Magnetic Reversal Nuclei

Part V.[1] Propagation of Large Barkhausen Discontinuities

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In a Ni-Fe wire in which a preferred direction of magnetization is created by application of tension, stable regions of antisaturated magnetization can be produced by short application of high local fields. These nucleus regions will not grow after removal of the local field, although the direction and magnitude of the uniform external field favors growth. This is explained by the fact that their demagnetizing field lowers the total field in the neighborhood below the value H_0, which in former papers was recognized to be the minimum field value at which propagation would proceed spontaneously. Propagation will start from a nucleus region if the external field is raised to a value H_S', where H_S' has to fulfill the condition: $H_S'=H_0+H_d$. H_d, the demagnetizing field of the nucleus, was calculated from its dimensions. The approximate size of a natural nucleus in a stressed wire was determined from the starting field H_S of that wire; it had a length of a few mm and a diameter of several μ.

1. Introduction

According to present views a ferromagnetic body is subdivided in small regions, each region being distinguished by having a uniform direction of magnetization which is different from the direction in its neighbors. Crystal orientation, local strain and external and internal fields determine the orientation of any region. There is evidence that its linear dimension is of the order of 10^{-3} cm. This small size, as well as the other factors just mentioned, make a detailed study of the process of magnetization in a region practically impossible.

The discovery of Preisach,[2] however, that uniform strain, such as tension, applied to a suitable material, such as, for example, ten percent nickel-iron wire, produces a uniformity in the direction of magnetization enables us to study the magnetic processes on a much larger scale. Thus the progress of magnetization was studied as a large magnetic discontinuity which traveled along wires.[1] It is probable that the results obtained apply also, with some modifications, to the case of magnetic reversal in unstrained material. The present investigation thus has possible significance along two lines. In the first place, it shows the conditions which have to be fulfilled in order to *start* a large discontinuity. Besides, it serves as a large scale model for the starting of a reversal in a small region.

The problem treated in this paper developed during the study of the propagation of large Barkhausen discontinuities. Some of the experiments were first carried out about four years ago. The major results were reported at the Physical Society meeting in Washington in April, 1934.

2. The Starting of a Large Discontinuity

In studying the propagation of magnetization along stressed Ni-Fe wires, a local adding field was employed to initiate the propagating reversal in a uniform field H where $H_S>H>H_0$ (Fig. 1). The total local field at a point has to exceed the local starting field, H_{Sl}, before the propagation can proceed spontaneously. The starting condition for a uniform wire is therefore:

$$H+H_a\geqq H_{Sl}. \tag{1}$$

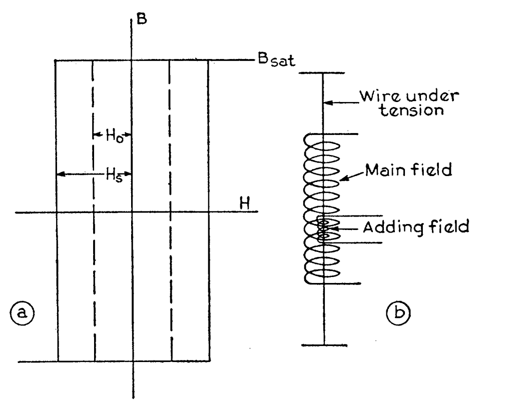

Fig. 1. a: Schematic hysteresis loop of a 15 percent Ni-Fe wire under high tension; b: schematic diagram of the experimental set-up.

[1] Part I: K. J. Sixtus and L. Tonks, Phys. Rev. **37**, 930 (1931); II: Phys. Rev. **42**, 419 (1932); III: L. Tonks and K. J. Sixtus, Phys. Rev. **43**, 70 (1933); IV: Phys. Rev. **43**, 931 (1933).

[2] F. Preisach, Ann. d. Physik **3**, 737 (1929).

