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INTERPRETATION OF $M - H$ LOOPS OF PERMANENT MAGNETS CONTAINING TWO HARD-MAGNETIC PHASES

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Abstract. — Often $M - H$ hysteresis loops of Nd-Fe-B type materials are constricted or show steps, which is currently ascribed to the presence of a soft-magnetic phase. By means of model calculations with a finite element method it is shown that the typical shape of the hysteresis loop is very sensitive to the relative amount and distribution of the hard- and soft-magnetic phases.

Introduction

Often the hysteresis curves of permanent magnets reveal the presence of second phases with low coercivity. Interpreting these curves in terms of crystallites with low coercivity is troublesome because of the magnetic interactions which are present. For this reason these interactions are often ignored. In this paper $M - H$ loops are shown which are derived by finite element calculations on simple geometries and combinations of crystallites with high and low coercivity. In these calculations the magneto-static interactions are taken into account. The computer program calculates magnetic potentials using a finite element method. As input the geometry and the material properties are required.

The geometry of the magnets was chosen according to a demagnetizing factor of 1/12 and they were built up from the structure units shown in figure 1. For the properties of the two materials used in the calculations, one having a high coercivity and the other having a low coercivity, the following values were taken: $M_s = 1.6$ T, $\mu_0 H_a = 7$ T ($\mu_{r,1} \approx 0.25$) for both, while $jH_c = 600$ kA/m and $0$ kA/m.

Results

In figure 1 the calculated $M - H$ loops are shown together with the corresponding structure unit. The external field is applied in the vertical direction on an assembly of structure units. In the situation of series connection the resulting coercivity of the composite material is seen to decrease proportional to the decreasing volume ratio between the high- and low-coercive material. In the parallel situation a sharp decrease in magnetization is observed when a column of particles with low coercivity changes its magnetization direction.

This result can be approximated by a simple analytical approach such as used in magnetic circuit design. Consider the magnetic circuit in figure 2 for the series situation. The materials with the high and low coercivity (1 and 2 resp.) are described by:

$$\frac{B(H_1)}{\mu_0} = M_0 + \mu_{r,1}(H_1) \cdot H_1$$
$$\frac{B(H_2)}{\mu_0} = \mu_{r,2}(H_2) \cdot H_2.$$
The remanence is calculated under the condition

$$\oint H\,dl = H_1 I_1 + H_2 I_2 = 0$$

which results in

$$\frac{B_r}{\mu_0} = \frac{M_0}{1 + \frac{\mu_{r1}(H_1) I_2}{\mu_{r2}(H_2) I_1}}.$$ 

So $B_r$ is hardly affected if $\mu_{r2} \gg \mu_{r1}$. The other point of interest on the $B - H$ curve is the external field at which $B = 0$. Using $B_1 = B_2 = 0$ we obtain:

$$H_{\text{ext}} (I_1 + I_2) = H_1 I_1 + H_2 I_2 = \frac{-M_0 I_1}{\mu_{r1}(H_1)} = H_{c1} I_1$$

and

$$H_{\text{ext}} = H_{c1} \frac{I_1}{I_1 + I_2}.$$ 

The remanence and coercivity of a similar parallel circuit are approximated by the weighted superposition of the two $M - H$ loops.

Discrepancies between the simple analytical solutions and the results of the finite element calculations are due to the assumptions that in the analytical approach there is no demagnetization and $H_a$ and the permeability at $H_c$ in the direction of the magnetization are infinite.

Taking into account the demagnetization and the actual values of $H_a$ and $\mu_r$ at $H_c$ in the easy direction results in a non-linear weighted combination of the individual curves.

Discussion

In order to discuss the results some typical $M - H$ loops measured on Nd-Fe-B magnets are shown in figure 3. In the $M - H$ loop of the Nd-Fe-B magnet as sintered (curve 1) a step is observed around $H = 0$. By Hirosawa et al. [1] and Blank and Adler [2] a similar step is observed and attempts were made by these authors to calculate the volume fraction of the soft-magnetic phase.

From our analysis it is clear that the volume fraction can only be calculated if the geometrical distribution of the phases is known. Simple superposition of the $M - H$ loops of the two phases will never be in agreement with the actual distribution.

Curves 2 and 3 in figure 3 are the $M - H$ loops of a Nd-Fe-B magnet after heating in air at 330 °C for 20 and 40 minutes respectively. The oxidized parts lose their magnetic hardness and the marked effect on both coercivity and remanence is observed.
