The Magnetic Structure of Cobalt

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The magnetic powder method has been used to investigate the magnetic structure of cobalt crystals at room temperature. A stable colloid of gamma-ferric-oxide was deposited on suitable cuts of cobalt crystals by a magnetic field applied normal to the surface under observation. Smooth surfaces were prepared by metallurgical polishing followed by additional electrolytic polishing. (The latter method for polishing cobalt is described.) The surfaces chiefly studied approximated basal or prism planes. On all cuts three related patterns were found corresponding to no applied field or a normal field applied outward or inward. The two patterns with field were reciprocal in the sense that their spaces and deposits were interchanged. On basal planes the pattern appeared lace-like possessing considerable detail which was not easily modified by increasing the applied field. On prism planes the no-field pattern consisted of straight lines running parallel to the hexagonal axis. A small applied normal field spread the colloid in these lines into the alternate spaces between them. Further increase in field widened the resulting stripes in a somewhat erratic manner. Other interesting details of the patterns are described. In the discussion are listed the various energies involved in the demagnetization of an ideal crystal, i.e., one in which all energies concerned are reversible. The attempts of other authors to use these energies for devising magnetic structures are examined for their relation to magnetic powder patterns. It is concluded that the cobalt patterns do not accord with the structure demanded by simple theory which neglects irreversible energy changes accompanying demagnetization. The structure which seems best suited to explain the various patterns of cobalt is then proposed and discussed. To make this structure appear reasonable, the process by which a crystal goes from the fully magnetized to the demagnetized state (as suggested by various pattern observations) is described in terms of the dendritic growth of regions of reversed magnetization.

THE old magnetic powder method has recently been used with considerable success to establish new data concerning the magnetic structure of ferromagnetic crystals. Bitter[1] who first applied the method for this purpose published typical photomicrographs of patterns which he found on smooth (but unpolished) ingots of iron, nickel and cobalt. Other workers,[2,3] including the present writer, have improved the method and have extended the study of the iron and nickel patterns. No further investigation of the cobalt patterns has yet been reported.

Interpretation of the cobalt patterns in terms of a model should be easily made in view of the simplicity of the magnetic anisotropy of hexagonal cobalt which has but one direction of easy magnetization—the hexagonal axis. The present work shows that the structure is more complicated than that predicted by simple theory. It has been found possible, however, to propose a model which will account for the essential features of the various cobalt patterns.

[1] F. Bitter, Phys. Rev. **38**, 1903 (1931); **41**, 507 (1932).
[2] For a brief discussion with references see F. Bitter, *Introduction to Ferromagnetism* (McGraw-Hill Book Co., New York, 1937), p. 59.
[3] For more recent work see W. C. Elmore, Phys. Rev. **51**, 982 (1937) and T. Soller, Zeits. f. Physik **106**, 485 (1937).

SPECIMENS AND EXPERIMENTAL DETAILS

Several cobalt specimens were kindly supplied by Professor P. W. Bridgman of Harvard who had earlier secured them from K. Honda in Japan. They were in the form of cylinders about one centimeter in diameter and several centimeters in length, containing a number of large crystal grains. Various cuts of selected grains were prepared by careful sawing followed by the usual metallurgical polishing. Many of the surfaces were then electrolytically polished by the method devised by Jacquet[4] for copper and brass. The orientation of exposed grains was determined by etch reflections. The surfaces chiefly studied were either approximately parallel or perpendicular to the hexagonal axis, the direction of easy magnetization in cobalt at room temperature.

To polish cobalt by Jacquet's method an electrolyte of orthophosphoric acid (specific gravity about 1.35) was used. A satisfactory polish resulted with 1.2 volts between a comparatively large cobalt cathode and the specimen anode. Lower voltages, or agitation at 1.2 volts, produced an excellent macroscopic etch useful in

[4] P. Jacquet, Comptes rendus **201**, 1473 (1935); **202** 403 (1936).

determining crystal orientations. Somewhat higher voltages were found to produce passivity. As with copper and brass, a black film appeared on the surface at the start of the polishing. For cobalt this film proved to be ferromagnetic, as will be made clear by the following observation.

The electrolytic polishing leaves a surface not completely flat. If there are parallel ridges these are found to coincide with no-field lines in colloid patterns (Fig. 3b). This variation in removal of surface material was at first interpreted as a "magneto-chemical" effect. However, a microscopic examination of the surface shortly after the appearance of the black film showed it to be distributed as in Fig. 1. The relief polish, therefore, was due to an interference of uniform electrolytic action by the magnetically held skin fragments (cobalt oxide?). To avoid this effect the black film was carefully wiped away with cotton as soon as it could be seen. Since this procedure temporarily destroyed in the electrolyte the concentration gradient necessary for the polishing action, but did not result in the formation of a new film, it seems probable that the film was formed during previous exposure to air and not in the electrolyte.

