Natural ferromagnetic resonance in cast amorphous magnetic microwires

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Abstract — **In the present work, cast glass-coated amorphous microwire with metallic core and diameter varies from 0.5 to 25 µm is considered. The discovery of natural ferromagnetic resonance (NFMR) in amorphous microwires was preceded by their study with standard FMR methods. We have studied FMR and NFMR in amorphous glass-coated microwires with different residual stresses. The residual stresses determine the shift of the resonance field position, and this indicated magnetoelastic anisotropy from the wire surface region.**

Index Terms — **glass-coated amorphous microwire, ferromagnetic resonance, magnetoelastic anisotropy.**

I. INTRODUCTION

Cast, glass-coated, amorphous magnetic microwires are produced by the Taylor-Ulitovsky method (see in Ref. [1-4]) as depicted in Fig.1. The alloy is heated , in an inductor, up to the melting point. The portion of the glass tube adjacent to melting metal softens, enveloping the metal droplet. Under suitable conditions, the molten metal fills the glass capillary and a microwire is thus formed, with the metal core completely covered by a glass shell.

The microstructure of a microwire depends mainly upon the cooling rate, which can be controlled when the metal-filled capillary enters a stream of cooling liquid on its way to the receiving coil. Critical quenching rates (10^5-10^7 K/s) for fabrication of amorphous material may be obtained.

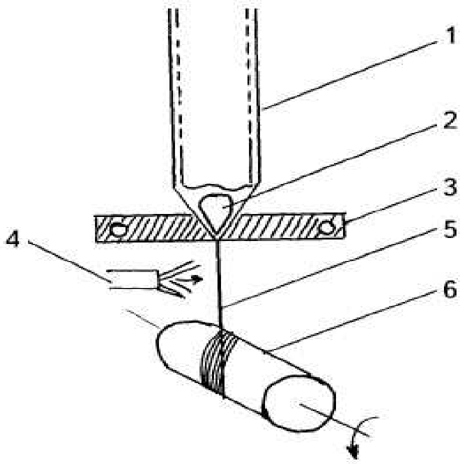

Fig. 1. Process of casting glass-coated amorphous magnetic microwires (see [1-4] and below).
1. Glass tube. 2. Drop of metal. 3. Inductor. 4. Water. 5. Glass-coated microwire. 6. Rotating support.

The glass coating of the cast amorphous magnetic microwires, in addition to protecting the metallic nucleus from corrosion and providing electrical insulation, induces large mechanical stresses in the nucleus. Coupled with its magnetostriction, these determine its magnetoelastic anisotropy, at the origin of a unique magnetic behaviour. The residual stresses are the result of differences in the coefficients of thermal expansion of the metal and of the glass. A simple theory for the distribution of residual stresses was presented in Ref. [2, 3]. In cylindrical coordinates, the residual tension is characterized by axial, radial and tangential components which are independent of the radial coordinate. The value of such stresses depends upon the ratio of the radius, r , of the metallic nucleus, to the total microwire radius, R,

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

$$\sigma_r = \sigma_\phi = P = \sigma_0 \frac{kx}{\left(\frac{k}{3}+1\right)x + \frac{4}{3}},$$

$$\sigma_z = P\frac{(k+1)x+2}{kx+1}, \qquad (1)$$

where $\sigma_0 = \varepsilon E_1$; ε is the difference between the thermal expansion of the metallic core and that of the glassy cover whose expansion coefficients are α_1 and α_2: ($\varepsilon = (\alpha_1 - \alpha_2)(T^* - T)$); E_1 is the Young's modulus of the metal core, T^* is the solidification temperature of the composite in the metal / glass contact region ($T^* \sim 800 \div 1000^0$ K), T is room temperature ($\varepsilon E_1 \sim 2$ GPa is the maximum stress in the metallic core).

The technological parameter, k, is the ratio of Young's moduli of glass and metal ($k = E_2/E_1 \sim (0.3 \div 0.6)$).

