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A New Grain Size and Volume Fraction Dependence of Coercive Field in $Fe_{58}Co_{25}Nb_7Cu_1B_9$ Alloy

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Abstract

For the system of soft magnetic nanocrystalline materials a new volume fraction and grain size dependence of coercive field is derived under the frame work of the Néel's theory of domain wall pinning. Derived equation is applied to partially devitrified $Fe_{58}Co_{25}Nb_7Cu_1B_9$ alloy revealing its importance from the point of view of experimental verification of the grain size and volume fraction dependence of coercive field for class of magnetic materials in which inter granular distance is comparable to the average grain diameter.

INTRODUCTION

Gradually devitrified Fe-based soft magnetic nanocrystalline materials have been the center of attraction for research because, apart from being promising candidate for industrial applications, these materials offer unique opportunity to study the physics of magnetization processes [1-6] The soft magnetic behaviour of these materials can be understood, in terms of the random anisotropy model [2,3], by introducing a correlation length (bulk domain wall thickness) over which the magnetic moments of nano-granular region are coupled via exchange interaction. Objective of the present work is to comprehend the situation, within the framework of Néel's theory of domain wall pinning [7], where the volume fraction of the crystalline phase is low enough such that the distance between the nano-grains is comparable to the average grain size that scales similar to the ferromagnetic exchange length. Consequently the nano-grains are weakly exchange coupled that eventually leads to less effective averaging of randomly oriented magneto crystalline anisotropies.

EXPERIMENTAL DETAILS

Amorphous ribbons (~20 µm thick and 10 mm wide) of nominal composition $Fe_{58}Co_{25}Nb_7Cu_1B_9$ were annealed between 370 to 430 °C for 30 min. (First crystallization peak temperature Tx_1 = 443 ^{0}C determined by differential scanning calorimetery measurements at a heating rate of 5 ^{0}C/min) in flowing Argon to obtain various stages of nano-crystallization. Cu-K_α X-ray diffraction measurements were done at room temperature and data was analyzed using pseudo-Voigt line profile to obtain average grain diameter (***D***) and the volume fraction of nanocrystalline phase (V_x).

Coercive field (H_c) was determined by recording hysteresis loops at 37 Hz using computer controlled set-up.

Saturation magnetization (M_s) was determined by Vibrating sample magnetometer using H_{max}= 700 kA/m.

THEORETICAL BACKGROUND AND RESULTS

Considering a unit volume of soft magnetic nanocrystalline material obtained by devitrification of amorphous alloy, containing ***n*** spherical crystallites each of average volume ***v*** such that the volume fraction of crystalline phase $V_x = n.v < 1$. The anisotropy energy of the nanocrystals (bcc Fe-Co) contained within the domain wall remains the only source responsible for the opposition of the domain wall motion.

The anisotropy energy of a nanocrystal is assumed to have dependence on the direction cosines of magnetization as –

$$E = vK_1 (\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2) \qquad (1)$$

The variation in anisotropy energy can be from 0 (easy axis) to vK_1 / 3 (hard axis). The fluctuations in anisotropy energy is given by [7,8]:

$$\Delta E = N^{1/2} vK_1 / 6 \qquad (2)$$

$N \rightarrow$ no. of nano-grains contained within domain wall. When the domain wall moves by a distance equal to the wall width under the action of applied magnetic field, the typical force that hinders the domain wall movement is proportional to the fluctuations of the domain wall energy and to the domain wall width over which these fluctuations take place. The force exerted upon the domain wall by the applied magnetic field can overcome this pinning force. Equating the pinning force offering the hindrance and the force applied by the magnetic field yields interesting volume fraction and grain size dependence of coercive field.

$$H_C = V_x^{1/2} \; [(D/L)^{3/2} \; K_1 / 12 \, M_S \,] \qquad (3)$$

L – bulk domain wall width

DISCUSSIONS

Table 1 depicts the experimentally obtained values of $\boldsymbol{V_x}$, $\boldsymbol{D}$, $\boldsymbol{H_c}$. and also reports the inter-granular distance $\boldsymbol{d}$ calculated as described in [6].

$$d = D\,(V_x^{-1/3} - 1) \qquad (4)$$

Increase of annealing temperature enhances the relative volume of the developing nano-grains and also affects the corresponding Co content in the bcc Fe-Co nano-grains affecting the stability of the alloy against crystallization. Taking $\boldsymbol{A} = 2 \times 10^{-11}$ Jm^{-1} and $\boldsymbol{K_1} = 5 \times 10^4$ Jm the domain wall width comes out to be ~ 20 nm and table 1 shows that for the present cases $\boldsymbol{L \sim D}$. It is worth noting that with increase of annealing temperature the $\boldsymbol{V_x}$ also increases (whereas $\boldsymbol{D}$ increases only slightly), but as expected at this level of crystallization, this does not result in magnetic softening due to averaging of random anisotropies [2,3].

Perusal of table 1 suggests that this behavior can be attributed to the fact that for the alloy under investigation, $\boldsymbol{d}$ is comparable to the average grain size $\boldsymbol{D}$ leading to a situation where the nano-grains are not effectively exchange coupled, but are acting as pinning centers.

Table 1: Annealing temperature dependence of V_x, D, H_c , d

Ann. Temp. (^oC)	**V_x (%) (±2)**	***D* (nm) (±2)**	**$D^{3/2}$**	**H_c (A/m) (±1)**	***d* (nm)**
370	**8**	**12**	**41.6**	**26.5**	**13.2**
390	**10**	**12**	**41.6**	**20.4**	**11.3**
410	**16**	**16**	**64**	**28**	**15.2**
430	**28**	**18**	**76.4**	**37.6**	**9.1**

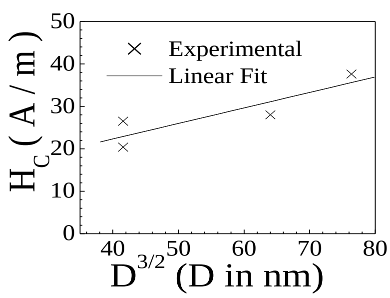

Fig.1 Grain size dependence of coercive field.

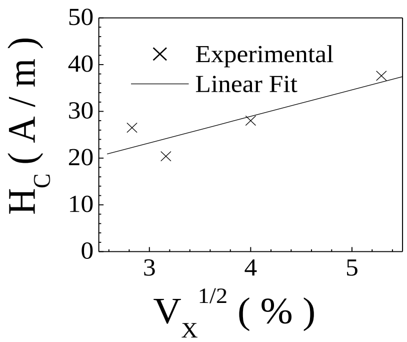

Fig.2 Volume fraction dependence of coercive field.

Perusal of equation (3) suggests that the grain size and volume fraction dependence of $\boldsymbol{H_c}$ is much different than those have been reported [2,3,5]. Figure 1 and 2 shows a good agreement for grain size and volume fraction dependence of coercive field as expected on the basis of Eq. (3). This deviation from the established sixth power grain size dependence of coercive field [2,3] is of different origin compared to that 3-rd power dependence of grain size [5].

CONCLUSIONS

The observed grain size and volume fraction dependence of coercive field for studied $Fe_{58}Co_{25}Nb_7Cu_1B_9$ alloy is a new result arising because of the fact that inter-granular region is comparable with average grain size, suggesting that the averaging of the random anisotropies is not effective enough in this situation where the nanocrystallites themselves are acting as the pinning centers.

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