Propagation of Large Barkhausen Discontinuities, III.[1] Effect of a Circular Field with Torsion

L. Tonks and K. J. Sixtus, *Research Laboratory, General Electric Company, Schenectady*

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The propagation of large Barkhausen discontinuities along a nickel-iron (15 Ni 85 Fe) wire which is under tension alone is practically unaffected by the presence of a large circular field caused by a current through the wire, but such a circular field creates large effects if the wire is twisted. By treating the critical field as a vector having the main field as one component and the circular field as the other, critical field characteristics were obtained from which a simple relation was found between the strain applied to the wire and the critical field. This analysis shows that the component of the field perpendicular to that principal strain axis along which the extension is a maximum has no effect on the reversal of magnetization, thus establishing this principal strain axis as a direction of preferred orientation of the magnetic domains in the strained wire. Certain deviations of the critical field characteristics from the ideal simple form can be accounted for by taking account of (1) the change of strain with depth in a twisted wire, (2) the change in circular field with depth, and (3) the incomplete suppression by the applied strain of heterogeneous internal strains near the axis of a wire which is under torsion alone. Turning from directional properties to an analysis of the magnitude of the critical field, dependence of this on strain magnitude alone was expected. It appears that another unknown factor is of vital importance here. Velocity (longitudinal) *vs.* field plots for torsion alone with a succession of values of circular field show in one case the usual increasing slope with decreasing propagation range, in another very little correlation between these factors. Hysteresis curves taken with constant circular field show in some cases negative coercive force and negative remanence. A "hysteresis" curve of longitudinal magnetization as a function of circular field, taken in zero longitudinal field, was a closed symmetrical loop showing a large discontinuity in each branch. This behavior is readily accounted for.

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1. Introduction

We have seen in I, p. 955, that the existence of the large discontinuity is in accord with Becker's theory relating the direction of magnetization in each domain to the stress tensor there, energy minima occurring for orientation in the direction of tension in material having positive magnetostriction. These considerations led naturally to investigating the effect of a transverse field on the propagation.

This field was obtained by sending a current through the wire under test, and although this gave a field proportional to radial distance throughout the wire, it was much easier to achieve than a uniform transverse field for the whole length of the wire would have been. Besides avoiding all difficulties arising from demagnetization effects, it had the additional advantage that, being circular, its geometry conformed to that of the wire. The magnitude of this transverse field at the surface of the wire will be designated by H_t.

In all the tests described below the wire used was 80 cm long, of 0.038 cm diameter and was from the 15 percent NiFe No. 37 ingot already mentioned in II, section III.

2. Effect of Circular Field Alone

The first observations were made with a circular field in addition to the usual tension and main field. Fig. 1 shows that even when H_t was as large as 8.4 oersteds,[1.5] the v–H curve (which lay en-

[1] K. J. Sixtus and L. Tonks, Phys. Rev. [2] **37**, 930 (1931) will be referred to as I. II appeared in Phys. Rev. [2] **42**, 419 (1932).

[1.5] Although *oersted* has been commonly used in this country as the c.g.s. unit of reluctance, it was adopted by the International Electrotechnical Commission Meeting at Oslo in 1930 as the unit of magnetic field strength. This action has been endorsed by authoritative bodies both in Europe and in this country, the National Bureau of Standards and the American Society for Testing Materials being among them. As references, the following articles by Professor A. E. Kennelly may be cited. *Magnetic-Circuit Units as Adopted by the I.E.C.*, Trans. AIEE, mid-winter convention, New York, January 29, 1931. *Magnetic-Circuit Units Adopted by the I.E.C.*, Elec. Eng. **50**, 141 (1931). *The Oersted Considered as a New International Unit*, Sci. Monthly **32**, 378 (1931).

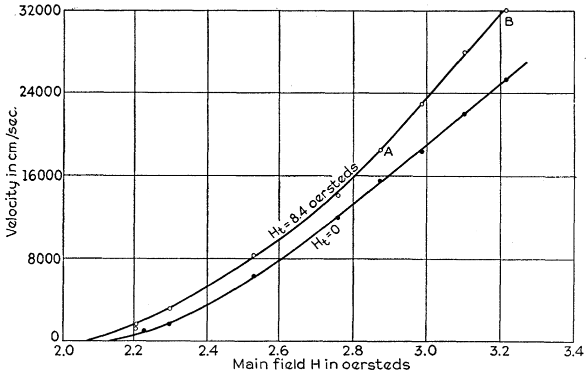

FIG. 1. Effect of a circular field H_t on propagation. Tension $=78$ kg/mm².

tirely below 3.2 oersteds) was only displaced a little and slightly changed in shape. Point A is the starting field with H_t in one direction, B with it reversed. A slight twist of roughly 45° brought these into coincidence at an intermediate value, thus indicating the existence of an initial torsional set which might have arisen in mounting the wire except that considerable care was exercized to avoid just this. Some slight asymmetry in the die which formed the wire may, possibly, have been responsible. In general, the application of a circular field reduced the starting field, and the greater H_t the less was H_s.

The bringing of A into coincidence with B by twisting the wire shows, as one should expect, that there is an intimate connection between torsional strain and circular field.

