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Barkhausen Effect. III. Nature of Change of Magnetization in Elementary Domains

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Transverse Barkhausen effect. It is found that the small sudden changes in magnetic moment which take place when material is magnetized, have components perpendicular as well as parallel to the direction of the magnetic field. Quantitative measurements of the transverse and longitudinal effects (changes in moment perpendicular and parallel to the direction of the field) show that the longitudinal effect is the larger when the magnetization is small and that the transverse effect is larger when the magnetization is large. Materials examined are (polycrystalline) annealed iron, hard-worked iron, and perminvar.

Domain theory of ferromagnetism. The results are interpreted in terms of the domain theory, according to which ferromagnetic materials consist of small regions or domains always magnetized to saturation. Changes in magnetization are accomplished only by changes in the *directions* of magnetization in the domains. Sudden changes from one to another of the natural directions of magnetization in the crystal give rise to the Barkhausen effect, and in general have definite transverse and longitudinal components, the former now observed for the first time. The experiments show that when the gross magnetization (that of the substance as a whole) is small, the application of an additional magnetic field causes *reversal* of the direction of magnetization in the domains for which this direction was initially nearly antiparallel to the field. Experiments on annealed iron with high gross magnetization indicate, on the contrary, that the direction of magnetization in a domain may be altered through 90°.

IN STUDYING the Barkhausen effect, experimenters have generally observed the voltage-impulses in coils encircling the material and oriented with their axes parallel to the varying magnetic field. These are ascribed to sudden changes of the magnetization of individual small domains of the metal: changes which may be either complete reversals, or rotations through angles smaller than 180°. It occurred to us that if this view is correct, voltage-impulses should appear in coils oriented with their axes at right angles to the magnetizing field; and that the study of these impulses, which we shall designate *the transverse effect*, should increase our knowledge of the elementary processes. Thus, if the transverse effect should be absent or small, it would be inferred that the magnetization in each domain affected by the field is always nearly parallel or antiparallel to the applied field. If on the other hand the transverse effect is of the same order of magnitude as the *longitudinal* effect previously observed, various other inferences can be drawn.

We have detected the transverse effect and measured it together with the longitudinal effect, on specimens of hard-worked iron, annealed iron, and perminvar. The data show that the relative importance of the two depends on the material and on the degree of magnetization of the specimen as a whole; the newly observed effect is relatively small when the magnetizing field H is less than the coercive force, and may be equal to or greater than the longitudinal effect when the magnetization of the material approaches its saturation-value.

METHOD

The magnetic specimens examined were in the form of tubes 60 cm long and about 5 mm in diameter. For measurements of the usual (longitudinal) Barkhausen effect the tube was placed in an axial field produced by a long magnetizing solenoid as shown in Fig. 1. To measure the small changes in magnetization taking place in a direction at right angles to that of the gross magnetization (transverse effect), a current was passed through a wire coaxial with the tube, the annular field produced by it being everywhere perpendicular to the axis. The component of the change in magnetization perpendicular to the field produced an e.m.f. in the search coils placed in the same positions as they were when measuring the longitudinal effect. For both longitudinal and transverse effects the search coils were connected to the amplifier and measurements of the Barkhausen "noise" made with a thermocouple and galvanometer connected to the amplifier output.

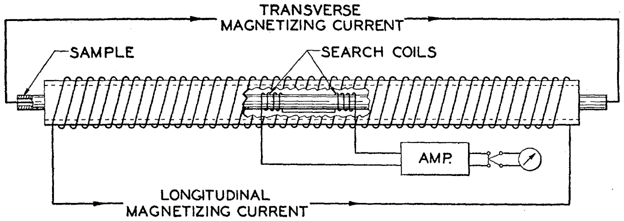

Fig. 1. Diagram of the apparatus for measuring both longitudinal and transverse effects.