As in previous experiments, magnetic fields were applied by mounting the specimen, usually irregular in shape, on the pole of a vertical electromagnet attached to the movable stage of a metallurgical microscope with vertical axis. The applied field was thus approximately normal to the surface under observation. It was never more than a few thousand gauss. Details concerning the use of magnetic colloid remained essentially as described for earlier experiments.[5]

Patterns on Basal Plane

The patterns of colloid on the basal plane of cobalt or on cuts inclined at small angles to this plane were similar to those previously reported by Bitter.[1] However, considerable improvement in the detail of the patterns was found to result from the use of a stable colloid instead of coarser powder which permanently settles out. Upon reversing the applied normal field these patterns always exhibited a shifting effect similar to that of the "maze" patterns found on polished iron crystals. Fig. 2b illustrates the typical pattern found with no applied field. An applied normal field changed this pattern to that of Fig. 2a or Fig. 2c depending on its direction. Careful comparison of the latter two patterns reveals a complete reciprocity, i.e., a detailed interchange of deposits with spaces.

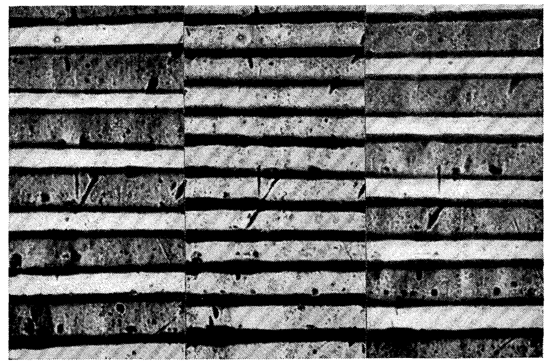
The colloid of the no-field pattern is spread out more evenly except in numerous small areas which are completely lacking in colloid. The position of these areas coincides with the centers of the meshes of the applied field patterns. The colloid of all cobalt patterns was found to be much more securely held by stray fields than that of patterns on polished iron or nickel crystals. Indeed, washing the surface with running tap water did not seem to disturb it. This procedure was found useful for removing excess colloid not yet congregated into the pattern.

In contrast to the "maze" patterns of iron crystals, none of the cobalt patterns required a cold-worked surface for their existence. In one experiment a mechanically polished surface was electrolytically polished to the extent of removing a layer 0.1 mm thick. The pattern on the new surface was very nearly identical with the old one. Patterns on other surfaces electrolytically polished to much greater depths possessed the same typical appearance. It was observed that the patterns on different grains and sometimes on different parts of the same grain varied considerably in scale.

Except for the shifting effect just described, the basal patterns proved to be very stable in the presence of the available normal field. This field, due to the large demagnetization factor of the specimen, was only sufficient to magnetize it to perhaps 25 percent of saturation. The stability of the basal patterns differs essentially from that of the line patterns on prism planes (see next section). The only change in basal patterns noticed was a sideward motion of some of the meshes near the edge of one grain. Bitter has shown (Figs. 7–9 of his second paper[1]) what happens to the basal patterns on applying intense fields parallel to the basal plane. No attempt has yet been made to investigate further these changes associated with intense fields. For purposes of discussion it seems correct to consider that the present patterns are produced by an

[5] For a discussion of technique see reference 2, p. 55.

FIG. 1. Distribution of film which was set free from the surface (a prism plane) early in the process of electrolytically polishing cobalt. No applied field. Magnification approx. 215×.



