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MAGNETIC AMORPHOUS NANO-STRUCTURED WIRES CHARACTERISATION USING IMPEDANCE SPECTROSCOPY

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Abstract: In this article, we apply impedance spectroscopy methodology to analyze the frequency response of as cast CoFeBSi wires in the 100 Hz to 300 kHz frequency range, at 10 mA ac current. Comparative evaluation performed for stressed and unstressed samples reveals major changes in the spectra of internal ac impedance of the wire. Physical concepts and problems of practical significance are discussed on the basis of the results.

Keywords: internal ac impedance, amorphous materials, impedance spectroscopy

1. INTRODUCTION

Non magnetostrictive amorphous alloys are known to be very attractive systems to study their peculiar magnetic behaviour. In particular, the Co-rich amorphous alloys exhibit the following characteristics:

1. stress and field induced anisotropies
2. high sensitivity to composition, thermal treatments and applied mechanical stress
3. severe dependencies on external magnetic field.

Due to their promising technological applications in growing areas such as the design and development of small and micro sensors for magnetic fields, sensors for mechanical stress, strain or torsion detection and measurement, the study of these materials has become a topic of increasing interest.

Most reports are using magnetoimpedance ratio for monitoring the variations in impedance response of amorphous wires. This is a useful technique when dealing with large impedance variations but it does not always allow simple physical interpretation. Moreover the frequency domain established for our investigation is between 100 Hz and 300 kHz and we do not expect impedance variation with the amplitude of those obtained in MHz region. By taking all these into account we decided to use the complex inductance formalism [6] as it gives a more clear physical insight in magnetization process.

At low frequencies the specific magnetization mechanism, consisting in reversible domain wall bulging and unpinning displacement of domain walls, can be emphasized through the evaluation of the complex permeability μ:

$$\mu = \mu_{RE} - j\mu_{IM} \tag{1}$$

In (1), μ_{RE} corresponds to the wire circumferential permeability and μ_{IM} is associated with dissipative processes.

Since most of the impedance analyzers are evaluating the complex impedance ***Z***, the permeability is obtained using the following transformation:

$$\mu = \alpha_G \frac{-jZ}{\omega} \tag{2}$$

where ω denotes the angular frequency of the ac current passing through the wire and α_G is a geometrical factor. For further calculations we preferred the normalized values of permeability components even if some reports [6] are considering $\alpha_G = 10^8\ H^{-1}$.

Impedance spectroscopy technique was used in order to evaluate the influences of tensile stress on internal AC impedance of CoFeBSi wires. The results are compared with the theoretical ones reported recently [7] and based on a domain model for conducting cylinder. Even if predicting the frequency dependencies of real and imaginary components of the complex impedance, the exact analytical expressions need some further improvements in terms of accuracy.

2. EXPERIMENTAL SETUP

We used as-quenched amorphous wire of nominal composition $(Co_{94}Fe_6)_{72.5}B_{15}Si_{12.5}$, 130 µm diameter prepared by the in-water-rotating technique. The sample, with 5 cm. length, was mounted in a special sample holder with firm electrical contacts, enabling the application of controlled tensile stress. Impedance measurements were carried out by means of a system build with a Novocontrol analyzer (Alpha type) controlled by a PC. We used the manufacturer's recommended configuration [8] special attention being paid to the impedance compensation of the line from the analyzer impedance inputs to the sample. The inductivities L_S and resistors R_S of the BNC lines contributing as a additional serial impedance to the measured one were taken into account using load short calibration and line compensation procedures. Because of the low value of the measured impedance, the R_P resistor has been considered large enough to be neglected. Also the capacitances C_P are requesting no compensation since they are eliminated by the virtual ground technique of the current input amplifier.

All data were measured at room temperature with wire axis established at 90 degrees in respect with earth's field. The ac current through the amorphous wire was kept constant (10 mA), and complete spectroscopic measurements were done at frequencies from 100Hz to 300 kHz. Tensile stress from 0 to 333 MPa (0, 74, 111, 260 and 333) was axially created using calibrated weights.

The results have been processed using some specific virtual instruments developed in LabVIEW graphical programming environment

3. RESULTS

Great interest have been paid in exploring the possibilities to build force sensors using the peculiar magnetic behaviour of $(Co_{94}Fe_6)_{72.5}B_{15}Si_{12.5}$ amorphous wire and therefore the experimentally acquired data have been processed in order to emphasize the dependencies of several complex impedance parameters on axial applied stress. The results are presented in Fig. 1 to Fig.3.

