JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN VOL. 17, SUPPLEMENT B-I, 1962
PROCEEDINGS OF INTERNATIONAL CONFERENCE ON MAGNETISM AND CRYSTALLOGRAPHY, 1961, VOL. I

Anisotropy in Polycrystalline Nickel-Iron Thin Films in the Composition Range 40-100% Nickel*

G. ROBINSON
Mullard Research Laboratories, Redhill
Surrey, England

The variation of the uniaxial anisotropy constant, K, in polycrystalline nickel iron films over the composition range 40 to 100% nickel has been obtained from torque curves of the form $K\sin 2\theta$, plotted by the normal high field torque method. The results are described and interpreted in terms of the theories of directional ordering and stress, The variation of the form of the torque curve with applied measuring field is compared with the theoretical single domain torque curves. Rotational hysteresis is also measured as a function of applied field.

The results of measurements of torque as a function of field applied in the hard direction, to a film initially saturated in the easy direction, are also compared with theoretical single domain behaviour. The theoretical torque rises to a maximum for an applied field of $H_k/\sqrt{2}\left(H_k=\dfrac{2K}{M}\right)$ and falls to zero at H_k. The form of these curves, together with the rotational hysteresis studies shows the effect of local variations in anisotropy.

1. Introduction

The measurement of anisotropy in evaporated thin films of nickel iron using the high field torque method, in which the torque on the specimen is measured as a function of the direction of magnetization, yields torque curves of the form $K\sin 2\theta$ from which the uniaxial anisotropy constant K may be deduced. It is, however, well known that the value of K measured in this way is a mean value, the anisotropy varying locally in magnitude and direction over the film[1),2),3)]. The overall uniaxial anisotropy constant has been measured as a function of composition in the range 40-100% nickel using the high field method, and the results compared with the theoretical behaviour due to ordering and stress mechanisms. The measurements have then been extended to low fields and the departures from uniaxial single domain behaviour observed; these measurements suggest that, in the higher nickel content alloys, the local anisotropy variations are random and may be associated with the magnetocrystalline anisotropy.

2. Film Preparation

The films were in the form of 16 mm discs, evaporated on to cover glass substrates at a temperature of 240°C and a pressure of 10^{-5} Torr, a field of 50 Oe being applied in the plane of the film during deposition. Four films of the same composition were prepared at each evaporation, three being used for anisotropy measurement and one for optical determination of the thickness, which was in the region of 1000Å. One of the samples was later used for chemical analysis of the alloy composition.

3. High Field Torque Measurements

The high field anisotropy measurements were made using a torque magnetometer in which the film was suspended, with its plane horizontal, from a quartz fibre and the torque on the specimen measured as a function of applied field direction. The measuring field was applied in the plane of the film and was not less than thirty times the anisotropy field, which ensured that the magnetization lay within one degree of the field direction. For all films, curves of the form $K\sin 2\theta$ were obtained, where θ is the angle between the easy direction and the field direction and K the anisotropy constant. The values of K obtained for films in the composition range 40-100% nickel are summarised in Fig. 1. Also shown is a theoretical curve based on the theories of directional ordering[4)] and stress. The ordering contribution to the anisotropy has been estimated using the expression found by Ferguson[5)] to apply to bulk alloys annealed in a field at a temper-

* This paper was read by K. Hoselitz.

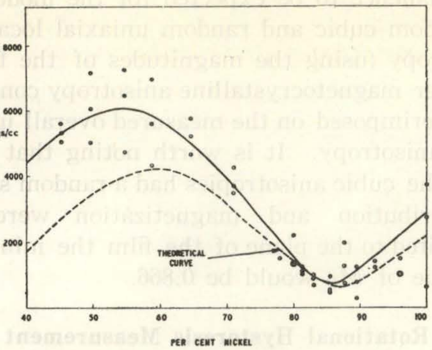

Fig. 1.

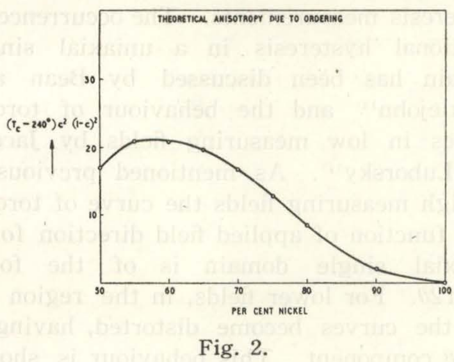

Fig. 2.

ature T_a;

$$K \propto (T_c - T_a)c^2(1-c)^2 \qquad (1)$$

where T_c is the Curie temperature and c the nickel concentration. The quantity

$$(T_c - 240)c^2(1-c)^2$$

has been plotted in Fig. 2 where it may be seen that the maximum in the anisotropy in the region of 55% nickel is in fair agreement with thin film results but that the finite anisotropy of a 100% nickel film is not consistent with this theory[6),7)].