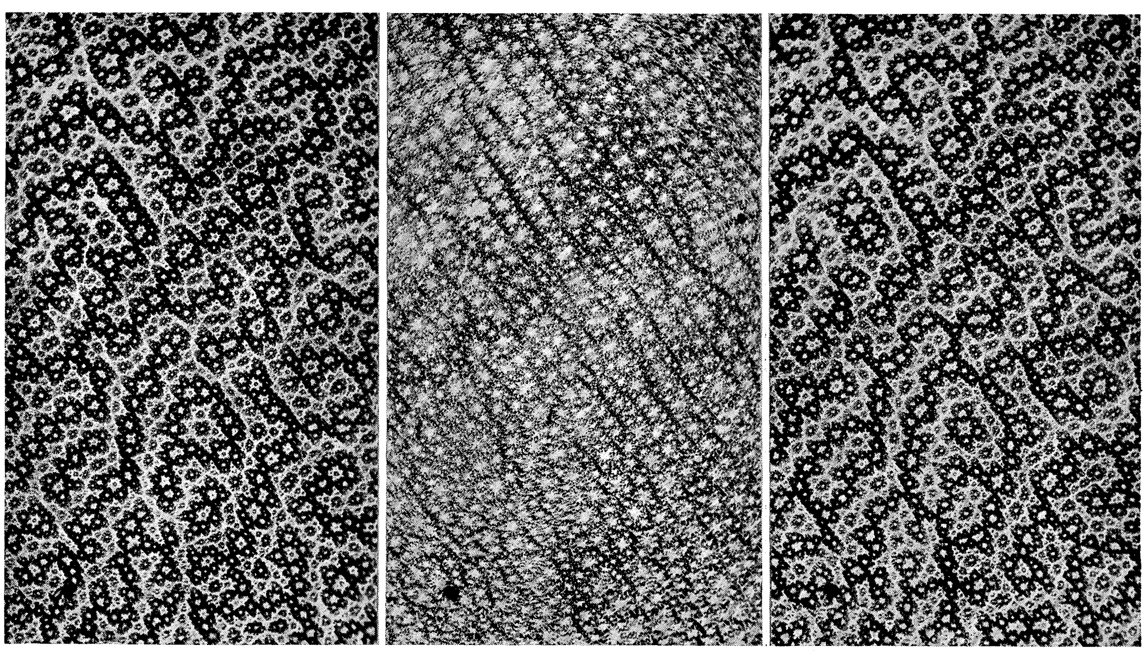
a b c

FIG. 3. Patterns of magnetic colloid on a cobalt surface approximately perpendicular to the basal plane with applied normal field (a) outward; (b) zero; (c) inward. The lines run parallel to the hexagonal axis. Magnification approx. 65×.

unchanging, or but slightly changing pattern of local fields with or without the superposition of an applied normal field.

PATTERNS ON PRISM PLANES

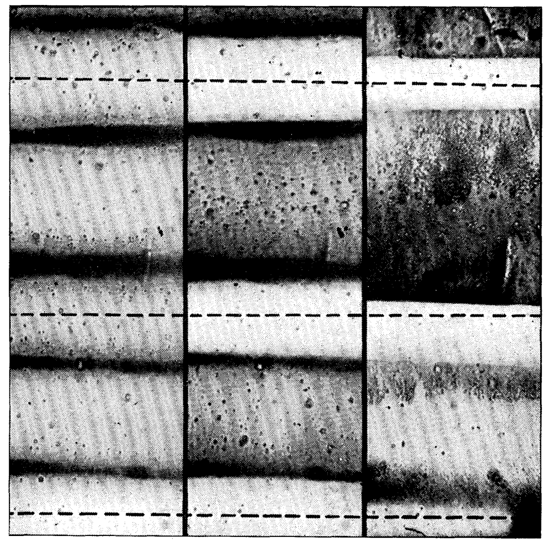
The patterns on planes approximately normal to the basal plane are illustrated in Figs. 3a, 3b and 3c. These patterns, whose general appearance does not depend on the angle between their plane and a type $\{10\bar{1}0\}$ plane, were obtained, respectively, with plus, zero, and minus applied normal fields. The no-field pattern consists of narrow lines whose general direction is parallel to the hexagonal axis. In Fig. 3b the average spacing of the lines is about 60μ. On other grains different spacings were found varying from a few microns



a b c

FIG. 2. Patterns of magnetic colloid on the basal plane of a cobalt crystal with applied normal field (a) outward; (b) zero; (c) inward. The spaces and deposits are interchanged in (a) and (c). Magnification approx. 75×.

FIG. 4. Line patterns on several crystal grains with no applied field. The lines are spaced closer together in the smaller grains. Lines on adjacent grains tend to join at the grain boundaries. The V shaped line deposits near these boundaries are especially to be noted. Magnification approx. 65×.



a b c

FIG. 5. Set of patterns which illustrate widening of bands when the applied normal field is increased. (a) No field; (b) small applied field; (c) applied field 5 times as intense as in (b). Magnification approx. 190×.

up to values slightly exceeding that of those shown. A variety of spacings can be observed in Fig. 4 which shows line patterns on several grains. The smaller grains exhibit the closer spacings.

The two patterns with applied field consist of bands of colloid located in alternate colloid-free stripes of the no-field pattern. They bear the now familiar reciprocal relation to each other. The width of these bands proved to be very sensitive to the magnitude of the applied field. For the patterns shown in Fig. 3 this field was the minimum necessary to spread some of the colloid into bands, though much of it, as can be seen, remained in the former no-field lines. The bands, however, are somewhat wider than the intervening spaces. When the field was gradually increased still further the bands continued to grow in width at the expense of the vacant spaces. At the same time the colloid spread itself out more evenly over the bands. The edges of the widening bands moved with a continuous motion punctuated locally by sudden jerks. It appeared as if a certain advancing edge would occasionally meet an obstacle which for a time prevented its progress. After other neighboring boundaries had advanced further the impeded boundary would abruptly jump into place, and then continue in its uniform motion. Two widening bands occasionally merged either by joining throughout their visible length, or quite often by first touching only at a point. In the latter case the apices of the two V-shaped spaces receded from each other with a continued increase of the applied field.

If at any time the field was diminished, the motion of the boundaries reversed. Soon, however, discontinuities in motion of the sort just described would again be observed. Upon complete removal of the field the no-field pattern was similar in scale but in detail apparently unrelated to that first observed. Fig. 5 illustrates the

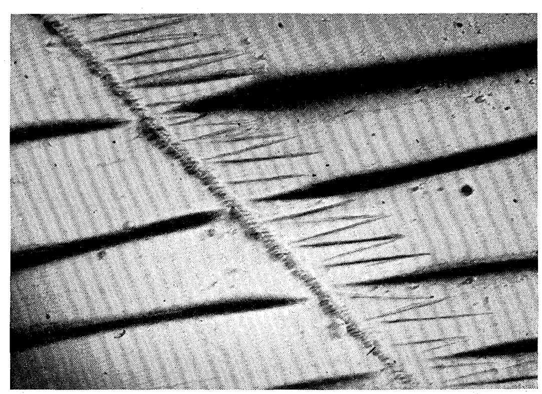


FIG. 6. Pattern of magnetic colloid associated with structure interpreted as a twin band. This pattern was found on the crystal grain which gave Fig. 3. Magnification approx. 215×.

widening of bands associated with increasing field.

