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The magnetic anisotropy of an aligned MnAlC magnet

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The magnetic anisotropy constants K_1 and K_2 have been measured for an aligned MnAlC magnet. The information is extracted from magnetization curves with the magnetic field parallel and perpendicular to the alignment axis. The anisotropy field $H_A = 2(K_1 + 2K_2)/I_S$ (I_S is the saturation magnetization) was determined from a break point in a plot of the perpendicular magnetization against the inverse square of the field. K_1 and K_2 were then found from modified Sucksmith–Thomson plots. The data is used to calculate the 180° wall energies and widths and an estimate of the temperature coefficient of coercive field variation is made and compared with experiment.

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As part of a program of arriving at a critical understanding of the magnetic hardness of an alloy, it is necessary to measure as precisely as possible the intrinsic magnetic properties of the material such as spontaneous magnetization, Curie temperature, and magnetocrystalline anisotropy energy. We are examining the properties of a Matshushita Electrical Company of Japan aligned MnAlC magnet. We find a coercive field, ${}_IH_C$, at room temperature of 2.93 kOe parallel to the alignment axis and 3.42 kOe perpendicular to it. A perfectly aligned sample would be expected to show zero coercive field in the perpendicular direction. Measurements by others on a similar alloy[1] gave parallel and perpendicular coercive fields of 2.95 and 3.5 kOe at room temperature. They also estimated the anisotropy field H_A as 66 kOe at 77 K and 60 kOe at room temperature. In the present work we have measured H_A by a more accurate method and have estimated the K_1 and K_2 anisotropy constant separately in order to derive values of the 180° wall energy and width which are as accurate as possible.

Prolate ellipsoidal specimens were prepared with long axes parallel to the alignment direction. Magnetization measurements with the field parallel to the easy axis and normal to it were made using a superconducting magnet and a ballistic technique. The observations were made as the field was reduced from its maximum value of 70–100 kOe at temperatures of 77, 200, and 294 K. The curve for 77 K is shown in Fig. 1 and indicates a significant remanent magnetization, I_R, for the perpendicular aligned sample. The saturation magnetizations I_S were determined by fitting the parallel aligned data to an approach to saturation curve $I = I_S - a/H^2 - b/H^3$. Values of I_R and I_S are shown in Table I. All field values were corrected for demagnetizing effects.

When the magnetization in the perpendicular direction was plotted as a function of $1/H^2$, a clear break point was found in the plot which was taken to be the anisotropy field H_A. Such a break is expected[2] when the easy axes of magnetization are aligned normal to the field. The plot for 200 K is shown in Fig. 2. The values of H_A are listed in Table I.

[a] On study leave from Defence Research and Development Laboratory, Hyderabad, India.

TABLE I. Measured parameters. I_S: saturation magnetization; H_A: anisotropy field; I_A: magnetization at H_A; I_R: remanent magnetization; ${}_IH_c\|$: coercive field in aligned direction; ${}_IH_c\perp$: coercive field normal to aligned direction.

	(erg Oe^{-1} cm^{-3})			(kOe)		
T(K)	I_S	I_A	I_R	H_A	${}_IH_c\|$	${}_IH_c\perp$
77	683	656	250	76	4.05	4.90
200	652	623	224	61	3.40	4.10
294	627	592	204	58	2.93	3.32

When domain wall processes are no longer active, any change in magnetization is assumed to be due to rotation of magnetic moment and can be treated by single domain theory.[3] The perpendicular alignment regime is particularly suited for this treatment. Consider a single crystal with its easy direction of magnetization normal to the field H and its magnetization making an angle θ with H. The energy per unit volume can be represented by

$$E = K_1 \cos^2\theta + K_2 \cos^4\theta - HI_S \cos\theta, \tag{1}$$

where magnetocrystalline energy constants of higher order than K_2 are neglected. Minimizing with respect to θ gives

$$HI_S = 2K_1 \cos\theta + 4K_2 \cos^3\theta. \tag{2}$$

The magnetization resolved along the H direction is $I = I_S \cos\theta$ so that Eq. (2) can be written

$$\frac{H}{I} = \frac{2K_1}{I_S^2} + \frac{4K_2}{I_S^4} I^2, \tag{3}$$

an expression first derived by Sucksmith and Thomson.[4] A

TABLE II. Derived parameters. K_1, K_2: anisotropy energies; A: exchange parameter; γ: 180° wall energy; t: 180° wall width.

