The Effect of Torsion Stress on the Circumferential Permeability of CoFeBSi Amorphous Wires

I. Betancourt and R. Valenzuela

***Abstract*—In this paper, a domain model and the complex inductance formalism are employed to study the effect of torsion stress on the low-frequency magnetoimpedance (MI) response of CoFeBSi amorphous wires (125 μm in diameter). In particular, the torsional dependence of the calculated circumferential permeability μ_ϕ is found to be very sensitive to the wire's scalar permeability $\mu_{\rm dc}$ which, in turn, depends inversely on the wire's induced anisotropy K_i. Calculated μ_ϕ exhibited a marked increase for increased $\mu_{\rm dc}$ and a decrease for reduced $\mu_{\rm dc}$. Experimental spectroscopic plots of μ_ϕ under various torsion stresses (counter- and clockwise-oriented) which resulted in various helically induced anisotropies K_h are consistent with an enhancement/counterbalancing effect of K_i through the addition/subtraction of K_h to K_i.**

***Index Terms*—Complex inductance, induced anisotropy, magnetoimpedance, torsion stress.**

I. Introduction

MAGNETOIMPEDANCE (MI) refers to the variations in the impedance response of soft magnetic materials (subjected to a high-frequency current $i_{\rm ac}$ of small amplitude) when a dc magnetic field is applied. Considerable interest has been raised in MI materials due to their sensing technology applications [1]. This phenomenon is large in vanishing negative magnetostriction amorphous wires because of their particular domain structure: an axially oriented core, surrounded by circumferential domains (bamboo-like structure). This domain configuration is afforded by the wire's induced anisotropy K_i, which arises from the coupling between magnetostriction and internal stresses during the fabrication process [2], [3]. Due to this magnetoelastic coupling, MI is strongly sensitive to both tensile stress [4] and torsional strain [5]. The frequently used magnetoimpedance ratio $\Delta Z/Z_0$ for monitoring MI response employed in most reports does not allow a simple physical interpretation, since at a low-frequency regime, no $\Delta Z/Z_0$ variation is observed [6]. In contrast, the complex inductance formalism [7] affords a more clear physical insight into the magnetization process, since magnetization mechanisms at low frequencies (e.g., reversible domain wall bulging and unpinning displacement of domain walls) can be resolved through the calculation of the complex permeability $\mu = \mu_{\rm real} - j\mu_{\rm imag}$ from the complex impedance, $\mathbf{Z} = Z_{\rm real} + jZ_{\rm imag}$ via the following transformation [8]:

$$\mu = G\left(\frac{-j\mathbf{Z}}{\omega}\right) \tag{1}$$

where ω is the angular frequency of $i_{\rm ac}$ (and, hence, of $h_{\rm ac}$) and G is a geometrical factor $G \sim 10^8 (\text{henry})^{-1}$ [8]. In (1), $\mu_{\rm real}$ corresponds to the wire circumferential permeability μ_ϕ (since the applied field $h_{\rm ac}$ has also a circumferential character), whereas $\mu_{\rm imag}$ is associated with dissipative processes. In addition, it is also possible to calculate circumferential magnetization curves $M_\phi(h_{\rm ac})$ by means of [6]

$$\mu_o M_\phi = h_{\rm ac}\left(G\left(\frac{Z_{\rm imag}}{\omega}\right) - \mu_o\right). \tag{2}$$

On the other hand, a domain model reported recently for the MI of ferromagnetic wires [9], [10] establishes exact analytical expressions for the real and imaginary components of the complex impedance Z. An important parameter for calculation is the scalar dc permeability $\mu_{\rm dc}$, which depends inversely on the restoring pinning force coefficient per unit wall area α: $\mu_{\rm dc} = C/\alpha\,(C = \text{constant})$. This restoring coefficient is proportional to the domain wall energy γ, which, in turn, depends on K_i [11] and, thus, $\mu_{\rm dc} = C/K_i$. By using the $Z_{\rm real}$, $Z_{\rm imag}$ exact expressions and (1), we study the effect of $\mu_{\rm dc}$ variations on μ_ϕ and compare with experimental μ_ϕ subjected to various torsional stresses which affect directly K_i.

II. Experimental Techniques

As-cast amorphous $(Co_{94}Fe_6)_{72.5}B_{15}Si_{12.5}$ wires, 10-cm length and 125-μm diameter, prepared by the in-rotating-water spinning method, were used for spectroscopic measurements. Samples were mounted in a special sample holder with firm electrical contacts that enabled the application of controlled torsional stresses both in the clockwise $(+)$ and in the counterclockwise $(-)$ directions. The measuring system includes an HP 4192 A impedance analyzer controlled by a PC. Our measuring software allows the determination of the complex impedance for 94 discrete frequencies within the range 5 Hz–13 MHz.

