PROPAGATION OF LARGE BARKHAUSEN DISCONTINUITIES

BY K. J. SIXTUS AND L. TONKS
GENERAL ELECTRIC COMPANY, SCHENECTADY, NEW YORK

(Received February 28, 1931)

ABSTRACT

Large Barkhausen discontinuities have previously been observed by Forrer and by Preisach in nickel wires and hard-drawn wires of the nickel-iron series respectively under stress. A prediction that these discontinuities occur in form of a propagation along the wire, starting at a nucleus, has now been substantiated. In the experiments an additional local field was used to start the propagation at a definite point on the wire, which was in a uniform magnetic field, and the velocity was determined by measuring the short time interval elapsing between the passage through two search coils around the wire. With a fixed value of tension on the wire, the velocity v was found to vary approximately linearly with the applied uniform field H, so that $v=A(H-H_0)$. A is the slope of the velocity-field characteristic and H_0 is called the *critical field*. Measured velocities range from 500 to 40,000 cm sec^{-1}. H_0 varies with composition, amount of cold working, and with the stress applied to the wire. Increasing tension reduces the critical field over the greater part of the Ni-Fe alloy composition range. The behavior of H_0 with increasing and decreasing tension shows the presence of elastic hysteresis. A is nearly constant for changes in tension, in diameter of wire, for composition of wire, and is the same for a strip. Its value is approximately 25,000 cm sec^{-1} $gauss^{-1}$.

The existence of eddy currents limits the speed with which magnetism can penetrate the wire. A rough calculation of this time gives values in the neighborhood of 10^{-2} sec. Thus a discontinuity travelling at 10^4 cm per sec. occupies a length of some 100 cm on the wire. This was substantiated both by measurements of the peak voltage induced in a search coil and by oscillograms taken of the induced voltage. The observed passage times agree well with the theoretical penetration times.

The constancy of the v-H slope for wires of different diameters is believed to indicate that the velocity depends upon surface phenomena rather than volume phenomena. The velocity would thus be determined by conditions existing near the front edge of the discontinuity where the penetration is still slight. The critical field is believed to represent a threshold value of magnetic field which must be exceeded at all points of the wire before reversal of magnetism can occur. The excess of the impressed field over the critical is nullified during propagation by the fields arising from the eddy currents. A possible picture of the discontinuity is one in which the reversal occurs within a minute distance of an approximately conical surface in the wire, the edge of the base of the cone forming the front of the wave.

The explanation advanced by Preisach for the asymmetric hysteresis loops found if one limit of the magnetization cycle was reduced has been extended. In this case magnetic inhomogeneities act as nuclei. Mechanical distortion introduces inhomogeneities of another type which also lead to the very easy formation of a nucleus. The phenomena found with torsion are more complicated than for tension. In some cases the slope of the v-H lines shows appreciable variation with direction of twist. The results of tests with various compositions of the nickel-iron series are described using both tension and torsion, but no new relations to other properties of these alloys can be given so far. Identifying H_0 with coercive field, R. Becker's theory has been compared with our results. It appears that in most cases increased elastic tension and increased cold working stresses shift H_0 in opposite directions.

1. Large Barkhausen Discontinuities

SINCE the discovery of the Barkhausen effect, it has been a well-established fact that a great part of the change in induction in a ferromagnetic when subjected to a varying field, is made up of discontinuous changes. These ordinary discontinuities can only be observed after amplification and are not detectable by the ballistic method. Large discontinuities were first observed by Forrer[1] in 1926 in the hysteresis loop of a strained nickel wire. Later Preisach[2] showed that wires of Ni-Fe alloys under the influence of any stress (tension, torsion, bending) gave large discontinuities in a longitudinal field. In some cases these discontinuities were equal to almost the whole change in induction between saturation in the two directions.

If one tries to picture the manner in which such a magnetization discontinuity occurs, one is struck by the difficulty of accounting for a simultaneous reversal in the whole length of a fine wire. This consideration led Langmuir to predict that the magnetization first reversed at one point in the wire, forming a nucleus, and that the two boundaries which were thus formed then travelled along the wire with a finite velocity which probably depended on the magnetic field strength and the elastic strain. This prediction has been well substantiated by the experiments which will be described in what follows. A preliminary report of this work has appeared in the Phys. Rev. **35,** 1441 (1930).

2. The Propagation of Magnetization

Several investigations on the propagation of magnetic waves have been carried out.[3] The method used has been the same in all cases. An iron wire or bar was subjected to an alternating magnetic field at one point and the phase shift and maximum value of induction a certain distance away were measured. Zenneck[4] proposed a theory for the observed effects, based on the assumption of eddy currents as a determining factor, and postulated the equivalence of electric and magnetic waves propagating along a ferromagnetic conductor. But the velocities corresponding to the observed phase shifts differed within a wide range (10^3 to 10^5 cm/sec), the whole phenomenon appeared to be very complex, and no effort was made to relate theory and experiment to each other.

The problem appears simpler in the case of the propagation of a single discontinuity, particularly a 100 percent discontinuity, by which is meant one in which the reversal of saturation is complete. In such a case we are dealing with a medium of finite conductivity and permeability unity but capable of reversing its magnetization at a point under a certain critical local condition.

[1] M. R. Forrer, Journ. de Physique [VI] **7,** 109 (1926).

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

[3] A. Oberbeck, Ann. d. Physik **21,** 672 (1884); **22,** 73 (1884). H. A. Perkins, Amer. Jour Sci. **18,** 165 (1904). Lyle and Baldwin, Phil. Mag. **12,** 433 (1906). C. V. Drysdale, Electrician **67,** 95 (1911).

[4] T. Zenneck, Ann. d. Physik **9,** 497 (1902).

This local condition is defined by two variables, the state of elastic strain and the magnetizing force.

It was thought that general energy considerations might enable us to make an attack on this problem. A change of intensity of magnetization ΔI in a field H represents an available energy density of $H\Delta I$. This must at least exceed the energy dissipated by the eddy currents accompanying the magnetization wave.[5] These losses can be estimated as follows. The whole change of magnetization intensity, ΔI, is assumed to occur in a

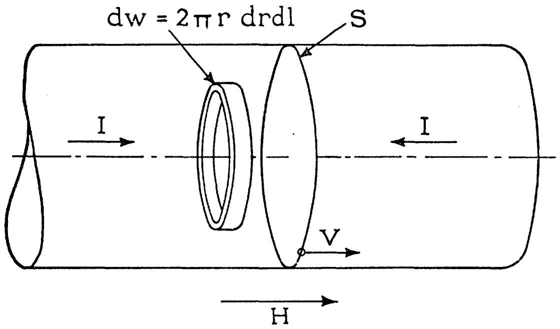


Fig. 1. Illustrating the induction of eddy currents by a moving magnetic discontinuity.

