Low-frequency magnetization processes in chemically etched Co-based amorphous ribbons

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In this report we present a study of the magnetization processes for Co-based amorphous ribbons at low frequencies (10 Hz–13 MHz) as a function of decreasing thicknesses attained by chemical etching. Reversible domain-wall bulging, characterized by initial permeability and relaxation frequency, was monitored by means of inductance measurements. The real part of inductance (proportional to initial permeability) exhibited a decreasing trend with diminishing ribbon thickness, together with an increasing tendency for the relaxation frequency. For high amplitude of the ac field (leading to domain-wall unpinning), reduced ribbon thickness showed a deleterious-enhancement effect on irreversible domain-wall displacement, which was observed for both real and imaginary inductance spectrocopic plots. Results are interpreted in terms of reduced domain-wall pinning distances resulting from thinner alloy samples. © *2005 American Institute of Physics*.
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I. INTRODUCTION

Magnetoimpedance (MI) in soft magnetic materials has been a topic of intensive research since the early 1990's both from the basic theoretical viewpoint and for their applicabiltiy in sensor technology.[1] Originally observed in nonmagnetostrictive amorphous ribbons and wires,[2,3] it was rapidly detected in other soft magnetic materials such as thin films among others.[4,5] In addition, MI effect has been largely used as an additional research tool to investigate intrinsic and extrinsic properties of soft magnetic materials.[1,6] For instance, a clear correlation between magnetization processes and MI can be established by means of the complex inductance formalism $\mathbf{L}=L_{re}+jL_{im}$ (where $\mathbf{L}=j\mathbf{Z}/\omega$; $\mathbf{Z}=Z_{re}+jZ_{im}$ and $\omega=2\pi f$), which allows the calculation of the complex permeability $\mu=\mu_{re}+j\mu_{im}$ by means of a simple tranformation.[7] According to this formalism, μ_{re} corresponds to the materials' initial magnetic permeability and μ_{im} is associated with dissipative processes. This methodology affords the monitoring of reversible and irreversible magnetization mechanisms (domain-wall bulging and domain-wall displacement, respectively) as a function of frequency in soft magnetic materials as well as the evaluation of contributions to permeability (rotational and domain-wall components, magnetoelastic or anisotropy contributions).[8–10] In this report, we study the variations of magnetic permeability through **L** measurements in Co-based amorphous ribbons as a function of the ribbon's thickness.

II. EXPERIMENTAL TECHNIQUES

Melt-spun amorphous ribbons of nominal composition $Co_{66}Fe_4Mo_2B_{12}Si_{16}$ (Vitrovac®6205) with 0.10-m length, 0.015-m width, and 28-μm thickness were chemically etched in a 50% CH_3–COOH+30% HNO_3+10% HCl+10% H_3PO_4 solution for 2 and 4 min, resulting in samples with 23 and 19 μm thickness, respectively, with good surface quality (hole-free and even surface). Magnetoinductance measurements were carried out by means of a Hewlett–Packard (HP) 4192 A impedance analyzer, with an axial applied field h_{ac} within the range of 0.07–7.0 A/m at variable frequencies between 100 Hz and 13 MHz. 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 ($f>10^3$ Hz) where the reversible and irreversible magnetization processes and relaxation dispersion occur, the experimental error is even less significant.

III. RESULTS AND DISCUSSION

Real inductance spectroscopic plots $L_{re}(f)$ as a function of h_{ac} amplitude for an as-quenched alloy sample are shown in Fig. 1. For h_{ac} intensities below 1.4 A/m and $f<100$ kHz, L_{re} exhibits a plateau independent of both the h_{ac} and frequency values. For f beyond 100 kHz, L_{re} goes through a relaxation dispersion toward very low values. In addition, for $h_{ac}\geqslant 2.8$ A/m, L_{re} exhibits no longer a constant trend, becoming a marked function of both h_{ac} and f, with increasing L_{re} values with higher h_{ac} intensities. These low h_{ac} results correspond to a field-independent magnetization mechanism for which domain walls are pinned (most probably at the ribbon surface), such as reversible domain-wall bulging, for which the permeability has a constant value, known as the initial permeability.[7] At higher h_{ac}, results point out to the presence of a second magnetization process which, unlike the preceding one, is clearly field dependent. This magnetization mechanism should correspond to irreversible domain-wall displacement (hysteresis), for which higher permeability values are required.[7]

