Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Non-Crystalline Solids 329 (2003) 155–158
JOURNAL OF NON-CRYSTALLINE SOLIDS
www.elsevier.com/locate/jnoncrysol

Low frequency magnetoimpedance for Co-based amorphous microwires

I. Betancourt *, R. Valenzuela

Materials Research Institute, UNAM, P.O. Box 70-360, Mexico, DF 04510, Mexico

Abstract

In this work, we present a study of the low frequency (5–13 MHz) magnetoimpedance response of amorphous microwires covered by glass. The domain wall magnetization processes active within this frequency range, namely reversible bulging of domain walls and hysteresis, are characterized through the complex inductance formalism, which allows the calculation of Cole–Cole plots. The characteristic semicircle formation of reversible bulging was observed and compared with a theoretical one based on a domain wall model for ferromagnetic wires, resulting in an excellent agreement. In addition, the wire's magnetoimpedance response was found to be strongly dependent on the application of torsion strain as a consequence of a higher wire's-induced anisotropy.

PACS: 75.50.Kj; 75.60.−d

1. Introduction

Recently, studies of glass covered ferromagnetic microwires (GCFM) obtained by the Taylor–Ulitovsky technique have become a subject of applied and basic research owing to their peculiar magnetic properties which in turn, result from their unusual magnetic structures [1,2]. These microwires comprise a tiny metallic nucleus (1–30 μm diameter) surrounded by an insulating glass coating (1–10 μm thickness). Magnetic bistability (manifested as a large Barkhausen jump) [3,4] together with giant magnetoimpedance [5,6] (associated with their magnetic domain structure) characterize the interesting magnetic properties of these GCFM. On the other hand, magnetoimpedance (MI) in soft magnetic materials has raised considerable interest along the last decade because of its promising applications in recording heads and magnetic sensors [2]. Thus, aside to their reduced dimensions, GCFM presenting MI are suitable candidates for such applications. MI at low frequencies (below 0.1 MHz), can be explained by the coupling between the domain structure and the h_{ac} field generated by the i_{ac} circulating along the wire, whilst for high frequencies (>0.5 MHz), this i_{ac} flows through a thin sheath close to the surface of the sample as a consequence of the skin effect. In addition, most reports concerning MI studies are carried out at the high frequency regime, since by using the complex impedance formalism, $\mathbf{Z} = Z + jZ_i$ no significant

---

* Corresponding author. Tel.: +52-55 5622 4654; fax: +52-55 5616 1371.

E-mail address: israelb@correo.unam.mx (I. Betancourt).

0022-3093/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnoncrysol.2003.08.031

variation in $\Delta Z/Z$ is observed at low frequencies range [7]. Nevertheless, a more clear insight into the physical phenomena of MI at low frequencies is possible through the complex inductance formalism, $\mathbf{L} = L_r + jL_i$ [8], which allows resolution of the GCFM magnetization processes at low frequency regime. In this report, the complex inductance formalism is used to investigate the MI effect in GCFM.

2. Experimental techniques

As-cast amorphous microwires (24 μm diameter, 10 μm glass coating) of nominal composition $Co_{69.7}Fe_{3.8}B_{13}Si_{11}Mo_{1.5}Ni_1$ prepared by the Taylor–Ulitovsky technique were used for inductance measurements carried out on 10 cm long wire pieces at room temperature, together with a dc field of 6.4 kA/m applied along the wire's axis. To ensure a good electric contact, the wire ends were firmly attached to the measurement clamps using a low-melt point welding paste. An HP4192A impedance analyzer system, controlled by a PC, was used for the inductance measurements. The frequency range was 100 Hz–13 MHz together with the rms voltage varying between 0.1 and 1.0 V, which led to ac currents through the sample within the range $i = 0.3$–3 mA (rms). The resulting rms field amplitude on the wire surface was of 3–35 A/m. Error bars are not included in our measurements since the equipment uncertainty for the impedance measurement is minute (<1%). In addition, the inductive reactance considered (ωL) is proportional to ω and thus, at high frequencies, ($f > 10^4$ Hz), where the reversible and irreversible magnetization processes and relaxation dispersion occurs, the experimental error is even less significant.