thin plane slab, S, moving with velocity v as shown in Fig. 1. The time integral of the e.m.f. induced in an annular volume dw of radius r will be that due to the change in flux, $\Delta\phi$, inside that ring, that is,

$$\int F dt = \Delta\phi/c = \pi r^2 \cdot 4\pi\Delta I/c \qquad (1)$$

where F is the e.m.f. induced in dw and c is the ratio of units. The chief contribution to this integral will occur while the discontinuity is within a distance of dw which is comparable with its radius r. Accordingly, instead of $\int F dt$, where F is the e.m.f., we may write $F\Delta t$, approximately, where $\Delta t = 2r/v$. Applying this to Eq. (1), we have

$$F = 2\pi^2 r v \Delta I/c. \qquad (2)$$

Since F is acting for a time Δt the eddy current loss in dw is $F^2\Delta t dr dl/2\pi r\rho$ where ρ is the specific resistance. Combining with Eq. (2) and integrating, the energy loss per unit length of wire of diameter a is found to be $E = (4/3)\pi^3 a^3 v(\Delta I)^2/\rho c^2$. The magnetic energy available is $E_m = \pi a^2 H\Delta I$. Equating the two we find for the velocity

$$v = (3/4\pi^2)\rho c^2 H/a\Delta I \qquad (3A)$$

in magnetic units or

$$v = 0.76 \times 10^8 \rho H/a\Delta I \qquad (3B)$$

in practical units.

[5] This reasoning obviously neglects any elastic energy changes which may occur.

Another calculation based on what appeared to be a less favorable hypothesis at the time was made by Dr. H. Poritzky. The assumption that the magnetization change occupies a length, λ, of the wire, long compared to a, gives

$$\Delta t = \lambda/v.$$

Reasoning as before, it follows that

$$v = (1/2\pi^2)\rho c^2 H\lambda/a^2\Delta I \quad (4A)$$

in magnetic units, or

$$v = 0.51 \times 10^8 \rho H\lambda/a^2\Delta I \quad (4B)$$

in pratical units for this case.

3. Apparatus

Theory of method. In measuring rectangular hysteresis loops of the same type as published by Preisach, it was noticed that the field strength at which the large discontinuity occurred, which will be called the *starting field*, was variable within a few percent in successive experiments. Since the occurrence

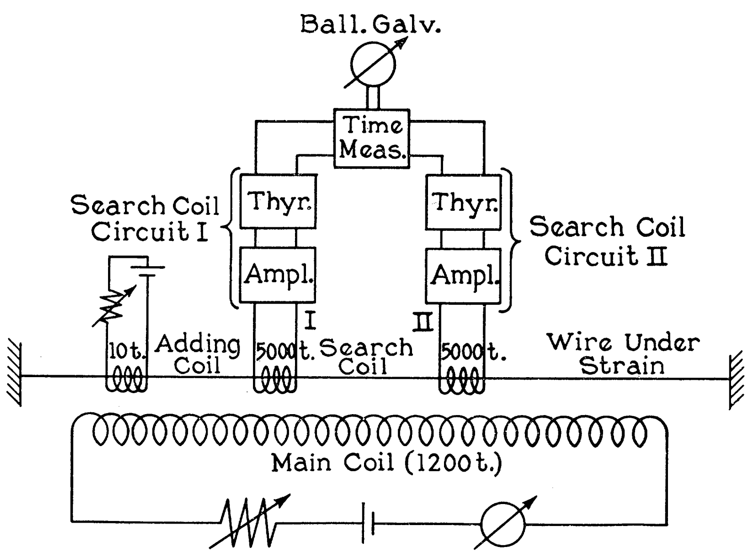


Fig. 2. Schematic diagram of circuit for velocity measurements.

of the large discontinuity depends upon the spontaneous formation of a nucleus, as described in Section 1, this erratic behavior can either mean that one nucleus was itself starting erratically or that different points along the wire were acting as nuclei. To control the creation of a nucleus an "artificial nucleus" was made by locally increasing the field strength by means of a current through a small magnetizing coil which created a local adding field. If then the homogeneous field, which will be called the *main field*, was set at a value below the starting field, the large discontinuity could be initiated by applying the local adding field. The change in magnetization then begins at this point and propagates into the homogeneous part of the field where its velocity can be determined in the following way. If we place two search coils around the wire at a known separation, the discontinuity in travelling along the wire will produce successive voltage surges in these coils. If their time interval be measured, the velocity can be calculated.

Design of apparatus. The main field (Fig. 2) was furnished by a helix of 65.5 cm length containing 1200 turns of copper wire of 0.051 cm diameter, wound on a glass tube. Thus the uniform part of the field is given by $H=23.0\,i$ (i being the magnetizing current in amperes). The decrease in H 23 cm from the middle of the coil is 0.5 percent. At first a liquid resistance allowing continuous variation of current was used, but later on a slide-wire resistance was found to give a sufficiently gradual variation.

The wire under investigation was held in the axis of the coil and could be subjected to tension or torsion or both in the same way as described by Preisach. The tension was read by a spring balance and the twist by a pointer connected to the wire. The wire was surrounded by a capillary glass tube so as to permit its easy replacement with the search coils in place.

Each search coil consisted of 5000 turns of copper wire of 0.008 cm diameter. Since the length of the winding was 0.65 cm and the inner and outer diameters were 0.4 and 1.8 cm respectively, the voltage induced in them could not be proportional to the change in flux in one point on the wire, but gave an average over a distance comparable with the outer diameter (i.e., approximately 2 cm). The coils were wound on hard rubber spools and could be moved separately along the capillary tube by means of strings connected to them, and their positions could be read by pointers fastened to the strings and sliding along a scale. In most cases their separation was kept at 20 cm, each being 10 cm from the center of the main field.

The additional local field was produced by a coil of 10 turns of copper wire of 0.051 cm diameter, wound on a spool which was also movable along the wire. Generally the adding coil was placed at a distance of 24 cm from the middle of the main field.

Time-measuring arrangement. For measuring the time interval between the voltage impulses induced in the two search coils by the passing discontinuity, a vacuum tube device (Fig. 3) was built. This system, which is similar to the one used by Turner for his Kallirotron amplifier,[6] has two stable states of current distribution, if voltages and resistances are properly adjusted. In State 1, plate current is flowing only in Tube I and there is no measurable plate current in Tube II; in State 2, current is flowing only in Tube II and there is no current in Tube I. To explain this let us assume that both tubes carry current. If a negative voltage impulse is now applied to the first grid, the plate current in Tube I decreases and in turn reduces the potential drop in R_I, which makes Grid II more positive. The plate current in II there-

[6] L. B. Turner, Radio Review **1**, 317 (1920).

fore rises, causing an increasing potential drop in R_{II}, and since this drop furnishes the grid bias for Tube I the grid voltage in I becomes still more negative. This cumulative action proceeds until practically no current is flowing in I, while the plate current in II has its full value. The current may now be shifted back to Tube I by applying a sufficient negative voltage to the grid of Tube II. Since the minimum value required increases as the resistances R_I and R_{II} are increased, the sensitivity of the circuit is under control. Two UX-112A tubes were used.