3. Circular Field and Torsion Combined

This has been confirmed in further experiments. In order to describe the relations between longitudinal field, transverse field, and twist, a convention in regard to signs must be adopted. The wire under test will be supposed to extend horizontally from left to right. The longitudinal field and induction are measured from left to right, the transverse circular field from bottom to top on the front of the wire, and the twist is positive when that principal strain which is the maximum elongation lies between the positive directions of the field vectors. That is, a right to left current in the wire gives a positive transverse field, while twisting the right-hand end of the wire in the sense that moves the front side upward gives a positive torsion. It is readily seen that the Wiedemann effect in iron gives a positive twist for small positive fields, in nickel a negative twist. It is likewise evident that the simultaneous reversal of any two of these quantities leaves the relationship of all three to each other unchanged. Finally, a positive jump is one in which ΔI is positive. For simplicity, and without loss of generality, the experiments will be confined to these.

4. Effect on Velocity

Although, in the absence of twist, a circular field of 8 oersteds produced only minor effects on the velocity of propagation, Fig. 2 shows that a field as low as 2 oersteds (applied to a different wire) produced marked changes in velocity even for small torsional strain. In the absence of a circular field the torsion resulting from two complete turns of one end of the wire 80 cm long caused a velocity increase from a minimum of 7000 to about 16,000 cm/sec. The shift of the

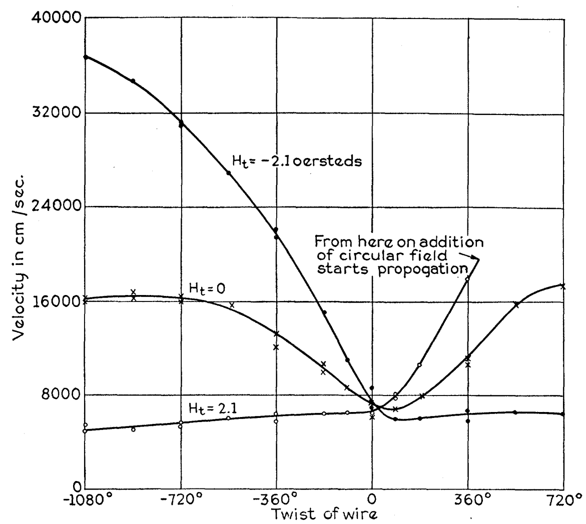

FIG. 2. Effect of twisting the wire on the velocity for different circular fields. Tension $=78$ kg/mm², $H=2.76$ oersteds.

minimum from the zero axis is mainly an elastic hysteresis effect. Its smallness shows that the constant velocity for torsion greater than 720° is in a range below the elastic limit so that the "saturation" of the velocity-angle curve cannot be attributed to a constant strain condition such as might conceivably arise with progressive plastic deformation.

5. Method of Analysis

The key to the complicated relations which exist under the combined action of H, H_t and torsion is the behavior of the critical field, together with the recognition of the importance of the vectorial nature of the variables.[2] The critical field can no longer be represented by a single coordinate as it can, when, under tension alone, only a single direction is involved. It must, rather, be shown as a point in a plane, the terminus of a (possibly undelineated) vector which can vary in direction as well as length. We were thus led to a diagram such as is shown in Fig. 3.

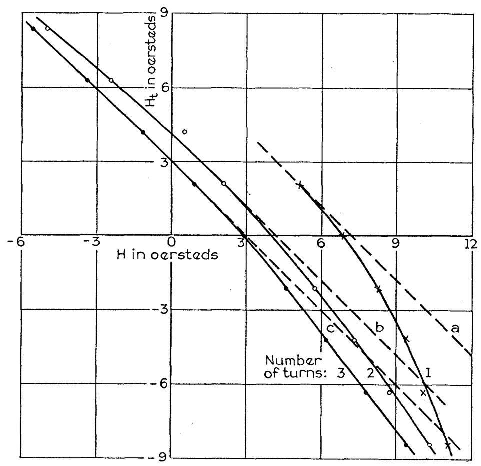

Fig. 3. Vector critical fields for torsion alone.

Here any point represents a magnetic field at the wire surface in both direction and magnitude. With the wire twisted, say 2 complete turns, and with H_t kept constant, H had to be increased beyond a certain minimum value before the large discontinuity propagated. This value and H_t are the two components of a critical field and determine a point on the plot. For a different H_t a different minimum field was found and another point was fixed. The curve marked "2 turns" was determined by a series of such points. Points determined by approaching this curve by various paths all lay on the curve. The same procedure gave the 1- and 3-turn curves. For each state of strain a whole set of critical fields was found.

[2] A preliminary note regarding this has appeared in Phys. Rev. **41**, 539 (1932).

6. Vector Critical Fields

Now Fig. 3 exhibits the results of measurements on a twisted but unstretched wire. At any depth in the wire the shear results in a maximum elongation at an angle of 45° to the axis, the elongation being, of course, greatest at the surface.

The significant features of the characteristics are, first, their approximate straightness, and second, their cutting of the axes at 45°. The straightness assures that the components along a normal to these lines of all the critical fields represented by any one characteristic are equal; and the 45° angle shows that this unique direction of resolution coincides with the maximum elongation. The conclusion is hardly avoidable that the component of the applied field along the direction of maximum extension is almost solely effective in causing the large Barkhausen jump. And the comparatively small effect of the other component, even when it is large, shows that this unique direction is one of preferred orientation for magnetization. This is a striking confirmation of R. Becker's theory relating the direction of magnetization to strain.

