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Coercivity of Nd(Dy)–Fe–B bonded magnets made from the inert-gas-atomized powders

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Abstract. The coercivity behaviour of bonded magnets made from sieved inert-gas-atomized Nd(Dy)–Fe–B powders has been investigated. For magnets with particle sizes 35–53 μm, the coercivity is controlled by a nucleation mechanism as in the sintered magnet. For the magnet with particle sizes of 10–20 μm, the hardening mechanism is mainly controlled by nucleation as in the sintered magnet but the hardening mechanism of domain wall pinning or the nucleation of a single domain, which usually appears in melt-spun materials, may also be involved. The coercivity behaviour of bonded magnets made from gas-atomized powders seems to be between those of the sintered and melt-spun magnets depending on the particle size. Meanwhile it has been found that the demagnetizing field of bonded magnets made from the inert-gas-atomized powders is very small.

1. Introduction

The powder-metallurgical sintering [1], melt-spun [2], HDDR [3] and mechanical alloying [4] methods are very important processing techniques for the manufacture of Nd–Fe–B hard magnetic materials. Recently the gas atomization technique has also attracted much attention [5, 6]. However, there are fewer reports on the magnetic hardening mechanisms of gas-atomized powders. In this paper we attempt to understand the origin of the coercivity in bonded magnets made from inert-gas-atomized powders.

2. Experiments

Isotropic inert-gas-atomized $(Nd_{0.9}Dy_{0.1})_2Fe_{14}B$-based powders have been produced in batches of 4 kg at a time using a laboratory-scale atomizer [6]. The powders were sieved and sorted into groups with different particle sizes. Cylindrical samples with a diameter of 3 mm and a length of 8 mm were made by mixing epoxy resin with the sieved gas-atomized powders with particle sizes 35–53 μm, 10–20 μm and less than 10 μm, respectively. The hard magnetic properties were measured using a pulsed high field in the temperature range 200–400 K. The microstructures of the powders were observed by SEM.

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3. Results and Discussion

The microstructure of the atomized powders is shown in figure 1(*a*). It is evident that atomized powders are spherical with a few surface features and that a distribution of particle sizes exists. The weight fraction dependence on the particle size of atomized powders is shown in figure 2. The microstructure of a particle of size 75–100 μm, whose grain sizes are in the range 2–7 μm, is shown in figure 1(*b*). The grain size in the particles decreases with decrease in the size of the sieved particles.

