4-15-1996

Dependence of energy dissipation on annealing temperature of melt–spun NdFeB permanent magnet materials

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Abstract

A model of magnetic hysteresis which was developed originally for soft magnetic materials has been applied to melt–spun ribbons of $Nd_2Fe_{14}B$-based material. The crucial ideas in the model description of hysteresis center on a dissipation of energy due to hysteresis which is proportional to the change in magnetization. The $Nd_2Fe_{14}B$ material was melt–spun amorphous and then annealed for a period of 24 h at temperatures ranging from 700 to 950 °C. This resulted in different grain sizes, depending on annealing temperature. Consequently the hysteresis curves represent the properties of the material as a function of both annealing temperature and grain size. It was found that the magnetic properties varied systematically with annealing temperature, and hence grain size, as would be expected. When modeling the magnetic properties it was found that the model parameters also varied systematically, in particular, the energy dissipation parameter k was to a first approximation a simple linear function of the annealing temperature and decreased with increasing annealing temperature as a result of grain growth. Therefore, this study revealed a basic relationship between materials processing conditions, microstructure, model parameters, and magnetic properties.

Keywords

Annealing, Magnetic hysteresis, Magnetic materials, Materials properties, Microstructural properties

Disciplines

Electromagnetics and Photonics | Engineering Physics

Comments

The following article appeared in *Journal of Applied Physics* 79 (1996): 5510 and may be found at http://dx.doi.org/10.1063/1.362294.

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Citation: Journal of Applied Physics **79**, 5510 (1996); doi: 10.1063/1.362294
View online: http://dx.doi.org/10.1063/1.362294
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/79/8?ver=pdfcov
Published by the AIP Publishing

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A model of magnetic hysteresis which was developed originally for soft magnetic materials has been applied to melt–spun ribbons of $Nd_2Fe_{14}B$-based material. The crucial ideas in the model description of hysteresis center on a dissipation of energy due to hysteresis which is proportional to the change in magnetization. The $Nd_2Fe_{14}B$ material was melt–spun amorphous and then annealed for a period of 24 h at temperatures ranging from 700 to 950 °C. This resulted in different grain sizes, depending on annealing temperature. Consequently the hysteresis curves represent the properties of the material as a function of both annealing temperature and grain size. It was found that the magnetic properties varied systematically with annealing temperature, and hence grain size, as would be expected. When modeling the magnetic properties it was found that the model parameters also varied systematically, in particular, the energy dissipation parameter k was to a first approximation a simple linear function of the annealing temperature and decreased with increasing annealing temperature as a result of grain growth. Therefore, this study revealed a basic relationship between materials processing conditions, microstructure, model parameters, and magnetic properties. *© 1996 American Institute of Physics.* [S0021-8979(96)31808-8]

I. INTRODUCTION

Permanent magnet materials based on $Nd_2Fe_{14}B$, have been the focus of attention of the hard magnet community for the last ten years. A wide range of materials properties has been reported,[1–4] but the overriding property of these materials has been their high maximum energy product, which can exceed 50 MG Oe ($\sim$400 kJ/m^3). The latest results reported indicate a maximum energy product of 54 MG Oe (430 kJ/m^3).[5]

While much work has been devoted to the processing and production of these alloys with even greater energy products, remanences, and coercivities, little attention has been paid to the description of these properties in terms of a physical model. Nevertheless, this is important because a model can provide a direct link between microstructure and magnetic properties. In this paper we focus on the application of a model, which was developed originally for soft magnetic materials, in which the crucial idea in the description of hysteresis centers on a dissipation of energy due to hysteresis which is proportional to the change in magnetization. This idea, which was originally developed through a consideration of domain wall displacement, leads to a pair of differential equations for hysteresis which are valid for a wider range of behavior provided that the energy dissipation is proportional to the change in energy.

The hysteresis equations for the model under consideration here have been described in detail elsewhere.[6] They are given here for completeness. The hysteresis-free curve, or anhysteretic curve, is described by

$$M_{\mathrm{an}}(H)=M_s\left[\coth\left(\frac{H+\alpha M}{a}\right)-\left(\frac{a}{H+\alpha M}\right)\right],$$

where M_s is saturation magnetization, α is the internal coupling of the domain magnetizations, and $a=k_BT/\mu_0\langle m\rangle$, where k_B is the Boltzmann constant, T is the temperature, μ_0 is the permeability of free space, $\langle m\rangle$ is the mean effective domain size, M_{an} is the anhysteretic magnetization, and H is the magnetic field.

