Stress dependence of the domain wall dynamics in the adiabatic regime

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1. Introduction

The magnetic domain wall (DW) motion is an important issue not only because of its potential technological application in several magnetic devices [1,2], but also due to the possibility of understanding the fundamental physics associated with the dynamical processes. In this context, amorphous glass-coated microwires are powerful tools to study a single domain wall dynamics and the magnetic behavior of systems with reduced dimensions. During the production of these microwires the frozen internal stress, associated to the amorphous state and magnetostriction, gives rise to theirs interesting properties [3]. One of the outstanding magnetic properties of microwires with positive magnetostriiction is the magnetic bi-stability, where the magnetization inversion occurs by a single large Barkhausen jump, a result of the displacement of just one magnetic DW along the wire [4]. During the wall propagation the interactions between the DW and pinning centers, or glass–metal interface, affect the DW dynamics and contribute to the richness of the phenomenon.

In this paper we studied the DW dynamics in the low field region in as-cast and annealed bi-stable amorphous glass-covered Fe77.5Si7.5B15 microwires. In particular, from the relation between the domain wall velocity and magnetic field in the adiabatic regime, the power-law critical exponent ($\beta$) and the critical field ($H_0$) and the domain wall damping ($\eta$) were analyzed as a function of the metal–glass thickness ratio, applied axial stress and Joule annealing.

2. Experimental

The DW dynamics was studied in amorphous glass-covered microwires, with nominal composition Fe77.5Si7.5B15, produced by the Taylor–Ulitovsky technique (see Ref. [5] for a detailed review of the Taylor–Ulitovsky preparation method). Two as-cast samples were studied: S1 with an amorphous metallic nucleus of 18.5 $\mu$m and total diameter of 40 $\mu$m and S2 with an amorphous metallic nucleus of 25 $\mu$m and total diameter of 47 $\mu$m, both samples with 30 cm in length. The diameters were estimated by comparing images, obtained by optical microscope, of the wires and a body with known width. The Fig. 1 presents a schematic diagram of the glass-coated microwire. The Pyrex glass cover associated with the fabrication method produces an internal frozen stress which is proportional to the glass' thickness. In order to partially relief this internal stress, the as-cast samples were submitted to Joule annealing during 20 min. Samples S1Ann and S2Ann have the same dimensions and composition of the S1 and S2, respectively, but they were Joule annealed at currents of 23.7 mA. The estimated temperature is 250 °C, and was calculated as described in Ref. [6]. The magnetostriction and frozen internal stress were estimated from the evolution of the anisotropy field as function of the axial applied stress. The samples S1 and S1Ann have presented a frozen stress of 220 and 200 MPa, respectively, while the estimated frozen stress for the S2 and S2Ann samples were 155 and 143 MPa, respectively. The measured magnetostriction of the studied samples was $22 \times 10^{-6}$.

The DW velocity ($v$) was measured using a Sixtus–Tonks based experiment [7]. The experimental setup consists of four coaxial coils: an exciting coil, two sensing coils and a pinning coil. The exciting coil, with 20 cm in length and 7 cm in diameter, is responsible by the magnetic field generation. All the measurements
were performed using a 1 Hz square waveform magnetic field. In order to detect the DW motion, two sensing coils, with length of 2 mm and separated by 3 cm, are placed in a region where the exciting magnetic field is homogeneous. To avoid the DW propagation before the magnetic field reaches a constant value, a pinning coil with 1 cm in length was placed close to one end of the sample, inside the exciting coil, producing a field opposed to the exciting one and with constant amplitude of 10 Oe. When this field is switched off the DW starts its running through the wires. The other end of the sample was kept out of the exciting coil in order to ensure that just one DW is put in motion. The voltage signal detected by the sensing coils was amplified and digitized by an analog-to-digital converter with 1 MS/s sampling rate, high enough to detect the details of the signal associated to the DW motion.