The anisotropy in a nickel film has been attributed by many workers to a stress mechanism[8),9)]. In order to estimate the compositional dependence of stress anisotropy it has been assumed that, on deposition, the alloy is deformed magnetostrictively in the field direction by λ_{240}, the magnetostriction at that temperature. On cooling in the field and with the removal of the magnetization from its former direction, the substrate prevents relief of this strain, giving rise to a stress $\lambda_{240}E$, where E is Young's modulus for the alloy, and a resulting magnetic anisotropy measured at room temperature of $(3/2)\times\lambda_{RT}\lambda_{240}E$. This quantity is plotted as a func-

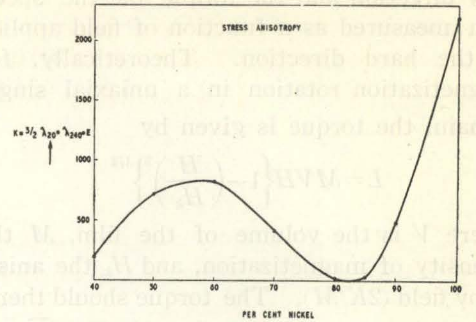

Fig. 3.

tion of composition in Fig. 3, using values of λ, $(3\lambda_{111}+2\lambda_{100})/5$ given by Bozorth and Walker[10)] and those of E given by Marsh[11)].

Since the theoretical stress contribution at 82% nickel is zero, the measured value for this composition has been attributed to ordering alone, and using this value and expression (1), the theoretical ordering contribution at other compositions calculated. The stress values shown in Fig. 3 have then been added to give the theoretical curve shown in Fig. 1.

4. Low Field Torque Measurements

A method by which the anisotropy field of a thin film may be measured in low fields was suggested by C. E. Fuller[12)]. In this method, the film is initially saturated in the

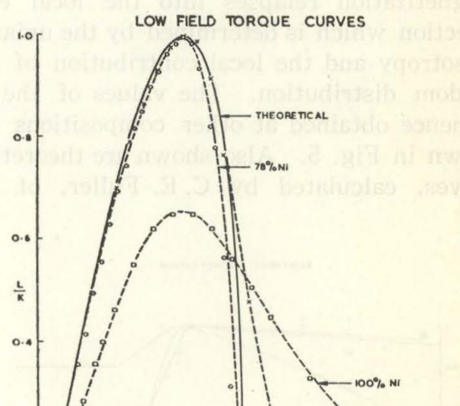

Fig. 4.

easy direction and the torque on the specimen measured as a function of field applied in the hard direction. Theoretically, for magnetization rotation in a uniaxial single domain, the torque is given by

$$L = MVH\left\{1-\left(\frac{H}{H_k}\right)^2\right\}^{1/2}$$

where V is the volume of the film, M the intensity of magnetization, and H_k the anisotropy field $(2K/M)$. The torque should therefore rise to a maximum for $H=H_k/\sqrt{2}$ and drop to zero for $H=H_k$. The theoretical behaviour is shown in Fig. 4, together with the experimental results for a 78% nickel film, a 50% nickel film, and a 100% nickel film. It can be seen that the curves for 50% and 100% nickel show tails which indicate the presence of high anisotropy components.

The initial slope of the curve in this method is equal to M_R, the remanent magnetization component in the easy direction after saturation in the easy direction and removal of the field. In the case of 78% nickel and 50% nickel, the value of M_R is approximately the bulk saturation magnetization but, for 100% nickel, M_R/M_S has the value 0.65. This fractional value of the remanent magnetization suggests that, superimposed on the uniaxial anisotropy, there is a random local anisotropy and that, after saturation in the mean easy direction, the magnetization relapses into the local easy direction which is determined by the uniaxial anisotropy and the local contribution of the random distribution. The values of the remanence obtained at other compositions are shown in Fig. 5. Also shown are theoretical curves, calculated by C. E. Fuller, of the remanence to be expected for the models of random cubic and random uniaxial local anisotropy (using the magnitudes of the fourth order magnetocrystalline anisotropy constant) superimposed on the measured overall uniaxial anisotropy. It is worth noting that even if the cubic anisotropies had a random spatial distribution and magnetization were not limited to the plane of the film the minimum value of M_R would be 0.866.

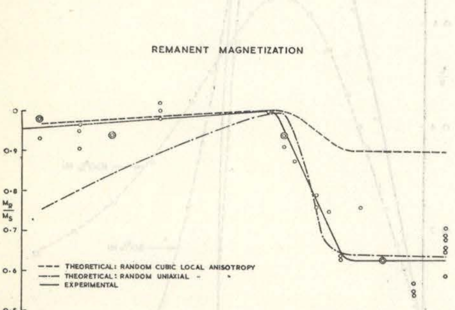

Fig. 5.

