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DISCUSSION

C.D. GRAHAM, JR.: Is there any significant difference between your values of the anisotropy constants of Co and the earlier values of Sucksmith and Thompson?

R. PAUTHENET: Nous avons retrouvé les valeurs des constantes K_1 et K_2 du cobalt, déterminées antérieurement par W. Sucksmith et J.E. Thompson, à mieux de 5 %, sauf dans la région où K_1 est voisine de zéro pour laquelle l'erreur relative est plus grande.

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The Temperature Dependence of the Magnetocrystalline Anisotropy of Face-Centered Cubic Cobalt*

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Single crystals of face-centered cubic cobalt have been examined between 4.2° and 850°K. The usual transformation to the hexagonal structure below 700°K is avoided by using two special forms of samples: (a) thin films evaporated onto MgO substrates, and (b) the precipitated cobalt-rich phase in a 2 per cent Co-Cu single crystal. In both cases the f.c.c. cobalt is stabilized by and has a close correspondence with the host lattice.

Standard ferromagnetic (electron-spin) resonance techniques have been used to determine the magnetocrystalline anisotropy parameters K_1/M and K_2/M over the temperature range indicated, and, in addition, the spectroscopic splitting factor, g, is found to be 2.06 ± 0.03 independent of temperature.

The temperature dependence of the anisotropy constants is in accord with the relation $K(T)/K(0)=[M(T)/M(0)]^n$. We have taken the determination by Jaccarino of the temperature dependence of the cobalt nuclear magnetic resonance frequency to be proportional to the magnetic moment. The results that are obtained indicate that the power n of the dependence noted is nearly 10 for K_1.

The magnetocrystalline anisotropy reflects the spatial symmetry of the crystal structure that it is associated with; that is, the spatial dependence of the magnetization energy is intimately connected with the crystal symmetry of the sample. In addition, the temperature dependence of the magnetocrystal-

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line anisotropy is also influenced by the crystal symmetry. The reason for the latter effect may be thought of as arising from the fact that, at temperatures greater than absolute zero, the magnetization locally deviates from its equilibrium direction and scans the surrounding spatial orientations giving rise to an averaging of the local anisotropies, that average in an observable value and since it depends on local values also reflects the crystal symmetry. The detailed theory of this behavior is to be found in the literature.[1)-4)] The general results obtained for cubic crystals are stated as

$$\frac{K_n(T)}{K_n(0)}=\left[\frac{M(T)}{M(0)}\right]^{p_n} \qquad (1)$$

with $n=1$, 2 and $p_1\cong 10$, $p_2\cong 21$; the "approximately" for the exponent arises from a thermal expansion correction.[5)]

The determination of magnetocrystalline anisotropy by ferromagnetic resonance is a relatively standard technique by which we have determined the equivalent "anisotropy fields" K_1/M, K_2/M from an analysis of the applied d-c magnetic field required for resonance as a function of orientation of the single crystal samples. The spectroscopic splitting factor, g, is also determined from the analysis and is found to be 2.06 ± 0.03 independent of temperature from 4.2 to 850°K. The measurements are at 9 kMc/s.

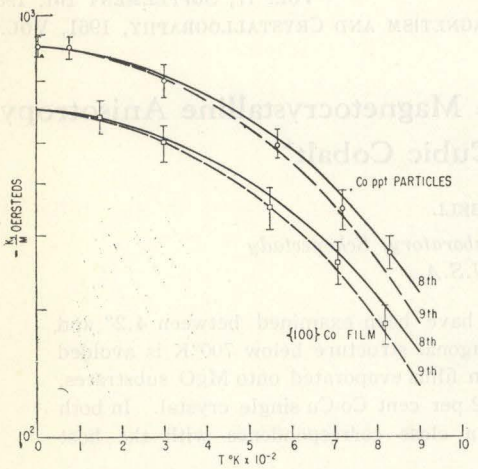

Fig. 1. The temperature dependence of the magnetocrystalline anisotropy "field" K_1/M for face-centered cubic cobalt. The specimen marked ○ corresponds to the cobalt rich precipitate particles in single crystal alloys of copper-2 per cent cobalt; the particles have average radii of 150 A. The specimen marked □ corresponds to a (100) plane evaporated film 6000A thick on a MgO single crystal substrate. The power law comparison with the nuclear resonance data of Jaccarino is made for $(p_1-1)=9$ and 8 in each case and normalized to the data at low temperatures.

