



Magnetic force microscopy characterization of heat and current treated Fe₄₀Ni₃₈Mo₄B₁₈ amorphous ribbons

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ABSTRACT

The domain structure of a magnetostrictive Fe₄₀Ni₃₈Mo₄B₁₈ amorphous ribbon has been studied using magnetic force microscopy (MFM) at room temperature. First, the evolution of the magnetic domain patterns as a function of the annealing temperature has been investigated. In samples heat treated at 250 and 450 °C for 1 h, a transformation from 90° to 180° domain wall has been clearly observed, while the sample heat treated at 700 °C for 1 h showed a magnetic phase fixed by the crystalline anisotropy. Additionally, the evolution of the magnetic domain structure by applying a DC current was recorded by the MFM technique. For current annealed samples at 1 A for 1, 30 and 60 min, a transformation between different domain patterns has been observed. Finally, in samples treated by the current annealing method under simultaneous stress, an increase of the annealing time gives rise to a different magnetic structure arising from the development of transverse magnetic anisotropy.

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1. Introduction

The domain structure in metallic glasses is mainly fixed by the magnetoelastic anisotropies arising from the internal stresses introduced during the fabrication process. As a consequence, in Fe-rich amorphous alloys exhibiting high value of saturation constant the magnetization direction is oriented parallel to the ribbon axis plane, corresponding to the region of the material where the internal stresses are of tensile nature. However, when the regions where the internal stress is of compressive character exist and when value of the saturation of magnetostriction is high the so-called “maze-domains”, or islands, where the magnetization is oriented perpendicular to the ribbon plane, appear. This is due to the overcoming of demagnetizing effects [1,2] in these islands by the magnetoelastic anisotropy. Thus, the appearance of the domain structure is related to the aforementioned magnetization direction.

In order to improve the soft magnetic properties of Fe-rich amorphous alloys (positive magnetostriction) these materials are generally treated employing different annealing treatments. These treatments are able both to relax the internal stresses [3–6] generated in the production process and to induce magnetic

anisotropies improving the magnetic behavior of the soft magnetic material [7–9]. The conventional method carried out is placing the sample inside a furnace with an inert atmosphere, which is provided to prevent the undesirable oxidation of the sample. Another type of annealing which has become successful due to its simplicity is called current annealing [10–13]. It is based on the Joule heating effect when an electric current flows along the ribbon axis, requiring shorter annealing time to get the desirable temperature when compared to the conventional method using a furnace.

In this sense, the amorphous alloy of composition Fe₄₀Ni₄₀B₂₀ has largely attracted considerable attention owing to its attractive soft magnetic behavior and mechanical properties [14,15]. In addition, this composition is one of easiest to produce as amorphous alloy by the melt-spinning technique. As stated before, nanocrystallization by means of thermal treatments of Fe-rich amorphous alloys leads to an improvement of the soft magnetic character. In the case of this amorphous alloy, the thermal treatment at high temperatures produces products which are generally large eutectic crystals [15]. However, nanocrystalline morphology would be more favorable for obtaining better soft magnetic properties, since the microstructure of the nanocrystals in an amorphous matrix gives rise to superior soft magnetic behavior compared to the amorphous counterpart [16,17]. Consequently, to promote the nanocrystallization process the addition of Mo has been found to be very attractive [18,19],

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because it is known that Mo has a strong influence on the crystallization mechanisms, leading to a microstructure similar to that required by the Herzer model of soft nanocrystalline alloys [17].

Magnetic force microscopy (MFM) is a useful technique to get information about local magnetic domains structure of mainly surface character. Pioneering work for the use of MFM was carried out in thin films by Rugar et al. [20] and in amorphous ribbons by Suzuki et al. [21,22].

Magnetic domain characterization in soft magnetic samples using the MFM technique is always challenging, requiring a very accurate adjustment of the configuration parameters. In spite of these inherent difficulties, MFM provides useful information to complete the magnetic characterization performed by standard macroscopic methods. In addition, in some nanometric magnetic structures [23,24] the MFM technique is the unique tool which provides magnetic phase images.

In previous works, MFM technique was used for morphological characterization of $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ ribbons. In both references it was reported MFM studies in this attractive alloy involves to several treatments such as annealing at different temperatures [25] and laser irradiation [26].

In this work, we report on magnetic domain structure evolution (as recorded by MFM) of amorphous ribbons of $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ before and after carrying out several annealing procedures: annealing at different temperatures under argon atmosphere; annealing by Joule heating at different electrical current intensities and using different treatment times and, finally, annealing under simultaneous current and mechanical stress.