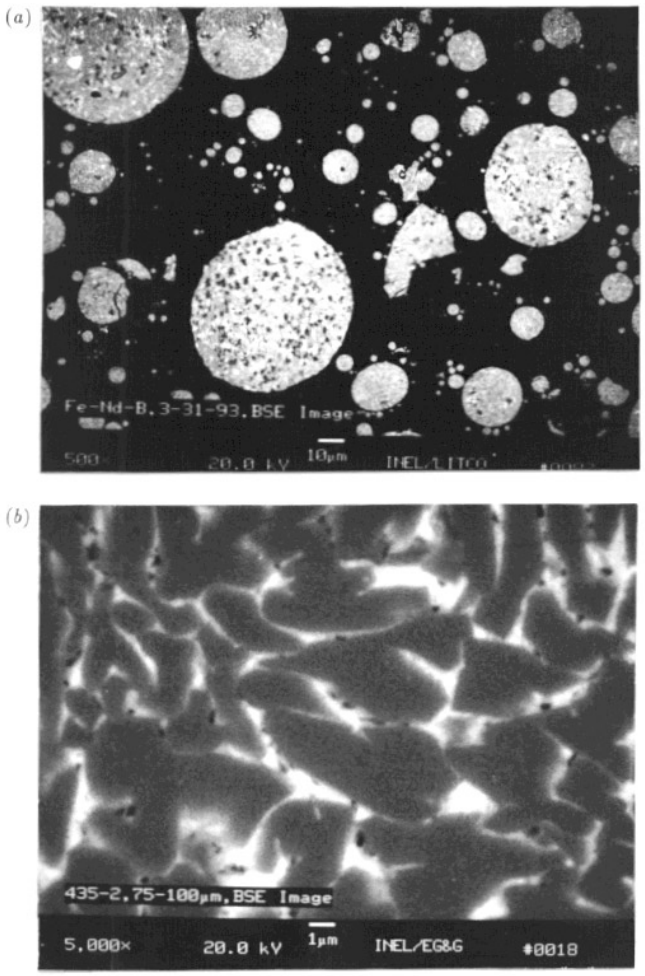

Figure 1. (*a*) The microstructure of atomized powders Nd(Dy)–Fe–B observed by SEM. (*b*) The microstructure of a particle with a size of 75–100 μm in atomized Nd(Dy)–Fe–B powders.

To investigate the magnetic hardening mechanism, the initial magnetization curves have been measured for two gas-atomized bonded magnets with particle diameters of 10–20 and 35–53 μm plotted in figure 3. The results show that with increasing magnetizing field the initial magnetization value increases rapidly for the magnet with particle diameters of 10–20 and 35–53 μm. Such rapid increases in the initial magnetizations imply that domains can

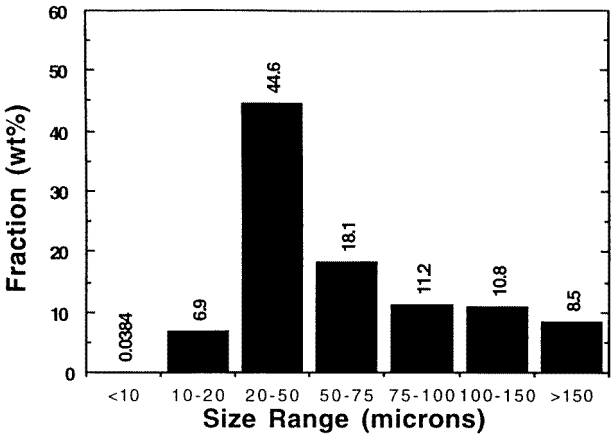

Figure 2. The weight fraction dependence on the particle size of atomized powders Nd(Dy)–Fe–B.

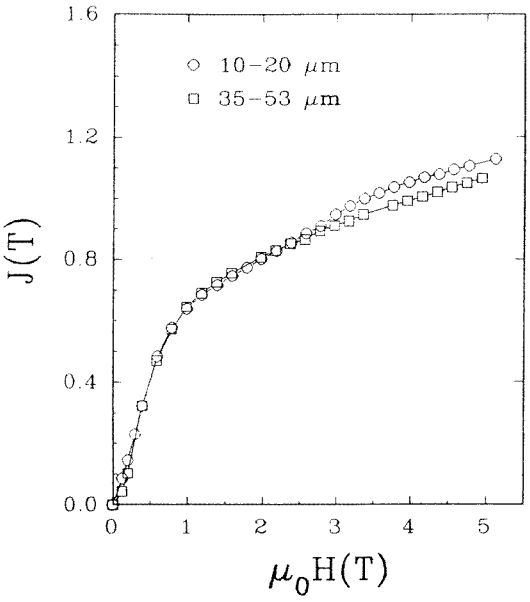

Figure 3. The initial magnetization curves for gas-atomized magnets with particle sizes 10–20 μm and 35–53 μm, respectively.

move easily inside most grains of the magnets and the coercivity mechanisms of the two gas-atomized magnets are mainly controlled by the nucleation model as in sintered magnets [7, 8].

For magnets with particle sizes of both 10–20 μm and 35–53 μm, the magnetizations do not reach their saturation values at a magnetizing field of 5 T; this is due to the isotropic distribution of the easy-magnetization directions of grains in particles of sieved gas-atomized powders.