The fact that additional large fields, transverse to the preferred direction, do not aid appreciably in the reversal of the magnetic vector along it, requires a revision of the ideas concerning the nature of the discontinuity which were advanced in I, section 8. That concept was based upon the assumed impossibility of developing large radial fields in the wire because the wire would respond magnetically. The present results make such a response extremely improbable. How the picture is to be changed will be taken up in a later paper after additional experiments bearing on this question have been described.

7. Calculation of Strain

For further confirmation we have looked to the more complicated case where tension as well as torsion was present. Interpretation of the results requires an analysis of the strain. Imagine a set of orthogonal coordinates in the surface of the wire, the x-axis lying in a circumference, the y-axis parallel to the wire axis. Relative to the origin, the point originally at x, 1 suffers the displacement $-\rho e$, e when the wire is given the extension e, Poisson's ratio being denoted by ρ. The addition of a shear, s, by twisting the wire causes the further displacement s parallel to the x-axis. By comparing the new distance from the point to the origin with the old, it is readily found that the extension in the direction making the angle $\tan^{-1} x$ with the wire axis is

$$e_x = (e + sx - \rho x^2)/(1+x^2). \quad (1)$$

This has, respectively, maximum and minimum values of

$$(e/2)(1-\rho) \pm [s^2 + e^2(1+\rho)^2]^{1/2}/2 \quad (2)$$

at

$$x = \{-e(\rho+1) \pm [s^2 + e^2(1+\rho)^2]^{1/2}\}/s. \quad (3)$$

The experiments of immediate interest are those in which s is increased from zero in the presence of a comparatively large fixed value of e. For this range

$$e_{\mathrm{max.}} = e + s^2/4e(\rho+1) \quad (4)$$

$$e_{\mathrm{min.}} = -\rho e - s^2/4e(\rho+1) \quad (5)$$

and the value of x for the direction of maximum extension is

$$x_{\mathrm{max.}} = [s/2e(\rho+1)]\{1-[s/2e(\rho+1)]^2\}, \quad (6)$$

maximum compression ($e_{\mathrm{min.}}$) lying at right angles to this.

8. Analysis of Observations Relative to Direction

Fig. 4 is a set of vector critical field characteristics for a 0.019 cm radius, No. 37 wire 80 cm long under 62 kg/mm² tension and various degrees of torsion. It is very clear that, from lying parallel to the axis when no shear is present, the direction of preferred orientation makes an increasing angle with the axis with increasing twisting as Eq. (6) requires.

The extension of the wire was $(4.0 \pm 0.1) \times 10^{-3}$. The shear per turn at the wire surface is easily found to have been 1.5×10^{-3}. A reasonable value of ρ is[3] 0.3. Accordingly, Eq. (6) can be written for this particular case

$$x_{\mathrm{max.}} = 0.144T(1-0.021T^2), \quad (7)$$

[3] Smithsonian Physical Tables, 7th Ed., Tables 81, p. 101.

where T is the number of turns given one end of the wire. Table I shows how good the quantitative agreement is between the tangent of the observed angle of deviation taken from Fig. 4 and the tangent of the principal-strain angle as given by Eq. (7).

Another set of characteristics made with only 23 kg/mm² tension appears in Fig. 5. The 0-turn

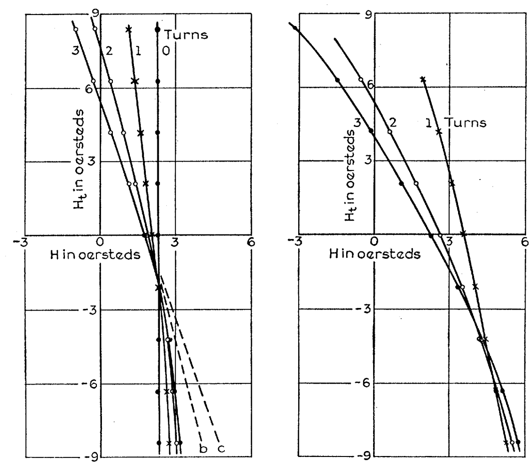

Fig. 4. Tension, 62 kg/mm². Fig. 5. Tension, 23 kg/mm². Vector critical fields for combined tension and torsion.

characteristic is missing because the tension was too low to give propagation without the additional strain introduced by torsion. Applying Hooke's law to find the longitudinal extension in this case we are again able to compare preferred orientation with principal strain axis. The results are given in the lower part of Table I. The agreement is not as good as when the higher tension was used.

Table I.

Tension kg/mm²	Torsion turns	Tangent of deviation angle		
		Magnetic	Max. extension	
			Direct calc.	Attempted corr.
62	0	0	0	
	1	0.11	0.14	0.13
	2	0.25	0.26	0.25
	3	0.34	0.35	0.34
23	1	0.23	0.34	0.29
	2	0.485	0.54	0.49
	3	0.58	0.66	0.60

A possible cause for these greater differences was thought at first to be the internal strains known to exist in the wire. By etching off successive layers and observing the changes in length, it was possible to estimate the inherent longitudinal extension in the wire surface. The method is that given by Heyn.[4] We concluded that this strain was roughly equal to that which would be caused by a tension of 10 kg/mm². There are, of course, ring strains in addition which remain undetected by this method.