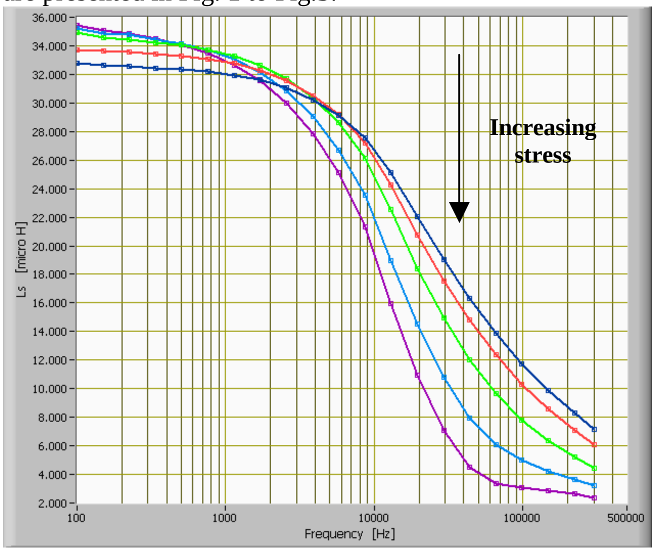

Fig. 1. Internal serial inductance of the amorphous wire

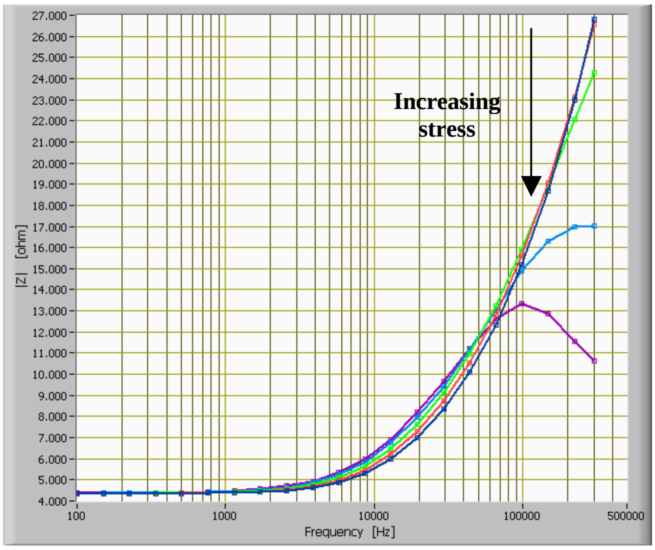

Fig. 2. Impedance amplitude

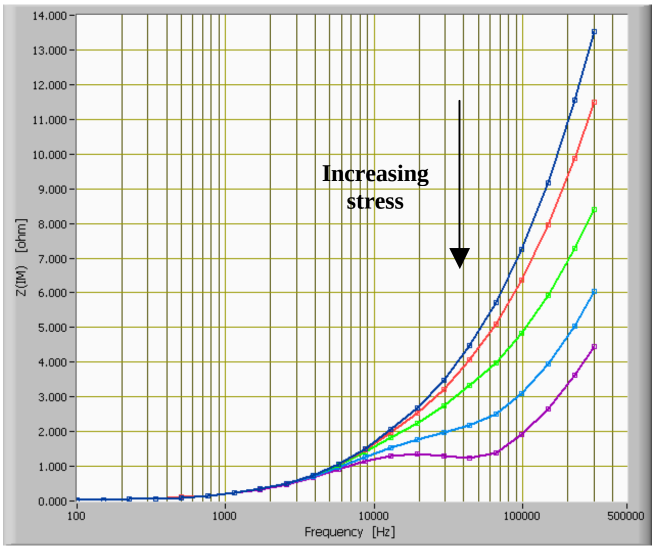

Fig. 3. Imaginary component of the complex impedance

The graphical representations are clearly revealing the strong dependencies of all analyzed parameters on tensile stress. This is in good concordance with previously reported results and consequence of "bamboo-like" domain structure with an axially oriented core surrounded by circumferential domains. It proves the existence of a magnetoelastic coupling between magnetostriction and internal stresses arised during the manufacturing process.

Increasing tensile stress modify the penetration depth by lowering the circular permeability (see Fig.1 and Fig. 3). Consequently the real component of complex inductance, the major part in impedance amplitude for the explored frequency domain, decrease, this behavior being depicted in Fig.3.

However the characterization of the relaxation domain is still difficult and therefore an additional frequency dependence (phase angle between magnetizing current and end-to-end sample voltage) has been taken into account. The experimental results are presented in Fig. 4.