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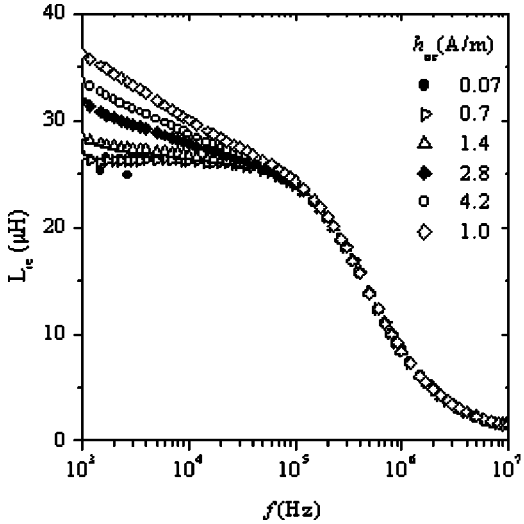

FIG. 1. Spectroscopic plots of the real part of induction as a function of h_{ac} amplitude for the as-quenched alloy sample.

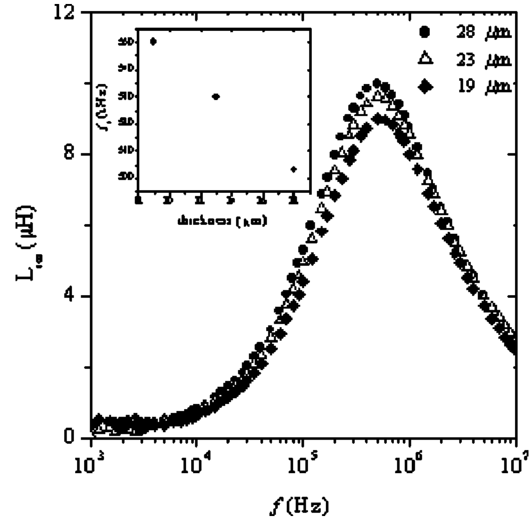

FIG. 3. Spectroscopic plots of the imaginary part of induction measured at $h_{ac}=0.7$ A/m for alloy samples with variable thickness.

Spectroscopic real and imaginary inductance plots $L_{re}(f)$ and $L_{im}(f)$, measured at $h_{ac}=0.7$ A/m for alloy samples with variable thickness (t), are displayed in Figs. 2 and 3. L_{re} decreases with diminishing t values, displaying the characteristic low-h_{ac} and f-independent constant behavior associated with reversible domain-wall bulging (Fig. 2). Beyond $f=1$ MHz, all the curves merge into one. On the other hand, L_{im} plots go through maximum values (Fig. 3), which move toward higher values with decreasing t (see inset Fig. 3). This maximum in $L_{im}(f)$ plots corresponds to the relaxation frequency f_x, at which the domain wall becomes unable to follow the alternating field and thus, the reversible bulging mechanism is no longer active. Instead, a spin-rotation contribution to permeability remains present, as indicated at $L_{re}(f)$, since L_{re} does not reach nill values for $f>f_x$. These variation in L_{re} and f_x with t can be interpreted in terms of a domain-wall dimension as follows: As the alloy thickness becomes smaller, the length for domain-wall pinning also reduces, since the domain walls are assumed to be pinned at the ribbon surface. This decrease results in a reduced free-bulging area, which leads to smaller initial permeabilities. The enhancement observed for f_x values is a direct consequence of shorter domain-wall distances, likewise, a vibrating string produces acute notes with reduced length. In addition, the modeling of reversible domain-wall bulging by means of an equation of motion[11] establishes also this $L_{re}-f_x-t$ dependence, since L_{re} appears proportional to the distance between pinning edges, while f_x exhibits an inverse dependence. The converse $L_{re}\cdot f_x \cong$ constant behavior has been previously reported for amorphous ribbons[12] and wires.[13]

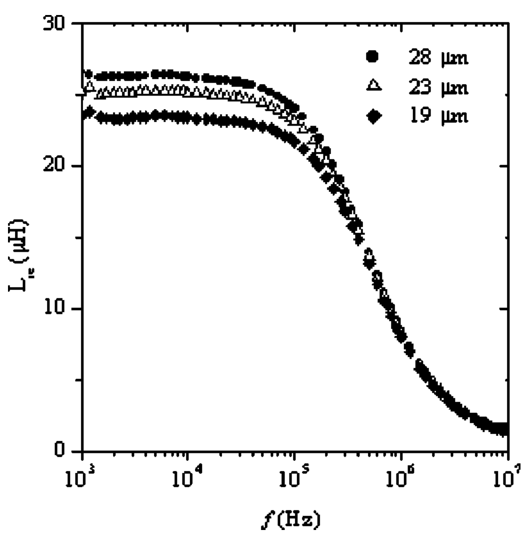

FIG. 2. Spectroscopic plots of the real part of induction measured at $h_{ac}=0.7$ A/m for alloy samples with variable thickness.