As described in a previous paper,[1] the quantities measured were the slope of the B-*vs.*-H curve dB/dH, the rate at which the field was changed during measurements dH/dt, the reversible permeability μ, and the amplifier output i^2 (or the equivalent galvanometer deflection δ) which is a quantitative measure of the noise. We previously[1] derived the following expression for the average change in magnetic moment:

$$\Delta M = \frac{2(10)^{-14}\mu^{3/2}\delta}{C^2 I_s \rho^{3/2}(dB/dH)(dH/dt)} \tag{1}$$

where C is a constant of the apparatus, I_s the saturation value of the magnetization of the material under investigation, and ρ its resistivity. Since now we are dealing only with the ratio of the Barkhausen effects parallel and perpendicular to the field, it is unnecessary to determine many of the quantities in Eq. (1). The ratio of the change in magnetic moment taking place at right angles to the direction of the applied (annular) field, to the change paral-

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[1] R. M. Bozorth and J. F. Dillinger, Phys. Rev. **35**, 733–752 (1930). See also the short accounts of the present work in Phys. Rev. **38**, 192–193 (1931); **39**, 353–356 (1932).

lel to the applied (axial) field, (transverse change divided by longitudinal change), is then given by

$$\frac{\Delta M_T}{\Delta M_L} = \frac{\mu_T^{3/2}\delta_T(dB/dH)_L(dH/dt)_L}{\mu_L^{3/2}\delta_L(dB/dH)_T(dH/dt)_T} \tag{2}$$

where the subscripts T and L refer to quantities measured in determining the transverse and longitudinal effects, respectively. In particular, the *transverse reversible permeability* μ_T is the ratio of the small change in induction parallel to the axis of the specimen, to the very small change in field strength applied in the same direction, when the specimen is magnetized principally annularly by the current flowing along the axis.

The rates of decay of eddy-currents caused by the discontinuities in magnetization measured, are affected by the geometry of the specimen in the same way for annular as for axial magnetization, since the search coils remain in the same position with respect to the specimen for both kinds of measurements. The eddy-currents which affect the rate of change of magnetization picked up by the search coils, are in all cases in a plane perpendicular to the axis of the specimen.

Measurements of μ, δ, dB/dH and dH/dt, were made as previously described.[1] The annular B and dB/dH were measured using an additional (third) search coil each turn of which passed inside of the tubular specimen along its length and returned on the outside. Since the cross section of magnetic material thus enclosed is relatively large, only a few turns were necessary. The axial current producing the annular magnetization was varied smoothly by means of a liquid resistance, a solution of copper sulphate into which a set of copper plates was lowered.

In a preliminary experiment the specimen was magnetized axially and the regular search coils (Fig. 1) connected to the amplifier as already described while at the same time the additional search coil wound as described above to detect the transverse change in magnetization due to an axial field, was connected to a second amplifier, the outputs of the two amplifiers being recorded simultaneously on the same moving photographic paper. It was thus observed that a single discontinuity in longitudinal magnetization was accompanied by a discontinuity in transverse magnetization. The direction of the deflection of the string recording the longitudinal effect was always the same, while the deflections of the string recording the sudden transverse changes were about half in one direction and half in the other. This showed that the average change in magnetization perpendicular to the applied field is zero, but that for any single event there was in general a change in one direction or the other. After this preliminary experiment we confined our experiments to the longitudinal effect occurring with axial field, and to the transverse effect with annular field.

RESULTS

The materials investigated were annealed iron, hardworked iron, and annealed perminvar containing 30 percent Fe, 25 percent Co and 45 percent

Ni. No analyses of these specimens were made, but analyses of similar specimens indicate that the following impurities were present: in annealed iron, 0.1 percent C and 0.5 percent Mn; in hard iron, no impurity more than 0.02 percent; in annealed perminvar, 0.1 percent Si. The tubes were all 60 cm long. The outside diameters of the perminvar and hard iron tubes were 0.47 cm and the wall thicknesses 0.025 cm. For the annealed iron specimen the corresponding dimensions were 0.63 cm and 0.056 cm. The annealed iron was heated in vacuum for 2 hours at 1100° C and cooled 400° C per hour. The perminvar was annealed for 1 hour at 875° C and cooled at a maximum rate of about 100° C per hour.