In Fig. 1 are presented the primary results of this investigation, the temperature dependence of K_1/M for (a) samples of cobalt precipitated in Cu-2 per cent Co single crystals* and (b) single crystals of cobalt in the form of thin films evaporated onto MgO single crystal substrates.** The precipitated particles of (a) have previously been determined[6)] to be of face-centered cubic crystal structure and essentially spherical in shape; the lattice parameter of these particles is estimated to be 1.5 per cent larger than bulk f.c.c. cobalt and, in addition, they contain about 10 per cent copper. The single crystals (b) are determined by x-rays to be f.c.c. and of a lattice parameter equal to that of bulk f.c.c.

The theories that yield for K_1 a 10th power dependence are primarily developed for a torque determined anisotropy. While there is no difference between torque measurements of anisotropy and the ferromagnetic resonance determined values at absolute zero, this same statement cannot be arbitrarily made at elevated temperatures and in at least one case has been shown to be false [see J. D. Livingston and C. P. Bean, J. Appl. Phys., **30**, 318S (1959)]. Lacking a better theory we assume a 10th power law to hold.

Since we measure K/M rather than K, the relation (1) should be recast as:

$$\frac{K_n(T)/M(T)}{K_n(0)/M(0)}=\left[\frac{M(T)}{M(0)}\right]^{(p_n-1)} \qquad (2)$$

Magnetocrystalline anisotropy may be viewed as a local property and there is some evidence for this even in the case of metals.[7)] This view would suggest that σ, the moment per gram, (ultimately per atom) rather than M, the moment per cm³ is of fundamental importance since the number M is diluted by thermal expansion directly [in addition to the correction by Carr[5)] that modifies the exponent p]. Because of the above, we shall

* Kindly made available by J. D. Livingston.
** Kindly made available by M. V. Doyle.

compare our data with the prediction of:

$$\frac{K_1(T)/M(T)}{K_1(0)/M(0)}=\left[\frac{\sigma(T)}{\sigma(0)}\right]^{(p_1-1)} \qquad (3)$$

Since the nuclear resonance frequency of a ferromagnet measures the product of σ with a coupling constant A we have taken Jaccarino's determination[8] of the nuclear resonance frequency *vs* temperature to be a measure of σ. It is known that for iron the coupling constant A of the nuclear resonance is explicitly temperature dependent.[9] We shall see to what extent a similar situation exists in cobalt.

The exponent is taken (after Carr) to be:

$$p_1=10-\frac{\kappa\omega(T)}{aT^{3/2}}$$

where

$$\kappa=\frac{1}{K_1}\frac{\partial K_1}{\partial\omega}-\frac{10}{\sigma}\frac{\partial\sigma}{\partial\omega}$$

is the strain dependence of the magnetocrystalline anisotropy, ω is the strain, and a is the coefficient of the $T^{3/2}$ law describing the magnetization falloff with the temperature $T(a=3.3\times10^{-6}{}^{\circ}K^{-3/2}$ from the fit of Jaccarino's data). We estimate κ from the difference between our two types of samples and the difference in their lattice parameters. Neglecting $10/\sigma\ \partial\sigma/\partial\omega$ we find that $\kappa\simeq4.1$ and is temperature independent. We take $\omega(T)T^{-3/2}$ to be $\simeq10^{-6}$ (as for iron and nickel above 300°K) and obtain:

$$(p_1-1)=9-\frac{4.1\times10^{-6}}{3.3\times10^{-6}}=7.8$$

The data of Fig. 1 are in agreement with Eq. (3) using our estimate above for p_1. Notice that at low temperatures better agreement is obtained with higher powers of p_1, *i.e.*, $p_1-1=9$, whereas at high temperatures $p_1-1=8$. This probably reflects the fact that $\omega T^{-3/2}$ is not temperature independent.

The data obtained for K_2/M by our experiment are shown in Fig. 2 and we remark first that the limits of error are broader in this case, and although the precipitate particles' behavior is reasonably described by a power of nearly 20, the film samples give more nearly a tenth power behavior. Since we anticipated $p_2\simeq20$ the one type sample is well behaved while the other is anomalous. We do not understand this discrepancy.