The correction of this nature which is able to give good agreement in the 23 kg/mm² case is an increase of 0.3×10^{-3} in e. This corresponds to a tension of only 4.6 kg/mm². The resulting strain axis deviation values for both tensions are given in column 5 of Table I. It is seen that while good agreement exists for the 2- and 3-turn cases, a large difference persists in a 1-turn case. If this correction is applied in these tension cases, it should also be applied in the pure torsion case, where it would spoil an otherwise good check. Altogether it appears that the inherent strain factor will not eliminate the discrepancies but rather has a negligible effect. This can come about if the ring strains in the surface are equal to the longitudinal strains there so that together they determine no principal strain axis.

Although the discrepancies of Table I remain unexplained, the evidence in it and in Fig. 3 proves conclusively the coincidence of preferred magnetic orientation with the direction of maximum extension.

9. Complicating Factors

In the analysis which has been made only surface conditions have been taken into consideration. The characteristics themselves show why the underlying layers have been without major influence upon those features of the phenomenon which have been discussed until now. The curves tell us that the greater the strain the less the minimum critical field. The strain at the surface being the greatest, the minimum critical field there is the least, and propagation, when it occurs, will traverse the surface layer. It must, of course, include a finite depth of material so that portions of the wire in which the deviation of the principal strain axis is less must also be reversed. This may be one cause of the discrepancy between the calculated direction of principal strain and the observed preferred orientation.

The strain condition which was responsible for the 1-turn characteristic in Fig. 4 when 1 turn was applied to the wire lies in the level at $a/3$ when 3 turns are used, and the 2-turn condition lies at $2a/3$. Thus the figure is a picture of the characteristics of all parts of the 3-turn wire. But here an important qualification enters. The theory which has been developed as well as the positions of the 3- and 2-turn characteristics in the range where $H_t>0$ require that they cross somewhere, so that the 3-turn line would lie to the right of the 2-turn line beyond the intersection. There a magnetic field which is able to reverse magnetization under a 2-turn strain would be unable to affect the 3-turn condition. But we must recognize that under the experimental conditions the field at the 2-turn level differs from that at the surface. In fact, in the range $H_t<0$ the proportionality of H_t to radial distance is more favorable to reversal at $2a/3$ than constant H_t would be.

Reference to Fig. 4 makes this clear. The linear portions of the 2- and 3-turn characteristics have been prolonged as lines b and c. Consider the observed critical field for the 3-turn case whose components are 2.95 and -6.0 oersteds. Since c lies to the right of the terminus of that vector, that field cannot reverse the surface layer of the wire. Neither would the *surface* field be able to reverse the $2a/3$ level. At $2a/3$ the field components are, however, 2.95 and -4.0 oersteds. Here the vector terminus lies on the prolongation of the 2-turn characteristic so that reversal in this level is just possible. Finally, at $a/3$ and the the axis, the fields 2.95, -2.0 and 2.95, 0, respectively, considerably exceed the critical values. It follows that for the particular field chosen, reversal in the interior of the wire out to $2a/3$ occurs.

If only an infinitesimal portion of the wire needed to reverse in order to give propagation, then no characteristic would cross another, but each would join the envelope of the family and this envelope would finally turn into the straight vertical 0-turn line. But the necessity of reversing an appreciable portion requires that the characteristics cross each other, while the resulting

[4] E. Heyn, *Physical Metallography*, page 231.

possibility of reversing the interior portions before the more highly strained exterior portion causes their deviation from straightness beyond their intersections.

Obviously, an analysis of the kind just described must be qualitative rather than quantitative because, in all probability, the inherent strains in the wire cause the conditions at $a/3$ under 3 turns to be not strictly comparable with surface conditions under 1 turn.

The same considerations concerning variation of H_t with radial distance must apply when the wire is under torsion alone, but in the case shown in Fig. 3 this explanation cannot account for the curvature. On the hypothesis that the bending does arise from this factor, we may draw in "ideal" characteristics, straight lines a, b, c at 45° to the axes and passing through the intersection of the actual characteristics with the 45° principal strain axis. Just as in the case of Fig. 4, we choose an actual 3-turn critical field, say that one having the components 7.6, −6.0 oersteds. The field at $2a/3$ is then 7.6, −4.0 and line b shows that no reversal will occur at this level. Similarly for the $a/3$ level. Nowhere along the 3-turn characteristic is it found that internal reversal can occur on the basis of the present hypothesis.

It must be concluded that another factor predominates here. It may very well be that the nonhomogeneous internal strains are not completely overcome by the applied strain. This would result in a certain scattering of both the direction of maximum elongation as well as its magnitude, so that domains with preferred orientations at other than 45° to the axis and with various critical fields exist in the wire. It is probably significant that the 1-turn curve having the least applied strain shows the greatest curvature.