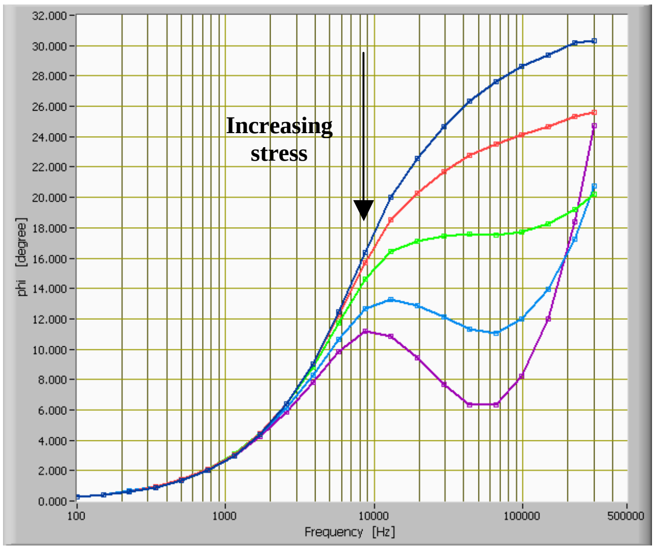

Fig. 4. Frequency dependence of phase angle

There are two observations highlighted by stress dependencies depicted in Fig.4.:

- there is a major dispersion domain located between 10kHz and 100 kHz
- as the tensile stress increase the rate of change of imaginary component of complex inductance is higher than the corresponding real component one.

Further accurate estimation of the relaxation frequency can be done by evaluating the real and imaginary components of the complex permeability as defined in (1) and (2). Their normalized values are graphically represented in Fig.5 and Fig.6.

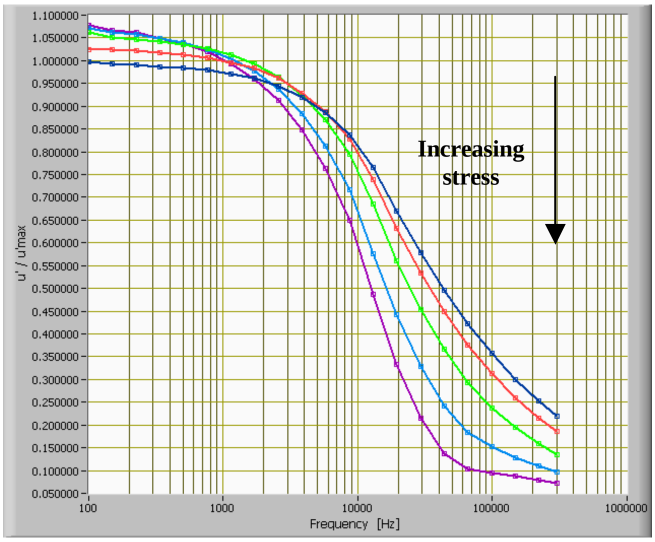

Fig. 5. Frequency dependence of real component of complex permeability (normalized values)

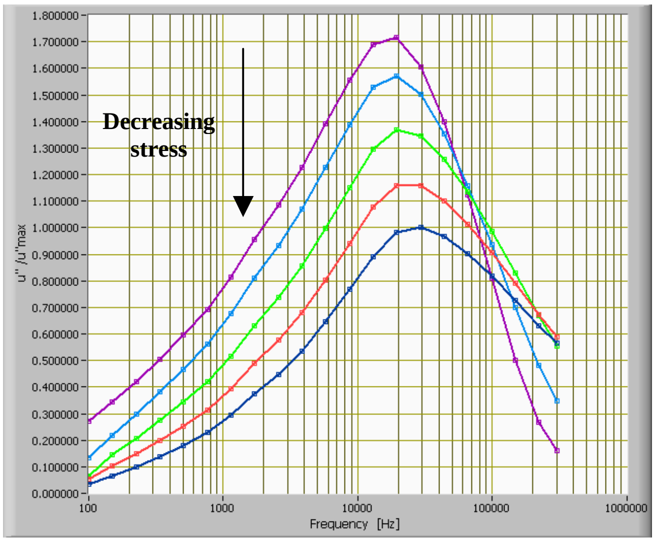

Fig..6. Frequency dependence of imaginary component of complex permeability (normalized values)

Both real and imaginary components have been normalized with the maximum value of μ_{RE} and respectively μ_{IM} obtained for unstressed sample.

This time a more precise determination of the relaxation frequency f_r can be done. For the unstressed sample f_r=30kHz and increasing tensile stress is lowering this value to f_r=19 kHz at 333 MPa. Also a consistent increase of the dissipative complex permeability component (roughly approximated at 80% in peak value) is revealed, in accordance with theoretical considerations regarding the domain wall mobility.

Some problems arise in approximating these dependencies by analytical expressions. A domain model, reported recently [7], gives two definitions, and consequently two formulas, for circular permeability:

- A fluxmetric definition:

$$\frac{\mu_{RE}}{\mu_{DC}} = 2\sum_{n=1}^{\infty}\left[\lambda_n^2 + \frac{\theta^4 c^2}{a^2}\coth^2\frac{\lambda_n c}{a}\right]^{-1}\left[1 - J_0^{-1}(\lambda_n)\right] \quad (3)$$

$$\frac{\mu_{IM}}{\mu_{DC}} = \frac{2\theta^2 c}{a}\sum_{n=1}^{\infty}\left[\lambda_n^2 \tanh\frac{\lambda_n c}{a} + \frac{\theta^4 c^2}{a^2}\coth\frac{\lambda_n c}{a}\right]^{-1}\frac{1 - J_0^{-1}(\lambda_n)}{\lambda_n}$$

where a is the wire radius, $2c$ is circular domain width, θ is a dimensionless parameter proportional to ω and μ_{DC} is the scalar DC permeability.