The hysteresis curve is given by

$$\frac{dM(H)}{dH}=\frac{M_{\mathrm{an}}(H)-M_{\mathrm{irr}}(H)}{k\delta-\alpha[M_{\mathrm{an}}(H)-M_{\mathrm{irr}}(H)]}+c\left(\frac{dM_{\mathrm{an}}(H)}{dH}-\frac{M_{\mathrm{an}}(H)-M_{\mathrm{irr}}(H)}{k\delta-\alpha[M_{\mathrm{an}}(H)-M_{\mathrm{irr}}(H)]}\right).$$

These equations can then be solved to give the hysteresis curves of the material. Here k is the energy loss per unit change in magnetization and c, which gives a measure of the amount of the reversible domain wall motion, can be related directly to the domain wall surface energy.

It should be noted that the anhysteretic curve used in the model calculation here is for isotropic materials. Therefore the model cannot be expected to exactly fit the part of the experimental curve where the change of magnetization is due to the reversible rotation of the magnetic moments with respect to the randomly oriented crystallographic easy axis.

II. EXPERIMENT

Amorphous $Nd_2Fe_{14}B$ was prepared by melt spinning with a wheel speed of 45 m/s. The resulting samples were annealed at temperatures ranging from 750 to 950 °C for a period of 24 h. The hysteresis data were taken using a Quantum Design dc SQUID. In order to make the measurements, about 40 ribbons were laid parallel in two layers on double-sided adhesive tape. Then the tape was wrapped onto a quartz rod. To minimize demagnetizing effects, the long axis of the ribbons was situated parallel to the applied magnetic field. No corrections due to demagnetization effects were made.

0021-8979/96/79(8)/5510/3/$10.00

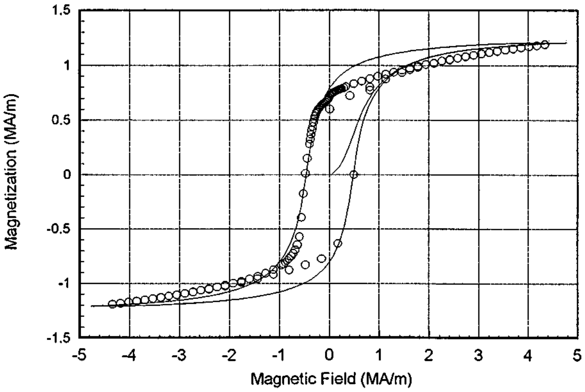

FIG. 1. Measured and modeled hysteresis curves for specimen 1. The measured data are the circles, the model calculation is the curve.

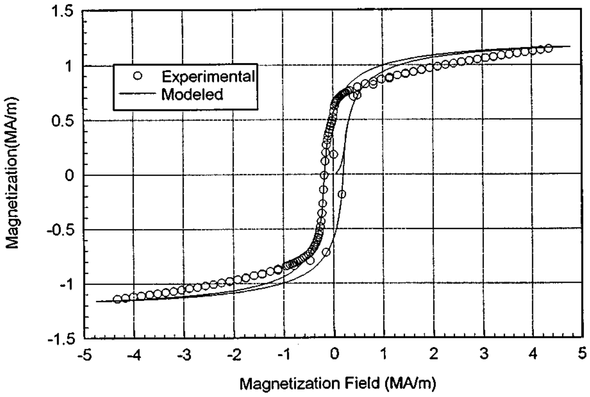

FIG. 3. Measured and modeled hysteresis curves for specimen 6. The measured data are the circles, the model calculation is the curve.

III. RESULTS

The hysteresis curves for seven specimens of NdFeB were measured and representative samples of these measurements are shown in Figs. 1–3. The magnetic properties changed progressively from one specimen to the next as the annealing temperature increased from 700 to 950 °C. For example, the coercivity in the specimen annealed at 700 °C was 487 kA/m while in the specimen annealed at 950 °C it was found to be 97 kA/m. In addition the differential permeability was greater at all points on the hysteresis loop in the materials annealed to higher temperatures, and there was a general decrease in remanence as the annealing temperature increased. A summary of the measured magnetic properties is given in Table I.

The grain sizes in specimens 2 and 7 were measured. These were 20–156 nm (with a mean of 75 nm) in specimen 2; and 154–740 nm (with a mean of 361 nm) in specimen 7.

IV. MODELING OF MAGNETIC PROPERTIES

The magnetic properties were used to determine the hysteresis model parameters. The values of the model parameters are shown in Table II for each of the materials investigated. From this it is clear that there was a progressive change in the hysteresis parameters such as k, the energy dissipation, and a, the effective domain density, as the annealing temperature was changed.

