Journal of Alloys and Compounds 509 (2011) 6139–6141

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Effect of exchange-coupling interaction on domain pinning mechanism in nanometer permanent materials

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ARTICLE INFO

Article history:
Received 4 January 2011
Received in revised form 28 February 2011
Accepted 28 February 2011
Available online 8 March 2011

PACS:
75.30.E
75.30.G
75.50.T
75.75

Keywords:
Nanostructured materials
Exchange-coupling interaction
Coercivity

ABSTRACT

The effect of exchange-coupling interaction on domain pinning mechanism in nanometer permanent materials has been investigated using random anisotropy model. Exchange-coupling coefficient α_{ex} has been studied, and α_{ex} corresponding to pinning fields is derived from coercivity formula, which is expressed as $\alpha_{ex} = \frac{3n}{\alpha\pi(1+\beta)^{1/2}(1+\beta-n)^{1/2}}$. Our results show that α_{ex} is related with the degree of exchange-coupling interaction and properties of grain boundary. Coercivity decreases with the increasing degree of exchange-coupling interaction. Our results are accordant with other relative theoretical results. In order to obtain higher coercivity, exchange-coupling interaction between magnetically hard–hard grains should be weakened.

1. Introduction

In recent years, nanocomposite magnets have attracted much attention due to their potential high properties. However, the measured maximum energy product is much lower than the theoretical value, which is attributed to low coercivity. Therefore, much attention is focused on mechanism of coercivity. Nevertheless, the underlying details on mechanism of coercivity are still unclear. Kronmüller et al. [1] proposed that coercivity of nanocomposite magnets was controlled by nucleation process of reverse domains, and introduced a microstructure parameter α_{ex} considering effect of exchange coupling between neighboring grain on coercivity. The coercivity is given by: $\mu_0 H_c = \alpha_k \alpha_{ex} \mu_0 H_N^{\min} - N_{\text{eff}} J_s$ (experiential formula of coercivity) where α_k describes reduced anisotropy of non-perfect grains and N_{eff} corresponds to an effective demagnetization factor describing internal stray fields acting on the grains. Bauer et al. [2] pointed out that the value of α_{ex} should vary from 0.2 to 0.38. Billoni et al. [3] expressed α_{ex} as $\alpha_{ex} = (1/\mu_0 H_N^{\text{ideal}} \alpha_\varphi \alpha_K)[\mu_0 H_c + n_{\text{eff}} J_s \ln(d_g/\delta)]$. However, Zhang et al. [4] suggested that both nucleation and domain-wall pinning model can be expressed as experiential formula of coercivity. In consideration of grain size D, coercivity has been written as: $H_c = (\alpha/1 + 6\beta_k l_{ex}/D)H_N - (N_{\text{eff}}/1 + 6\beta_s l_{ex}/D)M_s$, where β_k describes degree of exchange-coupling interaction. We agree with the opinion of Zhang et al. [4] except expression of α_{ex}. In this paper, pinning field of domain wall was calculated by considering the effect of exchange-coupling interaction between neighboring grains on anisotropy of nano-grain. And the expression of α_{ex} was investigated too.

2. Theoretical basis

2.1. Anisotropy at grain boundary

We assume that grains are cubes with edge length D [5]. Influenced by exchange-coupling interaction and defect, magnetic parameters at grain boundary have changed. For simplify, we only consider the change of the first anisotropy constant K_1.And considering the influence of degree of exchange-coupling interaction on anisotropy, anisotropy at grain boundary is written as

$$K_1(r) = K_1 - \frac{\Delta K}{1+\beta}\left(1 - \frac{2r}{L_{ex}}\right)^{3/2} \qquad (1)$$

where K_1 and L_{ex} are the first magnetic anisotropy constant and exchange-coupling length of materials, respectively. ΔK is corresponding to the reduction of K_1 within the grain boundary, $\Delta K = nK_1$ (is no larger than 1). β describes the degree of exchange coupling. Expression for $K_1(r)$ is not based on a micromagnetic or even

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doi:10.1016/j.jallcom.2011.02.169

atomistic model, therefore, β is not related to the true exchange properties of the grain boundary.

2.2. Coercivity

Experimentally, hard magnetic phase is surrounded by non-magnetic phase such as Nd in $Nd_2Fe_{14}B$ hard magnetic materials. With increasing reverse fields H, reverse magnetic domain is easily formed at grain boundary. When H is further increased, domain wall will be reversibly compressed towards hard phase and will invade into hard phase, thus leading to irreversible magnetization reversal of hard phase [6]. The reverse fields corresponding to irreversible magnetization reversal are pinning fields of domain wall, which is thought to determine coercivity and expressed as [7]

$$H_c = \frac{1}{2J_s}(d\gamma/dr_{\max}) - N_{\text{eff}}M_s \quad (2)$$

where J_s and γ are the saturation polarization and energy density of domain wall, respectively. Kronmüller et al. [8] gave the expression of γ

$$\gamma = 4\sqrt{A_1K_1} \quad (3)$$

We replace K_1 with anisotropy of domain wall plane $K_1(r)$ and obtain

$$\gamma = 4\sqrt{A_1K_1(r)} \quad (4)$$

with the equations above, the expression of pinning field can be given by

$$H_c = \frac{3h}{\pi}\frac{K_1}{J_s} - N_{\text{eff}}M_s \quad (5)$$

where $h = (n/(1+\beta)^{1/2}(1+\beta-n)^{1/2})$

Comparing Eq. (5) with the experiential formula of coercivity, the exchange-coupling coefficient α_{ex} corresponding to pinning fields is derived:

$$\alpha_{\text{ex}} = \frac{3n}{\alpha_k\pi(1+\beta)^{1/2}(1+\beta-n)^{1/2}} \quad (6)$$

where α_k is a micostructure factor describing the reduction of anisotropy due to non-perfect grains.