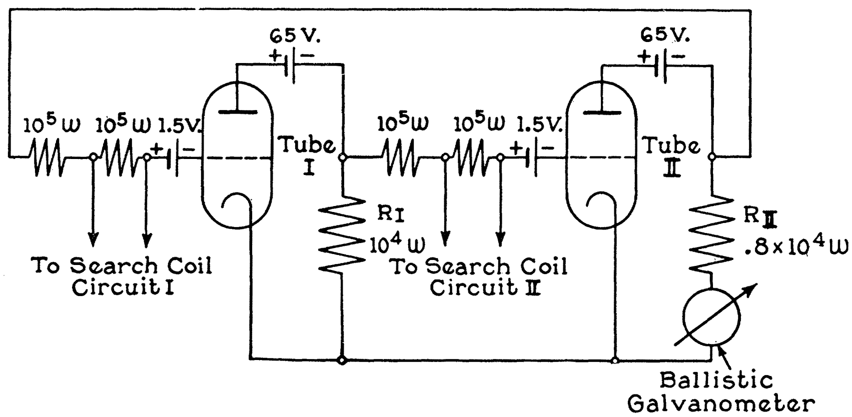


Fig. 3. Time-measuring circuit.

In making a time interval measurement this circuit was put into State 1 and a negative voltage impulse excited by Search Coil I was applied to the grid of Tube I. This shifts the current over to Tube II. After a time interval t the impulse from Search Coil II impressed on the second grid stops the current in Tube II. Thus the quantity of electricity which has passed through Tube II is a measure of the time t between the impulses. This quantity was measured by a ballistic galvanometer so that t was given by

$$i_P t = C\theta \tag{5}$$

where i_P is the plate current, C the ballistic constant of the galvanometer, and θ its deflection.

This relation was checked by means of a pendulum which opened two contacts in succession. Each contact was joined in series with a battery and the primary of a transformer, and the secondaries were connected respectively to the grids of Tubes I and II of the timing circuit. The opening of the contacts thus produced voltage impulses on the grids. The pendulum was calibrated by using a known condenser discharging through a known resistance. The time interval found from the pendulum calibration agreed with those calculated from Eq. (5). This means that the shift of the current from one tube to the other occurs in a time short compared with the time intervals to be measured.

The negative voltage impulse applied to tube I had to exceed a certain minimum value (for given voltages and resistances in the timing circuit) but if it were too large, the current, after shifting to II, failed to return with the negative impulse on II. Thus it was necessary to keep the impulses within a certain range. The timing circuit was so adjusted that impulses of 1 volt operated it, and this voltage was obtained independently of the magnitude of the voltage induced in a search coil in the following way: The impulse from each search coil was amplified by a two-stage resistance-coupled amplifier whose output was impressed on the grid of a thyratron[7] as shown in Fig. 4. The sudden rise of plate current, from 0 to 100 m.a. in the present circuit, being independent of the voltage impressed on the grid, always gives the same voltage of approximately 1v. across the secondary of the transformer in

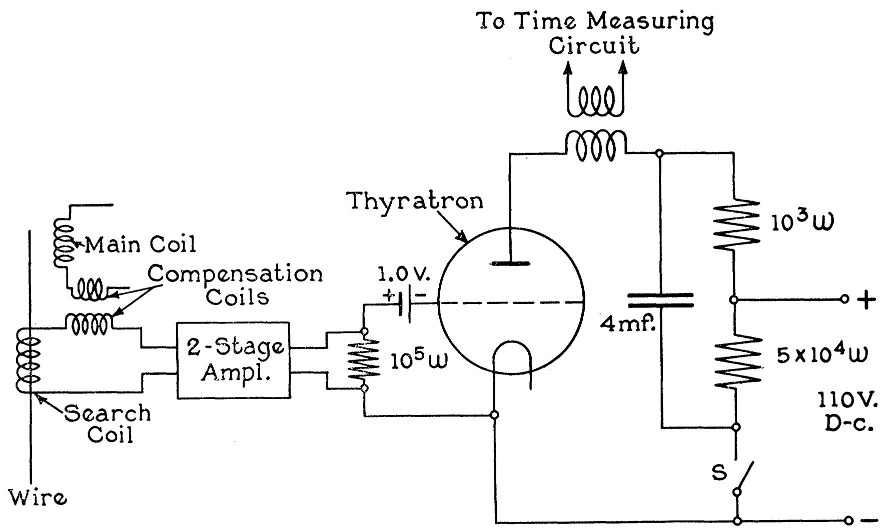


Fig. 4. Thyratron relay.

the plate circuit. The 4-μf condenser and 50,000-ohm resistance made it possible to stop the discharge in the thyratron by simply closing the switch S, thus setting the circuit for the next impulse.

The maximum voltages induced in the 5000 turn search coils were of the order of 0.1 v. The amplification of the amplifiers used was about 120. As the grid bias of the thyratrons was so adjusted that positive impulses of about 1 v. would start the discharge, both thyratrons were started before the voltage impulse reached its maximum (See oscillograms Figs. 11 and 12). The whole

[7] A thyratron is a three element tube containing a small amount of mercury. The cathode of the one used was oxide coated. In a thyratron which is initially carrying no current, current does not start to flow as long as the grid potential is less than a certain value. As soon as the grid voltage exceeds this critical value, however, the full plate current begins to flow, and from this moment on the grid has no further influence on this current. By using a proper value of grid bias this tube can be used as a relay, as in Fig. 4, or as a peak voltmeter. See: A. W. Hull, Hot-Cathode Thyratrons, Gen. Elec. Rev. **32,** 213, (1929) and **32,** 390 (1929); A. W. Hull and I. Langmuir, Proc. Nat. Acad. Sci., March 1929; A. W. Hull, Trans. A.I.E.E. **47,** 753 (1928).

arrangement, it was found, worked satisfactorily down to time intervals of 0.5×10^{-3} sec, since all time constants were kept as low as possible.

Hysteresis loops. Hysteresis loops were taken with the magnetizing coil and one search coil (Fig. 2). The latter was connected to a ballistic galvanometer (Leeds and Northrup Type HS No. 2285d) with a sensitivity as used of 1425 Maxwell/Sc. div. and a period of 30 sec. The direct effect of the magnetizing coil on the search coil was compensated as usual by a mutual inductance.

4. Velocity Measurements

Composition and treatment of specimens. The wires used in our experiments were made from ingots of electrolytic nickel and Armco iron plus 0.25 percent manganese to make the alloy ductile. The ingots were swaged and then drawn down to 0.10 cm diameter, sometimes to 0.076 cm, with annealing. From this diameter the wires were cold drawn to 0.038 cm. The percentage of Ni was determined for each wire investigated by chemical analysis. In this section we shall deal mainly with alloys of between 10 and 20 percent Ni since these show the phenomena of propagation very markedly. In Section 11 the results with wires of other compositions will be considered briefly.