Numerical calculation indicates that for small values of x the dependence $\sigma_z(x)$ is nearly linear, and that it reaches saturation (up to 1GPa) at about $x = 10$:

$$\sigma_z \sim (2 \div 3)P > \sigma_r,$$

$$(P \to 0{,}5\sigma_0 \sim 1 \text{ GPa})$$

The general theory of residual tension is presented in Ref. [5] where other calculations of residual tension are criticized. Here, we further analyze the case when the depth of the skin layer is less than the nuclear radius, r. In this case, Eq. (1) provides a good description of experiment (see below, Eqs. (11) - (13) and Figs. 2 - 4).

For materials with positive magnetostriction, the orientation of the microwire magnetization is parallel to the maximal component of the stress tensor, which is directed along the axis of the wire (see [1-3]). Therefore, cast Fe–based microwires with positive magnetostriction constant show a rectangular hysteresis loop with single large Barkhausen jump between two stable magnetization states and exhibit the phenomenon of natural ferromagnetic resonance (NFMR) (see [1-3]).

The ferromagnetic-resonance (FMR) method is often used for investigation of amorphous magnetic materials (ribbons, wires, thin films). Both macroscopic and microscopic heterogeneity of amorphous materials can be investigated by FMR. Residual stress is an important parameters for amorphous materials which can be studied by FMR (see [1-3]). FMR is also used for diagnostics of the uniformity of amorphous materials. Extrinsic broadening of FMR lines due to fluctuations of the anisotropy, magnetization, and exchange-interaction constant in amorphous materials has also been investigated. Microwave experiments are very useful for investigation of spin-wave effects. In particular microwave generation and amplification are of great interest. Investigation of structural relaxation of amorphous materials during heat treatment, using FMR is also important. Differential FMR curves combined with hysteresis curves can give important information in this case.

In the present work, cast glass-coated amorphous microwires with metallic cores and diameters between 0.5 and 25 μm are considered. The amorphous structure of the core was investigated by X-ray methods. The thickness of the glass casing varied between 1 and 20 μm. Using microscopy, we have chosen samples with the most ideal form, and with lengths of about 3-5 mm, for investigation. Microwires based on iron, cobalt, and nickel (doped with manganese), with additions of boron, silicon, and carbon, were studied. Microwires made from different materials have diverse magnetostriction. We have studied microwire from the same spool, whose glass casing was removed by etching in hydrofluoric acid.

In almost all cases, standard FMR spectrometers from 2 to 32 GHz were used. The magnetic field was measured using a Hall sensor (with accuracy within 0.1 %). In addition, magnetometer measurements determined the magnetization, needed for calculation.

The basic measurements were made in a longitudinal field configuration (external magnetic field was directed along the microwire axis). In this case, a signal of the correct form was obtained from good samples. This gives the possibility of measuring resonant-curve width.

For thick cores, skin effect must be taken into account. In this case the resonant frequency was described by the Kittel formula for a plane (with longitudinal magnetization). The g factor was estimated at two resonant frequencies as ~ 2.08 ÷ 2.1 on average. Our results are in good agreement with literature data on the g factor for amorphous materials (see Refs. [1-4, 6-8]). In a transverse field (when the external field is perpendicular to the microwire axis), the signal was weak or not observed in samples with negative magnetostriction. Obviously, the presence of this signal is associated with non-uniformity of the high-frequency demagnetizing factor.

A microwire was considered to be a ferromagnetic cylinder with small radius r. For its characterization we introduce following parameters:

1. The depth of the skin layer is:

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

$(\mu\mu_0)_e$ is the effective magnetic permeability, and Σ is the microwire electrical conductivity. In the case of our magnetic microwires, with the relative permeability $|\mu|$ near resonance of the order 10^2, ($\omega \sim (8 \div 10)$ GHz) δ changes from 1 to 3 μm.