3. Results and discussion

Using the intrinsic magnetic parameters of $Nd_2Fe_{14}B$: $K_1 = 4.3\,\text{MJ}\,\text{m}^{-3}$ [2], $M_s = 1280\,\text{kA}\,\text{m}^{-1}$, and taking $\alpha_k = 0.9$, $n = 0.5$, we calculated the pinning fields and the corresponding α_{ex}.

Fig. 1 gives the variation of exchange-coupling coefficient α_{ex} with degree of exchange coupling β. It is shown that α_{ex} decreases with increasing β. That is to say, the larger the degree of exchange coupling is, the smaller the exchange-coupling coefficient. This is consistent with the results given by Zhang et al. [4]. According to Eq. (6), α_{ex} is related with the decrease of K_1 within the grain boundary too, which is related with the properties of grain boundary.

Fig. 2 shows the variation of α_{ex} with value of $\Delta K/K_1$ expressed by n. It can be seen that α_{ex} increases with enhancing the value of $\Delta K/K_1$.This is because that exchange-coupling interaction between grains decreases the value of anisotropy at grain surface, which results the increase of ΔK and $\Delta K/K_1$ with reducing β. This denotes that α_{ex} is determined by β and the properties of grain boundary. We can also see that for the given value of $\Delta K/K_1$, α_{ex} decreases with the increasing of β.

Fig. 3 gives the variation of coercivity with β. Coercivity decreases with increasing β. Exchange-coupling interaction between hard magnetic grains decreases anisotropy of individual grain, which is a key role in determining coercivity. So coercivity decreases due to exchange-coupling interaction. And coercivity decreases with enhancing the degree of exchange coupling interaction. The existence of exchange-coupling interaction between hard magnetic grains decreases coercivity, and the effect of exchange-

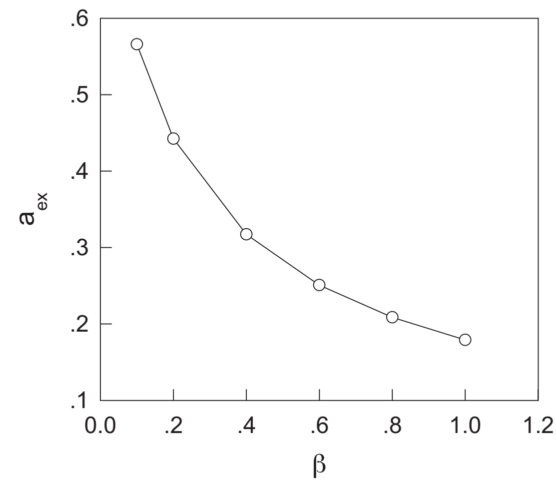

Fig. 1. Variation of exchange-coupling coefficient α_{ex} with degree of exchange coupling β.

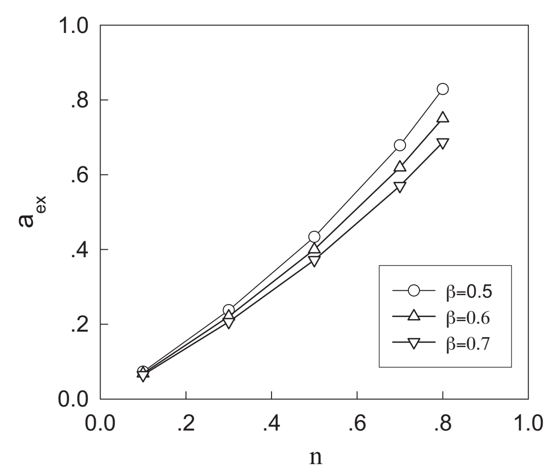

Fig. 2. Variation of α_{ex} with value of $\Delta K/K_1$ expressed by n.

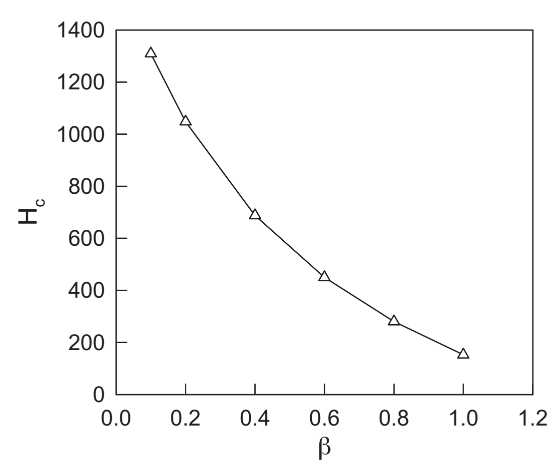

Fig. 3. Variation of coercivity with degree of exchange coupling β.

coupling interaction on coercivity can be expressed by a factor α_{ex} in coercivity formula.

4. Conclusion

Pinning field of domain wall and the corresponding α_{ex} have been studied by considering effect of exchange-coupling interaction between neighboring grains on anisotropy of nano-grain. Our results show that α_{ex} is related with the degree of exchange-coupling interaction and the properties of grain boundary. This is consistent with the relative theoretical results given by Zhang et al. Coercivity decreases with increasing the degree of exchange-coupling interaction, which is accordant with the experiential formula of coercivity. In order to obtain high coercivity, exchange-coupling interaction between magnetically hard–hard grains should be weakened.

Acknowledgement

The work is supported by the National Natural Science Foundation of China (50671055).

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