Domain wall pinning, bulging, and displacement in circumferential domains in CoFeBSi amorphous wires

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A detailed study of the complex inductance response of as-cast CoFeBSi wires as a function of frequency (100 Hz–13 MHz range) and circular field amplitude [0.1–17 A/m room mean square (rms) on the surface of the wire] in the giant magnetoimpedance arrangement is presented. The analysis of experimental results show evidence of magnetization processes associated with circumferential domain walls, such as domain wall pinning, bulging, and displacement. The unpinning field was measured as 0.2 A/m (rms) at 5 kHz. It is shown that the analysis of spectroscopic plots of real and imaginary inductance leads to characterization of the magnetization process involved. © *2000 American Institute of Physics.* [S0021-8979(00)20708-1]

I. INTRODUCTION

Giant magnetoimpedance[1,2] (GMI) has raised great interest because of the technological applications derived from the possibility of sensing magnetic fields (and electric currents) by means of changes in the impedance response of a ferromagnetic material submitted to a small rf current. Since total impedance is the most important parameter, most scientific papers dealing with GMI use the total impedance, Z, or the percentage of change, $\Delta Z/Z_{(H\max)}$, where $Z_{(H\max)}$ is the total impedance at the maximum applied dc field, to evaluate the GMI performance of a given material. To investigate the basic magnetization phenomena associated with GMI, however, we have shown[3,4] that the study of the separate components of the complex inductance formalism $L = L_r + jL_i$, where L_r and L_i are, respectively, the real and imaginary components of inductance and j the base of complex numbers $[j=(-1)^{1/2}]$, leads to more direct insight.

In this article, we present a detailed study of the inductance response of as-cast CoFeBSi amorphous wires as a function of frequency and also as a function of ac field amplitude at selected frequencies. The analysis of the results show that they can be associated with various magnetization processes that involve circumferential domain walls, such as pinning, bulging, and displacement.

II. EXPERIMENTAL TECHNIQUE

We used as-cast amorphous wires of nominal composition $(Co_{0.94}Fe_{0.06})_{72.5}B_{15}Si_{12.5}$, and 125 μm diameter, prepared by the in-water-rotating quenching technique,[5] that were kindly supplied by Unitika Ltd., Japan. Inductance measurements were carried out on pieces 8 cm long at room temperature; to ensure a good electric contact, the wire ends were cleaned with a soft acid solution and attached to the measurement clamps with a silver paste. A HP 4192A impedance analyzer controlled by a PC was used for measurements, with measurement software developed in our laboratory, which allows a frequency run (94 points in the 5 Hz–13 MHz frequency range) in less than 3 min. The measuring voltage was varied between 0.005 and 1.1 V, which taking into account all the impedances in the circuit, leads to electric currents through the sample in the range $i=0.1$–22 mA. The root mean square (rms) field amplitude on the wire can be calculated as $h=ir/2\pi a^2$, where r is the radial point considered on the wire cross section and a is its total radius. The rms range of ac radial fields on the wire surface (where it is maximum) is therefore 0.1–17 A/m.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Complex inductance components were derived from complex impedance (directly measured by our system) by means of the basic relationship $L=(j/\omega)Z$, where ω is the angular frequency ($\omega=2\pi f$). Note that the presence of j leads to a crossover dependence: real inductance depends on imaginary impedance and, conversely, imaginary inductance is determined by real impedance. For low frequencies, where the skin depth effect can be neglected, magnetic permeabilities (real and imaginary) are simply proportional to the corresponding L (real and imaginary) through the pertinent geometrical factor.[4] Recent calculations[6] have shown that, for high frequencies, magnetic permeabilities can also be calculated as a function of L or Z.

Spectroscopic plots of the real part of inductance at selected amplitudes of h are shown in Fig. 1. At low fields and low frequencies, L_r showed a plateau, followed by a dispersion with a relaxation character. The relaxation frequency is about 40 kHz. All experiments carried out at fields $h \leq 0.2$ A/m resulted in the same curve. For higher fields, the inductance value depended on the field amplitude, but as the frequency increased, all the curves merged into the low field plot and exhibited the same relaxation dispersion. For $f>20$ kHz a common curve is observed, regardless of the field value.