III. Results and Discussion

Calculated $\mu_{\rm real}$ and $\mu_{\rm imag}$ plots are shown in Fig. 1. The variations for an initial value of $\mu_{\rm dc} = 0.004\,241$ H/m (determined for a torsion-free 10-cm-length CoFeBSi amorphous wire) are taken as 2 $\mu_{\rm dc}$ and 0.5 $\mu_{\rm dc}$. The low-frequency initial constant

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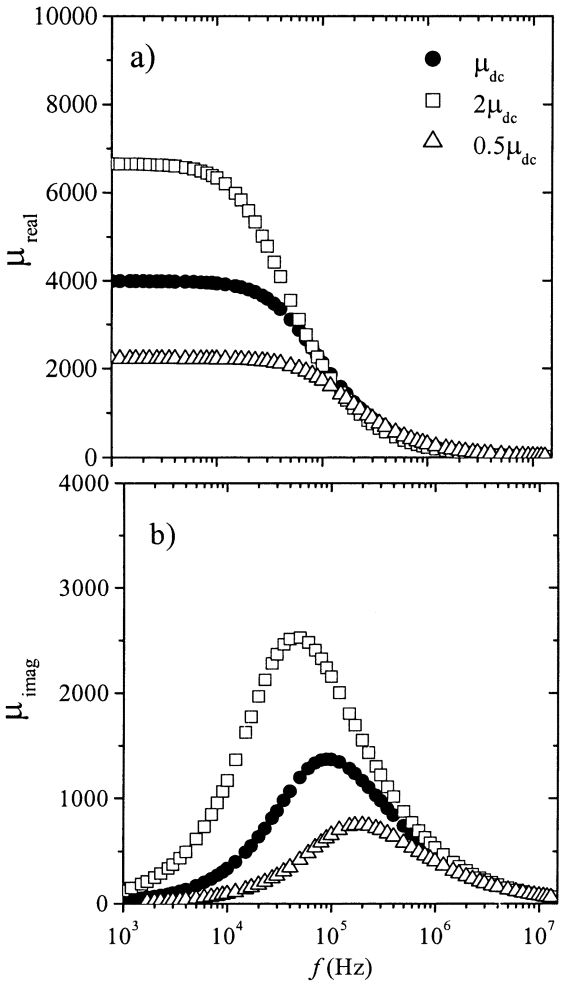

Fig. 1. Calculated spectroscopic plots of a) $\mu_{\rm real}$ and b) $\mu_{\rm imag}$ for various $\mu_{\rm dc}$ values.

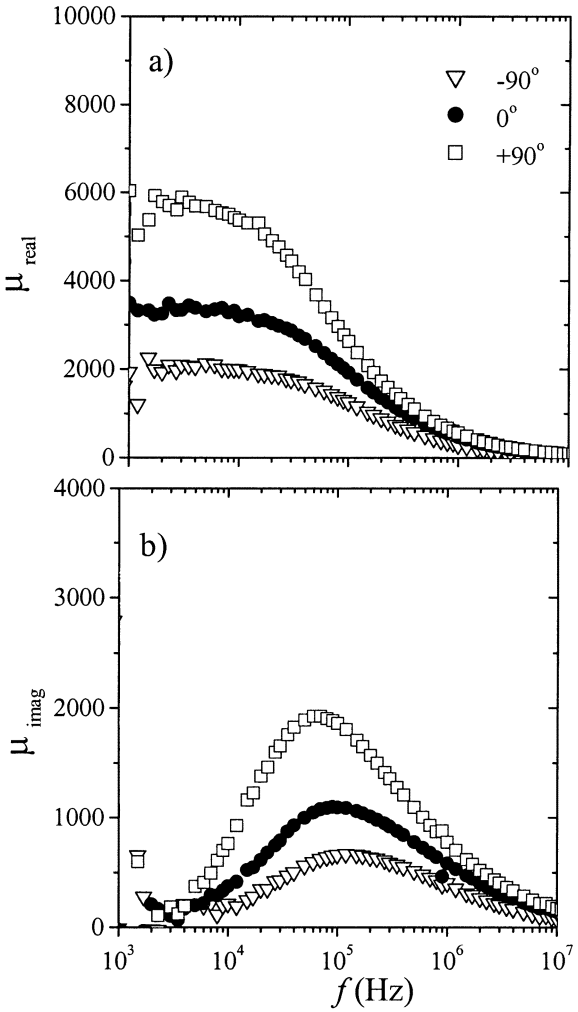

Fig. 2. Experimental spectroscopic plots of a) $\mu_{\rm real}$ and b) $\mu_{\rm imag}$ for various torsion angles.