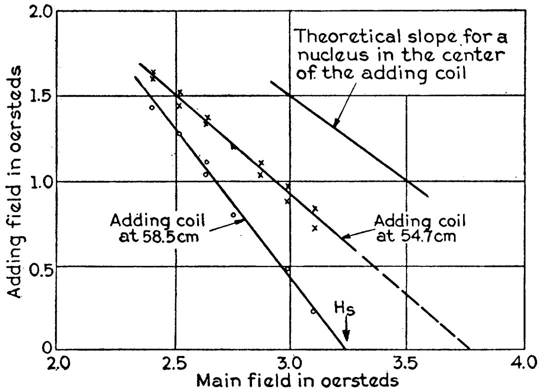

FIG. 2. The adding field necessary to start propagation as function of the main field in a 15 percent Ni-Fe wire.

The magnetic field symbols used here and in the following sections have the following meaning: H, main field; H_0, critical field; H_S, starting field; H_{Sl}, local starting field, H_S being the minimum value of H_{Sl} along the wire; H_a, adding field; H_{a0}, minimum adding field at a point necessary to start propagation at a given H.

In order to test Eq. (1) we have plotted in Fig. 2 both the straight line relation satisfying Eq. (1) and the experimental results at two different points along a cold drawn, 15 percent Ni, 85 percent Fe wire. If the adding coil is placed at 58.5 cm., it obviously controls the starting of the weakest nucleus on the wire since the curve intercepts the axis of abscissas at $H=H_S$. The deviation in slope from the theoretical one can be explained by assuming that the weakest nucleus was not situated in the center of the coil for which H_a was calculated from the coil constants but lay near the end of the coil where the field was smaller than in the center. At another place (54.7 cm) a higher adding field had to be applied, but the nucleus in this case was closer to the center of the adding coil; hence the close agreement between the experimental and the theoretical slope.

We thus find that for every value of main field a minimum value of adding field, H_{a0}, which will vary along the wire, is necessary to start propagation.[3] If, however, the adding field was not applied continuously, but only for a short time interval, fields in excess of the minimum value could be used without initiating propagation. It became apparent in several ways that the short field pulse caused local magnetic reversals in the coil region. These local changes will be discussed after describing the surge circuit used.

3. Surge Circuit

The problem of producing flat-crested current pulses of a duration between 0.0001 and 1 sec. can be solved with the help of a Helmholtz pendulum. Contact troubles, however, developed when this method was tried, and the suitability of two different tube circuits was tested. A. J. Maddock[4] used a circuit containing two Thyratrons which can furnish large currents, but it was found that the minimum time interval was 0.0005 sec. and that it was impossible to produce sufficiently rectangular shapes. Therefore a high vacuum tube arrangement was chosen finally which supplied perfectly rectangular surges with a maximum current of 50 ma and of a minimum duration below 0.0001 sec. Fig. 3 shows the circuit used. At the beginning current is flowing in tube B only. By throwing switch S a damped oscillation is initiated in the timing circuit, making grid B negative and positive in short succession. The current accordingly will shift from B to A and back to B again, a process described in I, p. 934. The grid bias of tube B has to be adjusted to such a value that only the first negative and positive crest voltage on C will be effective in shifting the current. UX-245 tubes were selected because, besides giving a high plate current, their high filament current reduced the effect of plate current on filament temperature.

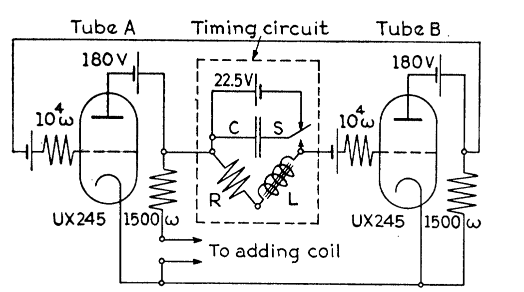

FIG. 3. Tube circuit for the production of short, square current impulses.

[3] Cf. K. J. Sixtus and L. Tonks, Phys. Rev. **39**, 357 (1932).

[4] A. J. Maddock, Proc. Phys. Soc. (4) **43**, 371 (1931).