This view is consistent with the greater deviation of the characteristics at negative transverse fields than at positive. Since the applied strain is a maximum at the wire surface, the preferred orientation there will lie, in general, nearest to 45°, and the critical field will be a minimum. This is represented by the vector OB in Fig. 6. Below the surface, say at $a/2$, where the applied strain is less and the critical field is greater, there will be domains characterized by the vectors OA and OC. The critical field characteristics correspond-

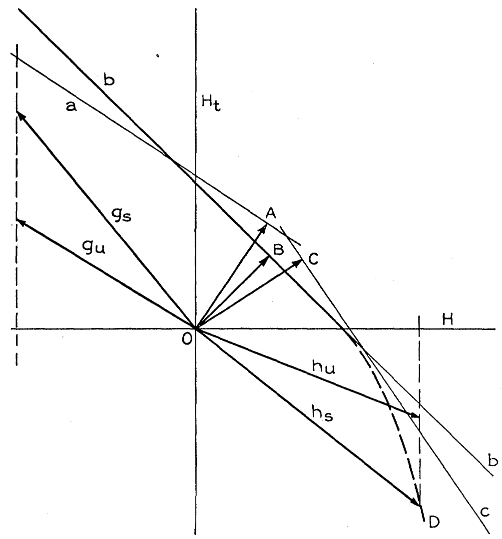

FIG. 6. Effect of incomplete alignment of preferred orientations on the critical field characteristic.

ing to these three vectors are a, b and c. It is evident that a surface field h_s which is unable to reverse the surface domains becomes h_u at $a/2$ and is able to reverse the domains represented by OC. Thus the actual characteristic might very well have the shape BD in this region. On the other hand a surface field g_s, symmetrical to h_s relative to the principal strain, can cause no similarly pronounced deviation, for the variation here of H_t with depth operates against the possibility of interior reversal when surface reversal cannot occur.

Torsion tests on other wires have not shown the same exactness as appears in Fig. 3 in conforming to the theory, although none have been so divergent as to cast doubt on its validity. One wire, for instance, gave an angle between axis and preferred direction whose tangent was only 0.58 for 3 turns, but this wire also gave propagation under no applied strain. Under this condition the critical field characteristic lay perpendicular to the H-axis, so that we must conclude that a surface strain was present whose principal axis of elongation lay parallel to the wire axis. The normals to the characteristics made angles with the wire axis whose tangents are given in column 2, Table II. From Eq. (3) it is readily found that

$$e=(1-x^2)s/2(1+\rho)x, \qquad (8)$$

and, remembering that for an 80 cm 0.019 cm

TABLE II.

Turns T	Angle tangent x	Inherent axial elongation, e_i
1	0.32	1.62×10^{-3}
2	0.48	1.84
3	0.58	1.97

radius wire $s=1.5\times10^{-3}T$, the inherent elongation values e_i in column 3 were calculated. The approximate constancy of e_i roughly confirms the hypothesis of internal strains. Incidentally, the average value corresponds to a tension of 25 kg/mm².

Another wire, under two turns torsion, showed an angle tangent of 1.27. The points for this plot were assembled from data taken in other connections and the wire later broke so that further tests with a view to explaining this type of deviation were impossible.

A wire from ingot No. 37 which had been annealed at 370°C gave the critical field characteristics of Fig. 7. At 1 turn no large jump occurred. The deviation angle tangents are 0.71, 0.78 and 0.78 for the successively larger torsions. An inherent longitudinal surface extension e of 0.80 $\times10^{-3}$ would lead to the tangents 0.71, 0.79, 0.84, respectively. The agreement between the 2- and 3-turn characteristics is good, while the plastic deformation which occurred with 4 turns and

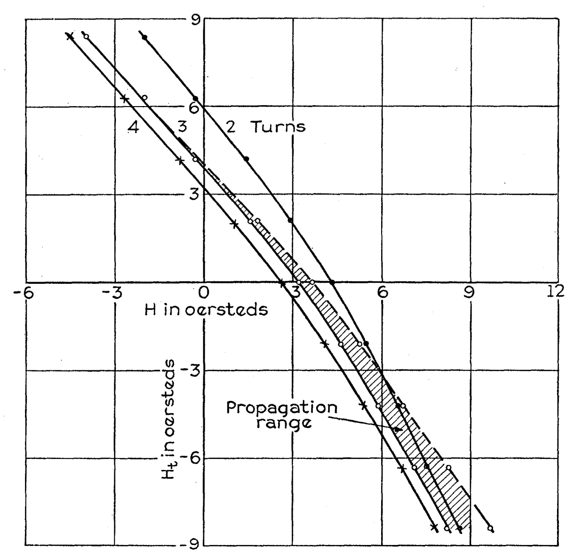

FIG. 7. Vector critical fields for an annealed wire under torsion only.

amounted to a permanent set of about 1/3 turn accounts for the discrepancy there.

