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Frequency dependence of the single domain wall switching field in glass-coated microwires

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Abstract

The frequency dependence of the switching field in glass-coated FeNiMoB microwires has been studied in the temperature range from 77 to 373 K. Two contributions to the domain wall switching mechanism were recognized: a magnetoelastic contribution coming from the magnetoelastic interaction of the magnetic moments with the stresses, and a relaxation contribution coming from the structural relaxation of the atomic level defects. The structural relaxation results in the unusual increase in the switching field at low frequencies, whereas the increase in the switching field at high frequencies was assigned to the frequency dependence of the magnetoelastic contribution, which obeys the power law $H_{sw} \sim f^{1/3}$.

1. Introduction

Amorphous glass-coated microwires are novel materials that are interesting from the application point of view as well as from the theoretical point of view [1, 2]. The peculiar magnetic properties result from the domain structure that is determined by the micromagnetic energy balance between local stray fields and magnetoelastic anisotropy distributed according to the internal stresses that are frozen in during the quenching process. Finally, the domain structure of the microwires with positive magnetostriction consists of a single domain with axial magnetization, which is surrounded by an external domain structure with radial magnetization. Moreover, closure domains appear at the end of the wire in order to decrease the stray fields. As a result of such a domain structure, the magnetization process in the axial direction runs through depinning and subsequent propagation of the single closure domain wall [1]. Therefore, glass-coated microwires are ideal materials for studying the magnetization process of the single domain wall.

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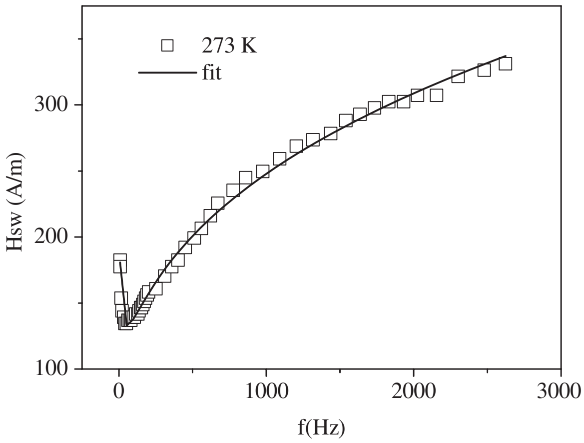

Figure 1. Frequency dependence of the switching field in FeNiMoB microwire.

Coercivity is commonly considered to be one of the most important parameters in applied magnetism [3–5]. Coercivity is associated with the pinning well of the domain wall.

The goal of this contribution is to present a more complex study of the frequency dependence of the switching field (which reflects the coercivity of the single domain wall) in glass-coated microwires and to show how it can be used to study the different contributions to the single domain wall potential.

2. Experimental details

This study has been performed on glass-coated amorphous microwires with a nominal composition of $Fe_{40}Ni_{38}Mo_4B_{18}$ prepared using the Taylor–Ulitovsky method [6]. The diameter of the metal core was 8 μm and the total diameter was 12 μm. Pieces of microwire 7 cm long were taken for measurements by the induction method [7] within the frequency range 10–3000 Hz. The amplitude of the applied field, 450 A m^{-1}, was constant for all measurements. The frequency dependence of the switching field was measured in the temperature range from 77 K up to 373 K without an applied stress. The influence of the stresses on the frequency dependence of the switching field was measured at room temperature (300 K) under tensile stresses up to 140 MPa. The applied tensile stress within the metallic nucleus was calculated according to [8].

3. Results and discussion

The simple frequency dependence of the coercivity was previously found in magnetic wires or ribbons [4, 5]. It was shown that the coercivity in amorphous wires at low frequency f can be expressed as:

$$H = H_{co} + \mathrm{const}(f H_0)^{1/n}, \qquad (1)$$

where H_{co} is the static coercivity, H_0 is the amplitude of the applied field, and n is a coefficient ranging from 1 to 4 depending on the geometry and hysteresis mechanism of the materials.

