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Low-field magnetization process and complex permeability of FeCoBSiTa wires coated with hard magnetic CoNi layer

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Abstract. Biphase wires consisting of a soft magnetic amorphous nucleus surrounded by a hard magnetic CoNi layer of variable thickness were obtained by means of rotating water-quenching method and subsequent electroplating technique. Magnetization processes for all the biphase wires were resolved in terms of reversible bulging of magnetic domains and spin rotation by means of complex permeability measurements within the frequency range of 10 Hz–13 MHz. Results are interpreted in terms of CoNi layer effect on the magnetic anisotropy of the soft core.

Keywords. Biphase wires; soft/hard magnetic materials; amorphous wires.

1. Introduction

Amorphous metallic materials hold a prominent position among functional alloys because of their favourable combination of mechanical, electrical, magnetic and chemical properties, derived from the absence of atomic long range order (Konno *et al* 1990; Hernando and Marín 2005; Pirota *et al* 2005; Vazquez 2007). In particular, Fe-based amorphous alloys in the shape of wires with diameters of around 0·1 mm, obtained by means of rotating water-quenching process, present an outstanding soft magnetic behaviour including high magnetization saturation and large magnetic permeability values besides very low coercivity. In addition, these ultra-soft magnetic amorphous wires possess a characteristic magnetic domain structure consisting of a central core with a longitudinal domain structure surrounded by a sheath of perpendicular magnetization with either radial or circular orientation depending on the sign of the wire's saturation magnetostriction, λ_s ($\lambda_s > 0$ for radial direction and $\lambda_s < 0$ for circular orientation, whereas vanishing λ_s destroys the single inner domain structure) (Konno *et al* 1990; Hernando and Marín 2005; Pirota *et al* 2005; Vazquez 2007). These magnetic features have led to the implementation of a variety of technological applications for these materials as active elements in magnetic sensors and/or transducer devices.

Recently, amorphous wires have elicited a considerable interest in the development of biphase wires consisting of a soft magnetic metallic nucleus (Fe-based amorphous wire) surrounded by a hard magnetic layer deposited by electrochemical process (Pirota *et al* 2004). This hard magnetic layer allows the control of the biphase wires magnetic properties by its magnetic interaction with the soft magnetic nucleus through: (i) the modification of the easy axis of magnetization of the wire from radial to longitudinal orientation depending on the hard layer thickness (i.e. on the electrochemical deposition parameters, viz. current density and time of electrochemical exposure), (ii) the possibility of obtaining controllable magnetostatic or eventually exchange bias response (similar to the bias effect used in spin valves) and (iii) the tailoring of their magnetic domain formation and thus, their magnetic performance from non-hysteretic to bistable behaviour (Vázquez *et al* 2001).

In earlier studies, attention was focused on biphase wire systems where the core phase is prepared by quenching and drawing technique containing an insulating interphase layer. However, less attention was paid to alternative biphase systems where the core is prepared by the in-rotating-water quenching technique where both soft and hard phases are in direct contact (Vázquez *et al* 2007). This paper presents a detailed study on the low-field magnetization process of a particular biphase soft/hard system for which external magnetic layer is directly made to grow on the amorphous core. This certainly corresponds to the behaviour of the soft core under the influence of the harder shell. Particularly, we pay attention to the low-field hysteresis loop and complex permeability.

2. Sample preparation and experimental techniques

Amorphous wires with nominal composition, $Fe_{64}Co_8B_{19\cdot2}Si_{4\cdot8}Ta_4$ and 140 μm in diameter, were obtained

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*Author for correspondence (sbp@iim.unam.mx) in our laboratories by the in-rotating water quenching method at 2600 rpm circular velocity under 4·25 Psi injection pressure. The as-cast wires were subsequently subjected to an electroplating process to deposit a $Co_{90}Ni_{10}$ magnetic hard layer using a chemical bath composed of $NiCl_2$, $NiSO_4$, H_3BO_3, $CoCl_2$ and $CoSO_4$ under an electric current density of 12 mA/cm^2 with exposure times of 5, 10 and 30 min, for which layers of thickness, $t = 1{\cdot}5$, 3 and 6 μm, respectively were generated. Earlier studies by energy dispersive spectroscopy (EDS) showed that the deposited CoNi layers correspond to crystalline phase (Torrejón 2008). On the other hand, in the same research, composition analysis of the generated CoNi layer, performed by EDS, indicated a content of 10% Ni when the electric current density was constant ($j = 12$ mA/cm^2) to exposure time at a range of 0·0–60 min (Torrejón 2008). The soft nucleus diameter and hard CoNi layer thickness were measured by scanning electron microscopy (SEM) (Jeol JSM 7600F) operated at 20 keV and 700 pA. The magnetic properties (i.e. *M–H* hysteresis loops and their parameters) were measured by inductive methods at 50 Hz using *M–H* loop tracer based on digital signal processing for low frequency, which reaches a maximum magnetic field of 2·1 kA/m (Butta *et al* 2009). Complex permeability, $\mu^* = \mu_{re} + j\mu_{im}$, was determined from complex impedance, $Z^* = Z_{re} + jZ_{im}$, measured according to the relation (Valenzuela 2004, 2007):

