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Anisotropy field distribution in soft magnetic Hitperm alloys submitted to different field annealing processes

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ABSTRACT

The magnetic anisotropy field distribution is discussed for Hitperm alloys annealed under different field conditions leading to different induced magnetic anisotropies: zero (ZF), transversal (TF), and longitudinal (LF) field annealing and compared to that of as-quenched (AQ) melt-spun amorphous ribbon. In order to accurately use the present method, the demagnetizing factor has been obtained by analyzing the field dependence of the inverse of the field derivative of the magnetization. The coherence of the analysis is supported by testing the normalization of the complete distribution of anisotropy fields. Independently of the composition, two groups can be distinguished among the studied samples: those with mainly perpendicular anisotropy field contributions (ZF and TF samples) and those with mainly longitudinal anisotropy field contributions (LF and AQ samples). Behavior of TF samples is well reproduced using Stoner–Wohlfarth model and, in the case of as-quenched amorphous samples, the anisotropy field depends almost linearly on the thickness of the ribbon.

1. Introduction

One decade after the discovery of the excellent soft magnetic properties in nanocrystalline Finemet alloys by Yoshizawa et al. [1], Hitperm alloys were proposed by Willard et al. [2] to extend the range of applicability of nanocrystalline alloys to higher temperatures. In fact, the ultrasoft character of these systems is achieved by averaging out the magnetocrystalline anisotropy due to magnetic coupling between the nanocrystals [3]. However, to be effective, this mechanism requires the presence of a ferromagnetic amorphous matrix [4]. Therefore, beyond the Curie temperature of the amorphous phase, T_C^{Am}, coupling is lost. In Hitperm alloys, the partial substitution of Co for Fe leads to an enhancement of T_C^{Am}, extending the maximum temperature at which the magnetic coupling between crystallites is effective for reducing the magnetocrystalline anisotropy [5].

The typical procedure to obtain a nanocrystalline alloy implies a controlled partial crystallization of a precursor amorphous alloy produced by rapid quenching methods. Crystallization requires annealing above T_C^{Am} for Finemet alloys but below T_C^{Am} for Hitperm alloys [5]. In the latter case, stabilization of domain walls occurs due to pair ordering mechanism in conventional annealing treatments and producing an unwanted magnetic hardening [6–9]. However, this problem can be overcome after annealing under magnetic fields large enough to saturate the sample [10–15].

Field annealing, as well as stress annealing and production technique (e.g. melt spinning [16]), can induce magnetic anisotropies in the samples. The induced magnetic anisotropy has been shown to be closely related with magnetoimpedance effect as it has been widely studied in stress annealed samples [17–19]. Barandiaran et al. [20] developed a method to obtain the distribution of anisotropy fields perpendicular to the applied field using the demagnetization $M(H)$ branch of the hysteresis curves (i.e. from saturation to remanence), where M is the magnetization and H is the magnetic field. In this model, the probability of a certain anisotropy field H_k is described as:

$$P(H_k) = -\frac{H}{M_S}\frac{d^2M}{dH^2} \tag{1}$$

This expression concerns the anisotropies perpendicular to the applied field, being M_S the saturation magnetization. The normalization of this probability requires that:

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Table 1
Width and thickness of the different ribbons used in this study.

Composition	Annealing temperature (K) [27]	Width (mm) ±0.05	Thickness (μm)
$Fe_{18}Co_{60}Nb_6B_{15}Cu_1$	736	4.75	26.7 ± 0.4
$Fe_{18}Co_{60}Nb_6B_{16}$	748	5.00	18.3 ± 0.3
$Fe_{39}Co_{39}Nb_6B_{15}Cu_1$	739	4.75	26.3 ± 0.5
$Fe_{39}Co_{39}Nb_6B_{16}$	766	4.40	30.0 ± 0.4

$$m_r + \int_0^\infty P(H_k)dH_k = 1 \qquad (2)$$

where the relative remanence, $m_r = M_r/M_S$ (M_r is the magnetization at remanence), takes into account the anisotropy contribution parallel to the applied field. This method was initially applied to describe the induced anisotropies in soft magnetic amorphous alloys [20] and later on to soft magnetic nanocrystalline alloys [21–23] and to other systems [24,25]. The analysis of the applicability of this method to nanocrystalline systems conclude that misalignment leads to an asymmetrical broadening of $P(H_k)$ with a shift to lower values of the field with maximum $P(H_k)$, H_{pk}, and a shift to higher values of the average of the field over the distribution, $\langle H_k^{dist} \rangle$. Moreover, the presence of interactions shifts $P(H_k)$ to lower anisotropy field values [26].