3. Results

Spectroscopic plots of the real part of inductance at dc magnetic fields of 0 and 6.4 kA/m and $h_{ac} = 3$ A/m are shown in Fig. 1. At $H_{dc} = 0$, L_r exhibits an inductance value of 10 μH at low frequencies, followed by a dispersion. For non-zero dc field value, a constant trend of L_r is observed along the entire frequency range, with a small inductance value very close to the zero-field result at high frequencies (above the dispersion). Complex permeability plots L_r–L_i (also known as Cole–Cole plots) for two distinct h_{ac} amplitudes of 3 and 31 A/m are shown in Fig. 2. A well defined semicircle

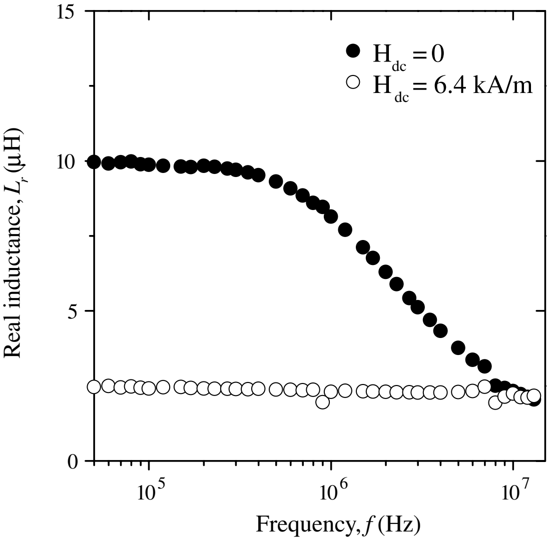

Fig. 1. Experimental spectrocopic $L_r(f)$ plot for the Co-based GCFM, at two distinct dc magnetic fields.

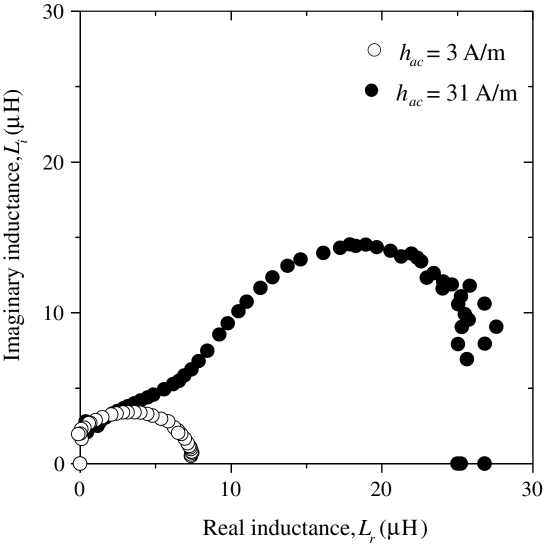

Fig. 2. Experimental Cole–Cole plots for the Co-based GCFM, at different h_{ac} amplitudes. Note some dispersion at high dc field and low frequencies, as explained in the text.

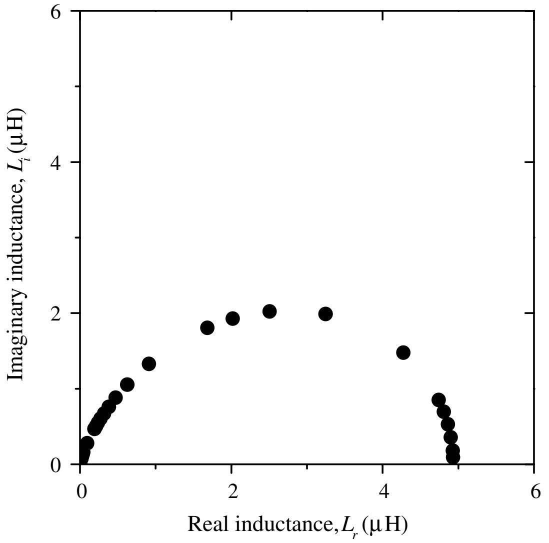

Fig. 3. Calculated Cole–Cole plot for a Co-based GCFM.

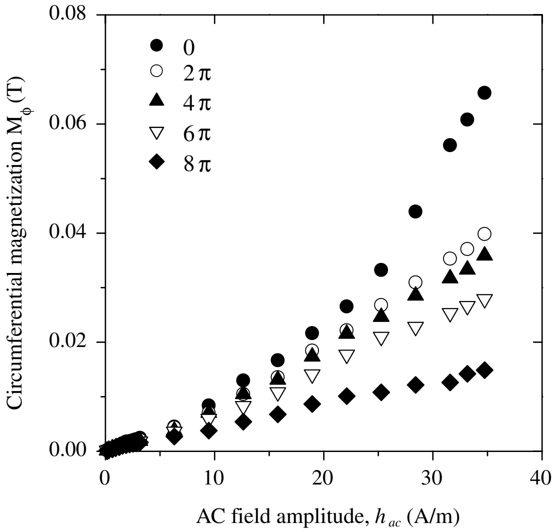

Fig. 4. Experimental M_ϕ for various torsion strains at a fixed frequency $f = 20$ kHz.

formation (each point obtained at a different frequency) is observed for $h_{ac} = 3$ A/m with a diameter of 7.5 μH, whilst for $h_{ac} = 31$ A/m, two half-circles of different diameter are apparent, the larger one being of 15 μH diameter. A calculated Cole–Cole plot using a domain model for MI in ferromagnetic wires and the complex inductance formalism [9] is shown in Fig. 3, exhibiting a theoretical diameter of 5 μH. Circumferential magnetization plots M_ϕ, obtained from experimental L_r measurements [7] as a function of torsion strains at a fixed frequency $f = 20$ kHz are shown in Fig. 4. As the torsion strain is applied, M_ϕ exhibits a diminishing tendency with increasing torsion strain.