10. MAGNITUDE OF THE CRITICAL FIELD

Since the direction of the minimum critical field follows a principal strain axis, it is to be expected that the magnitude of this field depends on the principal strains alone. The data already given in connection with Figs. 3, 4 and 5 are suf-

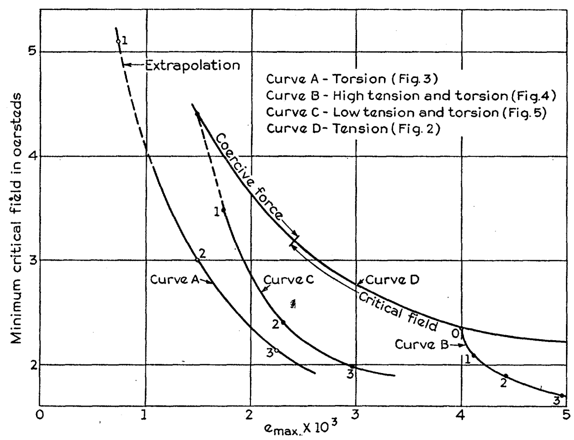

FIG. 8. Relations between minimum critical field and maximum elongation for tension and torsion.

ficient to calculate $e_{max.}$, using Eqs. (2) or (4) for each curve in all three cases. Fig. 8 is a plot of the observed field strengths against the maximum extension. The number beside each point is the number of turns in the wire. The pure tension curve is replotted from II, Fig. 2.

The infinite slope of curve B can only be interpreted as meaning that some factor other than $e_{max.}$ is of predominating importance where the torsion is small. This behavior of the curve arises from the circumstance that the minimum critical field decreases almost linearly with torsion whereas $e_{max.}$ increases with its square, Eq. (4). Thus, this unknown factor must itself vary linearly with s. The compression, Eq. (5), does not do this. In fact, symmetry considerations prove that there is no factor within the simple concept of coincidence between preferred orientation and principal strain which has this type of variation. We do not know, as yet, how the present ideas must be extended.

Curve C shows a tendency similar to that of B, but as the jump does not occur under such low tension alone, this curve cannot be followed to zero torsion.

A shear s causes a maximum extension $s/2$ and a reduction of the transverse cross section of an equal amount. Tension which causes an extension e causes a cross-section reduction of $2\rho e$, which, with the current value of ρ, is only 0.6 as great. Thus, if transverse compression cooperates with longitudinal extension in lowering the minimum critical field, as might be expected, curve A should lie uniformly below curve D, as it does, yet the magnitude of the observed effect is out of all proportion to the quantitative difference in strain. For instance, measuring the strain by the sum of the transverse compressions plus the extension, we have for equal extension, 2 units of strain with torsion and 1.6 with tension, a difference of 20 percent. Yet a torsional $e_{max.}$ of 2.3×10^{-3} gives a critical field of 2.1 oersteds, while

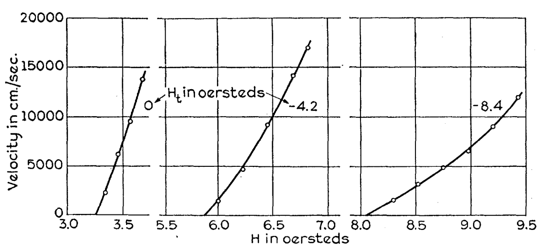

FIG. 9. Velocity-field curves for the same wire as in Fig. 7 under 3-turns torsion for different critical fields.

at a tensional $e_{max.}$ of 5×10^{-3}, the critical field still lies above this value and is only falling slowly with increasing $e_{max.}$. Besides, a qualitative distinction appears, for below an $e_{max.}$ of about 2.4×10^{-3} tension no longer produces large discontinuities, whereas torsion produces them for values of $e_{max.}$ below 1.5×10^{-3}. These differences between tension and torsion are undoubtedly connected with the anomalous shape of curve B.

11. Velocity-Field Characteristics

The Figs. 9, 10, and 11 each show a series of velocity *vs.* (longitudinal) field plots for a succession of values of circular field. (Figs. 9 and 11 are for wires whose critical field characteristics appear in Figs. 3, 4, 5, and 7 according to the legend on each figure.) Although no consistency is obvious from the figures, yet a partial explanation of their behavior can be given which is based

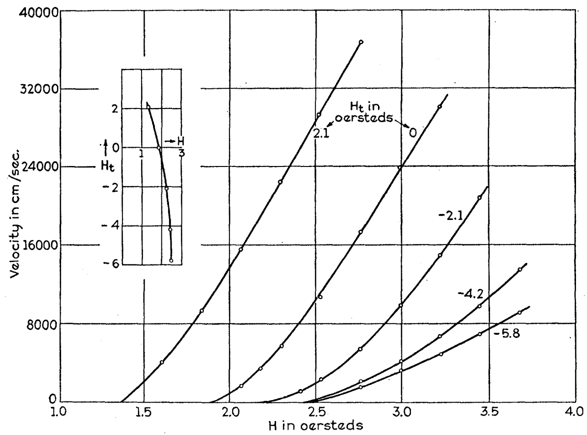

FIG. 10. Velocity-field curves for a wire under 78 kg/mm² tension and 3-turns torsion for different circular fields. Insert is the critical field characteristic.

on the general relation between propagation range, $H_s - H_0$, and slope, A, which has already been remarked upon, and which will be considered in greater detail in a later paper. It will be remembered that the increase of the one accompanying a decrease in the other has already been reported in II for etched as compared with unetched, hot as compared with cold wires, and for one portion of a single wire as compared with another portion.