Our primary result, *i.e.*, K_1/M *vs* T is that the nuclear resonance frequency describes in f.c.c. cobalt a measure of the magnetization with a temperature independent coupling constant. We verify this in part by a comparison of the data of Myers and Sucksmith[10] to the extrapolated predictions of Jaccarino's measurements. Fig. 3 gives the comparison

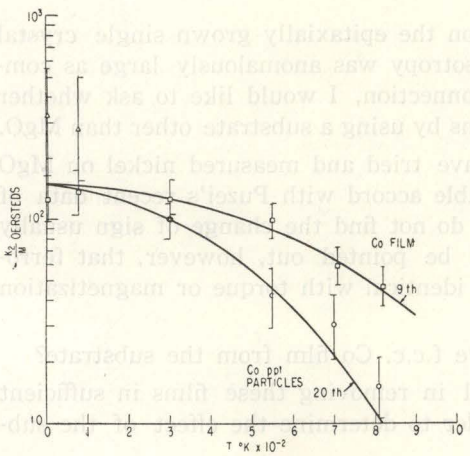

Fig. 2. The temperature dependence of the magnetocrystalline anisotropy field K_2/M for face-centered cubic cobalt. Two samples of cobalt particles are included, one marked △ is oriented so that a (110) plane is exposed to observation while one marked ○ exposes a (111) plane. The former contains primary information about K_1/M and secondary information about K_2/M, while this is reversed in the latter sample. The (111) Co film sample indicated was a film 1000A thick evaporated onto a MgO single crystal substrate. The power law is drawn to correspond to the data at 300°K.

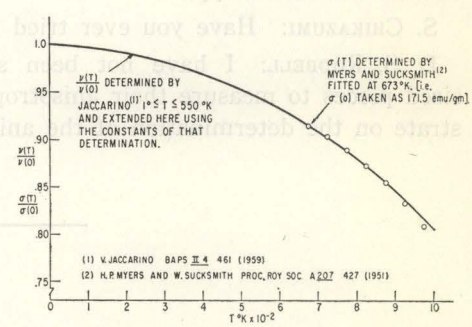

Fig. 3. The data of magnetization obtained by Myers and Sucksmith on bulk face-centered cubic cobalt in the stable temperature range of that material compared with the nuclear resonance data of Jaccarino on fine powders of f. c. c. cobalt extrapolated to high temperatures.

graphically where the σ data are fitted at 673°K. The fit obtained is quite good to 900°K and further predicts $\sigma(0)=171.5$ emu/g, an entirely reasonable estimate.

Conclusions

Face-centered cubic cobalt between 4.2° and 800°K (1) obeys a "10th power law" relating $K_1(T)$ to $\nu(T)$ suggesting that $\nu(T)\propto\sigma(T)$; furthermore, (2) since $\nu(T)$ maps onto $\sigma(T)$, this implies that the hyperfine coupling constant is not strongly temperature dependent. (3) The strain dependence, $1/K_1\,\partial K_1/\partial\omega$ has a temperature independent value of approximately 4, and (4) the splitting factor, g, is 2.06 ± 0.03, independent of temperature.

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DISCUSSION

W. SUCKSMITH: Since your results extrapolate the saturation intensity of cobalt at absolute zero to be 171.5 emu/gr, could you say how much this differs from the extrapolated value of Myers and Sucksmith?

D. S. RODBELL: The value I obtain from the extrapolation with the nuclear resonance data is $\sigma_0=171.5$ emu/gr whereas if I recall your paper correctly the magnetization at 0°K obtained by a law of correspondence states with nickel was found to be 169. Rather remarkable agreement for such widely different courses of approach used in the determination.

S. CHIKAZUMI: According to my experience on the epitaxially grown single crystal film of Fe and Ni, the magnetocrystalline anisotropy was anomalously large as compared to that of bulk materials. In this connection, I would like to ask whether you have ever tried to grow single crystal films by using a substrate other than MgO.

D. S. RODBELL: I have not. However, I have tried and measured nickel on MgO and found the value of K_1 to be in reasonable accord with Puzei's recent data of bulk nickel except that at high temperatures I do not find the change of sign usually observed in K_1 of nickel near 250°C. It must be pointed out, however, that ferromagnetic resonance measurements may not be identical with torque or magnetization determined anisotropy.

S. CHIKAZUMI: Have you ever tried to remove f.c.c. Co film from the substrate?

D. S. RODBELL: I have not been successful in removing these films in sufficient sized pieces to measure their anisotropy in order to determine the effect of the substrate on the determination of the anisotropy.