The transition of a prism pattern to a basal pattern was studied at the rounded corner connecting the two planes. On approaching the corner V-shaped line deposits appeared which multiplied the number of lines at the edge of the prism pattern. These lines merged with a pattern resembling that of Fig. 2 when viewed at an oblique angle, the distortion decreasing further until the typical basal pattern appeared. The increase in the number of pattern lines was very similar to that found at the grain boundaries in Fig. 4. A somewhat similar group of V-shaped deposits was noticed near certain line markings found on many of the grains showing prism patterns as illustrated in Fig. 6. In this figure the narrow band, possessing a fine magnetic structure and crossing the black no-field lines, was also revealed by etching. This structure may therefore be identified as the trace of a twin band.[6] The plane of such a twinned lamina will in general approach the surface making an acute angle with it on one side of the trace, thus accounting for the unsymmetrical occurrence of the V-structures which according to this analysis depend for their existence upon large demagnetizing fields.

Discussion

Before discussing the experimental results the basic facts of ferromagnetism will be reviewed briefly. In this review the attempts of other authors to explain the nature of magnetic secondary structure will be considered. According to the Weiss-Heisenberg theory,[7] a ferromagnetic crystal will be at all times spontaneously magnetized to a saturation value which depends on the temperature and becomes zero at the Curie point. Actual crystals, however, possess little or no net magnetic moment unless placed in a magnetic field. To resolve this apparent contradiction the crystal has long been considered to be subdivided into numerous small domains each saturated, so that the crystal as a whole appears unmagnetized. This division into domains can be most simply dealt with by considering the various energies involved in the absence of applied fields.

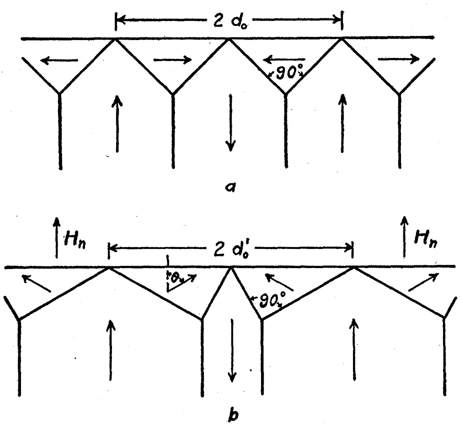


FIG. 7. (a) Schematic diagram (according to Landau and Lifshitz) showing arrangement of magnetization in plane perpendicular to a surface which is perpendicular to direction of easy magnetization. (b) Previous diagram so modified as to include the presence of an applied normal field H_n. Neither of these arrangements of magnetization demanded by minimum total energy of the crystal gives rise to superficial stray fields which can produce magnetic powder patterns.

(1) An energy density E_w associated with the Weiss field (exchange interaction)

E_w is increased by changes in direction of the local magnetization $\mathbf{I}_s$. Explicitly

$$E_w = -\tfrac{1}{2}NI_s^2 + \tfrac{1}{6}Na^2\{(\nabla I_{sx})^2 + (\nabla I_{sy})^2 + (\nabla I_{sz})^2\},$$

where N is the Weiss field constant, "a" is the lattice separation of nearest neighbors and $\mathbf{I}_s$ is the intensity of magnetization (varying only in direction). The first term is well known.[7] The second term, used by Landau and Lifshitz[8] in a manner to be mentioned presently, may be obtained readily by averaging the energy of interaction of a particular elementary magnet with its nearest neighbors. This interaction is assumed for each pair to be of the form $-c\mathbf{I}_s\cdot\mathbf{I}_s'$ where

$$\mathbf{I}_s' = \mathbf{I}_s + (\Delta\mathbf{r}\cdot\nabla)\mathbf{I}_s + \tfrac{1}{2}(\Delta\mathbf{r}\cdot\nabla)^2\mathbf{I}_s,$$

in which $\Delta\mathbf{r}$ gives the position of the selected neighbor. Here $c=\tfrac{1}{2}N$ since $E_w = -\tfrac{1}{2}NI_s^2$ when $\mathbf{I}_s$ does not vary in direction. In what follows E_w will be taken to stand for the second term alone.

[6] The twinning of cobalt has apparently not been reported. The present twinned regions are tentatively identified as occurring on the $\{10\bar{1}2\}$ pyramidal planes, as found for other close-packed hexagonal crystals.

[7] E. C. Stoner, *Magnetism and Matter* (Methuen and Co., London, 1934), Ch. XI.