2. The size of the domain wall (according to Landau-Lifshits theory) is:

$$\Delta \sim (A/K)^{1/2} \sim (10 \div 0{,}1)\ \mu\text{m}, \qquad (3)$$

where A is the exchange constant and K is the anisotropy energy of the microwire ($K \sim \lambda\sigma$, where λ is the magnetostriction constant and σ is the effective residual stress from the fabrication procedure (see Refs. [2, 3] and Eq. (1))). The full theory gives $\Delta_f \sim 0{,}1$ μm for the size of the domain wall of glass-coated microwires (see Ref. [5]).

3. The radius of a single domain (according to Brown theory) is

$$a \sim A^{1/2}/M_S \sim (0{,}1 \div 0{,}01)\ \mu\text{m}, \qquad (4)$$

where M_s is the saturation magnetization of microwire.

According to Refs. [2, 3] the frequency of the *NFMR* is:

$$\left(\frac{\omega}{\gamma}\right)^2 = \left(H_e + 2\pi M_S\right)^2 - \left(2\pi M_S\right)^2 \exp\{-2\delta/r\}, \qquad (5)$$

where γ is the gyromagnetic ratio ($\gamma \sim 3$ MHz/Oe). The anisotropy field is $H_e \sim 3\lambda\sigma/M_s$ (for exact calculations of anisotropy field, see below).

If $r < \delta$, we have:

$$\frac{\omega}{\gamma} = H_e + 2\pi M_S \qquad (6)$$

If $r > \delta$, the *NFMR* frequency is given by (see Refs. [1 - 3]):

$$\left(\frac{\omega}{\gamma}\right)^2 = H_e\left(H_e + 4\pi M_S\right). \qquad (7)$$

The discovery of natural ferromagnetic resonance (*NFMR*) in amorphous microwires [3] was preceded by their study using standard *FMR* methods [4]. Then, the shift in the resonant field, due to core deformation of the microwire associated with fusing the glass and core at the temperature of microwire formation, was observed. The *FMR* line width is also of interest because it characterizes, in particular, the structural parameters [2, 3].

Since the skin penetration depth of a microwave field in a metallic wire is relatively small in comparison with its diameter the resonant frequency of *FMR* can be determined by means of Kittel formula (Eq. (6 -8)). Taking into account the magnetoelastic stress field [2, 3], for a thin film magnetized parallel to the surface, we can obtain:

$$\left(\frac{\omega}{\gamma}\right)^2 = \left[H + (N'_Z - N'_X)M_S + 4\pi M_S)\right] \times (H + (N'_Z - N'_Y)M_S), \qquad (8)$$

where H is the FMR field; N'_X, N'_Y, N'_Z are components of tensor of effective demagnetizing factors in case of magnetoelastic stress:

$$N'_i = \frac{3|\lambda|\sigma i}{2M_S^2}\left(\cos^2\theta i - \frac{1}{3}\right); \qquad (9)$$

where:

$$\theta_1 = \theta_2 = 90^\circ, \theta_3 = 0.$$

Components σ_i (see Eqs. (1)) are residual stresses (see in Ref. [2, 3]). Then,

$$N'_X = N'_Y = -\frac{|\lambda|P}{2M_S^2}; \quad N'_Z = \frac{|\lambda|P}{2M_S^2}\frac{(k+1)x+2}{kx+1}; \qquad (10)$$

Substituting the σ_i values obtained in our previous work [2, **3**] (see Eqs. (1)), and taking into account Eqs. (8), (9), we can calculate conditions for *FMR*:

$$\left(\frac{\omega}{\gamma}\right)^2 = \left[H + \frac{(3|\lambda|P)}{2M_S}\frac{x\left(k+\frac{2}{3}\right)+\frac{5}{3}}{kx+1} + 4\pi M_S\right] \times \left[H + \frac{(3|\lambda|P)}{2M_S}\frac{x\left(k+\frac{2}{3}\right)+\frac{5}{3}}{kx+1}\right]. \qquad (11)$$

If the glass is removed, the stress is completely removed. Then the *FMR* resonant field of wire without glass casing, H_0, is determined from:

$$\left(\frac{\omega}{\gamma}\right)^2 = H_0\left(H_0 + 4\pi M_S\right). \qquad (12)$$

We have shown (see Ref. [1-4, 6-8]) that these relations quantitatively explain all of the basic features of *NFMR* and *FMR*. Note that the value of M_S required for the calculations was determined both by standard methods on a vibration magnetometer and with the use of interpolation formulas given here. The error relative to tabular values for the given alloys is not greater than 5%.