For the magnet with particle diameters of 10–20 μm the initial magnetization first increases sharply, which is almost identical with that of the magnet with particle diameters of 35–53 μm in magnetizing fields less than 2.5 T, then undergoes a small step increase in the magnetizing field range 2.8–3 T and finally increases gradually with increase in the magnetizing field. The trend of initial magnetization behaviour of the magnet is mainly similar to that of the sintered magnet; however, the appearance of the step is similar to the situation in melt-spun alloys. Different from the melt-spun alloy, the coercivity of the whole magnet with particle diameters of 10–20 μm is only about 1.13 T, much smaller than the critical magnetizing field (2.8–3 T) where the step increase occurs in the initial magnetization curve. The possible explanation is that there may be two kinds of particle in the magnet with different hardening mechanisms. In the magnet the coercivity of most particles with relatively larger diameters is controlled by nucleation as in the sintered magnet [7, 8] and the coercivity of a few particles with small diameters is controlled by domain wall pinning [9, 10] or nucleation of a single domain [11] similar to that in melt-spun alloys. With decreasing diameter of the particles, it can be expected that the characteristic hardening mechanism of the whole magnet may be similar to that in melt-spun alloys. In other words, the coercivity behaviour of gas-atomized alloys seems to be between those of the sintered and melt-spun magnets depending on the particle size.

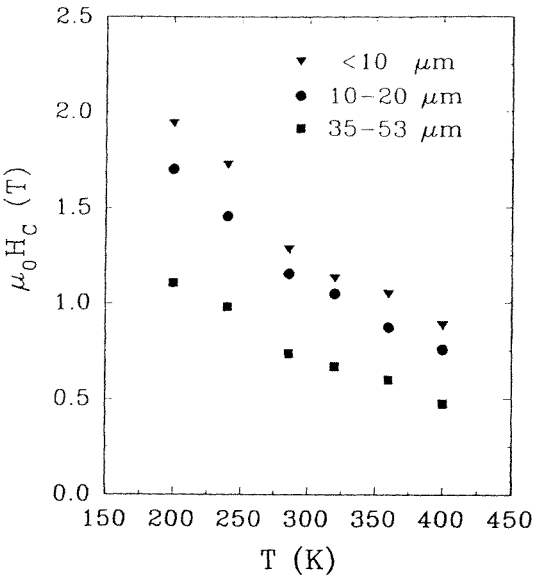

Figure 4. The temperature dependence of the coercivity for gas-atomized Nd(Dy)–Fe–B samples with three typical particle sizes.

Figure 4 shows the temperature dependence of the coercivity for three samples with particle diameters less than 10 μm, 10–20 μm and 35–53 μm for gas-atomized (Nd, Dy)–Fe–B; it is evident that the coercivity increases with decreasing average particle size.

In the case of the nucleation mechanism the ideal coercive field is given by Brown's expression for the nucleation field $\mu_0 H_n$ as

$$\mu_0 H_N = \frac{2K_1}{M_s} - N J_s \tag{1}$$

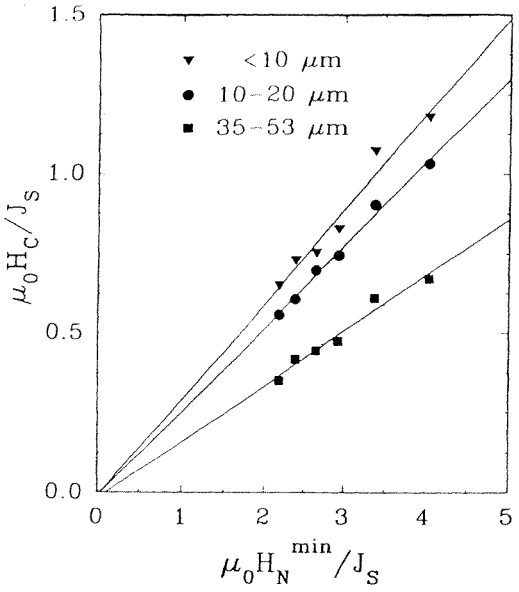

Figure 5. Data $\mu_0 H_c/J_s - \mu_0 H_n^{min}/J_s$ for gas-atomized Nd(Dy)–Fe–B samples with three typical particle sizes.