$$\mu^* = G\left(\frac{-jZ^*}{\omega}\right), \tag{1}$$

where G is an appropriate geometrical factor and ω denotes the angular frequency. Impedance measurements were carried out with a HP4192A impedance analyser at a frequency range of 10 Hz–13 MHz under an a.c. applied field, $H_{ac} = 0{\cdot}5$ A/m, along the wire's longitudinal direction.

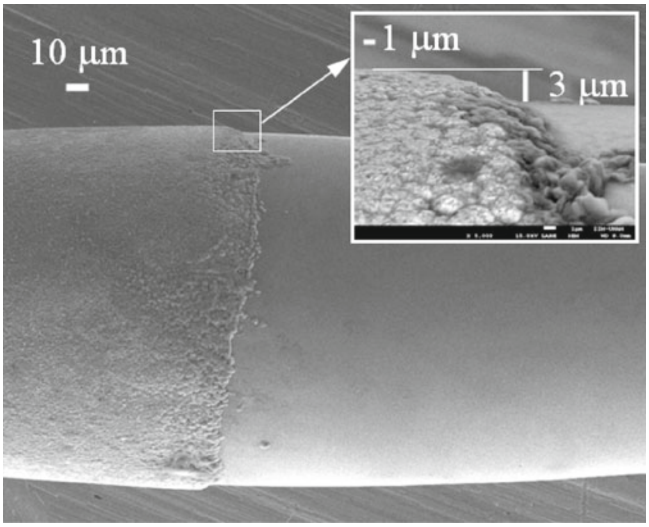

Figure 1. SEM images showing soft magnetic amorphous nucleus and hard magnetic CoNi layer within 10 min of exposure time. Inset shows CoNi layer thickness corresponding to 3 μm.

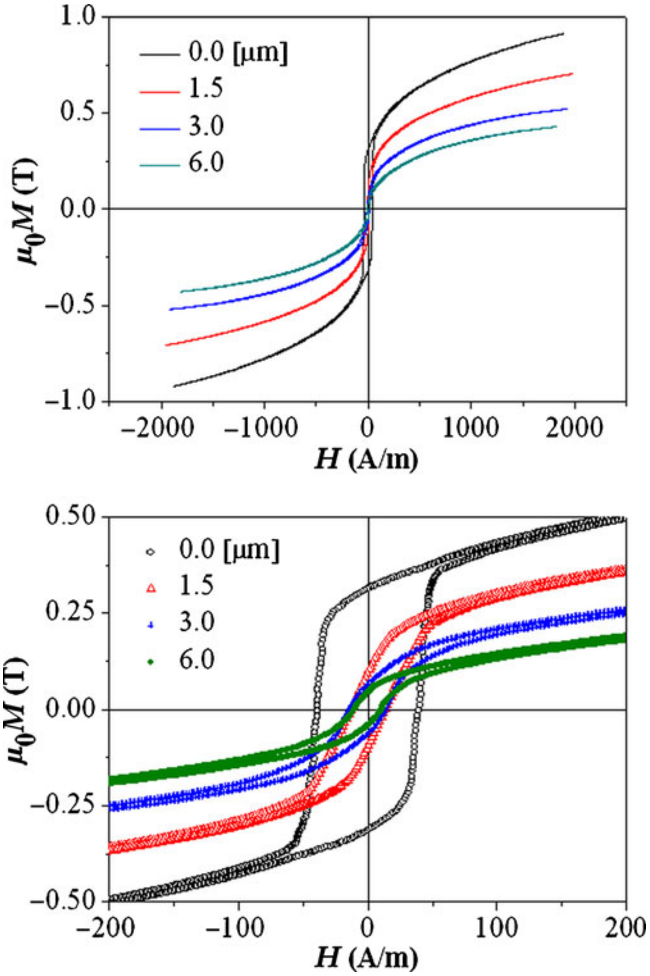

Figure 2. *M–H* hysteresis loops for $Fe_{64}Co_8B_{19.2}Si_{4.8}Ta_4$ amorphous wire and same wire after growth of $Co_{90}Ni_{10}$ external layer with different thicknesses, t (top), and a detail of loops to low-field (bottom).