In this work, the anisotropy field distribution as well as the longitudinal anisotropy are determined by applying the method developed by Barandiaran et al. to a series of Hitperm-type alloys submitted to different field annealing treatments. Both field annealing and compositional effects are discussed.

2. Experimental

Amorphous ribbons of $Fe_{78-x}Co_xNb_6B_{16-y}Cu_y$ (x = 39, 60; y = 0, 1) compositions were produced by melt-spinning. Thickness and width of the different ribbons are collected in Table 1. 60 mm long pieces were annealed during 1 h at the DSC peak temperature of the primary crystallization process (see Table 1 for the corresponding annealing temperatures and Ref. [27] for DSC results) and under three different conditions, besides the as-quenched (AQ) amorphous samples: a) zero magnetic field (ZF), b) applying a magnetic field of 20 kA/m longitudinal to the axis of the ribbon (LF) and c) applying a field of 640 kA/m transversal to the axis and in the plane of the ribbon (TF). Hysteresis loops were acquired using a Forster type B–H loop tracer using flux-gate sensors. A minimum of ten hysteresis loops were recorded per sample, keeping its position inside the tracer in order to get an average experimental curve with a reduced noise to signal ratio. A vibrating sample magnetometer was used to measure the saturation magnetization. The density of the samples was 8.1 and 8.3 g/cm^3 for alloys with 39 and 60 at % of Co, respectively.

3. Results and discussion

Fig. 1 shows the inverse of the derivative dM/dH_{app} in the range from saturation to remanence for the complete set of studied samples annealed under different annealing conditions, where M is the magnetization and H_{app} is the applied field. This parameter is the inverse of the technical susceptibility, $1/\chi^*$, which is equal to the inverse of the actual magnetic susceptibility, $1/\chi$, plus the

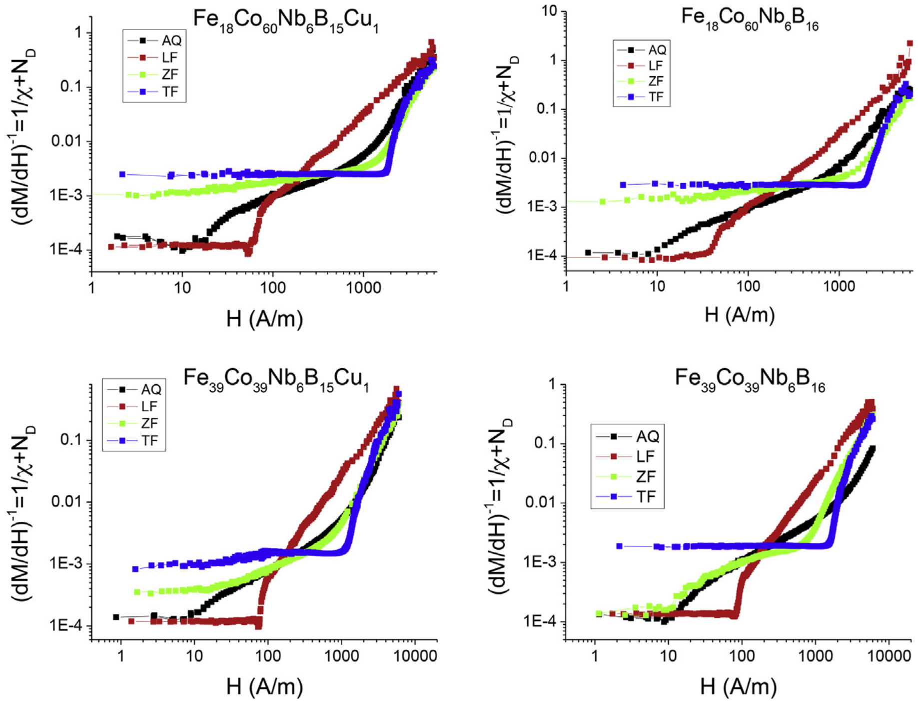

Fig. 1. Inverse of the technical susceptibility for all the studied samples.