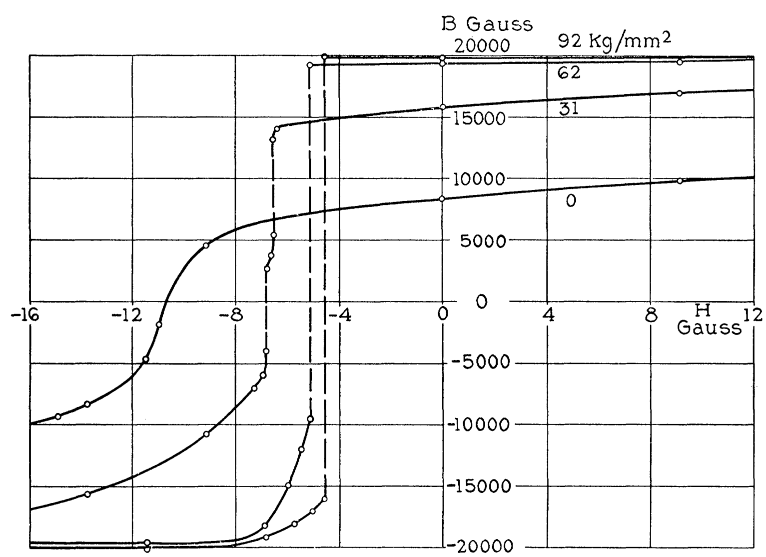


Fig. 5. Hysteresis loops for a wire under different tensions. Wire of 0.038 cm diameter from ingot No. 32, 15 percent Ni-Fe (only half of the total loop is shown).

The wires were aged by stretching them for about 1 hour with loads near to the elastic limit, because more consistent results were obtained in this way. The aging load was never exceeded by the tensions used in the course of an experiment. Incidentally, in these hard drawn wires the breaking point lies only slightly beyond the elastic limit.

Effect of tension on hysteresis loops. Fig. 5 shows hysteresis loops for a wire of 15 percent Ni Fe and 0.038 cm diameter (cold drawn from 0.076 cm) under different tensions. These loops are of the same type as the ones observed by Preisach. With no load only the ordinary Barkhausen discontinuities occur and these cannot be detected by the galvanometer. With rising tension the formation of large discontinuities begins until with high tension a great part of the whole change between negative and positive saturation occurs in one single discontinuity. The maximum magnetizing field was in all cases 34.5 gauss. The curves show that for increasing tension the remanence

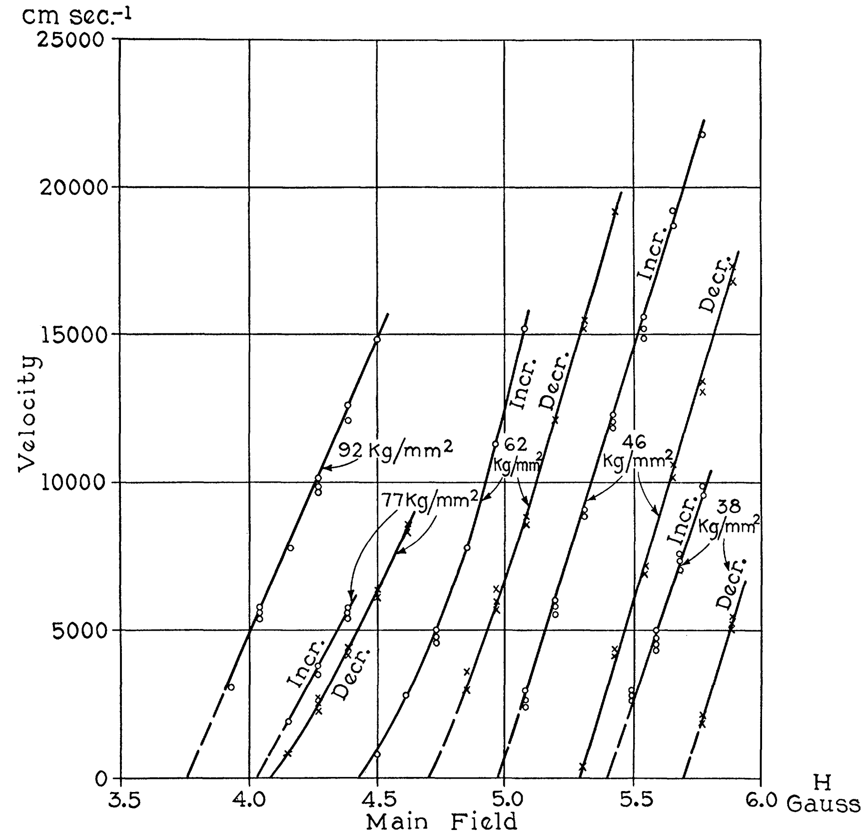


Fig. 6. Velocity-field curves for a wire under different tensions. Wire of 0.038 cm diameter from ingot No. 14, 14 percent Ni-Fe.

increases until it equals 100 percent saturation as exactly as we could measure. The coercive field on the other hand is reduced by increasing tension.

Velocity measurements. A complete set of velocity measurements covered both variation of tension and of magnetic field. This was accomplished by finding the relation of velocity to field at each of a series of values of tension. In this series the tension was increased from zero to a maximum and then decreased again. At any one tension the starting field (see Section 3) was determined so that it might serve as an upper limit to the fields which could be used in the velocity determinations The main field was then set at a value below this, and the propagation was started by sending a current through the adding coil. The velocity of propagation was obtained from the throw of the ballistic galvanometer in the timing circuit and the known separation of the coils.

The results for a wire, 14 percent Ni-Fe, 0.038 diameter, are given in Fig. 6 for several values of tension between 38 and 92 kg/mm^2, the range in which large discontinuities were found. These curves exhibit some very striking features. They are, except in two cases, straight lines and are approximately parallel to each other. The higher the tension the further are the curves shifted to lower field strengths. The failure of the curves taken with decreasing tension (marked "Decr.") to coincide with the curves taken with increasing tension (marked "Incr.") shows the presence of elastic hysteresis which was observed directly by stress-strain measurements. When the wire which had undergone the stress cycle described was allowed to "rest" without tension for an hour, it reverted almost completely to its original condition, so that approximately the same cycle could be reproduced.