3. Results and discussion

Figure 1 shows soft nucleus with ~140 μm in diameter and the external hard CoNi layer with 3 μm thickness within 10 min of exposure time. On the other hand, during 5 and 30 min of exposure time, CoNi-layer thicknesses of 1·5 and 6 μm were generated, respectively. The *M–H* loops of the as-cast single-phase $Fe_{64}Co_8B_{19.2}Si_{4.8}Ta_4$ amorphous wire and some wires after the growth of the CoNi hard phase with selected thicknesses are shown in figure 2. Note that the maximum magnetization value takes values between 0·91 and 0·43 T for the thickness interval of 0·0–6·0 μm under the maximum applied field H of 2 kA/m. One should understand that the loop mainly denotes magnetic behaviour of the soft core once the magnetization of the harder shell is not achieved by the maximum applied field.

The low-field magnetization traces for biphase wires and the soft magnetic wire precursor are displayed in figure 2. It is assumed that *M–H* curves mainly correspond to the soft phase (given that the $Fe_{64}Co_8B_{19.2}Si_{4.8}Ta_4$ amorphous core for which a coercive field, H_c, of 40 A/m is determined) that, probably, the magnetization of the hard CoNi layer is not reached with the maximum field applied by device (2·1 kA/m). It can be observed that in the lower portion of figure 2 since the thickness t of the external crystalline phase increases, both remanence and coercivity decrease, resulting in a reduced hysteresis. It reflects an increasing rotational contribution to the wire's magnetization process, as a consequence of the development of out-of-axis magnetization in the wire central core. Anisotropy is seemingly induced by the presence of hard CoNi external layer and denotes the existence of a magnetic coupling between phases possibly due to magnetoelastic origin.

The spectroscopy behaviour for real and imaginary components of complex permeability for single and biphase amorphous wires is shown in figure 3(a, b) for variable thickness of the external CoNi layer. These curves show resolution of the active magnetization mechanisms through the frequency range (Valenzuela 2002). For instance, the $\mu_{\mathrm{re}}(f)$ plot for the as-cast amorphous wire ($t = 0{\cdot}0$ μm, figure 3(a)) shows an initial plateau when frequency, f values increase up to 10^3 Hz. The evolution of μ_{re} has been attributed to the reversible bulging of the magnetic domain walls (DWs) and thus, it can be associated with the initial permeability, μ_{ini} of the soft core (Chikazumi 1978). Further increase in f causes a significant reduction in $\mu_{\mathrm{re}}(f)$, which can be attributed to a relaxation-type dispersion of the reversible bulging mechanism for which the DWs are no longer able to follow the a.c. magnetic variations. Beyond a threshold frequency, f_x (or relaxation frequency), μ_{re} becomes very small, it reflects an increasing rotational contribution for the only active magnetization process for $f > f_x$ (Chikazumi 1978).

