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HIGH FIELD MAGNETIC MEASUREMENTS ON SINTERED $SmCo_5$ PERMANENT MAGNETS

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ABSTRACT

Hysteresis loops in fields to 100 kOe have been measured at 300, 77, and 4.2 K parallel and perpendicular to the alignment axis in a series of sintered $SmCo_5$ magnets with compositions varying from 16.24 to 17.08 at% Sm. Analysis of the data taken perpendicular to the alignment axis permits evaluation of the effective anisotropy constant K_1 and also the degree of misorientation of the individual particles. Intrinsic coercive fields H_{ci} varied from 0.34 to 16.4 kOe at room temperature. In all samples, H_{ci} and K_1 increased rapidly with decreasing temperature, roughly doubling between room temperature and 77 K. This confirms more generally the result reported for two samples by Benz and Martin.[1] The values of H_{ci} and $(BH)_{max}$ depend strongly on composition, but the anisotropy does not. Variations in permanent magnet properties are therefore not directly related to variations in the bulk anisotropy.

INTRODUCTION

Benz and Martin[1] measured the magnetic properties of several sintered $SmCo_5$ magnets as a function of temperature and made the surprising observation that H_{ci} increased linearly with decreasing temperature, following quite closely the linear increase in K_1. The coercive field in these magnets is usually attributed to domain wall nucleation or pinning effects that are structure sensitive[2] and not necessarily linearly dependent on the bulk crystal anisotropy.

The present investigation was undertaken to see whether this temperature dependence of H_{ci} is general for $SmCo_5$ magnets, and more broadly to add to the understanding of the coercive field and the permanent magnet properties of $SmCo_5$ and related materials. The experiments also gave information about the degree of alignment of the individual particles in sintered magnets.

SAMPLES AND EXPERIMENTAL PROCEDURE

A series of samples, covering the composition range from 16.24 to 17.08 at% Sm ($SmCo_{5.16}$ to $SmCo_{4.85}$), was obtained from D. L. Martin of the GE Research and Development Center. The room-temperature properties of these samples were reported by Martin, Benz, and Rockwood[3], the samples show a wide range of quality as permanent magnets. Magnetization curves and hysteresis loops were measured parallel and perpendicular to the alignment axis at 300, 77, and 4.2 K on cube samples of 3.2 mm size in fields to 100 kOe using a mechanically-driven vibrating sample magnetometer. The demagnetizing factor was taken as $4\pi/3$, a value confirmed by measurements on an iron cube in the same apparatus. Magnetic saturation could not be attained in all samples at low temperatures even at 100 kOe, so the low temperature saturations were obtained from the room temperature values and the single-crystal temperature dependence.[4]

Conventional permanent magnet properties were obtained from the easy axis magnetization data, and the effective bulk anisotropy was determined from the hard-axis data. A perfectly-oriented single crystal with anisotropy described by a single constant ($E_K=K_1\sin\theta$) has a linear hard-axis magnetization curve with slope $M_s^2/2K_1$. In sintered magnets, the alignment of the individual particles is not perfect, so more complex magnetization curves result. The linear hard-axis curve reported by Benz and Martin were obtained by first magnetizing the samples in the easy direction to minimize domain wall motion. We chose instead to fit the hard axis curves measured in decreasing fields to a calculated curve in which there are two adjustable parameters: the uniaxial anisotropy constant K_1 and an angle β which measures the distribution of the polar angles ϕ (see Fig. 1) between the particle axes and the alignment axis. The angle ϕ is assumed to be described by a spherical normal distribution, $f(\phi) = ke^{-\phi^2/\beta^2}$, where k is a normalization constant. Direct observation by Martin[5] show this assumption to be reasonable. The distribution of particle axes is assumed independent of the azimuthal angle θ. To a first approximation, the standard deviation of ϕ is related to β by $\sigma = \beta(1-\frac{\pi}{4})$.

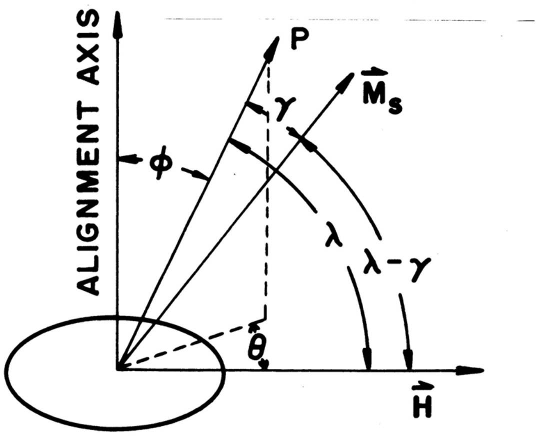

Fig. 1. Angles used in calculation of hard-axis magnetization curves. P is the axis of an individual particle. Angles ϕ and λ are not coplanar; angles γ and λ are coplanar.

A field applied perpendicular to the alignment axis causes the magnetization of the particle to rotate by an angle γ towards H. The angle γ is determined by a balance between the torque from the field, $L = M_s H \sin(\lambda - \gamma)$ and the torque from the anisotropy, $L = -\frac{dE_K}{d\phi} = -K_1 \sin 2\gamma$. The resulting magnetization is given by

$$M = M_s \int_0^{2\pi} \int_0^{\pi/2} f(\phi) \cos(\lambda-\gamma) \sin \phi d\phi d\theta$$
$$= f(H, K_1, \beta)$$

Tables of M/M_s were calculated for a series of values of $h = {HM_s}/{2K_1}$ and β, and the experimental hard-axis curves were fitted to the calculated values to obtain the quantities K_1, and β. In the fitting, greatest weight was given to the high field data, since in this region the magnetization should change by rotation rather than by wall motion, and the calculated curves assume only rotation.