	(J cm^{-3})		(μerg cm^{-1})	(erg cm^{-2})	(μm)
T(K)	K_1	K_2	A	γ	t
77	1.15	0.73	0.319	9.12	0.41
200	0.86	0.57	0.290	7.57	0.45
294	0.75	0.54	0.269	6.89	0.45

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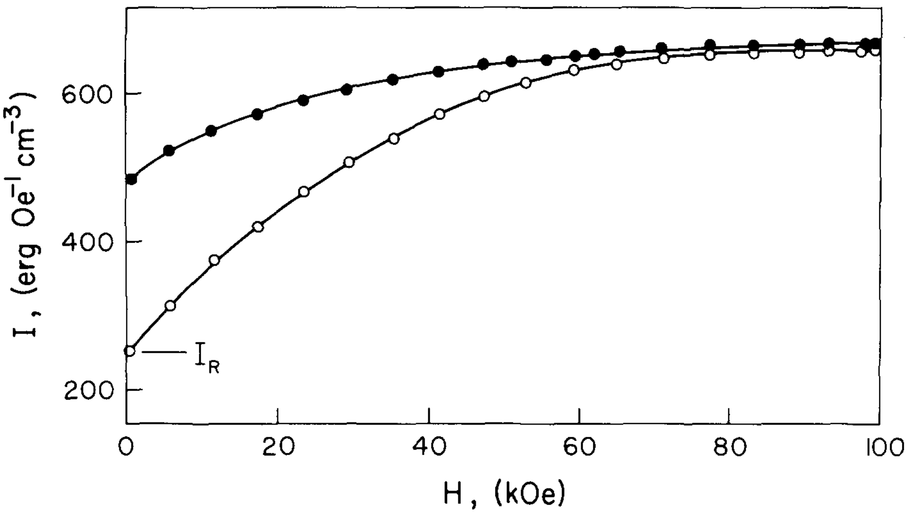

FIG. 1. Magnetization against field at 77 K in the aligned direction (solid circles) and normal to it (open circles).

plot of H/I against I^2 can therefore give $2K_1/I_S^2$ from the intercept and $4K_2/I_S^4$ from the slope. For partially aligned samples, the remanent magnetization I_R is a measure of the misaligned regions which have easy axes nearly parallel to the field rather than normal to it. A first estimate of the perpendicular aligned moment per cm^3 can therefore be obtained by subtracting I_R from the magnetization curve, suggesting a volume fraction of aligned material $\alpha = (I_S - I_R)/I_S$. Equation (3) indicates however that the 90° aligned fraction should saturate at the measured anisotropy field $H_A = 2(K_1 + 2K_2)/I_S$. The measured magnetization at H_A is in fact $I_A < I_S$. The increase in magnetization to I_S, as the field increases beyond H_A, is attributed to regions with easy axes making angles of less than 90° with the field direction. The linear portions of the curves were extrapolated back to $(I - I_R)^2 = 0$, where the truly 90° alignments have zero magnetization. The 90° regions saturate at the anisotropy field H_A. The dashed line in Fig. 3 simulates the behavior of the 90° fraction of the sample which has zero magnetization at $H = 0$ rising to saturation at H_A. The magnetizations plotted were however per cm^3 of a sample which contained only α cm^3 of 90° aligned material. To simulate 1 cm^3 of aligned material the $H/(I - I_R)$ axis values must be multiplied by $1/\alpha$ and the $(I - I_R)^2$ values by α^2. These procedures lead to the values of K_1 and K_2 listed in Table II. The essential features of the treatment are to use the intercept of the linear portion with the $H/(I - I_R)$ axis to determine K_1 and construct a simulated plot having a slope consistent with the relation $H_A = 2(K_1 + 2K_2)I_S$. The simulated straight line plots differ from the curved data plots because of the presence of orientations, at less than 90° to the field which never saturate. A similar upturn of the curve as I^2 approaches I_S^2 can occur for single crystals if $K_3 > 0$.[5] It also occurs, however, due to imperfect alignment, as can be shown by processing Stoner and