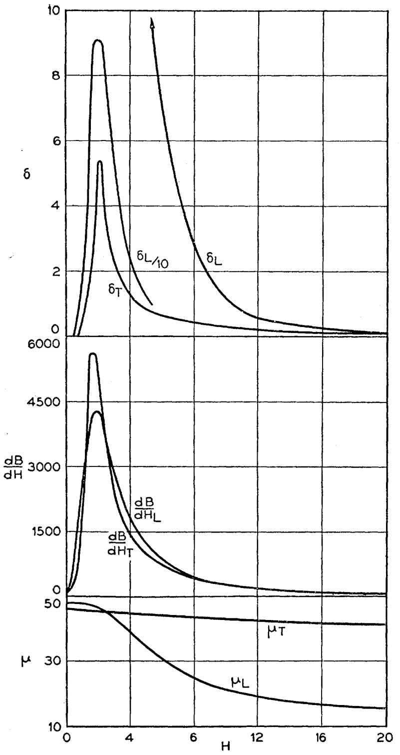

Fig. 2a

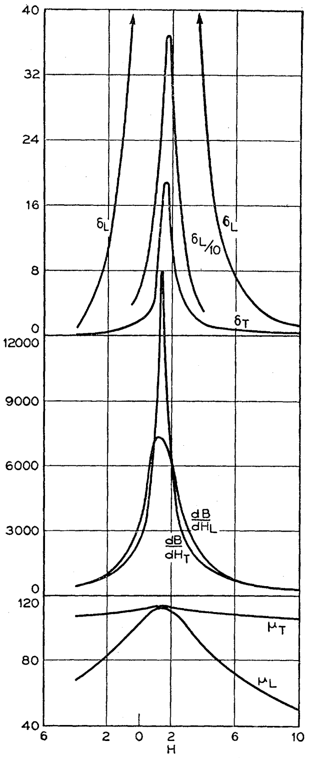

Fig. 2b

Fig. 2a. Values of δ (output power of amplifier), dB/dH and μ for the magnetization curve of annealed iron, measured with transverse and longitudinal magnetizing fields. The amplifier output δ is referred to a constant value of dH/dt.

Fig. 2b. Values of δ, dB/dH and μ for the hysteresis loop of annealed iron, measured with transverse and longitudinal magnetizing fields.

The values of dB/dH, μ, and δ for both longitudinal and transverse effects, for the hysteresis loop and magnetization curve of *annealed iron*, are shown in Fig. 2. The two hysteresis loops for annular and axial magnetization were almost identical, differing only on the steep parts of the curves where the demagnetizing factor has the greatest influence. The galvanometer deflections were observed for various values of dH/dt and from them δ_T and

δ_L were calculated for a constant value of dH/dt, using the relation $\delta \propto dH/dt$. The relative magnitudes of the longitudinal and transverse effects for the magnetization curve as shown in Fig. 3 where the average change in moment for each is plotted on the same scale as a function of the applied field H, and in Fig. 4 where the ratio of the effects is plotted as a function of the induction B. Since $H \ll B$ except when B is very small, the latter is practically proportional to the magnetization. Fig. 4 shows that the change in magnetization of a domain is greater in the direction of the applied field than in direc-

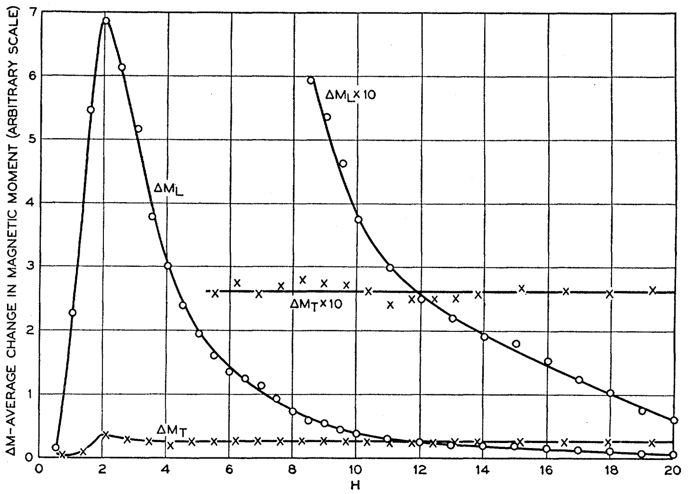

Fig. 3. Longitudinal and transverse changes in magnetic moment for the magnetization curve of annealed iron.