4. Discussion

According to the complex inductance formalism, L_r is proportional to the circumferential permeability μ_ϕ [8]. Thus, assuming a domain wall configuration consisting of circumferential magnetic domains for these Co-based GCFM [2], the magnetization processes for $h_{ac} = 3$ A/m are associated with reversible bulging of domain walls since these domains are considered to be pinned to defects (such as the border metal–glass of the wire). Therefore, the main effect of the H_{dc} field (Fig. 1) is to produce a damping in domain wall bulging, reflecting an axially-induced anisotropy. The semicircle formation at low h_{ac} fields (Fig. 2) reflects a domain bulging process [8], whilst at h_{ac} fields beyond a threshold value of 25 A/m for these microwires (see Fig. 4, torsion-free plot) the formation of a second larger semicircle is a consequence of an irreversible magnetization mechanism of hysteretic character. On the other hand, recent theoretical modeling of MI effect in ferromagnetic wires [10] allows the simulation of the wire's MI response under various conditions: varying H_{dc}, different induced anisotropies constants, or reduced dimensions. The calculated Cole–Cole plot (Fig. 3) was obtained considering the reduced diameter (24 μm compared with 60 μm of melt-spun wires) of this Co-based GCFM. A characteristic semicircle corresponding to the domain wall bulging mechanism is observed, with an L_r value (at $L_i = 0$) very close to the experimental one at $h_{ac} = 3$ A/m. Due to the wire's magnetoelastic anisotropy, MI is strongly sensitive to both tensile and torsional strains. For zero torsion strain, a typical domain wall magnetization process is observed: an initial linear trend, corresponding to reversible pinned domain wall bulging, followed by a sudden increase in M_ϕ at the propagation field (at 25 A/m, Fig. 4), for which the irreversible wall displacement begins. Further increase in h_{ac} amplitude should exhibit a M_ϕ trend to saturation, where the spin rotation will complete the magnetic moment alignment towards h_{ac} orientation. The diminishing tendency observed for M_ϕ with increasing torsion strain (Fig. 4) is attributed to the development of a helical magnetoelastic anisotropy in the wire [11] due to the torsion strain. This torsion-induced anisotropy enhances the intrinsic helical stress, which in turn, leads to a decrease in L_r (i.e. μ_ϕ) and hence, to lower M_ϕ values. The highest torsion stress τ at the wire's surface, due to the applied maximum torsion angle (8π) is calculated as $\tau = G(\theta/L)\ r = 450$ MPa [12] (where G is the shear modulus and L, r the wire's length and radius respectively).

5. Conclusions

The low frequency MI response of GCFM has been studied by using the complex inductance formalism. High wire's-induced anisotropies were observed under the application of increasing torsion strains. Reversible magnetic wall deformation as magnetization processes, was reflected in both, experimental and calculated Cole–Cole plots.

Acknowledgements

Authors acknowledge financial support from UNAM-PAPIIT, through grant no. IN111200.

References

[1] A.F. Cobeño, A. Zhukov, J.M. Blanco, J. Gonzalez, J. Mater. Res. 9 (1999) 3775.

[2] A. Zhukov, J. Magn. Magn. Mater. 242–245 (2002) 216.

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

[4] A. Chizhik, J. Gonzalez, A. Zhukov, J.M. Blanco, Appl. Phys. Lett. 82 (2003) 610.

[5] V. Zhukova, A. Chizhik, A. Zhukov, J. Gonzalez, IEEE Trans. Magn. 38 (2002) 3090.

[6] A.F. Cobeño, A. Zhukov, J. Gonzalez, J. Magn. Magn. Mater. 234 (2001) L359.

[7] I. Betancourt, R. Valenzuela, Appl. Phys. Lett. 81 (2002) 94.

[8] R. Valenzuela, Physica B 299 (2001) 280.

[9] I. Betancourt, R. Valenzuela, M. Vazquez, J. Appl. Phys. 93 (2003) 8110.

[10] D.X. Chen, J.L. Muñoz, A. Hernando, M. Vazquez, Phys. Rev. B. 57 (1998) 10699.

[11] J.M. Blanco, A. Zhukov, J. Gonzalez, J. Magn. Magn. Mater. 196&197 (1999) 377.

[12] C.G. Kim, S.S. Yoon, M. Vazquez, J. Magn. Magn. Mater. 223 (2001) L199.