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Penetration Depth and Transverse Permeability in Amorphous Alloy

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Abstract

Effective penetration depth and relative transverse permeability is computed using experimentally measured values of the ac impedance of the ribbon shaped amorphous Co $_{67}Fe_4Mo_1Si_{16.5}B_{11}$ alloy prepared with different quenching rate. It is shown that computed effective penetration depth, relative transverse permeability can be used effectively in explaining magnetoimpedance effect. Variation of quenching rate affects the magnetic properties and magnetoimpedance ratio of the studied samples appreciably. At different frequencies the maximum magnetoimpedance ratio shifts to higher fields showing the field dependence of permeability at different frequencies.

INTRODUCTION AND THEORY

The giant magnetoimpedance (GMI) effect [1] refers to the huge changes in ac impedance of an electrically conducting magnetic element, usually in the form of a magnetically soft thin ribbon, wire or thin film, submitted to a simultaneous action of a longitudinal external dc magnetic field and a transverse ac field generated by flowing a high frequency (≈ 100 kHz) ac current through the magnetic element. GMI effect has a classical electromagnetic origin related to changes in the dynamics of the magnetization process. Such changes affect the magnetic permeability and consequently, the penetration depth (δ) of ac current through the magnetic conductor with increasing frequencies [1] given by:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_0\mu_t}} \qquad \textbf{(1)}$$

Where μ_t, - relative transverse permeability, ρ - electrical resistivity and ω - angular frequency of a driving current. As a consequence, GMI turns out to be very sensitive to composition, sample shape, annealing conditions, quenc-hed-in internal stresses and anisotropy, overall domain configuration. Magnetoimpedance has been a topic of intensive research since its discovery due to its perspective applications in recording heads and sensors [1]. Knowledge of the evolution of both, effective penetration depth and relative transverse permeability with axial dc field and frequency of the ac current flowing along the ribbon shaped specimen is helpful to understand and interpret the GMI response of the element. As the transverse permeability can vary by orders of magnitudes with a dc magnetic field, the penetration depth also strongly varies, resulting in large variations of impedance. Taking into consideration the above, it is obvious that the transverse permeability is the key factor, governs the GMI effect in the range of high enough frequencies and helps in the interpretation of GMI data. This permeability and its dc field dependence can be estimated using the model proposed by Kuzminski and Lachowicz [2], using equations:

$$R_a = \frac{\rho l}{2(a-2\delta_b)\delta_a} \quad \text{and} \quad R_b = \frac{\rho l}{2b\delta_b} \tag{2}$$

$$\delta_b \approx \delta^{eff\cdot} = \frac{aR_0}{2R_{ac}(H)}, \; \mu_t(H) = \frac{2\rho}{\mu_0 \omega [\delta(H)]^2} \tag{3}$$

Where *a*- thickness, *b*- width**,** *l* - length of sample, R_a resistance along thickness, R_b- resistance along width, R_{ac} - effective resistance, δ_a -penetration depth along thickness and δ_b - penetration depth along width, δ^{eff}-effective penetration depth, R_0 - dc resistance of the sample *H*- appli-ed dc magnetic field. It is worth noting that the model [2] is over simplified and, therefore cannot well approximate the experimental dependencies. However, the advantage of this model is that both the self-consistent quantities (δ and μ_t) governing the GMI effect can effortlessly be estimated. Variation of quenching rate (QR) influences intrinsic anisotropy within the specimen and can affect the δ and μ_t and will have considerable impact on GMI effect. In this work we report the influence of intrinsic anisotropy on GMI effect in amorphous $Co_{67}Fe_4Mo_1Si_{16.5}B_{11}$ alloy.

Table 1: Properties of the studied specimens.

Sample	H_c	J_s	H_k	K_u	σ_i
	(A/m)	(T)	(A/m)	(J / m^3)	(MPa)
A	0.30	0.54	10.6	2.9	10.6
B	0.65	0.61	18.7	44.7	18.7