The low frequency section of the plot, where L_r depends on the field amplitude, is therefore interesting, and is shown in Fig. 2 for $f=5$ kHz, well below the relaxation frequency to avoid its effects. A maximum is observed; since at this frequency the skin effect can be neglected, the real part of per-

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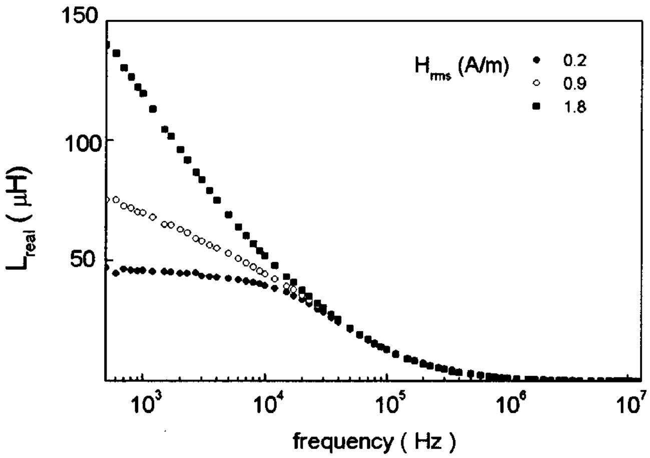

FIG. 1. Real part of inductance as a function of frequency. The field amplitude appears as a parameter.

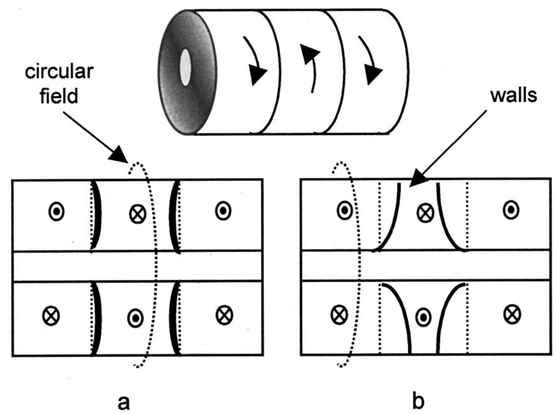

FIG. 3. Schematic representation of the magnetization processes. Cross sections of the wire show (a) domain wall bulging and (b) domain wall displacement by unpinning the wall from the wire surface. In this case, the wall remains pinned to the inner core–outer shell boundary.

meability is proportional[4] to the real part of inductance, L_r, and it can be shown that this curve is quite similar to that usually obtained for the case of permeability dominated by domain wall displacements. It can also be shown that for high fields (fields larger than the one for the observed maximum) L_r decreases with a hyperbolic character.

The low field end of Fig. 2, also interesting, has been expanded and is shown as an inset in Fig. 2. For fields below 0.2 A/m, the real part of inductance shows a constant value, as the field increases, L_r exhibits a strong increase for $h>0.2$ A/m. The constant L_r section is straightforwardly associated with the initial permeability, where domain walls are pinned to defects (such as the external surface of the wire, for instance), and therefore unable to displace. The applied field leads to a reversible bulging, shown schematically in Fig. 3(a). As the applied field increases and reaches the unpinning (or propagation) point, domain walls are unpinned and start to displace, producing a large increase in L_r. Unfortunately, to our knowledge, there are no determinations of unpinning

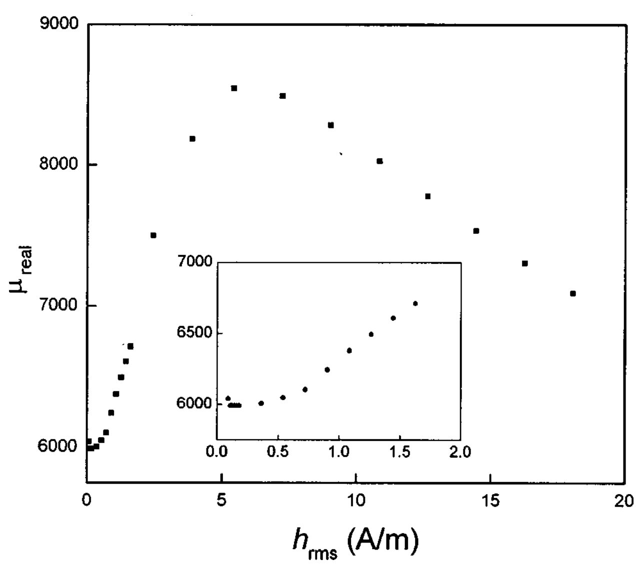

FIG. 2. Behavior of the real part of inductance as a function of field amplitude at a constant frequency $f=5$ kHz. In the inset is an expansion of the low field section.

fields in this or other amorphous alloys to allow a comparison with the value we have found. There is a recent, detailed report[7] on magnetization processes in these wires, but measurements are carried out for the longitudinal magnetization process. The reported value for the circular anisotropy field is in the 2–3 Oe range (160–240 A/m), but it should be kept in mind that in longitudinal field experiments the dominant magnetization process is domain rotation. Also, unpinning fields are considerably smaller than coercive and anisotropy fields.