where K_1 is the anisotropy constant, M_s the saturation magnetization and J_s the polarization. N is the demagnetization factor. The coercive fields of real magnets are smaller by a factor of 3–5 than the theoretical predication. This discrepancy, known as Brown's paradox, is due to the dominant role of the imperfect microstructure. The experimental results can be described by an equation taking into account the effects of the microstructure on the coercive field as [7]

$$\mu_0 H_c = \alpha_K \alpha_\phi \frac{2K_1}{M_s} - N_{eff} J_s \tag{2}$$

where N_{eff} represents the effective demagnetization factor describing the internal stray fields acting on the grains; α_K is related to the reduced surface anisotropy of imperfect grains, and α_ϕ represents the effect of the reduction in the nucleation field due to the misaligned grains. For grains coupled by exchange or dipolar interactions the expression, α_ϕ can be replaced by α_ϕ^{min} describing the unfavourably aligned grains in the magnet. The expression $\alpha_\phi^{min} 2K_1/M_s$ can be determined as H_n^{min}. The expression for H_n^{min} taking account of the effect of the second anisotropy constant K_2 has been given as [12]

$$H_N^{min} = \frac{1}{2\sqrt{2}J_s}\left[K_1 + \frac{K_2}{4}\left(W - \frac{K_1}{K_2} + 3\right)\right]\sqrt{W\left(\frac{K_1}{K_2}+1\right) - \left(\frac{K_1}{K_2}\right)^2 - 2\frac{K_1}{K_2} + 3} \tag{3}$$

with

$$W = \sqrt{\left(\frac{K_1}{K_2}+1\right)^2 + 8}. \tag{4}$$

Then we have

$$\mu_0 H_c = \alpha_K \mu_0 H_N^{min} - N_{eff} J_s. \tag{5}$$

For our experimental samples, H_n^{min} can be obtained using the temperature dependence of the anisotropy constants K_1 and K_2 and saturation magnetization J_s for the $(Nd_{0.9}Dy_{0.1})_2Fe_{14}B$ phase [13]. Data on $\mu_0 H_c/J_s - \mu_0 H_n^{min}/J_s$ for samples with particle sizes less than 10 μm, 10–20 μm and 35–53 μm are fitted by straight lines, which are shown in figure 5. The microstructural parameters α_K and N_{eff} are obtained as $\alpha_K = 0.299$, 0.262 and 0.175; and $N_{eff} = 0.011$, 0.010 and 0.017 for magnets with particle diameters less than 10 μm, 10–20 μm and 35–53 μm, respectively. It can be clearly seen that the parameters N_{eff} are almost zero. This small demagnetization factor implies that there is a small demagnetizing field acting on the grains, which are different in the cases of sintered magnets where the demagnetization factors are larger.

In conclusion, the coercivity is controlled by the nucleation mechanism for the magnets with particle sizes 35–53 μm, as in the case of the sintered magnet. For the magnet with particle sizes 10–20 μm, the hardening mechanism is mainly controlled by nucleation as in the sintered magnet but the hardening mechanism of domain wall pinning or the nucleation of a single domain, which usually appears in melt-spun materials, may also be involved. With a decrease in the diameter of the particles, it can be expected that the characteristic hardening mechanism of the whole magnet may be similar to that in the case of the melt-spun alloy. In other words, the coercivity behaviour of bonded magnets made from the gas-atomized powders seems to be between those of the sintered and melt-spun magnets depending on the particle size. Meanwhile it has been found that the demagnetizing field of bonded magnets made from the inert-gas-atomized powders is very small.

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