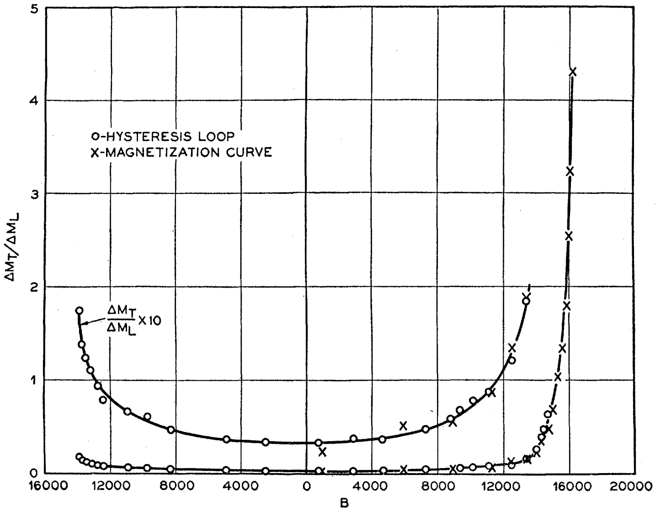

Fig. 4. Ratio of the transverse to the longitudinal change in magnetic moment in annealed iron.

tions at right angles until B is as large as 15,000. In relatively low fields, where the slope of the hysteresis loop is greatest, the direction of magnetization changes by very nearly 180°, and is antiparallel to the applied field before and parallel to it after the change. The modes of reversal of the domain will be discussed further below.

The values of dB/dH, μ, and δ for the hysteresis loop of *hard worked iron* are shown in Fig. 5. The coercive force of this material was 1.1 gauss.[2] The ratio of the transverse to the longitudinal change in magnetization in the domains is shown in Fig. 6 as a function of B. For the same value of B, this ratio is a little larger than that for annealed iron.

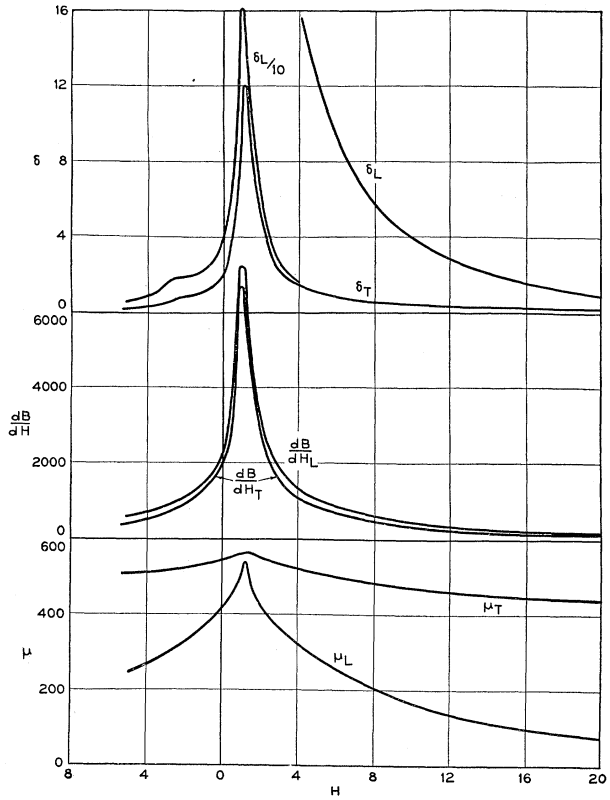

Fig. 5. Values of δ, dB/dH and μ for the hysteresis loop of hard iron, measured with transverse and longitudinal magnetizing fields.

The data for perminvar are shown in Fig. 7. The hysteresis loop for a maximum field strength of 4 gauss is shown in Fig. 8 because of its peculiar characteristic shape. The ratio of the transverse to the longitudinal change for this hysteresis loop is shown as a function of B in Fig. 9. No measurements were made at higher fields.

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[2] Although this material is hard worked, its coercive force is about that normally found for annealed iron. This specimen was given a special treatment in hydrogen (see P. P. Cioffi, Phys. Rev. **39**, 363–367 (1932)) and if annealed would have a coercive force of about 0.1 gauss.

