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THE HARD MAGNETIC PROPERTIES OF SINTERED Nd–Fe–B PERMANENT MAGNETS

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Summary

A permanent magnet based on Nd–Fe–B was prepared by liquid phase sintering ($(BH)_{\max}$ = 290 kJ m^{-3}, $_JH_c$ = 593 kA m^{-1}, B_r = 1.24 T). The temperature dependence of the coercive force was compared with the temperature dependence of the anisotropy field, the anisotropy energy, the ratio between wall energy and magnetization and the nucleation field for reversed magnetic domains. It was found that the coercive force is neither purely pinning controlled nor purely nucleation controlled.

1. Introduction

Permanent magnet materials obtained by the sintering of powders of Nd–Fe–B alloys have been shown to possess outstanding magnetic properties [1, 2]. A drawback of these materials is their limited corrosion resistance and the relatively high negative temperature coefficient of the coercive force. In this paper we report an investigation in which we have studied the temperature dependence of the coercive force $_JH_c$ in more detail. We include in this investigation the temperature dependences of the anisotropy field H_A, the anisotropy energy K_1 and the domain wall energy γ in an attempt to determine in how far the temperature dependence of $_JH_c$ is related to that of H_A, K_1 or γ.

2. Materials and methods

The sintered magnet body used was made from an Nd–Fe–B alloy close in composition to $Nd_2Fe_{14}B$. The various steps involved were particle

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alignment, pressing, sintering and heat treatments. These have been described in more detail elsewhere [3]. The measurements of $_JH_c$ were made in a pulsed-field system. For the measurements of H_A we used the singular point detection (SPD) method [4]. The temperature dependence of the saturation magnetization σ was measured on a conventional σ–T apparatus based on the Faraday method. The performance of the magnet body at room temperature can be specified by the following parameters: $(BH)_{max} = 290$ kJ m^{-3}, $_JH_c =$ 593 kA m^{-1} and $B_r = 1.24$ T.

3. Results and discussion

The temperature dependence of the anisotropy field H_A is shown in Fig. 1. The strong rise in H_A with decreasing temperature has a small discontinuity below about 250 K for which we have no explanation at the moment. The small structure near 250 K in the $H_A(T)$ curve is probably of minor importance since the overall behaviour of the $H_A(T)$ curve of the sintered magnet body is much the same as the $H_A(T)$ curve measured on a piece of an arc-cast alloy of the composition $Nd_2Fe_{14}B$ after homogenizing at 900 °C for 3 weeks [5].

The temperature dependence of $_JH_c$ and J_s is shown in Fig. 2. Separate measurements showed that the Curie temperature is close to 585 K.

An important parameter for describing the coercive fields in hard magnetic materials is the domain wall energy γ. The room temperature value of

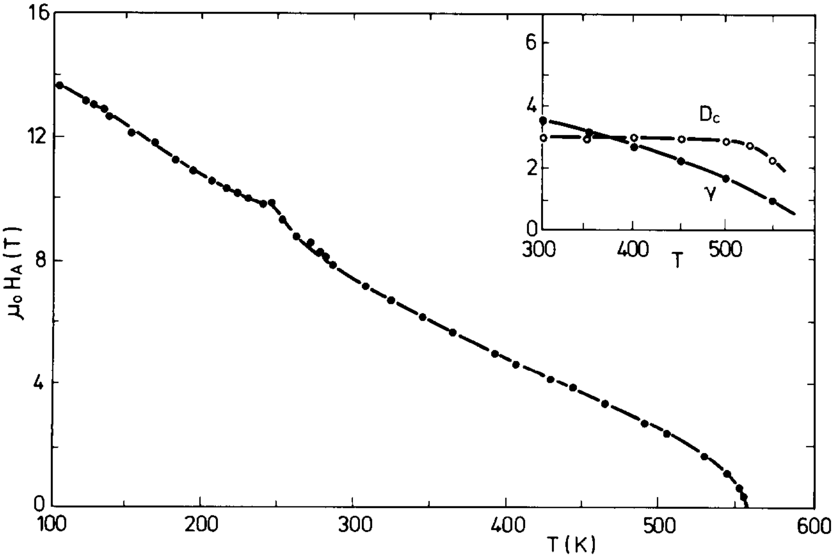

Fig. 1. Temperature dependence of the anisotropy field $\mu_0 H_A$ for a sintered permanent magnet body based on Nd–Fe–B. The inset shows the temperature dependence of the single-domain particle diameter D_c (in units of 100 μm) and the temperature dependence of the domain wall surface energy γ (in units of 10^{-2} J m^{-3}).

