powers of κ. To get this, we use the series expansion

$$i^l j_l(i\kappa y)=\frac{(\kappa y)^l}{1\cdot3\cdot5\cdots(2l+1)}\times\sum_{s=0}^{\infty}(-)^{l+s}\frac{1\cdot3\cdot5\cdots(2l+1)}{1\cdot3\cdot5\cdots(2l+2s+1)}(\kappa y/2)^{2s}.$$

Putting this into the integral, (A1), we get the desired expression

$$f_l(k,K_i,\beta)=\frac{\kappa^l l!(-)^{l+1}}{(K_i^2+k^2-\beta)1\cdot3\cdot5\cdots(2l+1)}\times\left[1+\sum_{s=1}^{\infty}(-)^{s}\frac{\{1\cdot3\cdot5\cdots(2l+1)\}(l+2s)}{1\cdot3\cdot5\cdots(2l+2s+1)}(\kappa/2)^{2s}\right].$$

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Ferrimagnetic Structure of a Magnetite Crystal as Revealed by Electron Diffraction

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The process of thermal perturbation in electron diffraction is used to find the direction of easy magnetization, [111], of the lattice of magnetite. In the diffraction pattern of magnetite with incidence along the [1$\bar{1}$0] direction, the thermomagnetic displacement of the diffraction spots takes place perpendicular to the [111] axis. This fact leads to the direction of the magnetization according to the Lorentz force.

INTRODUCTION

THE lattice planes in a crystal of magnetite which are parallel to the electron spin planes oriented magnetically can be assigned by means of neutron diffraction.[1] In the present study it is demonstrated that a procedure of electron diffraction is able to detect these ferrimagnetic net planes.

EXPERIMENTAL

A thin and homogeneous magnetic field is established at the two sharp edges of magnetized razor blades of hard steel (remanence: about 5000 gauss). Here these two sharp edges are situated in a narrow gap (0.5 mm), as shown in Fig. 1. The minimum thickness of the wedge-shaped truncated edge is about 0.5 μ. A thin layer of magnetite crystal which was prepared by mechanical polishing was employed as a specimen for the experiment. The thickness and the area of this specimen were 5 μ and 0.5$\times$0.5 mm^2, respectively, and it contained some pinholes (of about 1 μ). The specimen was magnetized in the field (5000 oe) described above (see Fig. 1). An electron beam was passed in grazing incidence through one of the pinholes in the magnetized specimen in order to give rise to a diffraction pattern.

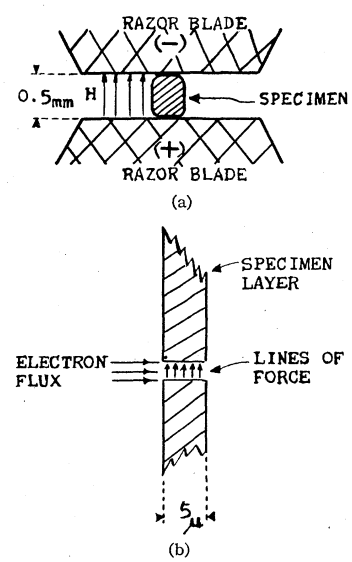


FIG. 1. Arrangement for the magnetization and for the diffraction experiment of the Fe_3O_4 layer. In (a) the electron beam runs perpendicular to the paper face; (b) shows the diffraction process through a pinhole of the magnetized Fe_3O_4 layer.

The Lorentz force of the specimen acting on the electrons was observed as a function of temperature. Here a procedure of double exposure was utilized to observe the thermally perturbed diffraction patterns. The diffraction pattern from the cold specimen (i.e., at 40°C) was first photographed, and then that of the hot specimen at 300°C was superimposed upon the former pattern. The position of the specimen and that of the photographic plate as well as the wavelength of the incident electron beam were all kept constant during this double exposure process. The double diagram obtained in this way is shown in Fig. 2, where the incident beam runs parallel to the [1$\bar{1}$0] axis of the magnetite crystal.

The temperatures of the specimen, 40°C and 300°C, were controlled by the irradiation of the electron beam.[2] The conditions of this electronic bombardment are characterized as follows: The current of the beam was

[1] G. E. Bacon, *Neutron Diffraction* (Clarendon Press, Oxford, 1955), p. 241.

[2] S. Yamaguchi, Z. angew. Phys. **13**, 253 (1961).