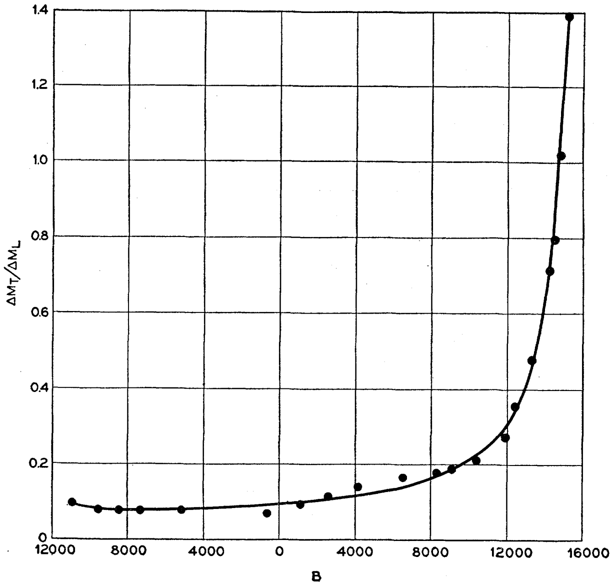

Fig. 6. Ratio of the transverse to the longitudinal change in magnetic moment in hard iron.

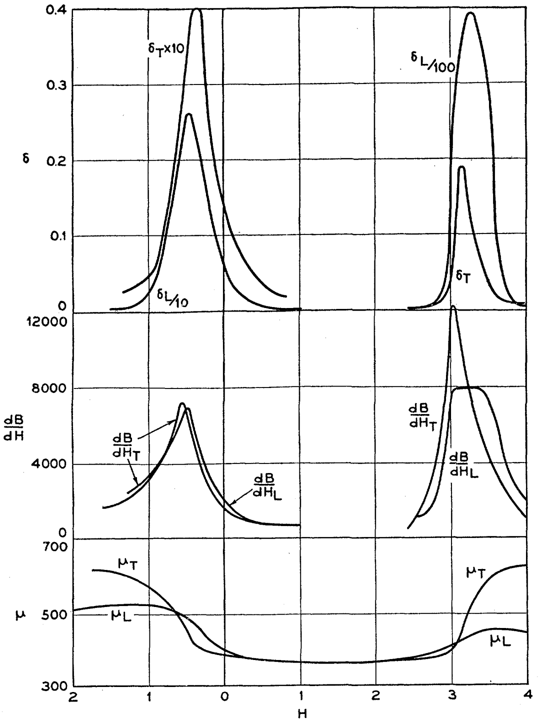

Fig. 7. Values of δ, dB/dH and μ for the hysteresis loop of perminvar, measured with transverse and longitudinal magnetizing fields.

Discussion

One of the most obvious characteristics of the curves of Figs. 4 and 6 is that when the magnetization is small the longitudinal components of the discontinuous changes in magnetization are larger than the transverse components, but that when the magnetization is large the transverse component is the larger. Two kinds of change of magnetization which are consistent with

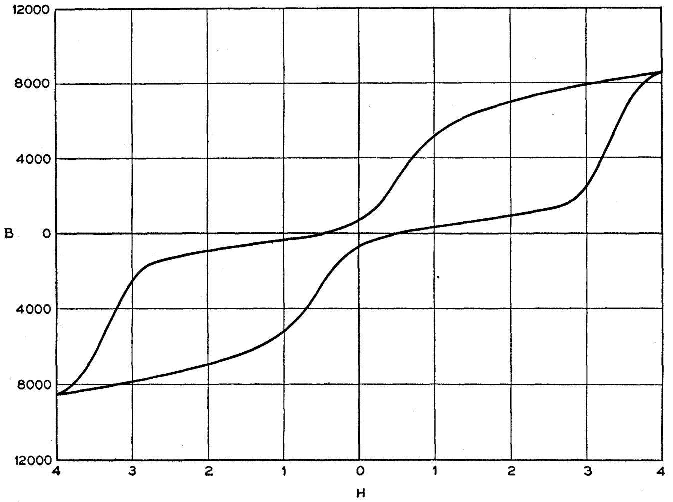

Fig. 8. Hysteresis loop for perminvar.