EXPERIMENTAL AND COMPUTATION DETAILS

Amorphous $Co_{67}Fe_4Mo_1Si_{16.5}B_{11}$ ribbons having thickness of 20 (sample A) and 45 (sample B) μm were obtained from Vacuumschmelze (Germany). One mm wide and five cm long pieces were used in the experiments. R_{dc} of the sample A and B was respectively 3.4 and 0.9 Ω. DC hysteresis loops, measured using a computer controlled dc loop tracer, were used to obtain coercive force (H_c), and saturation magnetization (J_s). Anisotropy field (H_K), anisotropy constant (K_u) and internal stresses (σ_i) were obtained using $H_K = J_s / \chi_i$, $K_u = J_s H_k / 2$ and $\sigma_i = J_s H_k / 3 \lambda_s$, where χ_i – initial susceptibility, λ_s - magnetostriction constant taken as -1.8×10^{-7}. Variation of impedance (Z) with axial dc magnetic field ($H_{max.} = \pm 60$ Oe), applied using Helmoltz coil was evaluated by ac voltage drop along the sample while passing a constant current of 1 mA (rms) between 1 –10 MHz. using HP 3589 A spectrum analyzer. Field depen-dent magnetoimpedance ratio ($\Delta Z/Z$) was obtained using –

$$\frac{\Delta Z}{Z}(\%) = 100 \times \frac{Z(H) - Z(H_{\max.})}{Z(H_{\max.})} \quad \textbf{(4)}$$

A program written in C++, uses the experimentally meas-ured values of the ac impedance of the rectangular shaped specimen as a function of applied dc field and calculates the values of δ and μ_t using model described in [2].

RESULTS AND DISCUSSIONS

Perusal of table 1 shows appreciable variation in H_c , H_k and σ_i, with variation in quenching rate. Specimen prepared with faster QR (i.e. lower specimen thickness) during the solidification process, there will be less chances of forma-tion of nuclei, which act as pinning centers for domain walls. Hence, H_c should be less in case of specimen A com-pared to B, is consistent with the observed values of H_c. Variation in QR affects the solidification process, matches well with the different values of σ_i obtained for specimens A and B. Variation in QR also influences H_k and K_u. Variation of internal stresses σ_i induces a transversal anisotropy exhibiting higher value of H_k and K_u. Figure 1 a shows that maximum values of ($\Delta Z/Z$) for sample A and B are respect-tively 56 and 18 %. According to the theory of GMI, maximum values of ($\Delta Z/Z$) are proportional to the thickness and skin depth. i. e. sample with higher thickness should exhibit higher values of ($\Delta Z/Z$) and δ agrees well with the experimentally obtained values of ($\Delta Z/Z$) and the computed values of δ obtained using the model [2] (shown in fig1 b). With increase of dc field the δ increases monotonically towards ribbon thickness, whereas μ_t decreases with increasing dc field reflected well in $\Delta Z/Z$ values. Thus computation of δ and μ_t helps in understanding GMI behavior of the sample under investigation. Comparison between δ and μ_t, computed for sample A and B shows that difference in QR affects significantly both δ and μ_t. Frequency response of the impedance depends on the behavior of skin effect, as the frequency increases, the current distribution is displaced towards the sample surface. On the other hand it also depends on the transverse magnetization of the sample through the permeability. At different frequencies the maximum in ΔZ/Z shifts to higher fields, indicating the field dependence of permeability for different frequencies.

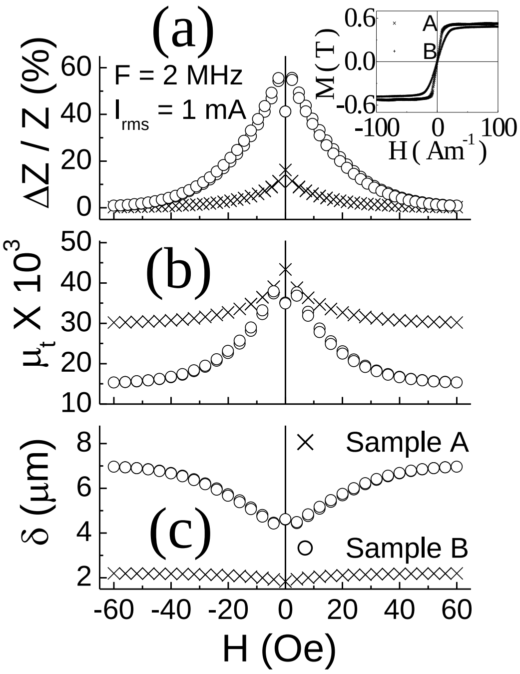

Fig. 1: Field dependence of (a) (*ΔZ/Z*),(b) μ_t and (c) δ.
Inset: Hysteresis loops of the studied samples.

In conclusion, quenching rate affects considerably the magnetic properties of the studied samples. It is shown that computed effective penetration depth, relative transverse permeability shows strong field dependence, which can be used effectively in describing magnetoimpedance effect.

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