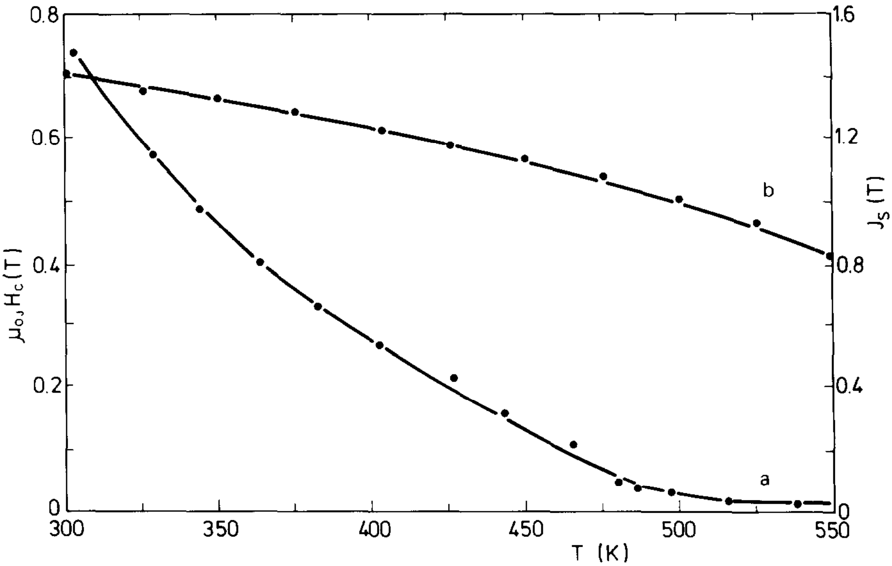

Fig. 2. Temperature dependence of the coercive field $\mu_{0J}H_c$ (curve a, left scale) and temperature dependence of the saturation magnetization J_s (curve b, right scale) for a sintered permanent magnet based on Nd–Fe–B.

this quantity was determined recently by Livingston [6], who reports $\gamma = 3.5 \times 10^{-2}$ J m^{-2}. We used this value and determined its temperature dependence by means of the relations

$$\gamma = \left(\frac{2kT_cK_1}{d}\right)^{1/2} \tag{1}$$

$$K_1 = \tfrac{1}{2}H_AJ_s \tag{2}$$

where the temperature dependences of H_A and J_s were taken from Figs. 1 and 2. In eqn. (1) k represents the Boltzmann constant and d is the distance between the magnetic atoms. The temperature dependence of γ obtained in this way is shown in the inset of Fig. 1. An important parameter related to γ is the single-domain particle diameter D_c, representing the diameter of an isolated sphere below which single-domain structures are energetically preferred to two-domain structures in zero applied field. Using $D_c = 1.4(4\pi)^2 J_s^{-2}$ Livingston [6] found that in Nd–Fe–B permanent magnets D_c is about 0.3 μm at room temperature. The temperature dependence of D_c was derived from the temperature of γ and the temperature dependence of J_s (Figs. 1 and 2). As can be seen in the inset of Fig. 1, the single-domain particle diameter shows virtually no temperature dependence in the region below 500 K. At all temperatures we may expect, therefore, that D_c will be much smaller than the grain diameter, being typically 10 μm.

In Fig. 3 we have analysed the temperature dependence of ${}_JH_c$ in terms of various models relating ${}_JH_c$ to one or more of the other magnetic