[8] L. Landau and E. Lifshitz, Physik. Zeits. Sowjetunion **8**, 153 (1935).

(2) An energy density E_θ associated with the magnetic anisotropy of the crystal

This energy may include the effects of strain as well as the natural crystal anisotropy. E_θ for unstrained cobalt at room temperature is found empirically to be represented fairly well by $E_\theta = K' \sin^2\theta + K'' \sin^4\theta$ where θ is the angle between the hexagonal axis and $\mathbf{I}_s$, $K' = 5.1\times 10^6$ and $K'' = 2.2\times 10^6$.[9] The behavior of E_θ, therefore, depends essentially on the quadratic term, and the approximation $E_\theta \doteqdot \frac{1}{2}\beta I_s^2 \sin^2\theta$ may be conveniently used in discussing magnetic structure. In the simplified expression β may be taken to be $2(K'+K'')/I_s^2 = 7.2$ so that E_θ is correct for both $\theta=0$ and $\theta=90°$.

(3) An energy density $E_H = -\frac{1}{2}\mathbf{H}\cdot\mathbf{I}_s$ where $\mathbf{H}$ is the macroscopic field due to the entire crystal calculated from the potential

$$\phi = \int \frac{\mathbf{I}\cdot d\boldsymbol{\sigma}}{r} - \int \frac{\nabla\cdot\mathbf{I}}{r} d\tau.$$

Frenkel and Dorfman[10] seem to have made the first approximately correct estimate of the diameter d_0 of magnetic domains. By a simple argument (neglecting E_θ) they are able to estimate that $\int_0^V E_w d\tau = C_1/d$ and that $\int_0^V E_H d\tau = C_2 d$ for a space-filling array of disorientated domains of diameter d within a crystal of volume V. It follows that $do = (C_1/C_2)^{\frac{1}{2}}$ for minimum energy. They find for iron crystals of moderate volume V that $d_0 \doteqdot 100\mu$.

Bitter,[11] working with a torque equation equivalent to minimizing $\int(E_w+E_\theta)d\tau$, integrated over regions of the crystal remote from the surface, has discussed what he terms the "elastic deformation of ferromagnetism." The particular cases which he studied are unfortunately chosen since in all of them $\nabla\cdot\mathbf{I}_s\neq 0$. The torques due to the resulting internal magnetic fields are sufficient to render his arrangements of $\mathbf{I}_s$ physically unstable. His attack on the problem, if carried far enough, should lead to the more detailed conclusions of Landau and Lifshitz[8] which will now be discussed.

Landau and Lifshitz minimize $\int(E_w+E_\theta)d\tau$ integrated over the entire crystal. They conclude that in the demagnetized state the magnetization should occur chiefly in plane layers magnetized alternately parallel and anti-parallel to the direction of easy magnetization. Near a surface perpendicular to this direction they propose the arrangement of $\mathbf{I}_s$ shown in Fig. 7a, for which $\int_0^V E_H d\tau = 0$ since $\nabla\cdot\mathbf{I}_s = 0$ and $I_n = 0$. The transition of $\mathbf{I}_s$ from one layer to the next is found to occur gradually, not abruptly. It takes place by a twisting of $\mathbf{I}_s$ about the normal to the boundary between layers, thus making $\nabla\cdot\mathbf{I}_s = 0$. Their equations indicate that the thickness of the transition layer for cobalt is about 45 lattice spacings. The thickness d_0 of the layers is found by minimizing the sum of the energy of the transition layers (of the form $E_i = C_1/d$) and the anisotropy energy in the regions of triangular cross section (of the form $E_s = C_2 d$). If l is the distance between two basal surfaces of a cobalt crystal they find that $d_0 = (8l)^{\frac{1}{2}}(\alpha/\beta)^{\frac{1}{4}}$ for minimum energy, where $\alpha = \frac{1}{3}a^2N = 8.3\times 10^{-12}$ and $\beta = 7.2$. This gives $d_0 \doteqdot 15\mu$ for $l = 0.3$ cm, the approximate size of the larger crystal grains in the specimens here studied. This spacing is less than that of the parallel lines of the prims patterns. It is more nearly a measure of the scale of the finer structure in the basal patterns. The minimum energy $\int_0^V(E_w+E_\theta)d\tau$ is somewhat increased if instead of layers, prisms of square or triangular cross section are assumed, together with the arrangement of $\mathbf{I}_s$ near plane surfaces which makes $\int_0^V E_H d\tau = 0$. Hexagonal prisms cannot be arranged so that $\int_0^V E_H d\tau$ vanishes, hence a model with these units would have a still greater minimum energy.

Landau and Lifshitz have also considered crystals with surfaces inclined to the basal plane. By suitable arrangements of $\mathbf{I}_s$ they retain the condition that $\int_0^V E_H d\tau = 0$ and calculate for the layer model the dependence of d_0 upon the inclinations of the exposed surfaces. If their condition that $\nabla\cdot\mathbf{I}_s = 0$ within the crystal be applied to the arrangement of Fig. 7a when an applied normal field is present, the situation becomes that depicted by Fig. 7b. For this arrangement

$$\nabla\cdot\mathbf{I}_s = 0, \quad I_n = I_s\cos\theta = H_n/4\pi,$$

and

$$d_0' = d_0[1-(I_n/I_s)^2]^{-\frac{3}{4}}.$$

The change in scale of the structure indicated by the last equation results from the decrease in E_s

[9] J. H. Van Vleck, Phys. Rev. **52**, 1178 (1937). All energy densities are expressed in erg. cm^{-3}.