However, our measurement of the FeNiMoB microwire shows a more complex frequency dependence of the switching field (figure 1). A similar dependence was also found in [9]. It consists of two parts: at low frequencies the switching field decreases with increasing frequency; in the frequency range above 50 Hz the switching field depends on $f^{1/3}$.

The dependence of H_{sw} in the frequency range 50–3000 Hz can be obtained from the solution of the equation of domain wall motion [4]:

$$H_{sw}^{\sigma} = (1/3)H_{co} + [4x_{cr}(L + 2M_s A)/M_s]^{1/2}(4fH_0)^{1/3}, \quad (2)$$

where x_{cr} is the critical displacement of the domain wall to be depinned, M_s is the saturation magnetization, and L is the damping coefficient. The field from the micro-eddy current is proportional to $A\mathrm{d}x/\mathrm{d}t$.

In any case, equation (2) does not describe the decrease in the switching field at low frequencies. Such behaviour has also been measured in [7], but no explanation is offered. Here we ascribe this effect to structural relaxation on the atomic level. It was shown previously [10, 11] that the single domain wall potential in amorphous glass-coated microwires consists of two contributions: a long-range magnetoelastic contribution and a short-range contribution, coming from structural relaxation on the atomic level.

Since the amorphous glass-coated FeNiMoB microwire has a large-enough positive magnetostriction (which is a necessary condition to obtain the bistable behaviour), it is reasonable to assume that the switching field will be driven mostly by magnetoelastic interaction between internal stresses and the domain walls at the closure structure at the ends. The magnetoelastic part depends on the frequency according to equation (2).

On the other hand, the decrease in the coercivity at low frequency can be explained satisfactorily in terms of magnetic after-effect [12, 13]. As a result of their preparation, the structure of amorphous wires is associated with the metastable state of the amorphous structure, and for this reason quite large relaxation effects can be expected. As the measuring frequency decreases, the measuring time increases and a stabilization of the domain structure through structural relaxation takes place. Such an effect has already been observed in amorphous glass-coated microwires [6, 14, 15].

For relaxation effects due to local structural rearrangements, the pinning field H_{sw}^{p} is considered [13]:

$$H_{sw}^{p}(T) \propto \frac{1}{M_s}\frac{\varepsilon_p^2 \rho_p}{kT}(1 - \mathrm{e}^{(-t/\tau)}), \quad (3)$$

where ε_p corresponds to the interaction energy of mobile defects with the spontaneous magnetization, ρ_p is the density of the mobile defects, t is the time of measurement, and τ is the relaxation time, which is given by the Arrhenious equation:

$$\tau = \tau_0 \mathrm{e}^{Q/kT}, \quad (4)$$

where τ_0 is a pre-exponential factor given elsewhere [16] and Q corresponds to the activation energy of the mobile defects.

As has been shown [6, 10], two contributions can be simply summed [12] giving the final frequency dependence of the switching field:

$$H_{sw} = H_{sw}^{\sigma} + H_{sw}^{p}. \quad (5)$$

It can be seen from figure 1 that the two contributions given by equation (5) fit almost perfectly the frequency dependence of the switching field in amorphous glass-coated FeNiMoB microwire. Moreover, the activation parameter of the structural relaxation ($\tau_0 = 5 \times 10^{-16}$ s and $Q = 0.93$ eV) corresponds to that measured for the same composition in amorphous ribbons [17].

To confirm the origin of both contributions, the temperature and stress dependences of the switching field were measured.

The slope of the high-frequency part increases with the temperature (figure 2), reflecting the changes in saturation magnetization M_s (which decreases with temperature) as well as the

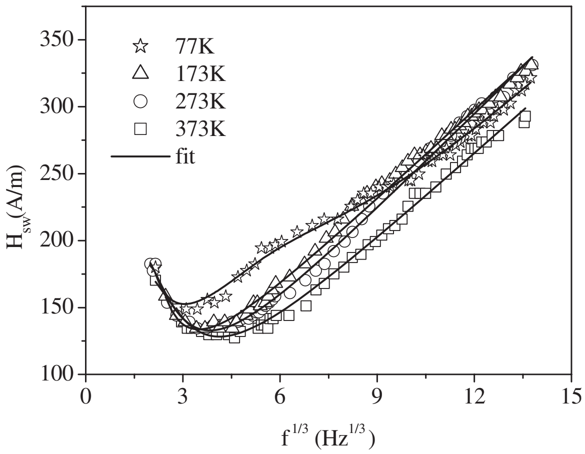

Figure 2. Frequency dependence of the switching field. Temperature as a parameter.

