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CALCULATION OF DEMAGNETIZATION CURVES OF NANOCOMPOSITE $Pr_2Fe_{14}B/\alpha$–Fe MAGNETS USING A ONE-DIMENSIONAL MODEL *

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The demagnetization curves of nanocomposite magnets have been calculated using a one-dimensional model. The results are in agreement with experimental results. The shoulders of the demagnetization curve have also been explained based on the model.

Keywords: nanocomposite magnets, exchange coupling, demagnetization curve
PACC: 7550K, 7560E, 7550B

I. INTRODUCTION

The maximum magnetic energy of oriented nanocomposite magnets is 1.0 MJ/m^3 in theory, which is more than double that of $Nd_2Fe_{14}B$. Hence, these magnets have attracted enormous attention from researchers studying permanent magnets.[1–8,11–14] The exchange-coupling model proposed by Kneller and Hawig[1] explains the properties of these magnets quite satisfactorily. Recently, we have managed to calculate the demagnetization curves of nanocomposite magnets using a one-dimensional model, indicating that the moment decreases exponentially with the increase of an opposite magnetic field. This roughly accounts for the appearance of a shoulder on the demagnetization curves.[9] In this paper, thorough results of the calculation are given.

II. EXPERIMENTAL DETAILS

The ingots of $Pr_{10}Fe_{84}B_6$ were prepared by arc melting the constituent materials Pr, Fe and Fe–B alloy in a highly purified argon atmosphere. Then the ribbons were obtained using a melt-spinning technique with the surface velocity of v_s=30m/s. These were subsequently heated at 973K for 10min.

The constituent phases and the size of the α-Fe grains in the ribbon were determined by X-ray diffraction. The demagnetization curves at 300K and 5K were measured using a SQUID magnetometer with a maximum field up to 6.5T.

III. EXPERIMENTAL RESULTS

Figure 1 shows an X-ray diffraction pattern of the $Pr_{10}Fe_{84}B_6$ annealed ribbon, which is composed mainly of two phases—$Pr_2Fe_{14}B$ and α-Fe. The average size of the α-Fe grains was calculated to be 20 nm according to the Scherrer method.[10]

Figure 2 shows the demagnetization curves at 300K and 5K. The demagnetization curve at 300K is smooth, but at 5K it contains a pronounced shoulder.

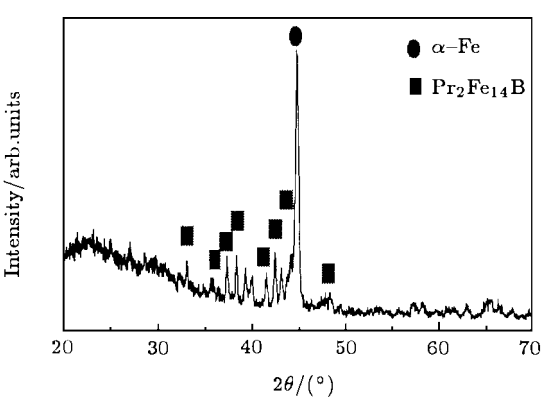


Fig.1. The X-ray diffraction pattern of the annealed $Pr_{10}Fe_{84}B_6$ ribbon.

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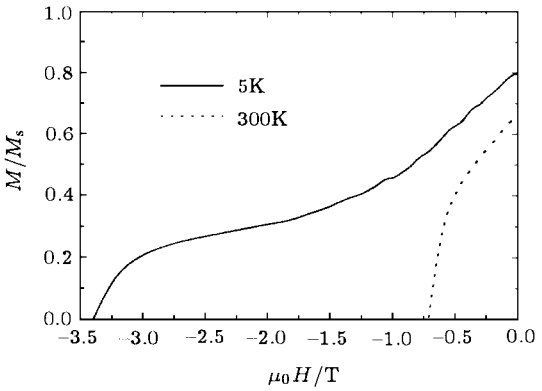


Fig.2. Demagnetization curves for $Pr_{10}Fe_{84}B_6$ samples at 5K and 300K.

IV. THE ONE-DIMENSIONAL MODEL OF NANOCOMPOSITE MAGNETS

The simplest one-dimensional model is selected.[1] As shown in Fig.3(a), the model consists of a sequence of alternating hard magnetic phases (with a width of $2d_k$) and soft magnetic phases (with a width of $2d_m$) located along the x-axis. It is assumed that the moments of the hard and the soft magnetic phases are initially parallel to the z-axis. When an opposite magnetic field is applied, the absolute value of the magnetic moments of atoms in the soft magnetic phase remains unchanged; only the magnetic moments rotate towards the direction of the magnetic field. The direction of the moment of the soft magnetic phase situated at the phase boundaries does not change owing to pinning of the hard magnetic phase, but in the interior of the soft magnetic phase it changes due to the action of the magnetic field. Fig.3(b) shows the projection of the magnetic moments in the vertical plane when the opposite magnetic field is applied, where θ is the angle between the z-axis and any magnetic moment and φ is the angle between the magnetic moment and the direction of the magnetic field.