4. Experiments on Nucleus Growth

Although experiments have been performed on a large number of different wires, only the results on three of them will be given, since they appear to be representative of the rest. Wire No. I was a cold drawn wire with 15 percent Ni and 85 percent Fe; No. II had the same composition but had undergone a heat treatment (1 min. at 930°C, cooled to room temperature, 1 hr. at 400°C), which made it more uniform and reduced its critical field considerably (see footnote 1, II); No. III was a permalloy (78.5 percent Ni, 21.5 percent Fe) wire which had been annealed at ~1100°C for 3 hr., at ~700°C for 2 hr., and was cooled rapidly to room temperature from 700°C.

The main field coil was 80 cm long and had a constant of 23.0 oersteds/amp. The adding field coil was, in most cases, wound directly on the wire. It consisted, in the case of Figs. 5 and 6, of 64 turns of 5-mil wire, with a coil constant of 80 oersteds/amp.

Two types of tests were performed with the surge circuit. At a given main field a time-adding field relation could be found by taking either time or field as independent variable and adjusting the other one, so that one surge would *just* start propagation. Incidentally, the start of propagation was indicated by a search coil, some distance away from the adding coil and connected to a galvanometer. The alternative method consisted in taking H_a as independent variable and applying a series of surges of short duration until propagation started. Both methods gave identical results, indicating that the *total* time during which the field was applied was of importance. One also can conclude from this observation that changes in the magnetic structure of the material proceeded only as long as the field was applied and that no readjustment took place between the periods of application of short pulses. Fig. 4 gives the experimental results for wire No. I under a tension of 75 kg/mm^2 and also the product $(t\times(H_a-H_{a0}))$ derived from them. The fact that this product, at a given main field, was constant made it appear as if an antisaturated region or nucleus had to grow to a certain size before it could initiate self-propagating reversal, the size, presumably, depending on the value of main field. Similar results, shown in Fig. 5, were found for wire No. III, although the main field had a value of only three percent of its value for wire No. I.

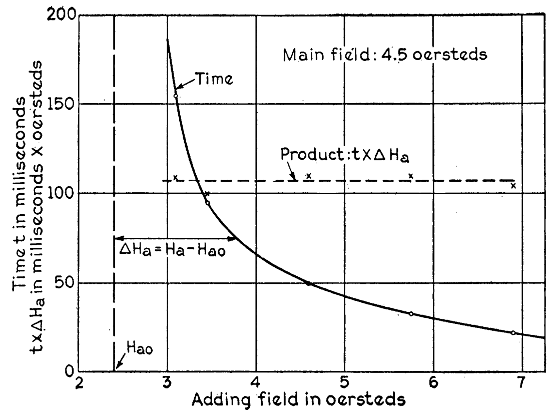

Fig. 4. Time intervals for which the adding field has to be applied in order to start propagation. Wire No. I, 15 percent Ni-Fe, unannealed.

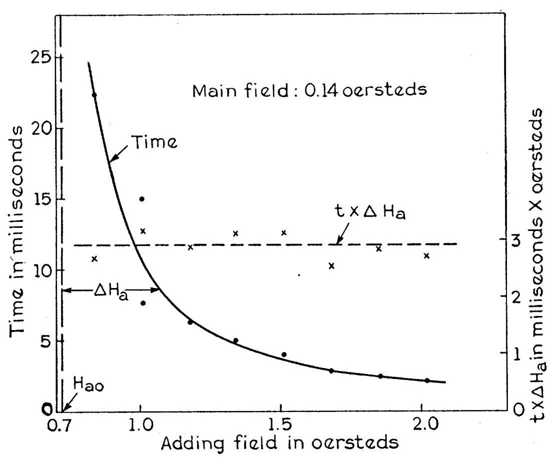

Fig. 5. The same relation as in Fig. 4, for wire No. III, 78.5 percent Ni-Fe, annealed.

This conjecture could be verified by direct measurement. By moving a search coil of 0.6-cm length connected to a ballistic galvanometer along that section of the wire where the anti-saturated region had been developed, the flux leaving the wire could be measured accurately, at least in the case of the larger nuclei. In Fig. 6 three stages during the growth of a nucleus are shown. These nuclei were created by successive applications of field surges and the flux curves measured by rapid movement of the search coil from different places within the nucleus region to a place beyond it. Wire No. II under a tension of 65 kg/mm^2 was used in this experiment.