[10] J. Frenkel and J. Dorfman, Nature **126**, 274 (1930).

[11] F. Bitter, Sci. Rep. Tôhoku Imp. Univ. (Honda Volume), 228 (1936); also reference 2, p. 186.

due to: (1) a decrease in volume of the triangular prisms seen end-on in Fig. 7; (2) a decrease in E_θ in these prisms resulting from the rotation of $\mathbf{I}_s$ therein. From the equation it appears that d_0' differs appreciably from d_0 only for large I_n. The difference in scale is important, however, in considering the regrowth of magnetic structure in a crystal which has been magnetized to saturation by an external field.

It is a characteristic of the crystal internally divided into layers or into square or triangular prisms, that $\int_0^V E_H d\tau = 0$. Hence, in the absence of an applied field, a crystal possessing one of these structures should give no pattern. Even an applied normal field should produce no pattern if Fig. 7b is correct, for the field above the specimen is uniform although the magnetization beneath possesses a definite structure. In most cases, however, some stray field will be present; the result of an effect neglected in the Landau-Lifshitz model. $\mathbf{I}_s$ in the surface prisms of triangular section will in general rotate so as to diminish $(E_\theta + E_H)$. This requires $E_H > 0$. This effect can be estimated for the arrangement of $\mathbf{I}_s$ in Fig. 7b, as follows: replace the triangular prisms by an extensive parallel slab of crystal initially magnetized parallel to its surface. By minimizing the energy $E = E_\theta + E_H - H_n I_s \cos\theta$ it is found that a normal field H_n will tilt $\mathbf{I}_s$ by an amount given by $\cos\theta = H_n/[(4\pi - \beta)I_s]$ rather than by $\cos\theta = H_n/4\pi I_s$. As $\beta \doteqdot 2\pi$ for cobalt, this effect is quite appreciable, hence in the event of a layer structure, some deposition of colloid should be expected.

For ideal crystals there seems little doubt that the treatment just outlined is essentially correct. The discrepancy between the ideal structure and the one indicated by the patterns probably arises during the process whereby the crystal goes from the magnetized to the demagnetized state. Irreversible energy losses accompanying this process dissipate some of the potential energy which would otherwise be available to establish the ideal structure. Nevertheless, the Landau-Lifshitz treatment is important since it justifies the description of magnetic structure in terms of geometrical models. Furthermore, it suggests arrangements of $\mathbf{I}_s$ likely to occur, such as that of Fig. 7a. For instance, if the layers should extend all the way to the surface, the resulting surface energy $(\int_0^V E_H d\tau)$ would be much greater than that when the triangular prisms lying in the surface afford a return path for lines of induction within the crystal. With this background the patterns can now be analyzed.

The prism patterns (parallel lines and bands) can be interpreted as indicating sections of regions magnetized alternately parallel and antiparallel to the hexagonal axis. The no-field patterns indicate that the surfaces so far observed have not been exactly parallel to the axis so that alternate strips have I_n plus and minus. This accounts satisfactorily for the observed patterns. The widening of the bands with increasing applied field is, of course, an additional feature. The component of the applied field parallel to the axis must be responsible for this. Thus by a suitable choice of field direction near the normal it should be possible to control independently the width of the bands and the particular set of strips preferred by the colloid.

Since the field $\mathbf{H}$ below the surface arising from the potential $\int \mathbf{I}_s \cdot d\boldsymbol{\sigma}/r$ is an image of the stray field above the surface, the magnetization near the surface will be rotated so as to decrease the stray field. This decrease amounts to perhaps 60 percent for surfaces slightly inclined to the hexagonal axis. It should not alter the essential features of the prism patterns.

The spacing of the parallel lines requires some comment. Its regularity is probably not typical of the magnetic structure existing before the surface was prepared. For surfaces not too oblique to the axis the number of regions should not be changed, but the energy will be minimized by making the areas of adjacent regions of opposite polarity more nearly equal.

A clear interpretation of the basal patterns is more difficult to achieve. As already pointed out none of the simple structures of layers, square or triangular prisms is adequate. A clue is found in the fact that the spacing of the parallel lines is about equal to the spacings of the irregular areas of light and heavy deposit in the basal patterns. It is suggested that the more or less definite boundaries between these distinguishable areas are traces of the boundaries separating regions of reversed magnetization deep in the crystal. The finer detail seems closely connected with dendrite-like reversed regions extending short distances into the crystal and producing in cross section the V-shaped line deposits. This picture is probably further complicated by the occurrence of dendrites within dendrites, as some of these deposits in Fig. 4 suggest. The following analysis, suggested by the behavior of the cobalt patterns studied so far, is an attempt to make this magnetic structure appear a reasonable one.

