it is different from that shown in Fig. 2. The GMI effect requires an external magnetization of the sample, which is not required in the NFMR method (see [6–8]).

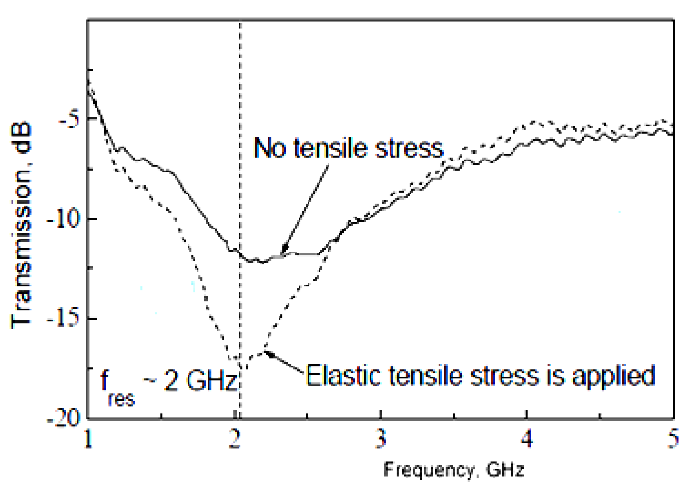

Fig. 3. Stress dependence of the transmission coefficient for a single-layer composite sample determined in near-field measurements in a free-space (see [21]).

According to the above, the proposed method (based on the NFMR effect) is more technologically advanced than the method based on the GMI effect.

4. Conclusions

The described studies provide the following basic conclusions.

(A) We have derived simple analytical expressions for residual and mechanical stresses in the metallic core of the microwire, which clearly show their dependence on the ratio of the external radius of the microwire to the radius of the metal core and on the ratio of Young's moduli of the glass and the metal. Our modeling based on the theory of thermoelastic relaxation shows that the residual stresses increase from the axis of the microwire to the surface of the microwire metallic core, which is in accordance with the previously obtained experimental data (see [4]). Thus, in the case of glass-coated cast microwires prepared by the Taylor–Ulitovsky method, the residual stresses achieve maximum values on the surface of the metal core (see [6–8]).

(B) Cast GCAMNWs exhibit NFMR, whose frequency depends on the composition, geometrical parameters, and deformation of the microwire. The NFMR phenomenon observed in glass-coated magnetic microwires opens up the possibility of developing new radio-absorbing materials with a wide range of properties. An important feature of cast microwires with an amorphous magnetic core is the dependence of the NFMR frequency on the deformation (stress effect). The calculations have shown (see (8), (9)) that the shift of the NFMR frequency caused by the stress effect can achieve 20% before the degradation of the composite.

(C) Therefore, this effect can be used for contactless diagnostics of deformations in distant objects (including critical infrastructures) reinforced by cast magnetic microwires with the stress effect of NFMR. To this end, these objects are periodically scanned with a floating-frequency radar to determine the deviation of the initial NFMR frequency due to potentially dangerous deformations of the monitored object.

References

[1] G. F. Taylor, Phys. Rev. 23, 655 (1924).

[2] M. Vazquez, in Handbook of Magnetism and Advanced Magnetic Materials (Ed. by H. Kronmuller and S. Parkin, New York, John Wiley and Sons, 2007, chapter 4, pp. 2193–2226).

[3] M. Vazquez and A. P. Zhukov, J. Magn. Magn. Mat. 160, 223 (1996).

[4] S. A. Baranov, V. S. Larin, and A. V. Torcunov, Crystals 7, 136 (2017).

[5] A. S. Antonov, V. T. Borisov, O. V. Borisov, A. F. Prokoshin, and N. A. Usov, J. Phys. D: Appl. Phys. 33, 1161 (2000).

[6] S. A. Baranov, Tech. Phys. Lett. 24, 549 (1998).

[7] S. A. Baranov, M. Yamaguchi, K. L. Garcia, and M. Vazquez, Surf. Eng. Appl. Electrochem. 44, 245 (2008).

[8] S. A. Baranov, Mold. J. Phys. Sci. 14, 201 (2015).

[9] P. Marín, D. Cortina, and A. Hernando, J. Magn. Magn. Mater. 290–291, 1597 (2005).

[10] H.-X. Peng, F. Qin, and M.-H. Phan, in Ferromagnetic Microwire Composites: From Sensors to Microwave Applications (Springer, Switzerland, 2016, chapter 12–14).

[11] F. Qin and H.-X. Peng, Progr. Mater. Sci. 58, 181 (2013).

[12] L. Kraus, G. Infante, Z. Frait, and M. Vázquez, Phys. Rev. B 83, 174438 (2011).

[13] L. Kraus, Czech. J. Phys. 32, 264 (1982).

[14] O. Reynet, A.-L. Adenot, S. Deprot, O. Acher, and M. Latrach, Phys. Rev. B 66, 094412 (2002).

[15] S. N. Starostenko, K. N. Rozanov, and A.V. Osipov, J. Magn. Magn. Mater. 298, 56 (2006).

[16] F. Yıldız, B. Z. Rameev, S. I. Tarapov, L .R. Tagirov, and B. Aktaş, J. Magn. Magn. Mater. 247, 222 (2002).

[17] D. Ménard, M. Britel, P. Ciureanu, and A. Yelon, J. Appl. Phys. 84, 2805 (1998).

[18] D. Ménard and A. Yelon, J. Appl. Phys. 88, 379 (2000).

[19] M. G. Nematov, A. M. Adam, L. V. Panina, N. A. Yudanov, A. Dzhumazoda, A. T. Morchenko, D. P. Makhnovskiy, and F. X. Qin, J. Magn. Magn. Mater. 474, 296 (2019).

[20] S. A. Baranov, Tech. Phys. 44, 853 (1999).

[21] D. Makhnovskiy, A. Zhukov, V. Zhukova, and J. Gonzalez, Adv. Sci. Technol. 54, 201 (2008).