The inset in Fig. 2 shows a well defined change of slope at the unpinning field. This seems unexpected because the circular field is very inhomogeneous; it varies from zero at the center to the wire to its maximum value (0.2 A/m for the unpinning) at the surface. A homogeneous domain wall pinning on the wire radius would lead to a wide variety of unpinning processes, starting at the wire surface (where h is maximum) and propagating toward its center. An L_r vs h plot of such a process would exhibit an extremely rounded change of slope around the unpinning field, instead of the well defined change obtained experimentally. An explanation for this result is that circumferential domain walls are preferentially pinned to the wire surface where, coincidentally, the circular field attains its maximum value.

The other pinning site for domain walls is expected to be the boundary between the inner core and the outer shell. This section is not a simple 90° domain wall since, as is well known, longitudinal magnetization processes proceed by domain rotation. It can therefore be expected that circumferential domain walls remain pinned to this site even for very high circular fields, unpinning only at the surface and displacing in a canted shape, as schematically shown in Fig. 3(b).

In agreement with the previous results, the high field part of the inductance response is associated with magnetic hysteresis. Since our measurement technique does not keep track of instantaneous values of field and inductance, no hysteresis loops can be observed. The imaginary part of inductance, however, can provide some evidence of hysteresis processes in the wire, since L_i is associated with dissipative processes.

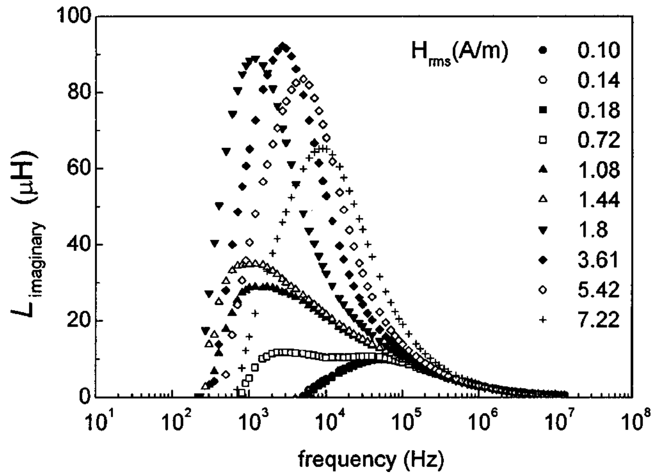

FIG. 4. Imaginary part of inductance as a function of frequency for various field amplitudes.

The frequency behavior of L_i for several field amplitudes is shown in Fig. 4. For field amplitudes lower than the propagation value (0.2 A/m), only a small maximum is observed which, following our previous discussion, represents the energy dissipated in the domain wall bulging process. As the field amplitude increases, the maximum remains essentially insensitive to the field, but an additional maximum appears at lower frequencies. This new maximum increases with h and becomes far larger than the high frequency one. At $h=0.72$ A/m both maxima are resolved. For larger fields, however, the low frequency maximum dominates and, since they are not well resolved, the high frequency maximum is hidden.

The large maximum should be associated with hysteresis processes, since they involve several steps (bulging, unpinning, displacement, pinning in a new position, etc.) and consequently are expected to possess a larger time constant than the bulging process alone. Also, hysteresis involves a far larger energy dissipation than just domain wall bulging, leading to a larger maximum.

As explained above, our system is unable to show instantaneous variations of field and inductance and gives only their amplitudes; this is equivalent to measuring only the total permeability. Since permeability goes through a maximum and then decreases (see Fig. 2), for high fields (larger than 361 A/m) the observed maximum exhibits a decrease.

An increase in the maximum frequency is observed for the higher applied fields. A simple explanation for this increase is that, as the field amplitude increases, overcoming the maximum permeability, domain rotation becomes significant (domains are not perfectly circumferential). Since rotation possesses a much higher dispersion frequency, the global frequency is shifted to higher values.

IV. CONCLUSIONS

We have shown that the inductance response of CoFeBSi wires at low frequencies ($f<40$ kHz) is clearly associated with circumferential domain wall processes of bulging, unpinning, and displacement; at such frequencies, GMI therefore depends on the magnetization processes. Also, we have shown that a detailed analysis of real and imaginary parts of inductance leads to a characterization of the involved magnetization processes.

ACKNOWLEDGMENT

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