5. Rotational Hysteresis Measurement

The nature of the local anisotropy may be further investigated by means of rotational hysteresis measurements. The occurrence of rotational hysteresis in a uniaxial single domain has been discussed by Bean and Meiklejohn[13] and the behaviour of torque curves in low measuring fields by Jacobs and Luborsky[14]. As mentioned previously, in high measuring fields the curve of torque as a function of applied field direction for a uniaxial single domain is of the form $K\sin 2\theta$. For lower fields, in the region of H_k, the curves become distorted, having a $\sin 4\theta$ component. This behaviour is shown in Fig. 6, where the experimental points for a 78% nickel film are compared with the theoretical curve for $H=H_k$. It is for measuring fields below H_k and above $H_k/2$, where the curves include discontinuous, irreversible portions, that rotational hysteresis should occur. The departure from this behaviour

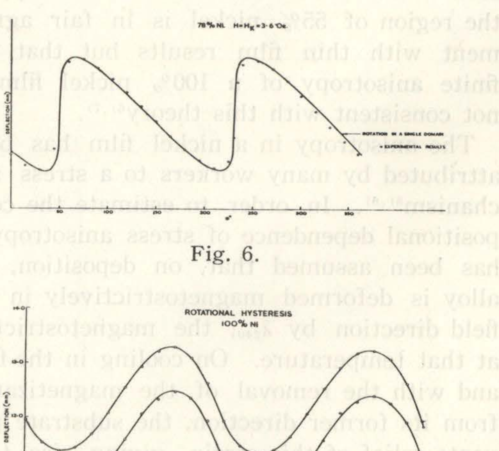

Fig. 6.

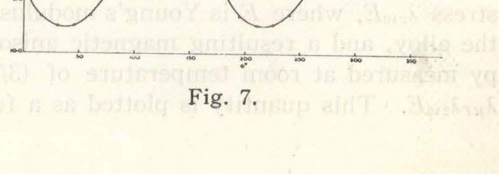

Fig. 7.

in a nickel film is shown in Fig. 7; the curve is not discontinuous and is predominantly of the form $\sin 2\theta$, but rotational hysteresis is still observed. This may again be attributed to a randomly oriented anisotropy distribution which does not contribute to the uniaxial anisotropy but does give rise to rotational hysteresis. The rotational hysteresis may therefore be expected to persist until the measuring field exceeds the maximum local anisotropy field present. Rotational hysteresis was measured as a function of field strength for a number of films, the field at which hysteresis disappeared being used as a measure of the local anisotropy field. It was found that, in general, the local anisotropy differed only slightly from the uniaxial anisotropy but that, above 90% nickel, the maximum anisotropy rose sharply, reaching approximately 260 Oe for 100% nickel. Using an arbitrary field value of 86 Oe, the rotational hysteresis in a nickel film was measured as a function of temperature; the result is shown in Fig. 8. The rapid decrease in hysteresis between room temperature and 100°C suggests a strong dependence of the local anisotropy on the magnetocrystalline anisotropy. Fig. 9 shows curves of rotational hysteresis as a function of field strength for pure nickel at room temperature and at 100°C; the room temperature curve was measured before and after the 100°C curve, to ascertain that the room temperature hysteresis reverted to its high value after the measurement at elevated temperature. The second room temperature curve, which is shown, did not however drop to zero, but to a constant low value.

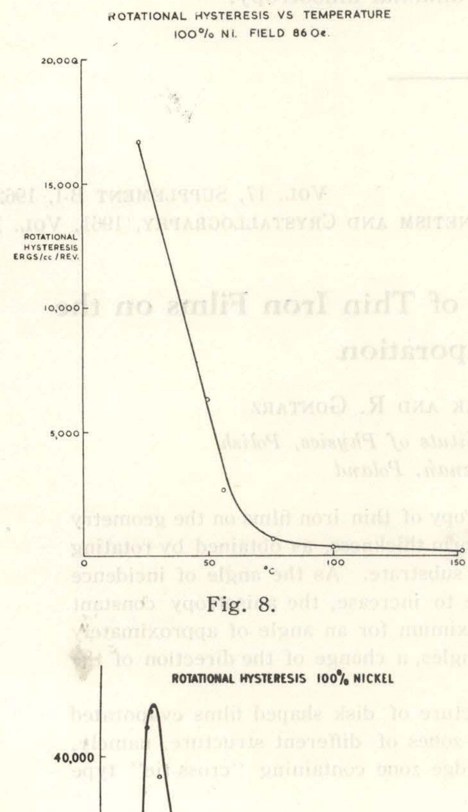

Fig. 8.