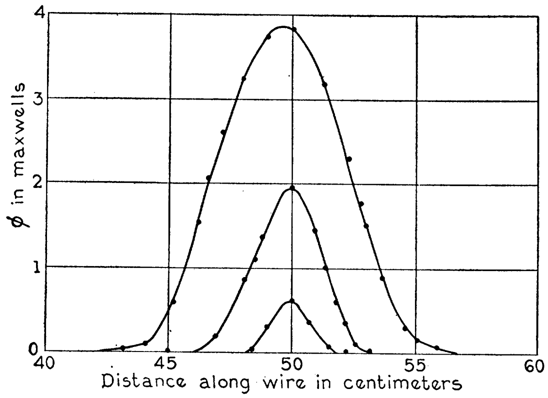

FIG. 6. The flux passing through the wire surface in a nucleus region as measured by a search coil for three nuclei of different size.

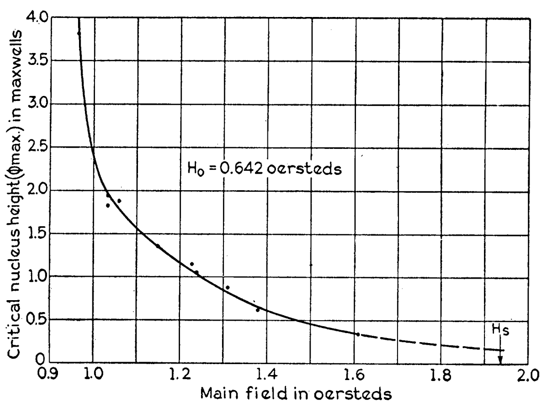

FIG. 7. Relation between nucleus height and the main field in which a given size nucleus would start propagation. Wire No. II, 15 percent Ni-Fe, annealed.

A nucleus once produced would not change its shape if the *main* field was increased until a certain value of main field was reached when it would start propagation. There was a definite, reproducible relation between nucleus shape, as measured by the height of its flux curve, and the main field in which a nucleus would initiate spontaneous propagation (Fig. 7).

5. Discussion of Results

Our experiments have shown that a nucleus may be stable in a surrounding antisaturated phase. If, however, the main field exceeds a certain value, the equilibrium becomes unstable and a spontaneous growth takes place. We shall call this value H_S' because it is closely related to the starting field H_S in a wire which does not contain "artificial" nuclei.

At this point it appears worth while to recall briefly the theory of condensation in supersaturated vapors, which offers a very close parallel to our magnetic two-phase problem. A drop of liquid can be in equilibrium with its supersaturated vapor because of the fact that it exhibits a surface tension as long as its size does not exceed a critical value. This critical size is for a given material determined by the degree of supersaturation, i.e., the ratio between the vapor pressures of the supersaturated to the saturated phase. If a critical size droplet is present, an infinitesimal amount of work will suffice to transform the vapor phase into the liquid phase.

If we want to apply these considerations to the case of a magnetic nucleus surrounded by an antisaturated phase, we find that instead of a surface energy we have to deal with a volume energy arising from the demagnetizing field H_d, caused by the nucleus itself and by the surrounding phase. In analogy to the vapor case we may assume that an amount of work

$$E = H_d \times I_s \qquad (2)$$

equal to this energy has to be supplied to the wire in order to make the nucleus self-propagating—in addition to the energy $H_0 \times I_s$ necessary to sustain propagation (see next section). Preisach[5] has expressed the same idea in more general terms in his discussion of the natural starting field H_S. It appears plausible to postulate that the critical size nucleus is determined by the condition

$$H_s' - H_0 = H_d, \qquad (3)$$

which infers that the field inside the nucleus has to have at least the value H_0 before that nucleus can grow spontaneously.

Experimental evidence speaks for the basic correctness of our assumptions (2) and (3). This conclusion was reached in the following way. From the measured flux curves of different size nuclei we calculated, with certain simplifications, the demagnetizing field, H_d, and compared it with the value of $H_s' - H_0$ for these cases. These simplifying assumptions were:

(1) The observed flux curve is caused by a coherent, saturated region with a definite boundary.