For the frequency of *NFMR* under the simple approximation taking εE_1 ~ *2* GPa and k ~ 0.4 this formula can be written as:

$$\omega(GHz) \approx \omega_0\left(\frac{0.4x}{0.4x+1}\right)^{1/2},$$
$$\omega_0(GHz) \approx 1{,}5\left(10^6\lambda\right)^{1/2}. \qquad (13)$$

As you can see, dependence for the frequency of NFMR (Eqs. (13), and Figs 2, 3,) is determined from two typical values, x, λ.

The basic contribution to the NFMR frequency and NFMR line width is due to the effective magnetostriction and parameter x (Eqs. (13), and Figs. 2, 3, 5). The residual stress in the microwire plays the dominant role in the formation of the absorption line width, as it will be shown below (Figs 5, 6).

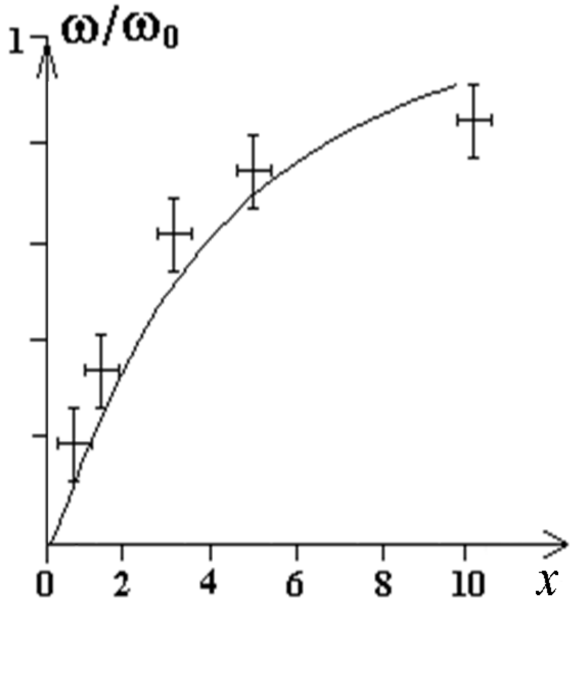

Fig.2.Theoretical curve of *NFMR* frequency as a function of x (according to Egs. (11) – (13)) and experimental data (see [2, 3])

When the penetration depth of the microwave field in the metallic wire is small relative to the wire diameter (on account of the skin effect), the resonant frequency in *FMR* and *NFMR* may be determined by means of Eqs. (1). (The general theory of residual tension is presented in Ref. [5], but here it is enough to use the simple theory from [2, 3])