While the curves of Fig. 9 corresponding to the 3-turn characteristic of Fig. 7 exhibit this beautifully, the other two sets fail to conform. In the case of Fig. 10, where the propagation range remains unchanged at 1.3 oersteds, a convincing

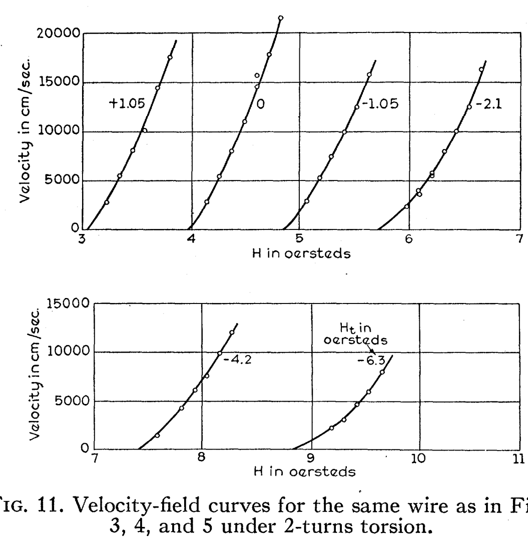

FIG. 11. Velocity-field curves for the same wire as in Figs. 3, 4, and 5 under 2-turns torsion.

explanation is possible. This case differs from all the others which have so far been examined in the important respect that here negative values of H_t lead, as has already been pointed out in paragraph 9, to propagation in a sub-surface level of the wire. The progress of the jump is thus hampered by additional eddy currents independent of any change in starting field with depth in wire. A similar decrease in A has been observed in a wire after surrounding it by a copper tube, which, obviously, had no effect on the starting field. This does not explain the constancy of $H_s - H_0$, but simply how the slope can decrease despite the constant propagation range.

Turning to Fig. 11, either the slope, at 10,000 cm/sec, or the quotient of maximum velocity and propagation range, when plotted against propagation range, gives a rather scattered array of points. Although the best straight line fit conforms to the general relation, this is a poor confirmation. Now in accordance with the considerations of Fig. 6, a certain amount of sub-surface propagation is occurring here just as in the case of Figs. 7 and 9. Yet if this was insufficient to supplant the reciprocal variation of $H_s - H_0$ and A in the former case, it is not evident why it should here. Altogether, we see no good reason for the nonconformity of this series, and it must be classed as an exception.

12. Hysteresis Loops

Connected with the large effects of torsion and circular field on critical field there are, necessarily, correspondingly great changes in the hysteresis loop. Fig. 12 shows these effects for the same wire that was used to obtain Figs. 3, 4, and 5. The wire was twisted 2 turns in 80 cm length.

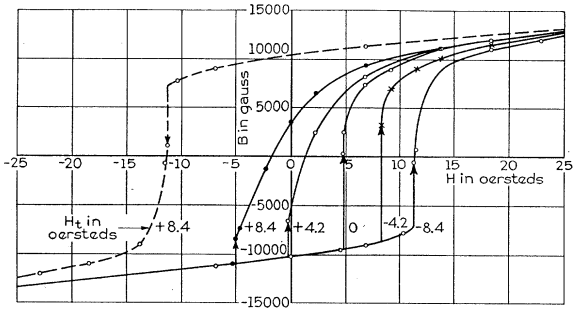

Fig. 12. Hysteresis loops for the same wire as in Figs. 3, 4, 5, and 11 under 2 turns torsion for different circular fields.

Each full line curve is one branch of the hysteresis loop obtained in a circular field whose strength in oersteds at the wire surface is denoted by the numbers attached to each curve. The breaks occur at the starting rather than the critical fields. The critical field is, of course, smaller algebraically.

An outstanding feature in the family of Fig. 12 is the negative coercive force and negative remanence of the sample for $H_t = 8.4$ oersteds. Although the axial component of the impressed field is negative, still its component along the 45° direction is effective in creating a sufficient net reversal of magnetization along this line so that the longitudinal component of induction becomes positive. In the reverse process this is compensated by a greater lag of induction behind field, shown by the other branch of the loop in dashes.

This reverse branch is simply the -8.4 branch projected through the origin as a point of symmetry, a relation which follows from the fact, noted earlier, that reversal of two of the three vectors, field, magnetization and torsion, leaves the interrelations unchanged. In the present case it is the first two vectors which are reversed.

13. Magnitude of the Large Discontinuity

Various factors make an analysis of variation in jump magnitude with transverse field impossible at the present time. It is, of course, certain that this magnitude is a measure of the fraction of the wire cross section participating in the jump. Under torsion alone the axial component of the magnetization at all radial distances is the same because the strain axis lies throughout at 45° to the wire axis. Accordingly, in this case the jump magnitude is directly proportional to the participating cross section. But where tension also is present, the axial component increases with depth. This is a factor which can be calculated in those cases where we know the levels included in the propagation.

On the other hand, jump magnitude in a twisted wire depends markedly on the main field alone, increasing with it. This is because the critical field increases with depth in the wire so that the larger main fields still exceed the critical field at smaller radial distances with the result that a greater fraction of the cross section reverses. Both the lower and upper limits of propagation are, however, fixed by the inhomogeneity of the wire, the lower limit by point to point variations in critical field, the upper by the minimum value of starting field for the whole wire. If it were certain that the same starting field was operative no matter what the ratio of transverse to longitudinal field might be, an analysis might be possible, but this is certainly not the case. For negative circular fields, for instance, it is very probable that the starting field may correspond to a sub-surface point while for positive H_t it corresponds to a surface point. We thus lack a basis for the comparison of jump magnitudes.

