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# Magnetoimpedance and magnetization processes in amorphous wires under torsion

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## Abstract

An investigation of the effects of torsion on magnetoimpedance of CoFeBSi as-cast amorphous wires is presented. For this study we used the complex permeability as a function of frequency in the range 100 Hz–13 MHz. An asymmetric behavior (a maximum for clockwise torsion, a monotonous decrease for counter-clockwise torsion) was observed for real permeability plots at constant frequency, as a function of torsion. This behavior is interpreted in terms of an induced anisotropy with helical geometry.

*Keywords:* Torsion; Magnetoimpedance; Magnetization processes

## 1. Introduction

Giant magnetoimpedance (GMI) has raised a strong interest due to its technological applications [1,2] in magnetic field and DC current sensors. Also, the high sensitivity of the impedance response to mechanical stresses [3,4] has led to more potential applications as strain gauges. The next natural step was the investigation of GMI as a function of torsion stress, with a view to applications in rotation devices [5–9].

In this paper, we present an analysis of the effects of torsion on the low frequency ($100\,\mathrm{Hz} \leqslant f \leqslant 13\,\mathrm{MHz}$) GMI response of as-cast, amorphous CoFeBSi wires. The presence of an induced anisotropy with helical geometry is clearly established.

## 2. Experimental techniques

We used pieces, ~10 cm long, 125 μm diameter, of as-cast amorphous wires of nominal composition $(Co_{94}Fe_6)_{72.5}B_{15}Si_{12.5}$, prepared by the in-water-rotation method [10] and kindly provided by Unitika Ltd, Japan. Samples were mounted in a special sample holder with firm electrical contacts while allowing the wire to be submitted to controlled torsion stresses, both in the clockwise and counter-clockwise manner. 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 in the range 5 Hz–3 MHz in less than 3 min.

## 3. Experimental results and discussion

We measured both the real, $Z'$, and the imaginary, $Z''$, parts of impedance. However, to

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have more insight into the magnetic nature of phenomena, we investigated the variations of complex permeability, $\boldsymbol{\mu}$ ($\boldsymbol{\mu} = \mu' - \mathrm{j}\mu''$, with $\mathrm{j} = \sqrt{-1}$). For this, complex impedance, $\mathbf{Z}$ ($\mathbf{Z} = Z' + \mathrm{j}Z$), was first transformed into complex inductance, $\mathbf{L}$ ($\mathbf{L} = L' + \mathrm{j}L''$), by the relationship

$$\mathbf{L} = (-\mathrm{j}/\omega)\mathbf{Z}, \tag{1}$$

where $\omega$ is the angular frequency. Note that the presence of j in Eq. (1) leads to a cross-over of terms: real inductance depends on imaginary impedance, and conversely, imaginary inductance depends on real impedance. Complex inductance was then transformed into complex permeability by using the geometrical factor, $G$, for cylindrical shape ($G = 2 \times 10^8/l$, where $l$ = length) [11], as $\boldsymbol{\mu} = G\mathbf{L}$. A physically rigorous derivation of permeability from impedance has recently been proposed [12], leading to the same relationship. Both derivation paths assume that the skin depth penetration is larger than the wire radius, and are therefore valid only at low frequencies (typically below ~5 MHz).

We have recently shown that at low frequencies ($f < 5\,\mathrm{MHz}$) and low amplitudes of the AC excitation current ($i_{\mathrm{ac}} \leqslant 1\,\mathrm{mA}$, RMS), the permeability response of wires is due to two magnetization processes: spin rotation and bulging of pinned domain walls [13]. At frequencies around 50 kHz, the domain wall process undergoes a relaxation dispersion, and at higher frequencies only spin rotation remains as an active magnetization process. The $\mu'$ plots as a function of frequency show a characteristic relaxation behavior [13], while the $\mu''$ plots exhibit a maximum at the relaxation frequency, $f_x$.

Torsion stresses severely affect the value of real permeability, while the general shape remains, as shown in Fig. 1. The low-frequency permeability (the initial or "quasistatic" permeability) showed much higher values for the "clockwise" turns (indicated as "positive" torsion in Fig. 1), than for the "counter-clockwise" turns ("negative" torsion). A similar behavior was observed for the imaginary part of permeability, as shown in Fig. 2. In fact, a sharp maximum appears for $\mu'$ at torsions about 120° when this permeability value is plotted as a function of torsion at a constant frequency ($f = 1\,\mathrm{kHz}$ in this case), as shown in Fig. 3. In contrast, $\mu'$ exhibits a monotonic decrease for negative torsions. Similar results were previously reported for FeSiB wires [9].