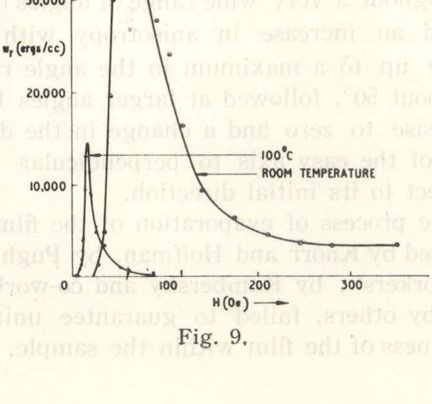

Fig. 9.

Acknowledgements

The author is greatly indebted to Dr. K. Hoselitz and Mr. C. E. Fuller for their advice and encouragement throughout this work and to Dr. R. W. Teale for helpful discussion. He would also like to thank Mr. R. A. Ford who prepared the films and made many measurements.

References

1 F. G. West, Nature, **188** (1960). 129.
2 Z. Frait, V. Kambersky, Z. Malek, M. Ondris: Czechoslovak Journal of Physics **10** (1960) 616.
3 K. J. Harte: Journal of Applied Physics **31** (1960) 283S.
4 L. Néel: Comptes Rendus **237** (1953) 1613.
5 E. T. Ferguson: Journal of Applied Physics **29** (1958) 252.
6 C. D. Graham, Jr. and J. M. Lommel: Journal of Applied Physics, **32** (1961) 83S.
7 W. Andra, Z. Malek, W. Schüppel, O. Stemme: Journal of Applied Physics **31** (1960) 442.
8 J. D. Blades: Journal of Applied Physics **30** (1959) 260S.
9 J. R. Macdonald: Phys. Rev. **106** (1957) 890.
10 R. M. Bozorth and J. G. Walker: Phys. Rev **89** (1953) 627.
11 J. S. Marsh: Alloys of Iron and Nickel **108** McGraw-Hill, New York and London.

12 C. E. Fuller, private communication.
13 C. P. Bean and W. H. Meiklejohn: Bull. Am. Phys. Soc. Ser II, 1 (1956) 148.
14 I. S. Jacobs and F. R. Luborsky: Proceedings of the Conference on Magnetism and Magnetic Materials, Boston, (1956).

DISCUSSION

S. METHFESSEL: You suggested that magnetostrictive stress is responsible for the additional anisotropy found in evaporated films. A consequence of this suggestion should be that the type of substrate will influence this anisotropy (e.g. by the value of the coefficient of thermal expansion). And the additional anisotropy should disappear after peeling off the film from the substrate.

K. HOSELITZ: The difference between thermal expansion of substrate and film makes only a contribution to the isotropic property of the film. It may influence the actual value of the magnetostrictive effect to a small extent. I agree that peeled films should not show the stress dependence of uniaxial anisotropy.

JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN VOL. 17, SUPPLEMENT B-I, 1962
PROCEEDINGS OF INTERNATIONAL CONFERENCE ON MAGNETISM AND CRYSTALLOGRAPHY, 1961, VOL. I

Dependence of Magnetic Properties of Thin Iron Films on the Geometry of Evaporation

S. SZCZENIOWSKI, H. RATAJCZAK AND R. GONTARZ

Laboratory of Ferromagnetics, Institute of Physics, Polish Academy of Sciences, Poznań, Poland

The dependence of the uniaxial magnetic anisotropy of thin iron films on the geometry of evaporation was investigated in samples of uniform thickness, as obtained by rotating an appropriately shaped diaphragm in front of the substrate. As the angle of incidence of the metal vapour onto the substrate was made to increase, the anisotropy constant was found to assume higher values, attaining a maximum for an angle of approximately 30° and then decreasing to zero; at still larger angles, a change of the direction of the easy axis occurred.

Moreover, investigation dealt with domain structure of disk shaped films evaporated at an angle. Here, single samples revealed two zones of different structure, namely, an inner zone of conventional structure and an edge zone containing "cross-tie" type walls. The edge zone revealed 90° domain walls.

Introduction

A number of authors[1-8] investigated the magnetic properties of thin ferromagnetic films with uniaxial magnetic anisotropy. In recent years interest is concentrated on the anisotropy of thin films as due to oblique incidence of the metal vapour onto the substrate in the process of evaporation[3-8]. Knorr and Hoffman[3], in iron films, found an increase in uniaxial anisotropy with the incidence angle. Cohen[7] and Kambersky *et al.*[8], who investigated permalloy films throughout a very wide range of angles (80°), found an increase in anisotropy with the angle up to a maximum in the angle range of about 50°, followed at larger angles by a decrease to zero and a change in the direction of the easy axis to perpendicular with respect to its initial direction.

The process of evaporation of the films as applied by Knorr and Hoffman, by Pugh and co-workers[6], by Kambersky and co-workers, and by others, failed to guarantee uniform thickness of the film within the sample. The