Finally, the deviations of the critical field characteristics, not only from the ideal straight lines or modified straight lines but also from the calculated inclinations, show the presence of factors whose effect on the magnitude may be considerable yet cannot be estimated.

14. Transverse Effects

Theory requires that accompanying the sudden changes in longitudinal magnetization there should be corresponding discontinuities in transverse magnetization, but as this flux forms a closed path within the wire itself, the only means for detecting it is a potential gradient along the portion of the wire occupied by the propagating jump. Such an e.m.f. has often been observed in twisted wires where no large jumps occurred so that it is only natural that it appeared here.[4.5]

But, interchanging the roles of longitudinal and circular fields, we see that transverse magnetization induced by a transverse field should be accompanied by a longitudinal component. The experiment is very like that described by Bozorth and Dillinger[5] on the ordinary Barkhausen effect, except that here the magnetic domains are polarized by the torsion so that all components perpendicular to the field have the same sense instead of lying half one way, half the other.

Strangely enough, such an effect for ordinary ferromagnetics seems not to have been reported on previously, although closely related phenomena such as the induction of longitudinal magnetization under varying torsion in a constant circular field has been described in some detail.[6]

Since the effect of circular field was more pronounced when tension as well as torsion was acting, the results for the wire when subjected to 23 kg/mm^2 and 3 turns will be described. A set of hysteresis curves similar to those of Fig. 12 are given in Fig. 13a. Fig. 13b was obtained in the following manner:

[4.5] *Footnote added in proof:* Using this (Matteuci) effect together with simultaneous observations of the changes in longitudinal induction, H. Ostermann and F. v. Schmoller (Zeits. f. Physik **78**, 690 (1932)) have recently given an independent demonstration of the coincidence of preferred magnetic direction and principal strain axis in twisted wires. In the succeeding article (p. 697) W. Schütz discusses the connection between their results and the theory of magnetization curves.

[5] R. M. Bozorth and J. F. Dillinger, Phys. Rev. **41**, 345 (1932).

[6] H. Gerdien, Ann. d. Physik **14**, 51 (1904).

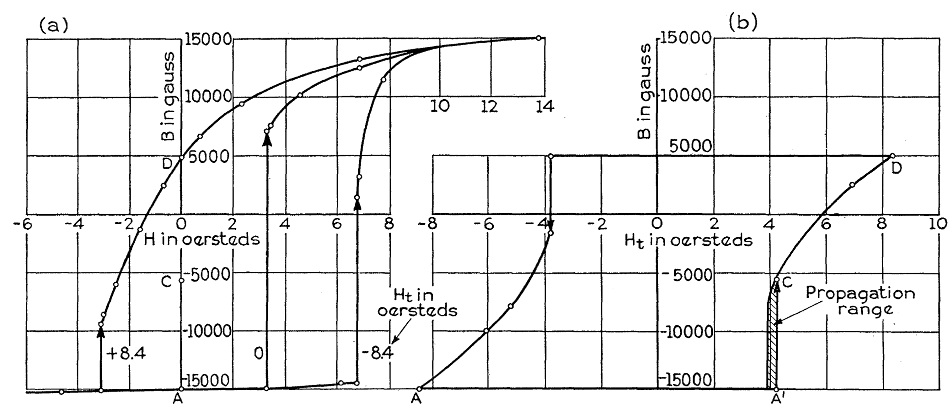

FIG. 13a. Hysteresis loops of a wire under 23 kg/mm^2 tention and 3 turns torsion for various circular fields.
FIG. 13b. Longitudinal component of induction *vs.* circular field for the wire under the same conditions as in *a*.

With $H_t = -8.4$ oersteds the wire was subjected to a strong negative longitudinal field which was then reduced to zero. This state of the wire corresponds to point A in Figs. 13a and 13b. H_t was then increased (algebraically), the wire state traversing the line AA' in Fig. 13b but remaining at A in Fig. 13a, where the effect of changing H_t was to bring the starting field closer and closer to zero. At $H_t = 4.2$ the starting field was exceeded and the jump ensued, carrying the wire to point C in both figures. Further increase in H_t up to $+8.4$ oersted brought the wire to point D. The change in magnetization between C and D can only be made up of reversals in domains controlled by the applied strain but whose vector critical fields were too large or insufficiently deviated from the wire axis to participate in the large jump.

Reduction of H_t from its extreme had no effect until the *critical* field on the negative side was reached. The occurrence of the jump at the critical rather than a slightly larger field when the wire has not been carried to saturation has been noted before (I, section 9). Allowing for this, the two jumps may well be equal and may well have the same critical field. Finally, the loop closed when -8.4 oersted was reached once more. We have thus found that accompanying a cycle of a purely transverse field there is a symmetrical longitudinal loop. Its unsymmetrical position on the induction axis arises from the longitudinal polarization of the axial portion of the wire which is unaffected (so far as longitudinal effects are concerned) by the transverse field.

Referring to the axial direction alone, the large discontinuities in this loop demonstrate that the presence of a circular field makes possible the propagation of a positive jump in a zero and undoubtedly even a slightly negative main field.