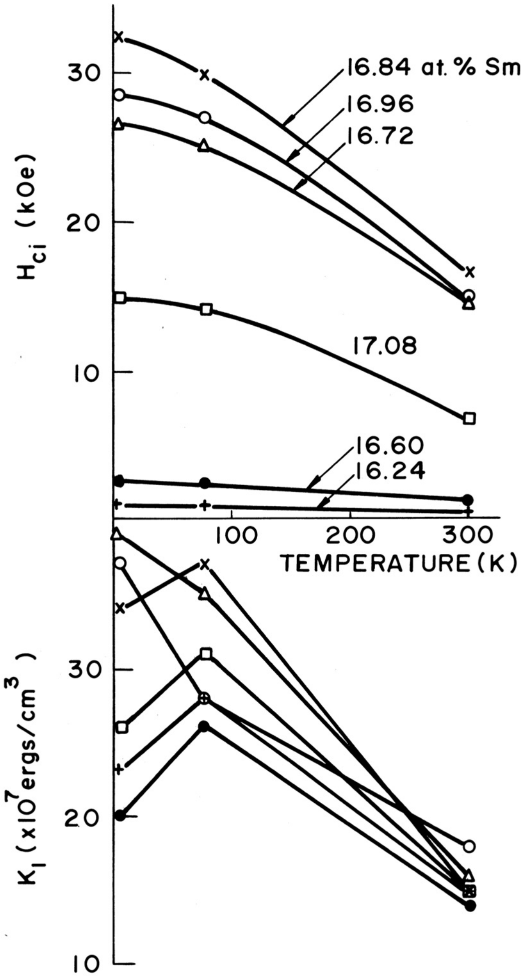

Fig. 2. H_{ci} and K_1 vs temperature for all samples.

RESULTS AND CONCLUSIONS

Numerical data are given in Table I and plotted in Figs. 2 and 3. The following points are worthy of note.

The coercive field increases rapidly with decreasing temperature in all samples, approximately doubling between 300 and 77 K. The absolute value of H_{ci} however, is strongly dependent on composition, varying by almost a factor of 50 from the best to the worst sample. Maximum H_{ci} is observed at about 16.8 at% Sm, in agreement with Martin, Benz, and Rockwood,[3] and the composition for maximum H_{ci} does not change with temperature of measurement.

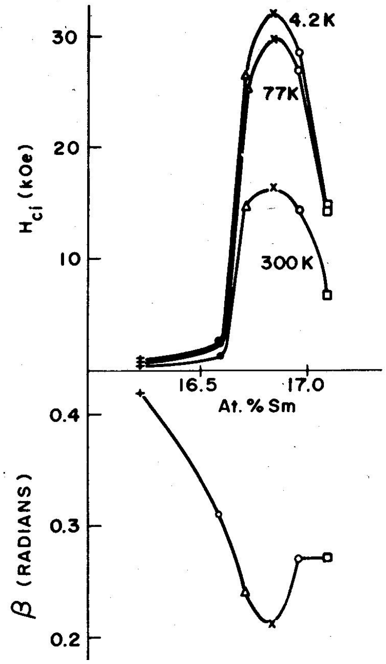

Fig. 3. H_{ci} (at three temperatures) and average β vs composition.

The room-temperature anisotropy is almost independent of composition, and the numerical value of about 1.5 x 10^8 erg/cm^3 is in reasonable agreement with single-crystal values.[4, 6] The measured K_1 increases with decreasing temperature, approximately doubling between 300 and 77 K. There is serious scatter in the values of K_1, at 4.2 K. This may be experimental error caused by the increasing difficulty of saturating the magnetization as the anisotropy increases; however, other investigators have found the anisotropy to drop at low temperatures.[1, 4, 6]

The degree of particle misalignment β is minimum in the samples of highest H_{ci}, but it is hard to say if there is any causal relation between the two quantities.

The results show clearly that H_{ci} does not depend directly on the bulk anisotropy, contrary to the suggestion of Benz and Martin.[1] If H_{ci} is controlled by a domain wall nucleation or pinning event, it is reasonable that H_{ci} would have the temperature dependence of the domain wall energy, which will be approximately the same as the temperature dependence of $(K_1)^{1/2}$. But the magnitude of H_{ci} will depend on some highly local structure and need not correlate with the magnitude of K_1.

TABLE I

at%Sm	H_{ci} kOe	$(BH)_{max}$ MGOe	K_1 10^8 erg/cm^3	β rad
	0.34	3.77	1.5	0.42
16.24	0.52	4.88	2.8	0.39
	0.84	5.23	2.3	0.40
	1.08	8.24	1.4	0.31
16.60	2.24	15.6	2.6	0.29
	2.44	16.6	2.0	0.32
	14.8	21.0	1.6	0.24
16.72	25.2	23.1	3.5	0.22
	26.6	21.5	3.9	0.21
	16.4	22.7	1.5	0.21
16.84	30.0	24.5	3.7	0.22
	32.4	23.8	3.4	0.19
	14.4	19.7	1.8	0.27
16.96	27.0	18.6	2.8	0.24
	28.6	19.2	3.7	0.25
	6.6	19.9	1.5	0.27
17.08	14.1	22.0	3.1	0.28
	14.7	21.8	2.6	0.25

The three sets of values for each sample are at 300, 77, and 4. 2 K.

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