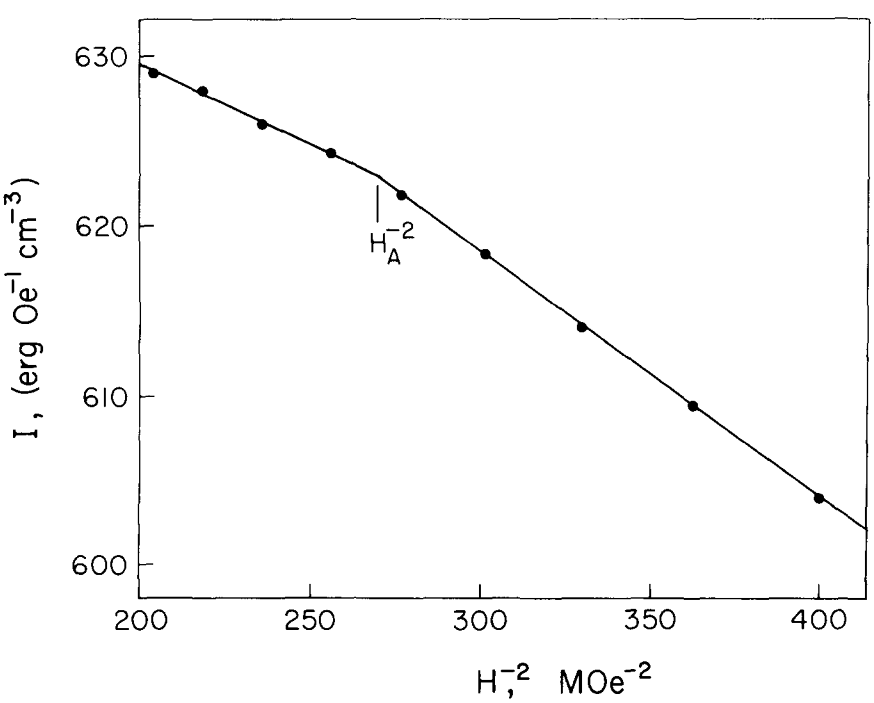

FIG. 2. Magnetization normal to the aligned direction plotted against the inverse square of the field at 200 K. The "break point" occurs at $1/H_A^2$.

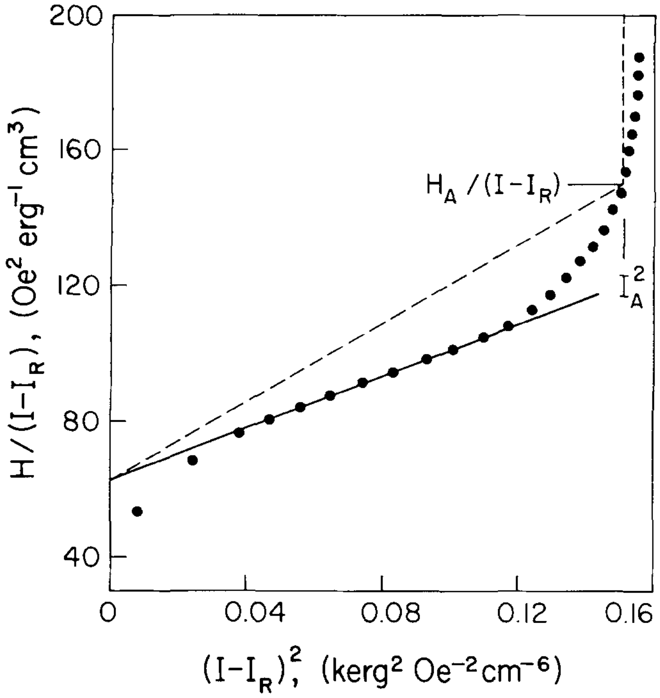

FIG. 3. $H/(I-I_R)$ against $(I-I_R)^2$ at 294 K. The dashed line is the simulated single crystal plot with the easy direction of magnetization at 90° to the field.

Wohlfarth[3] randomly oriented single domain curves in a similar way. In this case it is assumed that at these temperatures $K_3 \sim 0$.

The wall energy per unit area, γ, can be obtained by extending the usual treatment[6] to include K_2 giving

$$\gamma = 2\sqrt{A}\int_0^{\pi}(K_1 \sin^2\theta + K_2 \sin^4\theta)^{1/2}\, d\theta, \tag{4}$$

where A is an exchange constant. Substituting $x = \cos\theta$ and putting $K_2/K_1 = R$, the integral gives

$$\gamma = 2\sqrt{AK_1}\left\{1 + [(1+R)/R^{1/2}]\sin^{-1}\left(\frac{R}{1+R}\right)^{1/2}\right\}. \tag{5}$$

The wall width, t, becomes

$$t = \pi(A/K_1)^{1/2}/(1+R)^{1/2}. \tag{6}$$

The exchange constant was estimated using

$$A = kT_c I_S^2/(8dI_{SO}^2), \tag{7}$$

where T_c, the Curie temperature was taken as 558 K,[7] d the mean separation of Mn atoms as 3.02 Å. I_S is the saturation magnetization at observation temperature and I_{SO} at 77 K. Values of K_1, K_2, A, γ, and t are shown in Table II.

Values of H_c are shown in Table I both for parallel and normal alignment with the field. Measurements over a range of seven temperatures between 77 and 310 K showed a linear dependence on temperature as previously reported.[1] Our easy direction coercive force followed the relation

$$H_c/H_0 = 1 - BT, \tag{8}$$

where H_0 was 4.72 kOe and B was $1.31\times10^{-3}\ K^{-1}$. In a preliminary note on a theory of pinning by random inhomogeneties[8] an equation of the form of Eq. (8) was predicted with $B = 25k/(31\gamma b^2)$, where k is Boltzmann's constant and b is a range parameter for the parabolic pinning force. The minimum value of b for a point pin is $t/4$. Inserting our determinations of γ and t gives predicted values of B as 1.16, 1.18, and $1.26\times10^{-3}\ K^{-1}$ at 77, 200, and 294 K, respectively. These values differ from the observed slope of 1.31×10^{-3} K^{-1} by less than 13%. A more complete account of the theory and its application to magnetic viscosity and coercive field measurements will be published elsewhere.

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