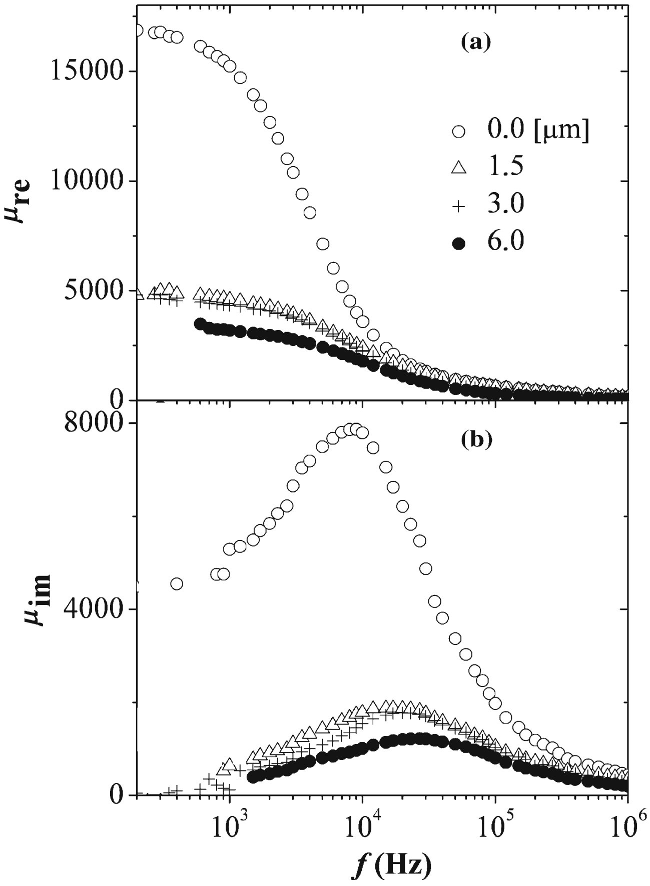

Figure 3. (**a**) Real and (**b**) imaginary permeability spectra for single and biphase wires with different hard layer thicknesses, t.

The CoNi layer thickness affects significantly the low-field reversible magnetization process of soft core since μ_{ini} decreases from 16738 (as-cast amorphous wire, $t = 0{\cdot}0$ μm) to 3205 ($t = 6{\cdot}0$ μm). This marked reduction for μ_{ini} can be attributed to the increase in the out-of-axis anisotropy developed by the biphase wires with the increase in hard CoNi layer thickness as a consequence of the accumulation of mechanical stress appearing at the amorphous-wire/CoNi-layer interface, for which, a higher CoNi layer thickness implies higher accumulated internal stresses.

On the other hand, the imaginary μ_{im} component (figure 3(b)) is associated with magnetic losses (hysteresis, eddy current or power losses) (Chikazumi 1978; Chen and Muñoz 1999). Consequently, the very presence of the external hard layer reduces significantly the losses (figure 2), confirming the low-frequency results in figure 3. The maximum in μ_{im} is observed at frequency, f_x. For the present biphase wires, f_x exhibits an increasing tendency (figure 3(b)) from 9 kHz ($t = 0{\cdot}0$ μm) to 27 kHz ($t = 6{\cdot}0$ μm) and follows an inverse tendency with t, which confirms influence of the variable anisotropy on the active spin rotation mechanism for $f > f_x$, for which the product $\mu_{\mathrm{re}} f_x$ results in a constant value of ~0·1 GHz. This converse correlation between μ_{ini} and f_x is verified in figure 4 as a function of t. This indicates that a reduced μ_{ini} correlates to the rigidity of the magnetic domain wall, leading to higher f_x values. A similar correlation between both parameters has also been found on ferrites as well as on amorphous ribbons and wires (Omata *et al* 1989; Nakamura 2000).

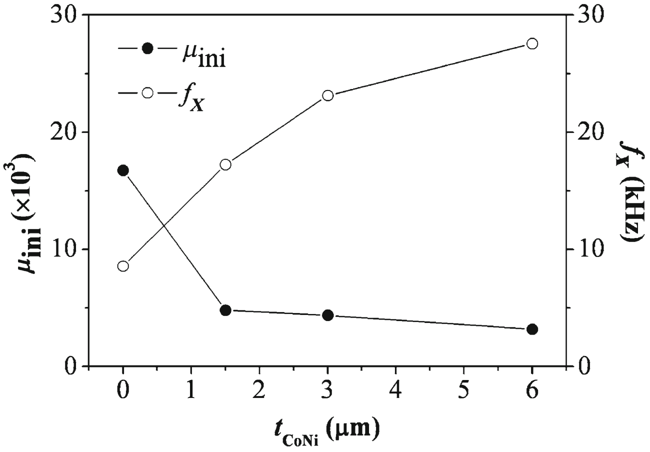

Figure 4. Plot of change in μ_{ini} and f_x as a function of hard layer thickness, t.

4. Conclusions

Biphase wire systems consisting of soft magnetic amorphous wire nucleus surrounded by a layer of hard magnetic $Co_{90}Ni_{10}$ of variable thickness were prepared by in-rotating water quenching method and subsequent electroplating technique. Low-field magnetization processes have been studied as a function of CoNi hard layer thickness. It is concluded that the external layer induces an out-of-plane magnetic anisotropy in the soft magnetic core that controls its magnetization process. Particularly, the losses are reduced, with a reduction in both coercivity and remanence, as well as a reduction in complex permeability.

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