0.1 ma; the diameter of the electron flux was 0.1 mm; and the exposure time for 40°C and that for 300°C were 0.5 sec and 2 min, respectively (room temperature was 20°C). The area of the specimen bombarded by the electron beam was limited to be so narrow that the temperature of the razor edges was not elevated, and consequently the magnetic field from the razor edges (5000 oe) was kept constant.

Figure 3 was obtained from the specimen whose temperature was kept at 300°C. This diagram serves as a reference for Fig. 2. As a matter of fact, every diffraction spot found in Fig. 2 is split by a constant separation and in a specific direction, whereas this type of splitting is not found at the diffraction spots in Fig. 3. This splitting in Fig. 2 tells us that the Lorentz force of the cold specimen (40°C) acting on the diffracted electrons differs from that of the hot specimen (300°C). The direction of the splitting of the diffraction spots shown as **Z** in Fig. 2 leads to the easy magnetization axis of the magnetite crystal according to the Lorentz law. This axis agrees with the [111] axis, as indicated in Fig. 2. The effect of thermal perturbation on the diffraction spots in the cases of other orientations of the specimen relative to the direction of incidence than in Fig. 2, was negligible.

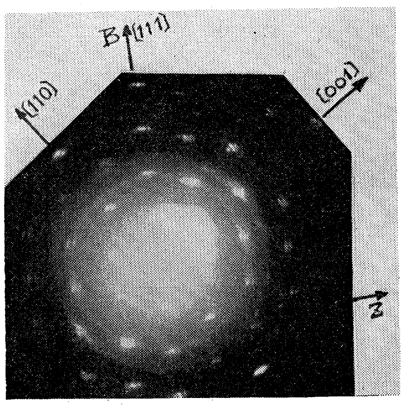


FIG. 2. Superposition of the two diffraction patterns from the cold (40°C) and the hot (300°C) states of the Fe_3O_4 specimen. Incident beam $\|[1\bar{1}0]$ axis. The splitting direction of the diffraction spots **Z** is perpendicular to the [111] axis, i.e., to the easy magnetization axis. The wavelength of the electrons was 0.0281 A, the camera length was 495 mm, and the positive was enlarged about 2 times.

FIG. 3. A single diagram of the Fe_3O_4 specimen at 300°C. There is no splitting at the diffraction spots here.

The thermomagnetic separation of the diffraction spots, ΔZ, measurable in Fig. 2, enables us to estimate the corresponding induction change, ΔI, of the magnetite specimen. We have the following relation between ΔZ and ΔI under the present conditions:

$$\Delta Z = (eL\lambda l/h)4\pi\Delta I, \qquad (1)$$

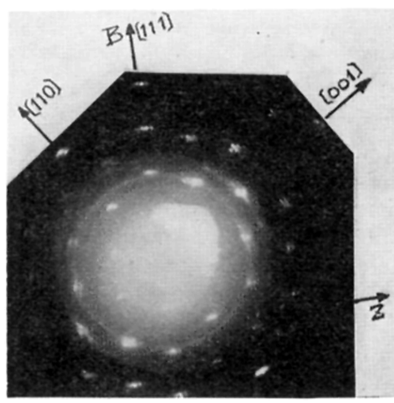
where e denotes the electron charge (1.6×20^{-20} emu), L the camera length (495 mm), λ the wavelength of the electrons (0.0281 A), h Planck's constant (6.6×10^{-27} erg sec), and l the magnetic path traversed by the electrons. This magnetic path is considered here to be approximately equal to the layer thickness of the specimen (5 μ, see Fig. 2). We measure $\Delta Z = 0.348$ mm on Fig. 2 and therefore we obtain $\Delta I \simeq 160$ gauss according to Eq. (1). This ΔI value is reasonable as the difference between the induction of magnetite at 40°C and that of 300°C.

DISCUSSION

The following two physical phenomena should be noted in the present procedure. The diffracted electrons run nearly parallel to the corresponding net planes in the diffraction of the rather fast electrons (Bragg angle: less than about 0.1°). These diffracted electrons are, therefore, quite suitable for the study of the magnetic induction lying perpendicular to the corresponding net planes.

The induction found in a material could be studied with one electron beam tunneling straight through it without diffraction. This beam is, however, so mixed with the incoherent electrons that it shows no definite wavelength and consequently it is not suitable for magnetic analysis.[3]

[3] Z. G. Pinsker, *Electron Diffraction* (Butterworths Scientific Publications, Ltd., London, 1953), p. 167.



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