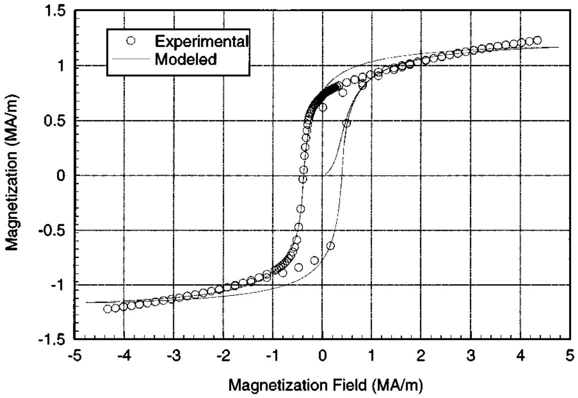

FIG. 2. Measured and modeled hysteresis curves for specimen 3. The measured data are the circles, the model calculation is the curve.

A comparison of the measured and modeled hysteresis curves is shown in Figs. 1–3. In the region near the coercive field, the model fits the data reasonably well. The model cannot, however, be expected to fit the part of the experimental curve where the change of magnetization is due to the reversible rotation of the magnetic moments with respect to the randomly oriented crystallographic easy axis, and in fact there are systematic differences between the measured and modeled curves in this region. If the anhysteretic curve of Eq. (1) is replaced by the minimum energy curves calculated by the Stoner–Wohlfarth model,[7] it would appear that the theory will fit the data rather well. Nevertheless, the present modeled values of magnetization are within 10% of the measured values along most of the curve, with some deviations of up to 20% in limited regions close to the knee of the demagnetization curve.

The variation of the energy dissipation parameter with annealing temperature is shown in Fig. 4. To a first approximation this appears to be linear with the relationship

$$k = k_0 - k_1 T_{\text{ann}},$$

where $k_0 = 2\times10^6$ A m^{-1}, and $k_1 = 2\times10^3$ A m^{-1} C^{-1}.

TABLE I. Measured magnetic properties of annealed NdFeB permanent magnet materials.

Specimen	Annealing temperature (0 °C)	M_s (T)	H_c (kA/m)	M_r (T)
1	700	1.19	487	0.72
2	750	1.19	466	0.71
3	800	1.23	397	0.73
4	825	1.17	409	0.67
5	850	1.15	264	0.65
6	900	1.14	192	0.57
7	950	1.17	97	0.58

TABLE II. Model parameters used to generate the modeled hysteresis curves.

	Model parameters					
Specimen	M_s (kA/m)	a (kA/m)	k (kA/m)	α	c	$3a\text{-}\alpha M_s$ (kA/m)
1	1300	358	545	0.685	0.18	183.5
2	1300	358	505	0.765	0.18	79.5
3	1250	373	439	0.845	0.18	62.75
4	1250	373	439	0.845	0.18	62.75
5	1250	386	248	0.845	0.18	101.75
6	1250	399	191	0.824	0.18	167
7	1150	400	81	0.960	0.18	96

V. CONCLUSIONS

The effects of different annealing temperatures on the magnetic properties of melt–spun NdFeB permanent magnet material have been studied. The measured hysteresis curves of these specimens have been used to calculate the model parameters for an established hysteresis model developed originally for soft magnetic materials. A comparison has been made between the measured and modeled hysteresis curves, showing good agreement, although indicating that the model could be made more appropriate for these materials by the introduction of anisotropy. It was found that the model energy dissipation parameter, k, which represents the rate of energy loss per unit change in magnetization, decreased linearly with annealing temperature.

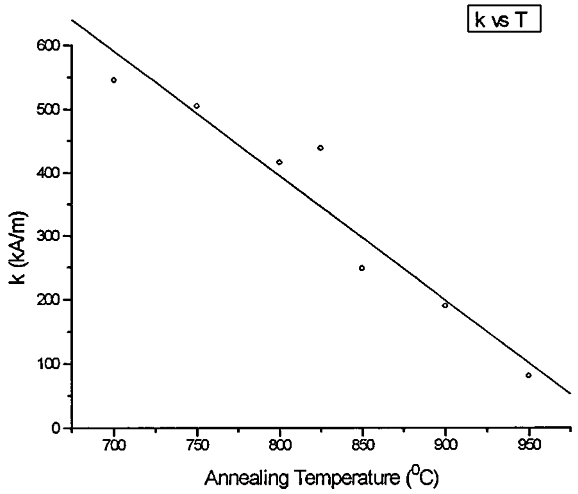

FIG. 4. Dependence of the model parameter k on the annealing temperature T_{ann}. This reveals that k decreases with grain size.

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences through the Center for Excellence in Synthesis and Processing, Program on Tailored Microstructures in Hard Magnets.

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