critical displacement of the domain wall x_{cr} (see equation (2)). This is a result of changes accompanied by the application of tensile stress arising from the different thermal expansion coefficients of the metallic nucleus and the glass coating. This change reflects the stress dependence of the frequency-independent magnetoelastic part, H_{co}, of H_{sw}. The lower the temperature is, the higher are the stresses σ and the higher the $H_{co}(H_{co} \sim (\lambda_s\sigma)^{1/2})$ is. On the other hand, the relaxation contribution changes as a result of the change in relaxation time. The relaxation time decreases with temperature according to the Arrhenius law given by equation (4). Therefore, the minimum in the frequency dependence of the switching field shifts to higher frequencies at higher temperatures. Using the pre-exponential factor $\tau_0 = 5 \times 10^{-16}$ s found for relaxation measurements in the ribbon of the same composition, we obtain the activation energies 0.26, 0.59, 0.93 and 1.27 eV for the temperatures 77, 173, 273 and 373 K, respectively. These activation energies belong to the range of activation energies found for the ribbon of the same composition (0–1.7 eV) [17].

On the other side, applying stress has almost no influence on the relaxation contribution (figure 3). The relaxation time and the amplitude of the structural relaxation, obtained by fitting, are almost the same for all measurements. This is because the relaxation time is not influenced strongly by the applied stress. However, the magnetoelastic contribution, which is defined by the stress applied on the sample, increases. Firstly, an increase in the frequency-independent part of the switching field H_{co} is observed at low applied tensile stress (below 30 MPa), whereas the slope of the frequency dependence changes slightly. At higher applied stresses, the slope of the frequency dependence increases, most probably because of the increase in the damping coefficient L [14, 18].

4. Conclusions

To conclude, the complex frequency dependence of the switching field in magnetic microwires is explained in terms of two contributions to the switching mechanism. The unusual increase in the switching field at low frequencies is explained by structural relaxation. The relaxation contribution was confirmed by measurements at different temperatures through the relaxation time change. Using the pre-exponential factor $\tau_0 = 5 \times 10^{-16}$ s, the activation energies of the structural relaxation were found to be 0.26, 0.59, 0.93 and 1.27 eV for the temperatures 77, 173, 273 and 373 K, respectively. On the other hand, the increase in the switching field at high

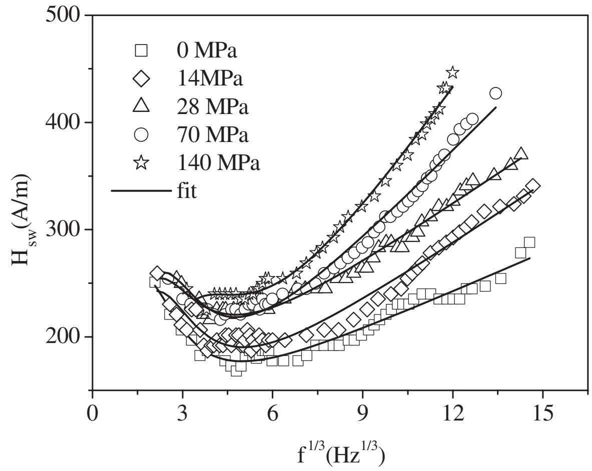

Figure 3. Frequency dependence of the switching field. Applied tensile stress as a parameter.

frequencies was assigned to the frequency dependence of the magnetoelastic contribution. This obeys the power law $H_{sw} \sim f^{1/3}$. The application of tensile stress leads to an increase in the frequency-independent contribution H_{co} as well as in the slope of the power law as a result of the change in domain wall damping L and the critical domain wall displacement x_{cr}.

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