Observations of velocity were made down to velocities as low as possible but in many cases the experimental points could not be measured below 1000 cm/sec. In this neighborhood the discontinuity, after passing the first coil, often failed to reach the second one. In view of the linearity of the curves it is quite reasonable to suppose that the failure to propagate at low velocities does not arise from any inherent limitation in the mechanism of propagation but rather from irregularities in the wire which, influencing relatively small portions of the material, are unable to affect seriously a discontinuity propagating under more favorable conditions. For this reason the curves have been extrapolated to zero velocity, and the intercept with the H-axis has been interpreted as the limiting field in which propagation at a velocity approaching zero would occur in an ideal wire. This field will be called the *critical field* and will be designated by H_0.

The behavior of the v-H curves with respect to the elastic hysteresis mentioned is peculiar in that the successive curves with decreasing tension instead of lagging with respect to the "Incr." curves, as they would if H_0 were a function of elongation, show the opposite behavior. This could be due to two types of response in the wire, one an immediate elastic response, and the other a slower and limited plastic yield. A lowering of H_0 by the elastic strain combined with an increase of H_0 with plastic deformation would account for the phenomenon observed. (See Section 12).

Judging from their general character, the curves may best be represented by an empirical formula of the type

$$v = A(H - H_0) \tag{6}$$

where v is the velocity of propagation, and A is the slope of the line which was within 25 percent of a value of 25,000 cm sec^{-1} gauss^{-1}.

When the velocity was measured over subdivisions of the usual 20 cm and over other portions of the wire still within the uniform 46 cm of field, this velocity was found to be always the same for the same conditions in the cases where the v-H characteristics were straight lines. When these characteristics were curved, however, the velocity showed some variation. This suggests that the curvature arises in some way from a variation in the state of the wire along its length.

One of the cases in which the characteristics showed the greatest curvature was that of the wire whose hysteresis loops were shown in Fig. 5. These characteristics are reproduced in Fig. 7 as an example of the greatest deviation from the simple relations usually found.

The above tests were originally made with a view to testing the constancy of the velocity of propagation. Another test consisted of varying the position and intensity of the adding field. It was found that for a certain position of

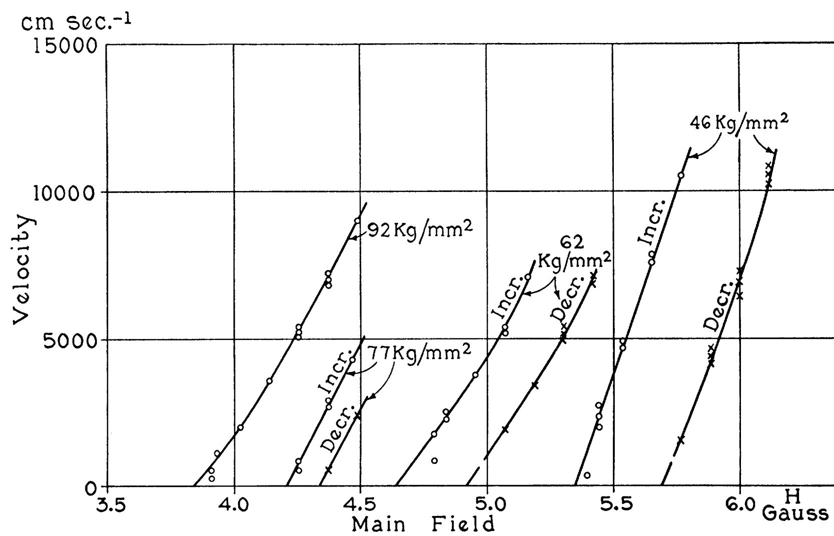


Fig. 7. Velocity-field curves for a wire under different tensions. Wire of 0.038 cm diameter from ingot No. 32, 15 percent Ni-Fe.

the adding coil a certain minimum current was required to start the discontinuity, but that this minimum varied in successive trials. The average of this minimum at each of several successive points along the wire was found to vary considerably, exhibiting maxima and minima even in the homogeneous part of the field. The velocity of propagation was independent of both position and magnitude of adding field as long as this field did not add to the uniform field between the search coils appreciably.

The magnitude of the discontinuity is nearly constant over the homogeneous part of the field; only at very low velocities do large differences at different points appear. Since large differences at the same point in successive trials were also found, we can only conclude that the behavior is erratic at low velocities.

It is significant to note that the general effect of the aging process referred to at the beginning of this section is to increase the critical field but to leave the slope of the characteristic in most cases unchanged. This suggests that while the critical field depends on the strain state of the wire, the slope depends on other factors.

5. Comparison of Experiments and the Eddy-Current Theory

It is now possible to make a direct comparison of the velocities appearing in Fig. 6 with those calculated from the eddy current formulas derived in Section 2. For 15 percent Ni-Fe $\rho = 30 \times 10^{-6}$ ohm cm and using an average value of H of 5 gauss and an average value of ΔI of 2400, Eq. (3B) gives $v = 250$ cm sec^{-1} compared to velocities well exceeding 10^4 cm sec^{-1} in many cases. A discrepancy in the other direction might well have been explained on the basis that the magnetic energy was only partially available for conversion into eddy currents. Eq. (4B), however, permits of velocities greater than those given by Eq. (3B) roughly in the ratio that λ exceeds a. Actually, the observed velocity of 10^4 cm sec^{-1} would require a ratio $\lambda/a = 60$. But how could a transition 60 times as thick as the diameter of its front characterize the definite self-propagating phenomenon we were observing?

At least, the formulas gave experimental hints and also served to emphasize certain features of the velocity-field characteristics. We have already remarked that these characteristics do not pass through the origin so that v is not proportional to H. This might be an indication that, for some reason, the magnetic energy available is not $H\Delta I$ but $(H - H_0)\Delta I$ so that on this hypothesis

$$v = 0.51 \times 10^8 \rho\lambda(H - H_0)/a^2\Delta I \tag{7}$$

On the other hand, such reasoning would increase λ/a over ten-fold since $H - H_0$ is some 0.4 gauss compared to the 5 gauss assumed for H at $v = 10^4$ cm sec^{-1}.

A comparison of velocity-field slopes with ΔI (or ΔB as in Fig. 8) shows no such correspondence as indicated by Eq. (3B) and a check of slope against wire diameter gave the values of slope shown in Fig. 9. The wires used were of 10 percent Ni-Fe and were cold drawn from 0.102 cm to the different diameters. Over a three-fold range of diameters, namely, from 0.020 to 0.061 cm the observed slopes, taken for one wire at different tensions or for different wires, lie scattered in the range 2 to 3×10^4 cm sec^{-1} gauss^{-1}, and show no evidence of an increase in slope with a decrease in diameter. The 0.071 cm diameter slope is probably not comparable with the rest because the magnitude of the discontinuity gradually decreased as it proceeded along the wire.

The successively smaller wires have been subjected to successively greater amounts of cold working thus raising the question as to how comparable the results can be on this account. It has been pointed out, however, (Section 4) that the aging process has a marked effect on the critical field but almost none on the v-H slope. And later it will be seen that annealing wires of various diameters, succeeded by cold drawing to a uniform size, again yields specimens having different values of H_0 but approximately equal v-H slopes. Thus the differences in cold working are probably of no significance as regards our present conclusions.