Fig. 2 presents the signal detected from the sensing coils, indicated by the blue and red squares, superposed to the exciting magnetic field, black circles, both as a function of the time. The dot-lines indicate the time interval between the peaks detected by the sensing coils when the DW crosses them. The solid black line shows the delay provided by the pinning coil in order to ensure that the DW is depinned just when the magnetic field is constant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results and discussion

The magnetic domain configuration in amorphous glass-covered microwires with positive magnetostriction is characterized by a core–shell structure, an inner core with a single axial domain, surrounded by a radial domain structure, the outer shell [2,8]. The Fig. 1 presents a schematic diagram of the estimated DW structure. In order to reduce the stray fields at the ends of the wire, a closure domain appears at the end of the axial domain, with a DW separating them. In particular, this is the single domain wall whose dynamics is analyzed in this work.

The DW dynamics can be described by the equation of motion of a driven and damped harmonic oscillator [9]

\[
m \frac{d^2x}{dt^2} + \frac{\eta}{m} \frac{dx}{dt} + 2\alpha x = 2\mu_0 M_s H_0,
\]

where, \(m\), \(x\), \(\alpha\), \(\mu_0 M_s\) and \(H\) are the DW effective mass, the DW displacement from the equilibrium position, the damping coefficient, the restoring constant, the saturation magnetization and the applied magnetic field, respectively.

In a viscous medium, as in the case where the DW moves, the DW reaches its maximum velocity in a very short time and propagates at a constant velocity under the applied magnetic field [10]. The relation between the DW velocity and magnetic field is [11]

\[
\eta v = (H - H_0)
\]

where \(H_0\) is the DW critical propagation field.

However, this relation is not always verified, especially at low applied magnetic fields. Results previously reported, showed that the DW can propagate below the switching field or even with a negative \(H_0\) [12,13]. On the other hand, it has been already verified that at low applied fields the DW dynamics can be well described by a power-law [14,15] as

\[
\eta v = (H - H_0)^{\beta}
\]

where, \(\eta\) is the effective DW damping coefficient and \(\beta\) is the power-law critical exponent.

Fig. 3 presents a typical result of the DW velocity as function of the applied magnetic field. For high field values, above 5 Oe in this case, a linear behavior is verified, being well described by the dynamics in the viscous regime. For low applied fields, a clear power-law behavior is observed, showing that the DW dynamics is in the adiabatic regime. The \(v \times H\) data, for fields below 5 Oe, of all samples and applied axial stress were fitted to the expression (3) and the \(\beta\), \(H_0\) and \(\eta\) analyzed as follow.

Fig. 4 shows the \(\beta\) values obtained for the different studied samples as function of the applied axial stress. It can be seen that the \(\beta\) values are close to 0.5, which is an indication of a planar DW in an adiabatic regime [15]. However, some few variations on the \(\beta\) can be identified as a function of both, applied stress and Joule annealing. The main effect of the annealing was to reduce the \(\beta\) dependence with the applied stress, keeping the values closer to 0.5, for the S1Ann and S2Ann. For the S1 sample, as the stress is
observed that the interactions. At no applied stress it can be
increased (from 0.55 to 0.72) as the applied stress is raised,
reduced, the $\beta$ value close to 0.5 is an indication of a planar DW in an adiabatic regime. These
values are resulting from fitting the $\nu \times H$ curves to the expression (3) in the low
field region ($H \leq 3$ Oe).

Fig. 5 shows the stress dependence of the critical field $H_0$. The contributions to the $H_0$ values come from the long-range
(magnetoelastic and magnetostatic sources) and short-range
(pinning centers) interactions. At no applied stress it can be
observed that the $H_0$ values for the as-cast and annealed samples are the same. This fact is an indication that the annealing
temperature used is not high enough to modify the short-range
interactions. The $H_0$ values for the S1 and S1Ann samples are higher than those for S2 and S2Ann, due to the higher frozen
stress in samples with higher glass to metal ratio. The $H_0$
evolution with the applied stress indicates the existence of two
stress ranges. In the first range, at low applied stress, ($\sigma \leq 50$ MPa for S1 and S1Ann and $\sigma \leq 100$ MPa S2 and S2Ann), the increase of $H_0$ is high, a feature related to the increase of the radius of inner
core axially magnetized, until the inner core radius reaches the
value of the radius of the metal core. In the second one, with
additional applied stress the $H_0$ values still increase but at a
smaller rate. These facts are indications that the dependence of the critical field with the applied stress is related to the long-ange interactions.