Spectroscopic $L_{re}(f)$ and $L_{im}(f)$, measured at $h_{ac}=7.0$ A/m with the alloy thickness as a parameter, are shown in Figs. 4(a) and 4(b). L_{re} displays the characteristic frequency dependence of an hysteretic behavior, with an initial decrease at $t=23$ μm (compared with the as-cast 28 μm) followed by a surprising enhancement at $t=19$ μm [Fig. 4(a)]. This trend is confirmed by $L_{im}(f)$ plots [Fig. 4(b)], for which a low-frequency event prefigures a maximum with a reduced value at $t=23$ μm (compared with the as-cast 28 μm) and an improvement for $t=19$ μm. The hysteresis relaxation frequency (f_{hx}), located at the first maximum of $L_{im}(f)$ and for which the hysteresis process becomes inactive, increases from 1.0 kHz (as-quenched alloy) to 2.1 kHz for 23 μm and again, exhibits a recovery (1.2 kHz) at $t=19$ μm, reflecting also a correlation $L_{re}\cdot f_{hx}\cong$ constant as the preceding reversible magnetization process. The initial decline of L_{re} at $t=23$ μm can be attributed again to a reduced free-bulging area resulting to a shorter wall pinning distance, which in turn, enhances f_{hx}. In contrast, the unexpected retrieval of L_{re} may be related to a reconfiguration of magnetic domains induced by the shortening of alloy thickness, which in turn, facilitates the bulging-depinning displacement of domain walls featuring this kind of irreversible magnetization mechanism. It should be noted that chemical etching can lead also to a relief of stresses induced during the ultrarapid cooling process, with an effect opposite to the reduction in ribbon thickness. Recent results on samples of nanocrystal-

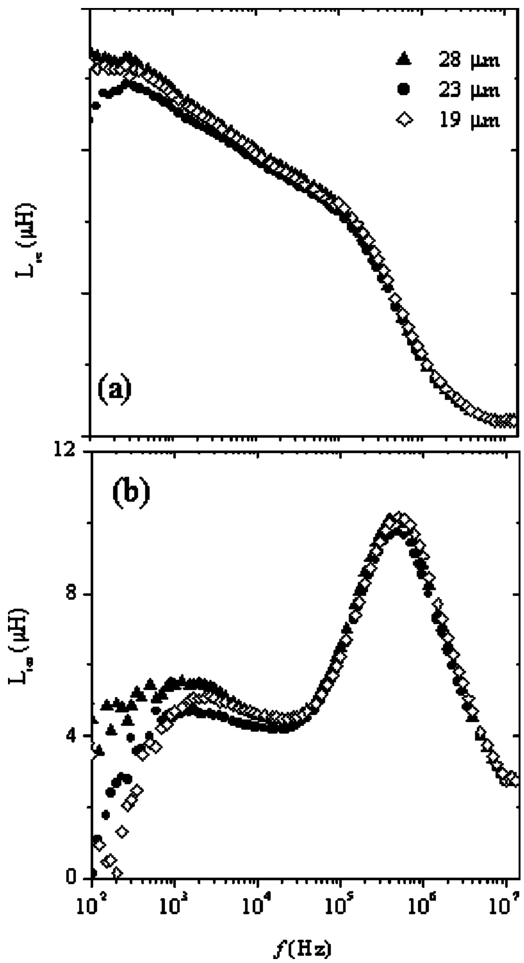

FIG. 4. Spectroscopic plots of the real and the imaginary inductance measured at h_{ac}=7.0 A/m with the alloy thickness as parameter. The error bar for $f \geqslant 1$ kHz is about the size of the symbols.

lized Fe alloys annealed prior to chemical etching showed only a monotonic decrease in real permeability upon thickness reduction.[14] Further experiments are in progress in order to clarify this point.

IV. CONCLUSIONS

Reversible/irreversible magnetization processes were studied in Co-based amorphous ribbons as a function of alloy thickness. Initial permeability, monitored through real inductance spectroscopic plots, showed a decreasing tendency with reducing thickness, while the relaxation frequency exhibited an inverse increasing trend with shrinking thickness, as a result of a reduced domain-wall free-bulging area. In contrast, the hysteretic magnetization process displayed an initial deleterious effect with thinner alloys, followed by an unexpected recovery, which can be interpreted in terms of a domain reshaping induced by further thickness reduction.

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