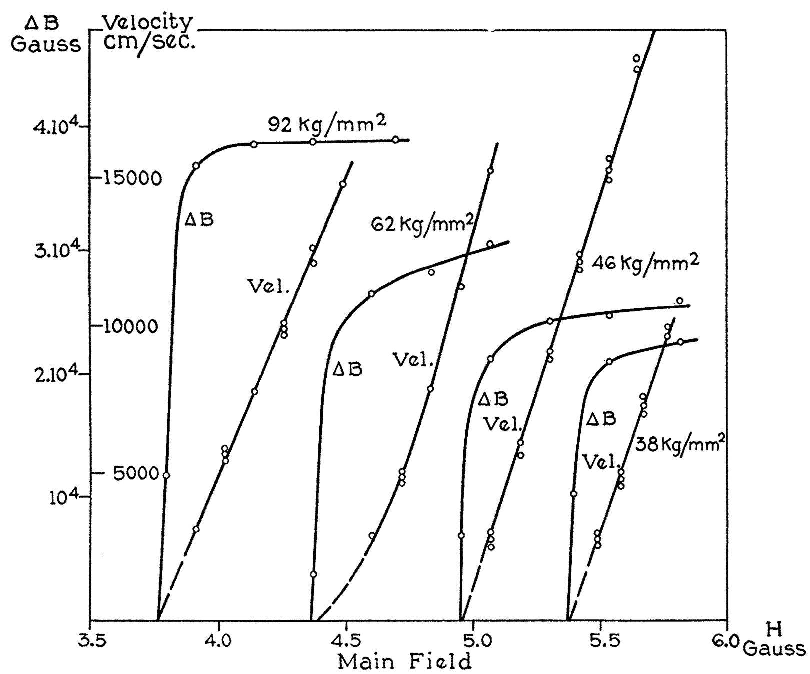


Fig. 8. Magnitude of the discontinuity and velocity as functions of field and tension. Wire of 0.038 cm diameter from ingot No. 14, 14 percent Ni-Fe.

The evidence against the eddy-current theory which we considered to be most convincing was given by the following experiment. A wire of 0.254 mm

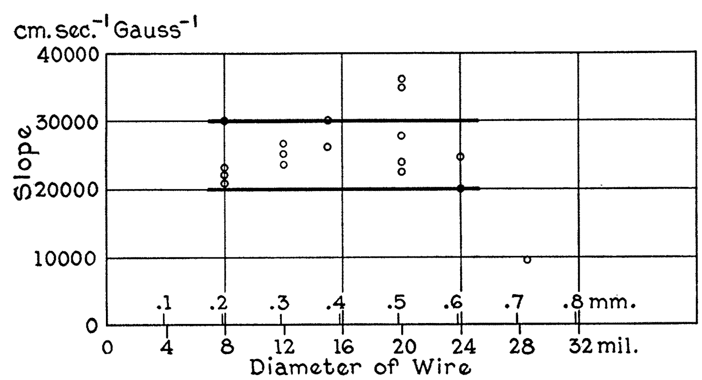


Fig. 9. Slope of velocity-field curves for wires of different diameters. Wires from ingot No. 24, 10 percent Ni-Fe.

diameter was rolled down to a strip 0.076 mm thick and 0.53 mm wide. Although the influence of eddy currents is, of course, reduced considerably in comparison with the round wire, the v-H slopes measured for the strip fall in the same range as the slopes found for wires.

At this stage in the investigation we found ourselves in the position of observing magnetic discontinuities travelling with such high velocities that for the phenomenon to be energetically possible this "discontinuity" must occupy a length on the wire of at least 60 times and perhaps 750 times (if energy available is $(H-H_0)\Delta I$) the wire radius. The proof that this actually occurs is a result of the measurements on the voltage induced in the search coils and of the oscillograms of the wave shape which are described in the next two sections.

6. Voltage Measurements

We have already mentioned the fact that the voltages induced in the search coils are of the order of several tenths of one volt, but we should expect much higher voltages on the basis of a plane wave front. Let us make the assumption that the total change in flux, $\Delta\phi=47$ lines (for a change in induction of $\Delta\phi=40{,}000$ gauss) in a 0.038 cm wire, produces a voltage in the coil during the time Δt, which the jump needs to travel a distance equal to the diameter (2 cm) of the coil. That will give us an average value of voltage to be expected, and the maximum voltage might be much higher than this. Now $v=10^{-8}n\Delta\phi/\Delta t$ where v is the voltage induced in a coil of n turns. Taking $n=5000$, and $\Delta t=2\times10^{-4}$ sec (for a velocity of 10,000 cm/sec), we obtain 11.8 volts as a lower limit for the peak voltage. The existence of any such voltages would have rendered the use of amplifiers in the original velocity measurements entirely unnecessary. It therefore became of interest to eliminate this large discrepancy by direct voltage measurements.

In our determinations a thyratron circuit, similar to the one shown in Fig. 4, was used as a peak voltmeter. By adjusting the grid bias in several trials, a bias value was found at which the single impulse just started the discharge. The difference between the known critical voltage and the applied bias is the peak voltage of that impulse. The voltage induced in a 200-turn search coil was amplified by two screen-grid stages, giving a uniform amplification of 120 in the frequency range between 30 and 10^4 cycles/sec. While a single search coil permits the measurement of the voltage peak only, it was thought that two search coils with variable separation and connected in series-opposition would allow a rough determination of the wave shape itself to be made simply by plotting the observed peak voltage against coil separation. A more detailed analysis made after numerous measurements had been taken shows that this experiment would give the same apparent wave-front shape for a variety of actual shapes.

Thus in Fig. 10 the shape of the curves which were obtained in this way is roughly that to be expected from the method used, leaving as significant features only the voltage maximum attained and the least separation of the coils which gives that maximum. The former yields the maximum rate of change of flux, the latter the distance from wave front to this point in the wave.

The curves of Fig. 10 depict measurements made with different values of main field, that is, with different velocities. Over a 3-fold range of velocities the maximum is seen to come between 4 and 6 cm from the beginning, and the plot to the right shows that the peak voltage is proportional to the velocity. This indicates that the discontinuity retains an approximately constant shape as its velocity changes.

Although the two-coil method fails to give the wave shape near the wave front it is reliable beyond the voltage maximum. This region was explored by connecting the coils in series-addition (the negative peak voltage with the series-opposition connection could also have been used) but as the oscillograms taken subsequently cover the same range in greater detail these results will not be given.