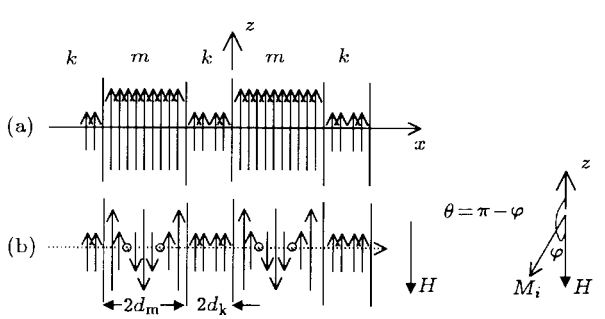


Fig.3. The one-dimensional model of the microstructure and the micromagnetic structure of the exchange coupled composite material: (a) H=0; (b) in field H.

V. DISTRIBUTION OF MOMENTS IN THE MAGNETIC FIELD

The anisotropy energy of the soft magnetic phase contributes little to the overall energy due to the small anisotropy constant. Therefore, only the exchange energy among moments and the magnetostatic energy are considered. The overall energy of the system is

$$E = E_{\rm ex} + E_{\rm H} = \int \left[A\left(\frac{{\rm d}\varphi}{{\rm d}x}\right)^2 - \mu_0 H M_{\rm S} \cos\varphi \right] {\rm d}x. \qquad (1)$$

When the system is stable, δE=0, the solution of equation (1) is

$$-2A\frac{{\rm d}^2\varphi}{{\rm d}x^2} + \mu_0 H M_{\rm S} \sin\varphi = 0. \qquad (2)$$

When the magnetic field is not very strong, the magnetic moment of the magnetically soft phase is pinned to the direction of the moment of the hard phase. Measuring x from the centre of the soft phase, the boundary condition is

$$\varphi = \pi, \frac{{\rm d}\varphi}{{\rm d}x} = 0, \quad \text{when} \quad x = \pm d_{\rm m}. \qquad (3)$$

Then we obtain

$$\frac{A}{\mu_0 H M_{\rm S}}\left(\frac{{\rm d}\varphi}{{\rm d}x}\right)^2 + \cos\varphi = 1. \qquad (4)$$

The differential equation with the theoretical boundary condition of (3) is solved as

$$\ln\left(\tan\frac{\varphi}{2}\right) - \ln\left(1+\sqrt{1+\tan^2\frac{\varphi}{2}}\right) = \sqrt{\frac{\mu_0 H M_{\rm S}}{2A}}(x - d_{\rm m}). \qquad (5)$$

In addition, there is another solution of Eq.(2), namely, $\varphi \equiv \pi$, which applies to the case of H=0 or small H. Equation (5) gives the relationship between x and the angle between the moment of the soft magnetic phase and the z-axis. As in Ref.[1], Fe is taken to be a soft magnetic phase with A=1.19×10^{-11}J/m and M_s=1.7×10^{6}A/m at room temperature. Fig.4 shows the relationship between θ and x/d_m under different external magnetic fields (the average size of the Fe grains is 20nm, i.e. d_m=10nm). Obviously, with the increase of the external magnetic field, the moment at the centre of the soft magnetic phase rotates towards the direction of the magnetic field. The two domain walls move toward the hard magnetic phases and the

domain wall width is reduced. This is in agreement with what is stated in Ref.[1].

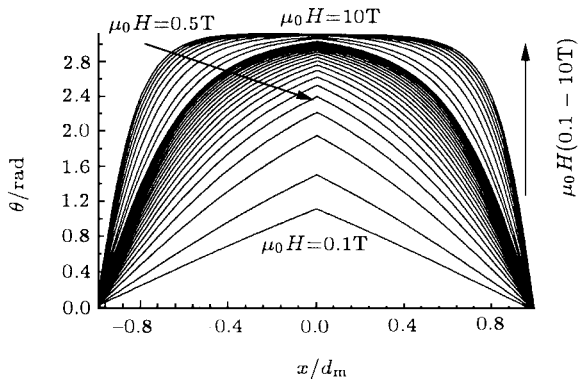


Fig.4. θ–x/d_m curves in different fields.