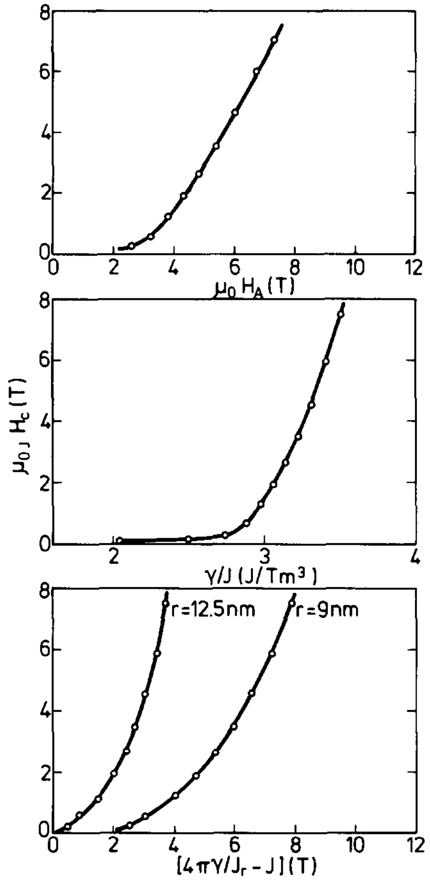

Fig. 3. Plots of the coercive force $\mu_{0J}H_c$ *vs.* the anisotropy field μ_0H_A (top part), the ratio of wall energy and magnetization γ/J (middle part) and the nucleation field $4\pi\gamma/Jr - J$ (bottom part). The quantity r in the bottom part represents the defect radius. For more details, see text.

parameters considered in this report. Inspection of the results in the top and middle parts of Fig. 3 shows that the coercive force is not proportional to the anisotropy field, as was proposed by for uniform pinning on extended planar defects by Kütterer *et al.* [7]. Zijlstra [8] considered discrete pinning and showed that if the coercive force originates from wall pinning at discrete sites one may expect $_JH_c$ to be proportional to γ/J. As shown in the middle part of Fig. 3, this proportionality is not found in the permanent magnet material investigated. Livingston [6] studied various Nd–Fe–B permanent magnet materials by means of microscopic investigations using the Kerr effect. He found indications that the coercive force in these materials is nucleation controlled rather than pinning controlled. For spherical defects of radius r the internal nucleation field was estimated by that author to be $H_n = 4\pi\gamma/Jr - NJ$, where NJ represents the demagnetizing field. Taking the temperature dependence of γ shown in the inset of Fig. 1 together with the temperature dependence of J given in Fig. 2 and taking N equal to unity we have calculated the temperature dependence of this nucleation field for various values of r. In none of these cases did we find a proportionality between ${}_JH_c$ and the nucleation field H_n. Two representative examples of such plots of ${}_JH_c$ *versus* H_n are shown in the bottom part of Fig. 3.

Surprisingly enough we found a satisfactory description of the temperature dependence of the coercive force (Fig. 4) when using the relation

$$ {}_JH_c \propto \left(\frac{K_1}{J_s}\right)^{5/2} \propto H_A{}^{5/2} \tag{3}$$

proposed by Kütterer *et al.* [7] for the case when ${}_JH_c$ is determined by volume pinning associated with the presence of atomic disorder. Kütterer *et al.* [7] successfully applied their model to the description of the intrinsic coercive force caused by pinning of narrow domain walls in a single crystal of $SmCo_5$. However, the magnitude of the coercive forces considered in this case was approximately 10^{-3} T, which is more than three orders of magnitude lower than the coercive forces considered in the present study. The applicability of this model to the Nd–Fe–B permanent magnet material seems therefore doubtful.

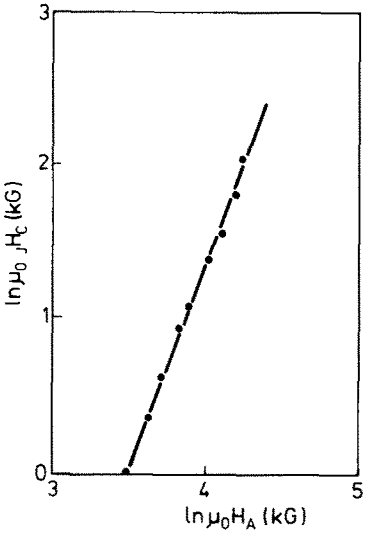

Fig. 4. Double logarithmic plot of the coercive field ${}_JH_c$ *vs.* the anisotropy field H_A.

4. Conclusions

Our study of the temperature dependence of the coercive force ${}_JH_c$ and the temperature dependence of the anisotropy field H_A for a sintered permanent Nd–Fe–B magnet revealed that the coercive force decreases more strongly with temperature than the anisotropy field. We found that a satisfactory description of the strong temperature dependence of the coercivity cannot be given in terms of current models in which this quantity is taken is be either pinning controlled or nucleation controlled. It is not unlikely that the underlying mechanism of $_JH_c$ itself depends on the temperature.

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