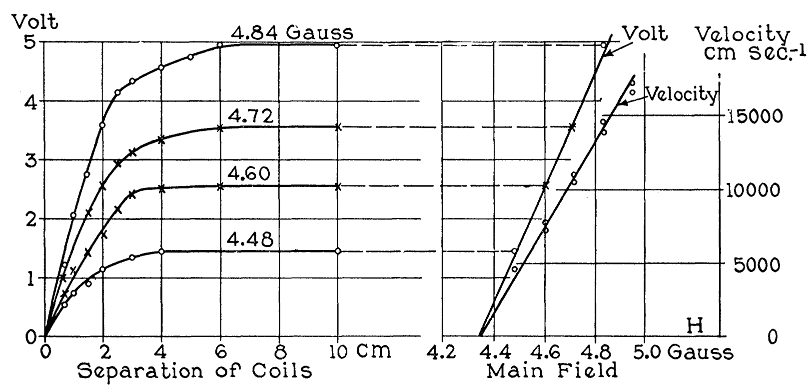


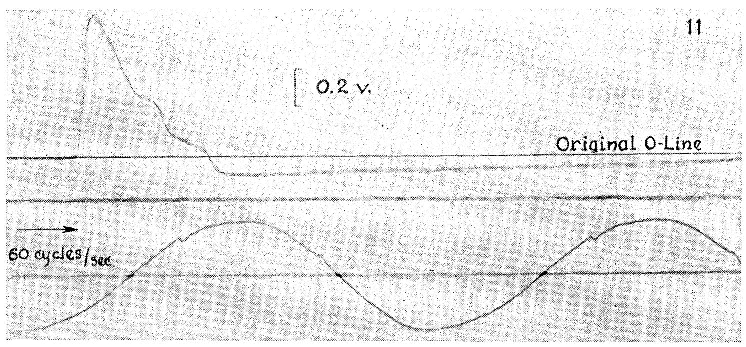
Fig. 10. Amplified peak voltage induced by the discontinuity in two search coils connected in series-opposition. Voltage amplification 120 times. Wire of 0.038 cm diameter from ingot No. 14, 14 percent Ni-Fe.

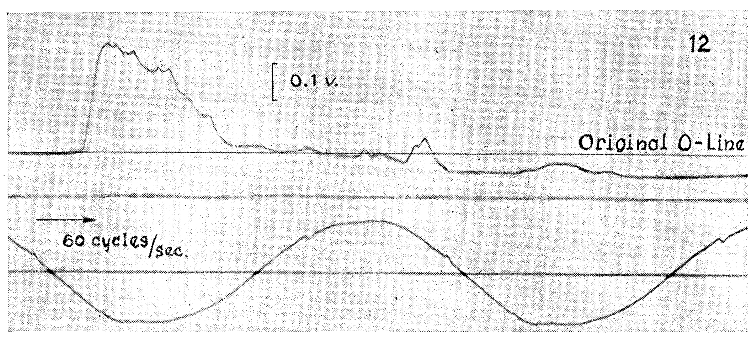
A comparison between the voltages induced in two coils of 200 and 5000 turns, respectively, was made to make sure that the internal capacity of the coils was not reducing the coil voltages. The ratio of voltages found, namely, $0.023/0.59=0.039$, so nearly checks the turn ratio as to prove that any such effect is negligible in these experiments.

7. Oscillograms

Further information concerning the nature of the discontinuity was obtained from oscillograms of the voltage induced in a search coil. The circuit connections were made in this order: 5000-turn search coil to high resistance potentiometer to amplifier to oscillograph. The potentiometer was used to obtain a suitable oscillograph deflection in each case. The amplifier had 3-resistance-coupled stages. The oscillograph was of the Blondel type. The vibrator used to reproduce the voltage had a sensitivity of 1.45 m.a./mm and a natural frequency of 1000 cycles/sec. Figs. 11 and 12 show the amplified voltage wave superimposed on the plate current of the last tube for a wire of 14 percent Ni-Fe and 0.038 cm diameter under a tension of 92 kg/mm^2. In

Fig. 11 the discontinuity is traveling at a rate of 17,000 cm sec^{-1} in a field of 4.25 gauss, in Fig. 12 the velocity is 7000 cm sec^{-1} in a field of 3.91 gauss. We note the steep rise of the voltage and the long tail with many irregularities. But in interpreting these curves we have to bear in mind that the resolution of the method is limited by three factors. First, there is the limited space resolution of the search coil, a factor also present in the method employed in Section 6. It has already been estimated that this limit is of the order of 2 cm for the 5000-turn coil used. But of more importance here is the second factor, the limited time resolution of the oscillograph vibrator. The maximum in





Figs. 11 and 12. Amplified voltage induced in a 5000-turn search coil by the discontinuity. Velocities: Fig. 11, 17,000 cm sec^{-1} (see Table I, Osc. No. 29); Fig. 12, 7000 cm sec^{-1} (see Table I, Osc. No. 28).

Fig. 11 occurs only 0.68×10^{-3} sec after the beginning of the deflection. Since the period of the vibrator is 10^{-3} sec, the oscillograms can give us no useful information concerning the fore-part of the wave.

The two factors mentioned are of little importance as regards the general shape of the tail of the wave, but here the third factor enters, the fact that the voltage surge produces a charge on every inter-stage condenser, which discharges comparatively slowly. This appears in the zero shift occurring in the oscillograms. In this connection it is interesting to note that the peak voltages were about 25 percent lower than those found in the preceding section, undoubtedly on account of the second factor.

The area under the oscillogram curve is proportional to the total change in flux through the search coil. The area when measured (allowing in any reasonable way for zero shift) gave a value of flux change only a few percent less than that found ballistically, Section 3. Thus the third factor can be estimated with fair accuracy.

It is essential to know which features of the wave are characteristic of a propagating discontinuity in general and which arise from special local conditions. Successive oscillograms at the same point are identical except for small variations in the details. Oscillograms taken at different points along the wire show greater variation in the minor discontinuities, but the total

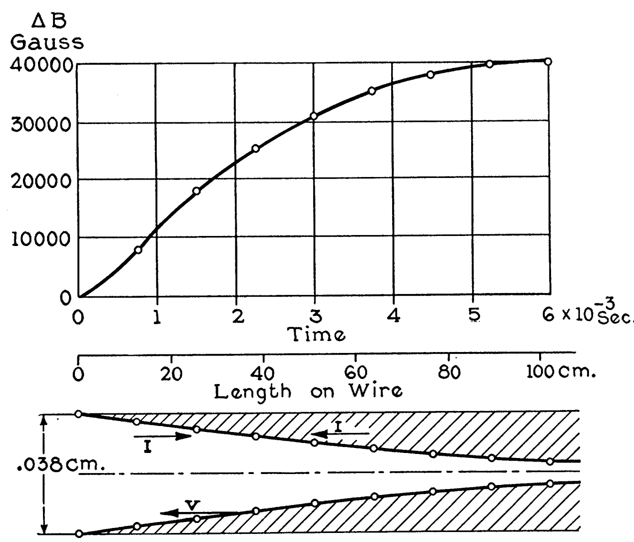


Fig. 13. Change of induction with time (upper part) and penetration of induction into the wire. (The shaded area represents the portion of the wire which has changed direction of magnetization). The radial dimensions are magnified 675 times with respect to the axial dimensions.

duration of the wave and for the most part the main structure, involving perhaps two or three major peaks, are preserved.[8] The main structure is unaltered if the main field is changed so that the wave velocity is different.