In order to obtain additional information on the DW dynamics it is possible to study the DW damping mechanisms. The current
models to the damping mechanisms (inverse of the mobility)
state that the main damping sources are associated to eddy current $\eta_{\text{eddy}}$ and spin relaxation $\eta_s$. These terms are given by [16]

$$\eta_{\text{eddy}} = \frac{\mu_0 M_s^2 r_C}{\rho} \left( \ln \left( \frac{r_M}{r_C} \right) + \frac{8}{\pi^2} \right)$$

(4)

and [17]

$$\eta_s \propto \frac{\tau M_s}{\sigma} \frac{\tau M_s}{\pi} \sqrt{\frac{3 \sigma \sigma}{2A}}$$

(5)

where $r_M$, $r_C$, $\rho$, $\tau$, $\sigma$, $M_s$, $\sigma$ and $\delta_0$ are, respectively, the metal and inner core radius, the metal resistivity, the damping term of the Landau–Lifshitz motion equation for the magnetization, saturation
magnetostriction, the applied stress and the DW thickness.
As it can be seen on the expression (5), the spin relaxation damping is inversely proportional to the domain wall thickness and proportional to the Landau-Lifshitz (L-L) damping factor. As all magnetic moment are exchange coupled to their neighbors, any change in the wall position implies in the precessing motion of the magnetic moments of the wall, which will be damped as determined by the L–L equation of motion for the magnetic moments. Also, as larger the domain wall is, slower need be the inversion of the direction of the magnetic moment of the domain wall.

Fig. 6 presents the effective damping as a function of the applied stress. The general behavior indicates that for low applied stress the damping is reduced as the stress is increased and, for additional applied stress, it increases. Consequently, a critical stress $\sigma_c$, where damping starts to increase, can be identified. In particular, the $\sigma_c$ values are slightly different from sample to sample and ranges from 50 up to 120 MPa. At the high applied stress region, the damping increases with the square root of the applied stress and the experimental data can be fitted using Eq. (5) added by a constant term, as shown by the solid blue lines in Fig. 6. The constant damping term has damping contributions from stress independent sources as, for example, the damping term from eddy current when $r_M = r_C$. The good agreement...
between data and fitting allows to infer that the main contribution to the stress dependent damping, at the high applied stress region, is the spin-relaxation term.

The spin relaxation contributes to the effective damping even in applied stress values smaller than $\sigma_C$. As the damping terms are additive, the spin relaxation contributions can be discounted from the effective measured one. Fig. 7 shows the resulting damping term $(\eta' - \eta_R)$ as a function of the applied stress and the resulting damping variations have the main contribution coming from the eddy currents. Considering the core-shell domain structure in microwires, it should be expected a change in the resulting eddy currents once the microwires, it should be expected a change in the resulting eddy currents. Considering the core–shell domain structure in

damping variations have the main contribution coming from the effective measured damping term.

Fig. 7. Resulting damping term, $(\eta' - \eta_R)$, as a function of the applied stress. The $(\eta' - \eta_R)$ values were obtained discounting the spin relaxation contribution from the effective measured damping term.

necessary to know the value of $r_C$ and its change with the applied stress. Nevertheless the reduction of the $(\eta' - \eta_R)$ values with the applied stress, presented in Fig. 7, can also be observed in the expression (4) for $r_C$ approaching $r_M$.

4. Conclusions

It was verified that in the low field region the domain wall dynamics can be well described by a power-law expression, considering a planar domain wall in the adiabatic regime. The parameters $\beta$, $H_s$, and $\eta'$ that characterize the DW dynamics were determined as a function of the applied axial stress or Joule annealing. It was possible to quantify the damping mechanisms and how the applied axial stress and the Joule annealing affects the parameters, which characterizes the DW damping. It was verified that until a critical stress $\sigma_C$ is attained, both the eddy current and spin relaxation contribute to the stress dependence of the DW damping. Above $\sigma_C$, as the eddy current damping is stress independent, the main modification in the damping coefficient has its origin in the spin relaxation phenomenon. The critical stress is probably attained when the axially magnetized inner core radius is equal to the metallic one. It was shown that annealing at 250 °C does not modify the short-range interactions of the domain wall. Finally, the understanding of the domain wall propagation over the microwires can be used to improve both: the dynamic behavior of the wall through magnetic structures and its future application in technical devices.

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References