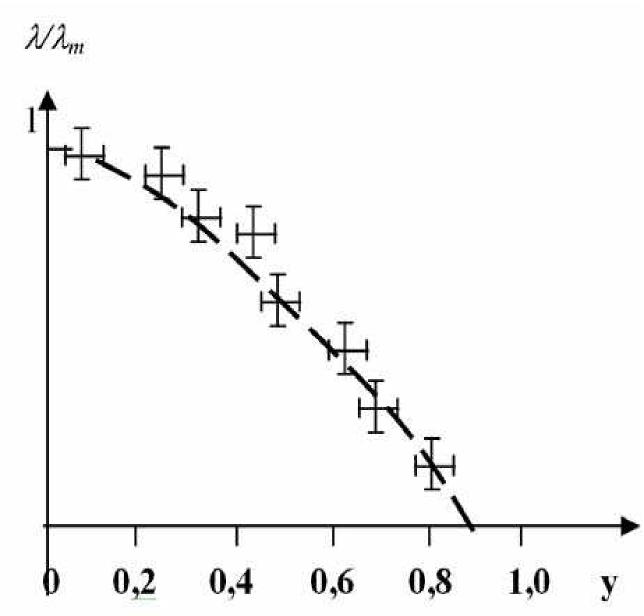

Fig.3. Dependence of relative magnetostriction λ/λ_m for alloy composition $(Co_y Fe_{1-y})_{75}(BSiC)_{25}$ series cast glass-coated amorphous magnetic microwires according to Eqs. (11) – (13), where
y= Co/(Co+Fe) (see [2, 3])

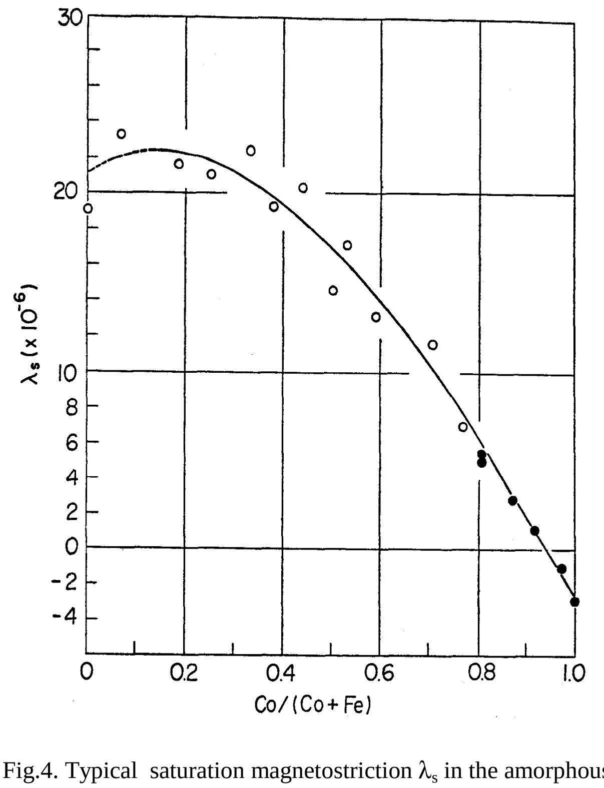

Fig.4. Typical saturation magnetostriction λ_s in the amorphous Co –Fe alloys: ○ $(Fe_{1-y}Co_y)_{80}(PC)_{20}$;
● $(Fe_{1-y}Co_y)_{75}(SiB)_{25}$ (according to Ref. [9]).

Substituting typical values of λ and x in Eq. (13) we reach numerical values of *NFMR* in a range from 1 to 12 GHz. A systematic study on the *NFMR* frequency for the alloy series $(Co_yFe_{100-y})_{75}(BSiC)_{25}$ has been performed as a function of the Co content (Fig.3). The magnetostriction has then been evaluated using Eq. (13). The result is plotted in Fig. 3 which shows good agreement with the magnetostriction values as determined through conventional techniques (Fig.4. according to Ref. [9]). Thus, the final theory quantitatively explains all the basic features of *NFMR* and *FMR*. However the area of experimental research in the case of small radius of a metallic nucleus radius of a microwire remains vacant.

II. CONCLUSION

When the penetration depth of the microwave field in the metallic wire is small relative to the wire diameter (on account of the skin effect), the resonant frequency in *FMR* and *NFMR* may be determined by means of Eqs. (1). (The general theory of residual tension is presented in Ref. [5], but here it is enough to use the simple theory from [2, 3])

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ACKNOWLEDGMENTS

This research received financial support the Department of Engineering Physics *École Polytechnique de Montréal.*

The author thanks A. Yelon and D. Menard for their participation in discussion of the results.

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