[5] F. Preisach, Physik. Zeits. **33**, 913 (1932).

(2) This region has the shape of an ellipsoid of rotational symmetry whose two axes can be derived from the flux curve.

The demagnetizing field for an ellipsoid surrounded by a medium of permeability 1 is NI_s, N being the demagnetizing factor. We are here concerned with ellipsoids whose ratio k of long to short axis is large, for which N has the value:[6]

$$N=(4\pi/k^2)(\ln 2k-1). \quad (4)$$

It can be shown that the surrounding anti-saturated phase contributes an equal amount NI_s to the field in the nucleus, and it follows that

$$H_d=(8\pi I_s/k^2)(\ln 2k-1). \quad (5)$$

The long axis was taken to be equal to the length of a flux curve such as are given in Fig. 6, whereas the short axis was determined from the height of the flux curve by assuming that the ratio of maximum nucleus cross section to wire cross section was the same as that of maximum nucleus flux to flux at saturation.

This procedure could be expected to give correct values for nuclei whose length was large compared with the coil dimensions, but to become, for two reasons, less and less accurate if this condition was not fulfilled. Firstly, there is a considerable leakage flux not intercepted by the coil if the nucleus length is of the same order or smaller than the coil diameter. Secondly, the fact that the search coil has a finite length will have the effect that instead of measuring the flux at one point we obtain a flux average over the length of the coil. The latter cause will make the measured flux curve longer than the actual one, and both causes will result in too low a maximum of the measured flux curve. If no corrections are applied, we obtain an apparent k larger than the actual value. It appears difficult to determine the error due to the first effect, whereas the second one could be compensated roughly by assuming the long axis to be equal to the difference between length of flux curve and coil length.

The check of Eq. (3) is contained in Fig. 8. The curve is a plot of Eq. (5) relating H_d to k, and the dots refer to four nuclei, created in wire No. II with different values of k, the ordinates giving the value of $H_s'-H_0$. The dots at both ends of an arrow refer to one and the same nucleus, the one on the right being plotted using the apparent k, the dot at the arrow point using the corrected k. The experimental points lie sufficiently close to the theoretical curve to furnish proof for the validity of Eq. (3).

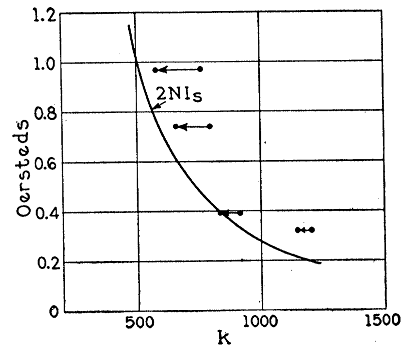

FIG. 8. Solid curve: Relation between demagnetizing field 2 NI_S of a nucleus and the length to thickness ratio k; Dots: H_S-H_0 for four nuclei with different values of k.

A similar test was performed with the permalloy wire No. III ($H_0=0.058$ oersted) in a field of 0.138 oersted, only one-tenth the field necessary for wire No. II. The critical size nucleus at this field had a diameter of 0.0156 cm and the remarkable length of 20 cm, resulting (with $I_s=950$ e. m. u.) in a demagnetizing field $2NI_s=0.057$ oersted. Although the agreement obtained here ($H_s'-H_0=0.080$ oersted and $2NI_s=0.057$ oersted) is not so close as with wire No. II, the discrepancy is not so large as to force one to abandon Eq. (3). It may be that nuclei of this extreme length no longer have the shape of an ellipsoid and that our method of field calculation becomes quite inaccurate for this reason.

Incidentally, these measurements have thrown some light on the rate of nucleus growth in axial and radial directions. They are not sufficiently complete to warrant the actual determination of these rates, but they show qualitatively that the rate of axial growth is larger than that for radial growth as could be expected from the propagation experiments. This accounts for the decrease in demagnetizing field connected with the growth of the nucleus.