Imagine a disk shaped crystal having basal planes as faces and magnetized to saturation by a field applied parallel to the disk axis. If H is reduced slightly below $4\pi I_s$ regions of reverse magnetization must form. Presumably many of them occur first at the two basal surfaces and then grow inward towards one another, finally meeting by pairs to form complete thread-like regions extending through the crystal. In their early stages of growth these regions resemble dendrites of a solid phase growing into the melt. The conditions are similar in respect to the gradual supply of energy necessary for the change occurring and in respect to the stability in space of the transformed regions.

As H is still further reduced, more dendrites form, those already present continue to grow inward and the completed threads (or prisms) increase in cross section. The surfaces of the disk will on the average be uniformly populated with reversed regions. The number of reversed regions will become greater as demagnetization proceeds. This corresponds to the change in scale of the ideal layer structure, previously pointed out. The requirement of finer scale at later stages necessitate that some of the new dendrites form within regions already anti-parallel to H, and hence be themselves parallel to H. Photographs have been taken of V-structures near the boundaries of prism patterns which, if one judges from the deposit on them, were magnetized parallel to H, and *which grew as H was decreased*. Finally, when H becomes zero, many of the dendrites started last will remain as such, there being insufficient energy available for them to grow far into the crystal. This is equivalent to stating that the residual magnetic field at the boundaries of the dendrites is insufficient to cause their further advance. The resulting magnetic structure near a basal surface is not one of plane parallel layers, but one more nearly described as consisting of hexagonal prisms of about the same size, arranged so that the energy $\int_0^V (E_w+E_\theta+E_H)d\tau$ is as small as possible. A short distance from the crystal surface many of these prisms pinch out leaving the much coarser structure responsible for the typical prism patterns.

Some of the hexagonal prisms will be completely surrounded at a basal surface by others of opposite magnetization. An arrangement of $\mathbf{I}_s$ corresponding to the layer model in Fig. 7a is demanded by minimum energy for such a grouping. Hence there will be locally no stray field above the surface. The absence of colloid in certain areas of the no-field basal patterns, and the very small amount appearing above these same areas in the normal field patterns may thus be accounted for. At other boundaries between oppositely magnetized prisms only a part of the lines of induction can return within the crystal. Indeed, the best possible arrangement of regular hexagonal prisms permits the return of but two-thirds of the lines of induction in this manner; the remainder give rise to the stray field which is chiefly responsible for the basal patterns.

In conclusion it should be pointed out that the erratic movement of the parallel lines is visual evidence of the Barkhausen effect. This effect in cobalt does not seem to consist of the sudden reversal of definite domains in the crystal, but may be ascribed to the uneven motion of boundaries between regions considerably larger than those usually assigned to account for Barkhausen discontinuities, containing about 10^{12} atoms. Local imperfections in the crystal are no doubt responsible for this effect. They also must be largely responsible for energy lost during the process of demagnetization.

The author is greatly indebted to Professor F. Bitter of the department of metallurgy for providing certain facilities for conducting this research, and to Professor L. W. McKeehan of Yale for reading and discussing the manuscript.

FIG. 1. Distribution of film which was set free from the surface (a prism plane) early in the process of electrolytically polishing cobalt. No applied field. Magnification approx. 215×.