2. Experimental section

Amorphous ribbons of nominal composition $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ (trademark *Metglas* 2826MB) exhibiting quite large positive magnetostriction ($\lambda_s \approx 12 \times 10^{-6}$) were supplied by Metglas Corporation. Samples of thickness $32 \mu\text{m}$, width 12 mm and length 12 cm and which were cleaned superficially employing ethanol have been employed in this work. Some of the samples were sealed inside alumina tubes in argon atmosphere for heat treatment at different temperatures (250, 450 and 700°C) for 1 h, at $100^\circ\text{C}/\text{min}$ heating rate. Current annealing treatment was carried out in air atmosphere. The above temperatures were selected based on previously reported differential scanning calorimetry (DSC) measurements of Metglas 2826MB [18,19,27] showing two phase transformation peaks at around 420 and

525°C . The first one (420°C) is related to the formation of $(\text{FeNiMo})_{23}\text{B}_6$ crystalline phase embedded in the amorphous matrix, while the second one (525°C) is related to the formation of the bcc-(Fe,Ni) ferromagnetic phase. Depending on the heating rate, the crystallization peaks move to higher temperatures. At $40^\circ\text{C}/\text{min}$, the crystallization peaks are placed at around 442 and 550°C as reported by Srivastava et al. [28]. Other samples were annealed using the Joule heating technique, by flowing a DC electric current through its longitudinal direction at different current intensities and varying time. Also some samples were annealed by using a combined current and stress treatment. Stress annealing was performed using a weight failed in each extreme of the ribbon, and compression treatment was carried out by bending the ribbon.

Magnetic phase images of as-cast and annealed samples were obtained, at room temperature, using scanning probe microscope (Molecular Imaging's PicoScan) and tips covered with CoCr supplied by MikroMasch (NSC35/Co–Cr). Cantilever ($130 \mu\text{m}$ length) having a tip nominal radius of curvature of 90 nm and resonance frequency around 150 kHz were used. The tips were magnetized in such a way that the tip moment was approximately perpendicular to the plane of the surface sample. Typical lift height was of the order of 150 nm and was properly adjusted to give better contrast.

3. Results and discussion

3.1. Magnetic domains configuration in conventional thermal treated samples

Fig. 1 shows topography and MFM images of $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ ribbon as was received. $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ amorphous ribbons treated in a furnace at 250°C showed a “flower” shape magnetic domains configuration. The presence of easy axes which are normal to the ribbon plane is observed after 90° domain walls take a “flower” pattern configuration, which could represent the interaction with the surface of two 90° walls separating domains through the thickness and width directions as a consequence of the complex internal stresses in these regions of compressive nature [29] such as those shown in Fig. 1. The traces of these walls on the ribbon surface appear to be generally oblique to both the ribbon length and the ribbon wide (surface ribbon). Where this oblique orientation alternates rapidly, the walls take on a flower appearance. These complex patterns are seen when the normal anisotropy becomes large (in competition with the strong demagnetizing effect in this direction) and can be believed to

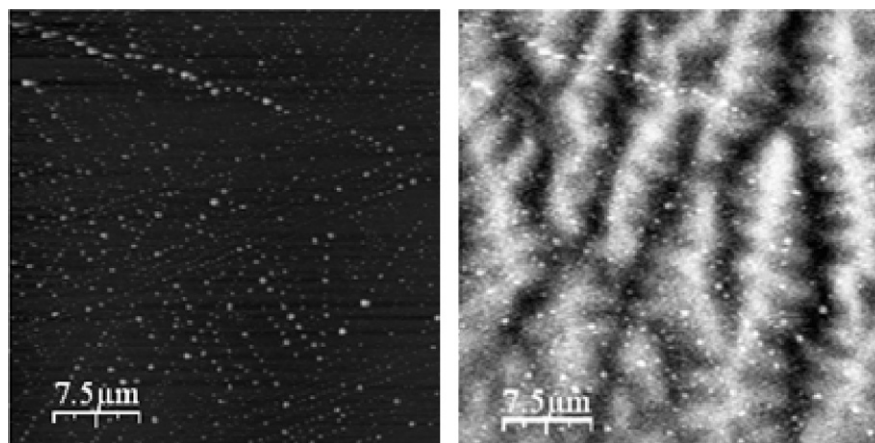


Fig. 1. Topography (left) and MFM (right) image of $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ ribbon without treatment.

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