Thus by comparatively crude considerations we have obtained an almost quantitative check for the condition expressed in Eq. (3). This equation, however, only describes the field in

[6] L. Graetz, *Handbuch d. Elektrizität u. des Magnetisms,* (1920), p. 151.

that part of the wire which contains the middle portion of the ellipsoid, and the field in the neighborhood of the ends may be quite different from it. A detailed study of local field distribution seems quite impossible at present, particularly on account of the unknown contribution of boundary effects, forcing us to content ourselves at present with energy considerations as given above.

6. The Starting Field H_S

Preisach has expressed the idea[5] that H_S formed a measure for the surface energy which has to be supplied to a natural nucleus in order to make it self-propagating. From our findings on artifical nuclei we must conclude that H_S-H_0 rather than H_S is the important quantity determining this energy.

H_0, according to the theory developed by Bloch[7] and Preisach is made up of two parts, H_{0R} and H_{0Z} (see the schematic diagram, Fig. 9). H_{0R} is a measure of the energy necessary to shift a boundary when the preferred orientation has been made axial by high tension; it is probably due to local variations in atomic distances. H_{0Z} measures the energy which has to be supplied to move the boundary through regions where the magnetization is not lined up in the direction of the field H due to insufficient applied stress. H_{0Z} vanishes when the applied tension exceeds the internal stresses σ_i. If the discontinuity is traveling in a field $H>H_0$, the additional energy $(H-H_0)\ I_s$ is converted mainly into eddy currents, which is shown by the correctness of the penetration formula (footnote 1, II) derived on that basis.

We want to consider H_S in a wire free of all "accidental" starting nuclei which are due to large scale distortions in the wire, such as bends, or which are formed by regions which have not been lined up with the rest because of the use of insufficient fields. Bloch has shown that there is a certain probability for the formation of small antisaturated regions, which we shall call "natural" nuclei, where the energy is supplied thermally. These "spontaneous reversal nuclei" will grow in a small applied field until stopped by a lattice distortion for whose overcoming a field H_0 is needed.

In the preceding section we have found a

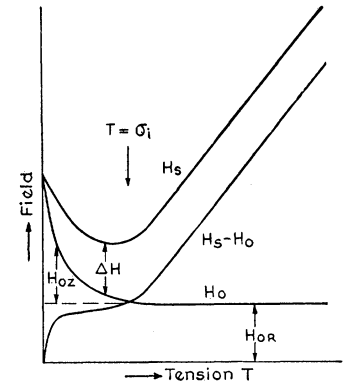

Fig. 9. Schematic relation between H_0, H_S and H_S-H_0 and tension for a well-annealed wire.

relation between nucleus size and starting field. It would be possible, therefore, to take the field H_S-H_0 as a measure of the nucleus size if we could be sure that the conditions remain fundamentally the same for the much smaller natural nuclei. The increase in H_S-H_0 with increasing tension would, in that case, be an indication of the accompanying reduction in nucleus size. Two influences have to be considered in a more rigorous treatment. The first is the interaction of different nuclei, the second is the role of the molecular field. Disregarding these complications, we have derived the approximate size of a natural nucleus as follows.

For the well-annealed 15 percent Ni-Fe wire No. II under a tension of 77 kg/mm^2, which, presumably, did not contain any accidental nuclei, the curve relating maximum flux of nucleus region to H_S' was extrapolated to the natural value of H_S for this wire (Fig. 7). The same was done for the curve showing the dependence of H_S on nucleus length. In this manner a rough value for the size of the natural nucleus which caused propagation in the wire at H_S was obtained: its diameter lay between 10^{-4} and 10^{-3} cm, and its length was of the order of a few mm. Its volume thus agrees with the average volume (10^{-8} cm^3) of the Barkhausen regions,[8] which are responsible for the Barkhausen effect.

The author is greatly indebted to Dr. L. Tonks for valuable advice and for many stimulating discussions on the subject.

[7] F. Bloch, Zeits. f. Physik **74**, 333 (1932).

[8] R. M. Bozorth and J. F. Dillinger, Phys. Rev. **35**, 733 (1930).