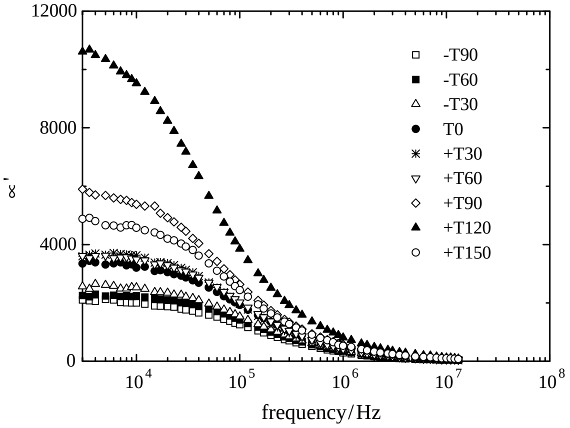

Fig. 1. Real part of permeability, $\mu'$, as a function of frequency (at $i_{\mathrm{AC}} = 1\,\mathrm{mA}$, RMS), and at various torsion stresses.

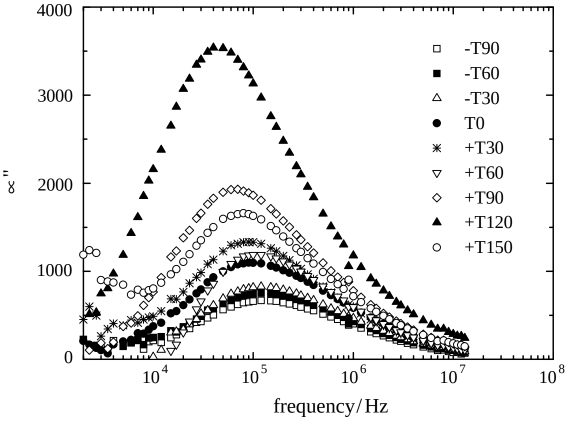

Fig. 2. Imaginary part of permeability, $\mu''$, as a function of frequency (at $i_{\mathrm{AC}} = 1\,\mathrm{mA}$, RMS), and at various torsion stresses.

The relaxation frequency is also an important parameter that indicates the frequency at which the domain wall bulging becomes unable to follow the excitation field. It can easily be obtained from the maximum of each curve in Fig. 2. $f_x$ is also plotted in Fig. 3, and clearly shows a reciprocal behavior as compared to $\mu'_{(f=1\,\mathrm{kHz})}$, i.e., a minimum appears at a torsion of ~120°, and a

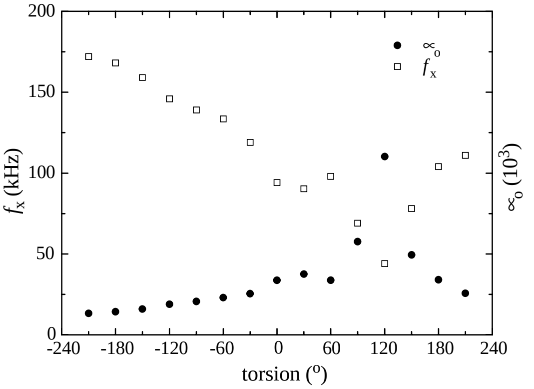

Fig. 3. Variations of $\mu'$ (measured at $f = 1\,\text{kHz}$) as a function of torsion; the variations in relaxation frequency, $f_x$, are also shown.

monotonous increase is observed for negative torsions.

This asymmetry in the behavior of both real permeability and relaxation frequency clearly points to a stress-induced anisotropy with a helical geometry. Some authors have interpreted such an anisotropy as the result of the fabrication method [5,6,9]. The fast cooling process can effectively lead to this inhomogeneity in stresses resulting from thermal contraction [14]. The inverse relationship between $\mu'_{(f=\text{constant})}$ and $f_x$ has been observed in many of cases [15,16] and suggests a kind of Snoek limit [17] for domain wall processes.

## 4. Conclusions

The effects of torsion have been investigated in as-cast amorphous CoFeBSi wires by analyzing the magnetization processes at low frequencies. The results obtained can be explained on the basis of an asymmetrically induced anisotropy, with helical geometry. An inverse relationship between real permeability (at $f = 1\,\text{kHz}$) and relaxation frequency has been confirmed for samples submitted to torsion.

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