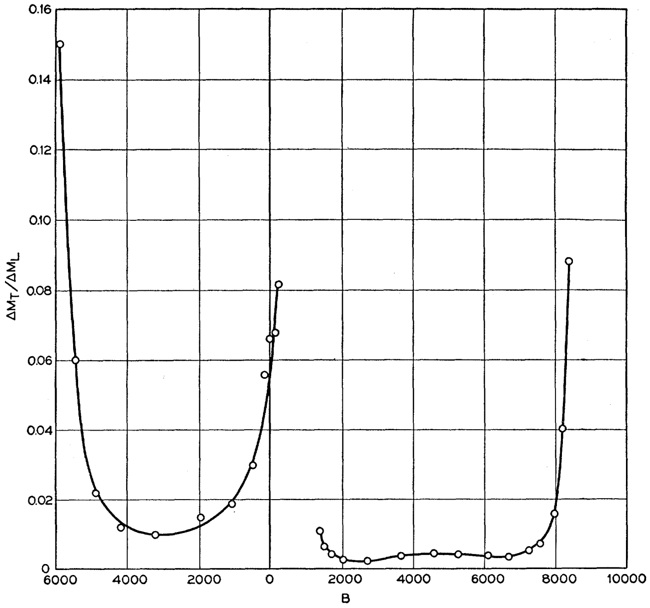

Fig. 9. Ratio of the transverse to the longitudinal change in magnetic moment in perminvar.

this result are illustrated in two dimensions in Fig. 10. Here a shows a reversal of the magnetization-vector from the initial position (dotted line) to a final position making an angle $\theta = 15°$ with the direction of the field. In this case $\Delta M_T/\Delta M_L = 0.27$. If θ is 75° as in (b), this ratio is 3.7. In (c) and (d) the vectors rotate by 90° instead of 180° as in (a) and (b), and for final positions defined by $\theta = 15°$, the values of $\Delta M_T/\Delta M_L$ are 0.58 and 1.73 respectively. It is evident that the ratio becomes large without limit as θ approaches 90° in (b) or 45° in (d). Since we should expect that the latter changes would occur at relatively high magnetizations, and changes of kind (a) at low magnetizations, we have here a qualitative correspondence with the data as shown in Figs. 4 and 6.

Consideration of Fig. 10 (d) also shows that as θ approaches 45° the transverse change, equal to $\sin\theta + \cos\theta$, approaches asymptotically the definite limit $2^{1/2}$, taking the radius of the circle as unity. Since θ approaches 45° when

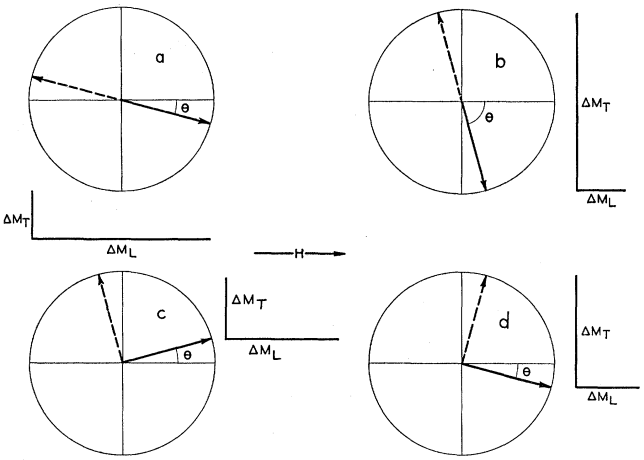

Fig. 10. Possible modes of reversal of magnetization in elementary domains, with the corresponding transverse and longitudinal components.

the magnetization is high, we should expect that then also the transverse effect should become constant. This constancy was observed as shown in Fig. 3.

The two kinds of changes shown in Fig. 10 correspond to two views of the changes which take place in ferromagnetic materials. Both are based on Weiss' idea that a ferromagnetic substance is composed of small domains, each of them initially magnetized to saturation along some direction of *natural magnetization*. According to one view (Webster's[3] and Heisenberg's[4]) which is suggested by experiments on single crystals, the directions of natural magnetization in a domain are the six <100> directions of the crystal which contains the domain; an applied field may shift the magnetization from one of these directions to another making a smaller angle with its own. According to the other view (resembling R. Becker's[5]) the directions of natural magnetization

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[3] W. L. Webster, Proc. Phys. Soc. London **42**, 431–440 (1930).

[4] W. Heisenberg, Zeits. f. Physik **69**, 287–297 (1931).

[5] R. Becker, Zeits. f. Physik **62**, 253–269 (1930).

are controlled by the strains in the substance, and the only effect which an applied field can produce in a domain is a reversal of the magnetization. The changes shown in (a), (c), and (d) of Fig. 10 are compatible with the former view, (a) and (b) with the latter.