$\mu_{\rm real}$ dependence (which corresponds to μ_ϕ [7]) increases with increased $\mu_{\rm dc}$ and decreases with diminished $\mu_{\rm dc}$. On the other hand, the maximum in $\mu_{\rm imag}$ (associated with the relaxation frequency f_x for which the domain bulging mechanism is no longer active and for which $\mu_{\rm real}$ manifest a relaxation dispersion when $f > f_x$ [7]) shifts to lower frequencies with enhanced $\mu_{\rm dc}$ and moves forward with smaller $\mu_{\rm dc}$ values.

As mentioned above, $\mu_{\rm dc}$ is inversely proportional to K_i. Therefore, it is reasonable to ascribe $\mu_{\rm dc}$ variations to a varying K_i, which can be affected directly by helically induced anisotropies K_h produced by torsion stresses. This assumption is in agreement with Fig. 2 for which experimental spectroscopic $\mu_{\rm real}$ and $\mu_{\rm imag}$ plots corresponding to $(+)$ and $(-)$ torsion angles are shown. The $+90^\circ$ curve exhibits an enhancement of $\mu_{\rm real}$ together with a decreased f_x in $\mu_{\rm imag}$, while for the -90° curve, a reduced $\mu_{\rm real}$ accompanies higher f_x values in $\mu_{\rm imag}$. This enhancement/detrimental behavior on $\mu_{\rm real}$ is consistent with a counterbalancing effect of K_h on K_i for $(+)$ torsion angles, whereas $(-)$ torsion angles produce K_h, which reinforce K_i. Notice the remarkable agreement between calculated and experimental plots (Figs. 1 and 2) on both real and imaginary components. In addition, calculated $\mu_{\rm real}$ plots merge into a single curve for $f > f_x$ as their measured counterpart. On the other hand, calculated $\mu_{\rm imag}$ at

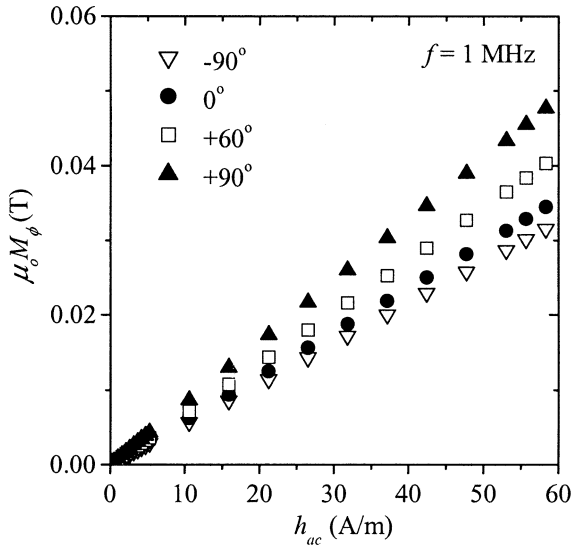

Fig. 3. Measurements of circumferential magnetization as a function of $h_{\rm ac}$ field at $f = 1$ MHz, for various torsion angles.

original $\mu_{\rm dc}$ exhibits a maximum at ~100 kHz, which agrees very well with the experimental one. The effect of the torsion stress on wire's anisotropy is also manifested in Fig. 3, where

circumferential magnetization, M_ϕ, is plotted as a function of the applied ac field $h_{\rm ac}$ at a frequency of 1 MHz, well above f_x. At this frequency, the domain wall displacement mechanism is no longer active and spin rotation remains as the only magnetization process, leading to a linear dependence of $M_\phi(h_{\rm ac})$. As the torsion stress compensates K_i at $(+)$ angles, the slope of the plot increases, which affords higher M_ϕ; conversely, for (-) torsion angles, the decreasing slope reflects an increment in K_i.

IV. Conclusion

By using a model for MI in ferromagnetic wires, we have shown that torsion stresses add (or subtract) to the helically induced anisotropy in a CoFeSiB wire, leading to a decrease (or an increase, depending on the torsion direction) on its scalar dc permeability and, thus, to an enhanced/reduced circumferential permeability.

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