- An energetic definition:

$$\frac{\mu_{RE}}{\mu_{DC}} = \frac{4X}{\theta^2 R_{DC}} \qquad \frac{\mu_{IM}}{\mu_{DC}} = \frac{4(R - R_{DC})}{\theta^2 R_{DC}} \quad (4)$$

with R and X being the real and imaginary complex impedance components respectively

Even if the first model is consistent with the traditional definition of longitudinal permeability and has a clear physical meaning it is almost impossible to identify its parameters by experimental procedures. Therefore the second one was used, as its components can be derived directly from measured complex impedance.

The scalar DC permeability μ_{DC} was determined both from $\mu_{RE}(\omega)$ and $\mu_{IM}(\omega)$ curves, for the first case, the following formula being used:

$$\mu_{DC} = \frac{8\pi L}{l} \quad (5)$$

where L and l are the low frequency inductance and the wire length respectively.

In Table 1. are presented the results, in absolute value and also normalized.

Table 1. Experimentally determined μ_{DC}.

	L $|_{\sigma=0}$ [μH]	$\mu_{DC}=8\pi L/l$ [H/m}	$\mu_{DC}/\mu_{DC}|_{\sigma=0}$ determined on μ_{RE} curves	$\mu_{DC}/\mu_{DC}|_{\sigma=0}$ determined on μ_{IM} curves
σ_z=0	32,81	0.01648	1	1
σ_z=74 MPa	33,68	0.01692	1.027	1,053
σ_z=111 MPa	34,90	0.01753	1.064	1,126
σ_z=260 MPa	35,20	0.01768	1.073	1,196
σ_z=333 MPa	35,41	0.01778	1.079	1,273

As resulting from this table the low flexibility of analitycal expressions, reflected in only one adapting parameter μ_{DC}, leads to relative errors up to 18%.

3. CONCLUSION

The analysis of the frequency response of complex inductance in as-cast $(Co_{94}Fe_6)_{72.5}B_{15}Si_{12.5}$ wires, here presented, highlighted the necessity of developing more accurate analytical expressions for complex permeability components if relative errors less than 18% are to be expected.

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REFERENCES

[1] L.V. Panina, K. Mohri, T. Uchiyama, M. Noda, K. Bushida, “Giant magneto-impedance in Co-rich amorphous wires and films” IEEE Tran. On Magn, vol.31, pp.1249-1260, 1995

[2] S. Sandacci, D. Makhnovskiy, L. Panina, K. Mohri, Y. Honkura, “Off-diagonal impedance in amorphous wires and its application to linear magnetic sensors”, IEEE Tran. On Magn, vol.40, pp.3505-3511, 2004

[3] K. Mohri, T. Uchiyama, L.P.Shen, C.M. Cai, L.V. Panina, Y. Honkura, M. Yamamoto, “Amorphous wire and CMOS IC-based sensitive micromagnetic sensors utilizing magnetoimpedance (MI) and stress-impedance (SI) effects” IEEE Tran. On Magn, vol.38, pp.3063-3068, 2002

[4] R. Valenzuela, M. Knobel, M. Vasquez, A. Hernano, “Effects of bias field and driving current on the equivalent circuit response of magnetoimpedance in amorphous wires”, J. Appl. Phys., 28, pp. 2404–2410, 1995

[5] R. Valenzuela and I. Betancourt, “Giant Magnetoimpedance, Skin Depth and Domain Wall Dynamics”, IEEE Tran. on Magn, vol.38, pp.3081-3083, 2002

[6] I. Betancourt and R. Valenzuela “The Effect of Torsion Stress on the Circumferential Permeability of CoFeBSi Amorphous Wires”, IEEE Tran. on Magn, vol.39, pp.3097-3099, 2003

[7] D.-X. Chen and J.L. Munoz “AC Impedance and Circular Permeability of Slab and Cylinder”, IEEE Tran. on Magn, vol.35, pp.1906-1923, 1999

[8], *** “Alpha and Beta, Dielectric, Conductivity, Impedance and Gain Phase Analyzers - USER's Manual” Novocontrol Technologies issue 1/2005

[9] S. Song, S. Yu, K. Cheol and M. Vazquez, “Mechanism of Relaxation Dispersions of Permeability Spectra in Co-Based Amorphous Wire”, IEEE Tran. On Magn, vol.36, pp.3065-3067, 2000.