The way in which these views fit in with our results is illustrated in Fig. 11. If the directions of magnetization in the domains are controlled by the lattice of the crystal, discontinuous changes in a polycrystalline specimen can occur only until the directions of magnetization in the domains all make angles of 45° or less with the direction of the field. When this condition is attained the material is about 85 percent saturated, and the ratio $\Delta M_T/\Delta M_L$ is indefinitely large as indicated by the vertical line (a) in Fig. 11. If the control is by strain alone, the corresponding limit is designated by (b) which indicates that discontinuous processes cease when the directions of magnetization in the domains make angles of 90° or less with the direction of the field, in which case the material as a whole is only half saturated. Curves (c) and (d) represent the actual data for annealed and hard worked iron, respectively, for comparison. The curves suggest that in each material the magnetization is controlled in some of the domains by strain and in some by the lattice, the domains of the former class being increased in relative number by hard working. By interpreting the data in this way, strain has some influence even in well annealed iron, and in hard worked iron there is still a considerable amount of crystallographic control. The interpretation of the difference between the experimental curves at the lowest values of B is not yet clear; the explanation of this difference may influence the conclusions already drawn. It is intended to make a more quantitative comparison between theory and experiment in a later paper.

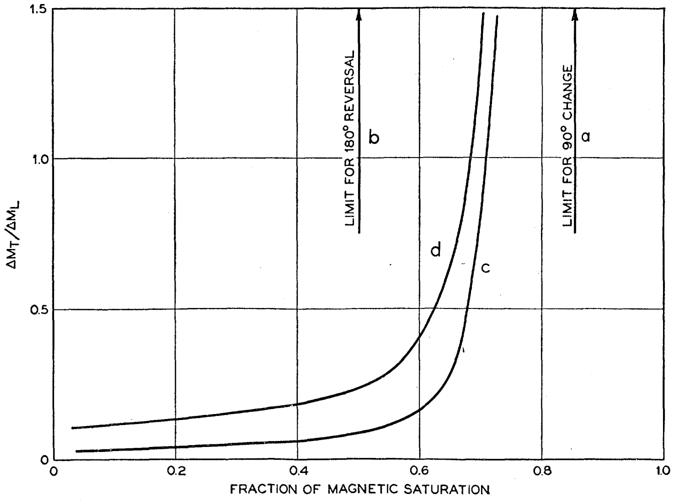

Fig. 11. Ratios of the transverse to the longitudinal change in magnetic moment in (c) annealed iron and (d) hard iron and their relation to the theoretical limits (a) for 90° changes and (b) for 180° reversals.

The curve of Fig. 9, for perminvar, is different from those for iron in that $\Delta M_T/\Delta M_L$ has relatively high values near $B=0$ as well as when B is large. This is in accord with other peculiarities of perminvar which have been regarded[6] as indicating that it is a mixture of two kinds of magnetic materials. Although the nature of the difference (if any) between these materials is yet undetermined, the data here reported are such as would be expected if about half of the material approached saturation before the other half began to change its magnetic state appreciably, and for each portion the ratio $\Delta M_T/\Delta M_L$ went through the usual changes during the cycle.

In summary, our data are in good agreement with the following conceptions: Magnetic materials are divided into small domains each of which is magnetized to saturation. In annealed materials the direction of magnetization in each domain is one of the directions of easy magnetization in the crystal which contains the domain; these, in the special case of annealed iron, are the directions of the crystal axes. With an increase in the magnetization of the material as a whole, the magnetization in each domain changes from one of these directions to another making a smaller angle with the applied field. When the net magnetization is small, most of the changes are reversals in the domains in which the initial magnetization is almost anti-parallel to the applied field. When the net magnetization is large (one half to three quarters of the saturation value), other domains are affected in which the initial magnetization is inclined at smaller angles to the field and changes of 90° occur. When saturation is almost attained a new phenomenon appears, the directions of magnetization in all of the domains cease to be controlled by the crystal lattice and approach parallelism to the applied field. This final approach to saturation is a continuous one and is not believed to be accompanied by Barkhausen effect.

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[6] G. W. Elmen, J. Frank. Inst. **260**, 317–338 (1928); **207**, 583–617 (1929); U. Meyer, Phys. Zeits. **28**, 919–920 (1927); H. Kühlewein, Wiss. Veröff; Siemens-Konz. **10**, No. 2, 72–88 (1931), and Phys. Zeits. **31**, 626-640 (1930).