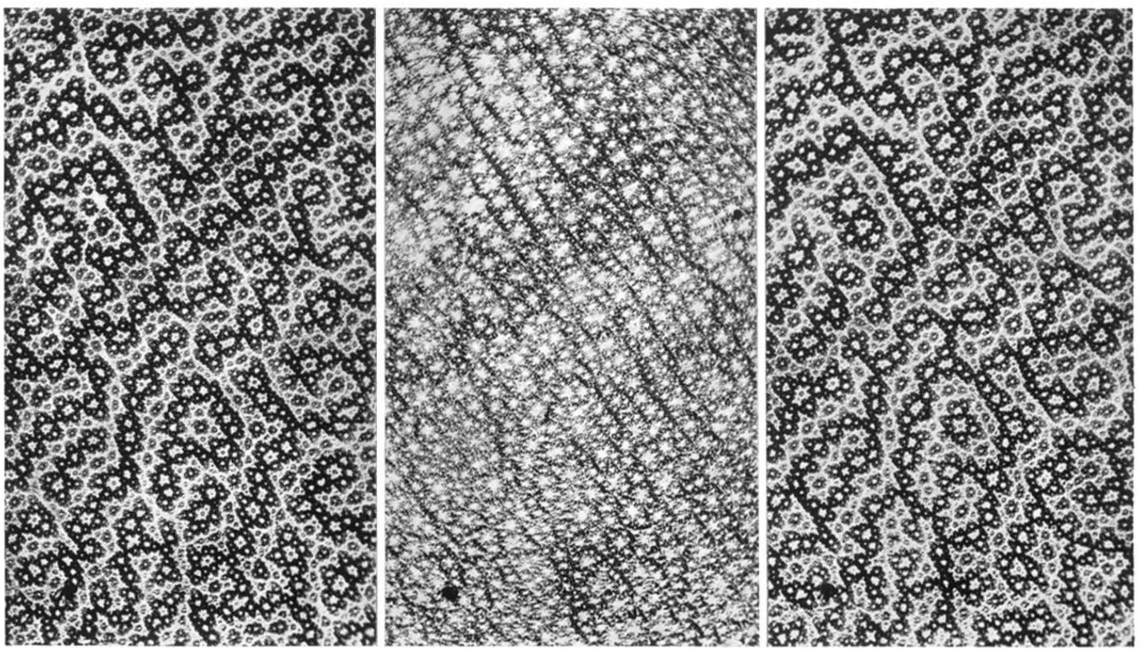


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FIG. 2. Patterns of magnetic colloid on the basal plane of a cobalt crystal with applied normal field (a) outward; (b) zero; (c) inward. The spaces and deposits are interchanged in (a) and (c). Magnification approx. 75×.

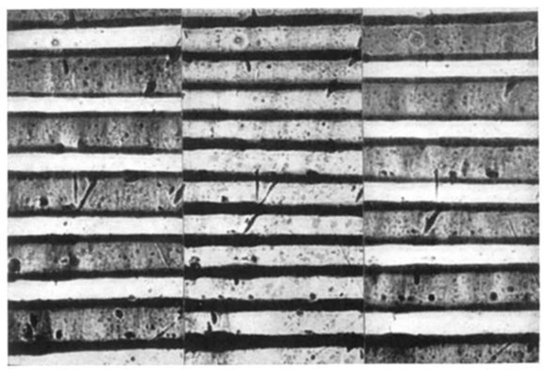

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FIG. 3. Patterns of magnetic colloid on a cobalt surface approximately perpendicular to the basal plane with applied normal field (a) outward; (b) zero; (c) inward. The lines run parallel to the hexagonal axis. Magnification approx. 65×.

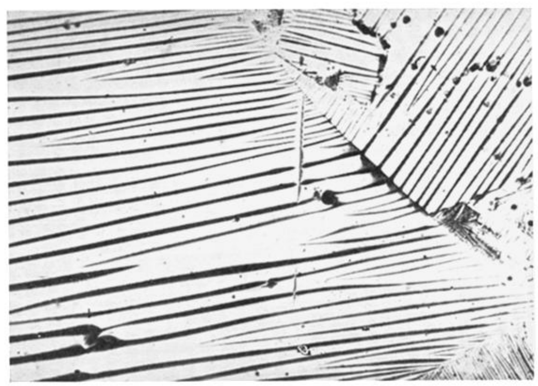
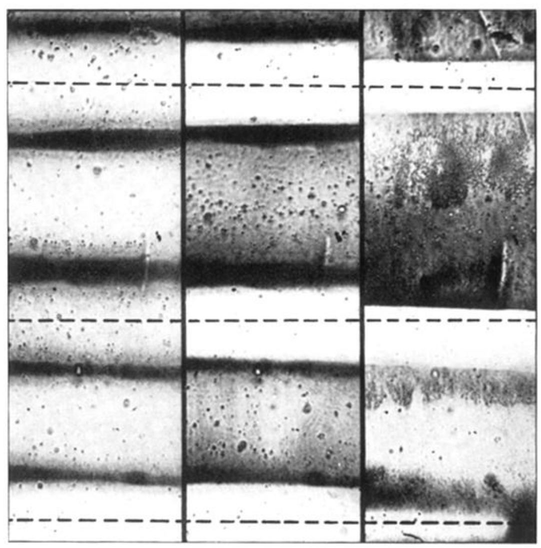


FIG. 4. Line patterns on several crystal grains with no applied field. The lines are spaced closer together in the smaller grains. Lines on adjacent grains tend to join at the grain boundaries. The V shaped line deposits near these boundaries are especially to be noted. Magnification approx. 65×.



a b c

FIG. 5. Set of patterns which illustrate widening of bands when the applied normal field is increased. (a) No field; (b) small applied field; (c) applied field 5 times as intense as in (b). Magnification approx. 190×.

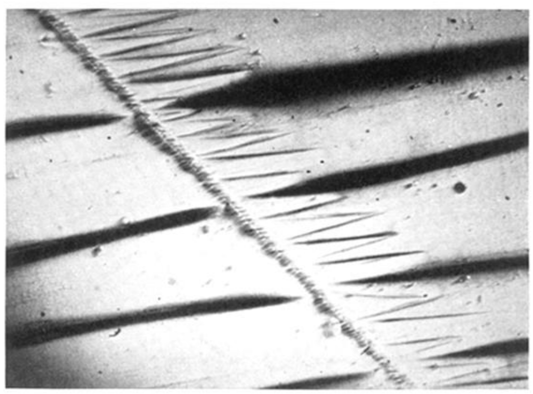


FIG. 6. Pattern of magnetic colloid associated with structure interpreted as a twin band. This pattern was found on the crystal grain which gave Fig. 3. Magnification approx. 215×.