VI. DEMAGNETIZATION CURVES OF NANOCOMPOSITE MAGNETS

In the one-dimensional model, we let the distance between two neighbouring Fe atoms be 0.25nm, thus 40 magnetic moments can be arranged in a length of d_m. The contribution of these moments is

$$\frac{M}{M_\mathrm{S}} = \frac{1}{N}\sum_{i=1}^{40}\cos\theta_i. \tag{6}$$

In Fig.5, which shows the result of the calculation of Eq.(6), the moment of the soft magnetic phase decreases as the opposite magnetic field increases.

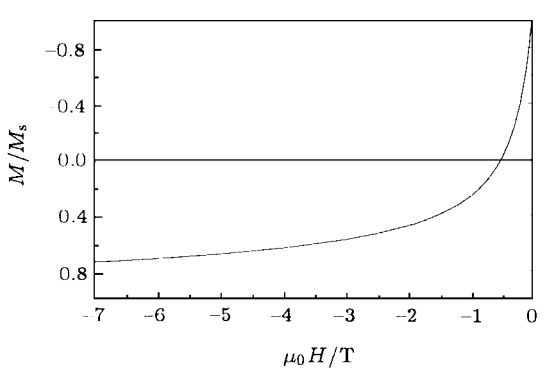


Fig.5. The moments of the soft magnetic phase as a function of field.

The overall energy (the average contribution of every atom) of the system under the external magnetic fields is calculated through Eq.(6)

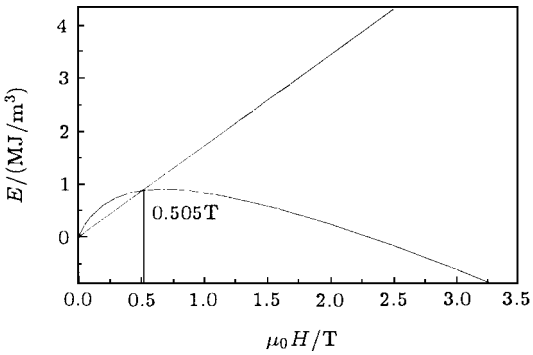


Fig.6. The overall energy of the $\theta \equiv 0$ and normal system under the external fields.

$$E = \frac{1}{N}\sum_{i=1}^{40} A\left(\frac{\theta_{i+1}-\theta_i}{\Delta x_i}\right)^2 \Delta x_i - \mu_0 H M_\mathrm{S}\frac{1}{N}\sum_{i=1}^{40}\cos\theta_i \Delta x_i. \tag{7}$$

When the solution of Eq.(4) $\theta \equiv 0$ is adopted, the overall energy of the system is

$$E = -\mu_0 H M_\mathrm{S}\Delta x_i, \tag{8}$$

where Δx_i is 0.25nm. The energy at room temperature is calculated in accordance with Eqs.(7) and (8). As shown in Fig.6, the overall energy of Eq.(8) is lower when the external magnetic field $\mu_0 H$ is less than 0.505T ($\mu_0 H < 0.505\mathrm{T}$). The overall energy calculated by Eq.(7) becomes lower when $\mu_0 H > 0.505\mathrm{T}$. Therefore, when the opposite magnetic field is applied, the energy will change along the straight line until it reaches the crossing point, and then it will follow the lower curve. Then the calculated demagnetization curve consists of two parts. Fig.7 shows the demagnetization curve when the action of the hard magnetic phase is considered.

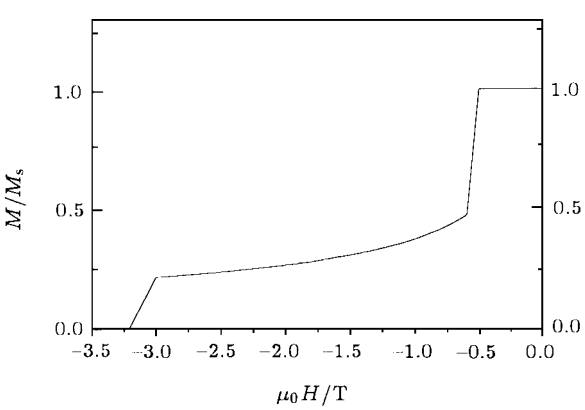


Fig.7. The calculated demagnetization curve of the $P_{10}Fe_{84}B_6$ sample at 5K.

Now we compare the calculated results of Fig. 7 with the demagnetization curve of the nanocomposite magnet at 5K in Fig. 2. The shape is basically similar, indicating the feasibility of explaining the demagnetization behaviour of nanocomposite magnets on the basis of the one-dimensional model. Because the calculation process does not take into account the exchange interaction and the thermal disturbance perfectly owing to which it is impossible for all the moments of the soft magnetic phase to be arranged in the direction of the z-axis ($\theta \equiv 0$), the calculated demagnetization curve shows a step in the initial stage rather than maintaining a smooth curve as the experimental curve does.

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