Incidentally, the oscillograph was used to obtain a check on the velocity measurements made with the timing circuit by recording the impulse from the two search coils connected in series at a known separation. The agreement was exact.

Since the integral of the voltage curve from its beginning gives the total flux change in the wire up to the corresponding time, an oscillogram enables us to plot this flux as a function of distance along the wire if we make use of the known velocity. In addition to the plot of the integral in Fig. 13, we have

[8] In the single experiment made, the voltage maximum decreased with distance travelled by 20 percent in the central 20 cm of the main field, although ballistic measurements have shown in general that the magnitude of the whole discontinuity remains unchanged.

shown the change as progressing from the surface of the wire inward, assuming that each element of the wire completely reverses magnetization instantaneously.[9] The existence of eddy currents definitely requires that the progress of the change shall be inward, and the instantaneous reversal is plausible if a quantum phenomenon is involved.

Such an analysis applied to the oscillogram of Fig. 11 gives Fig. 13. In this particular case the jump was 97 percent of saturation reversal, and as shown, the 3 percent deficiency has been localized at the axis of the wire. The justification for this is not clear-cut but has some basis in the consideration that the orienting forces are probably least at the axis.

The most striking feature is the experimental demonstration of the fact that the wave occupies a length of some 100 cm in the 0.038 cm wire, a length of the same order of magnitude as calculated in discussing Eq. (7). The comparison of experiment with theory will, however, be based on time of passage rather than length of discontinuity for two reasons. First, because the oscillograph measures time directly and second because the formulas developed in Section 2, being based fundamentally on skin-effect considerations have to do with the time required for a magnetic field to penetrate to a certain depth. They are not concerned with conditions at other points relatively large distances away. On this basis, the only possible interpretation of these formulas is in terms of the time required for the change at a single cross-section to complete itself. Eq. (3) has been definitely found to be inapplicable. Eq. (4), as modified in Eq. (7), gives for this time,

$$\delta t = \lambda/v = 1.96 \times 10^{-8} a^2 \Delta I/\rho(H - H_0) \tag{8}$$

Table I sets forth our most representative comparisons between the directly observed times required for the discontinuity to pass (Column 5) and

TABLE I. *Comparison between the experimental and calculated times of penetration.*

Osc. No.	Main Field Gauss	ΔI Gauss	Velocity cm sec^{-1}	Time δt in 10^{-3} sec. Exp.	Calc.	Ratio $\delta t_{exp}/\delta t_{calc}$	Length λ cm
18	4.48	1740	4000	13.5	4.0	3.4	54
11	4.60	2110	7400	11.1	2.5	4.4	81
14	4.72	2250	10700	6.2	1.8	3.4	66
15	4.84	2300	14000	4.8	1.4	3.4	66
48	4.48	1740	4000	18.7	4.0	4.7	79
49	4.60	2110	7400	9.4	2.5	3.8	70
50	4.72	2250	10700	10.2	1.8	5.7	109
51	4.84	2300	14000	6.6	1.4	4.7	92
28	3.91	3240	7000	22.5	4.2	5.4	157
29	4.25	3240	17000	6.0	1.7	3.5	102

Nos. 28 and 29 are taken with 92 kg/mm^2 tension (H_0=3.68 gauss), the rest with 62 kg/mm^2 (H_0=4.35 gauss).

the times calculated from Eq. (8) (Column 6). The small numerical value of the ratio of these two (Column 7) constitutes a satisfactory check in view of the manner of deriving Eq. (7), and the constancy of this ratio for velocity

[9] In this connection see Section 8.

ratios of 3.5 to 1 lends strong support to the fundamental correctness of the calculation. Unfortunately, simultaneous velocity and oscillograph measurements on wires of other diameters have not been made so that the dependence of δt on a has not yet been checked.

The question as to whether the whole hysteresis loss is an eddy-current loss or whether appreciable transfer to heat occurs through magnetostrictive vibrations, quantum transitions, and possibly other mechanisms, has never been conclusively answered. The present results, however, furnish a very strong indication that at least for large Barkhausen discontinuities only a small fraction $(H-H_0)/H$ of the magnetic loss goes into eddy currents.

The possibility presents itself that the remaining energy appears as magnetostrictive energy. An experiment in which we tried to detect either a momentary or permanent change in length of the wire accompanying a reversal gave a negative result. The accuracy was not quite good enough, however, to be able to reject this hypothesis definitely.

In view of the large penetration times found by us, it becomes of some interest to inquire just what Preisach (reference 2, p. 778) was measuring when he detected harmonics to 10^7 cycles/sec in a stretched wire subjected to a 6000 cycle magnetizing field. It is impossible to say conclusively in the absence of definite data, but it may be pointed out that in 0.5×10^{-7} sec. 0.01 cm of wire surface to either side of a nucleus can reverse by propagation and that the increase of field in that time interval may well cause a large number of magnetic elements to reverse spontaneously, thereby becoming nuclei. The combination of propagation and nucleus formation may easily cause the reversal of an appreciable fraction of the surface of the wire during this time. On this basis the reversal time of a nucleus or any small portion of the wire may be far less than the minimum fixed by Preisach's experiment.

8. The Nature of the Discontinuity

Experiments have enabled us to outline roughly the flux distribution in the discontinuity, Fig. 13, and an eddy-current theory has been advanced which gives the penetration time. The only results, however, so far obtained which throw the slightest light on the longitudinal velocity are those which show that the slopes of the v-H curves for different size wires and even for the strip are all approximately the same. This indicates that the velocity, which corresponds to a given $H-H_0$, being independent of cross-section, is determined only by conditions existing within a small distance of the surface. Since the front edge of the wave lies in the surface, we have been led to the view that the forces at the wave edge determine the velocity, the rest of the wave penetrating the wire as fast as eddy currents allow. It seems plausible to assume that the force required to reverse an element of the wire is H_0 itself or is directly related to it. On such a basis a too-rapid progress of the wave would either give rise to eddy currents or alter the wave configuration near the front in such a way as to reduce the force at the wave front below the minimum reversing value. In this case no new elements could reverse until eddy currents had decreased or later portions of the wave had advanced sufficiently to reestablish the minimum field.

Any theory must take cognizance of the electromagnetic field set up by the discontinuity. As a solution of Maxwell's equations for the discontinuity shown in Fig. 13, travelling at a high velocity, seems to be extremely complicated at the best, the attempt might be made to disentangle the various factors for the simpler case of very low velocities. As a first step we shall assume as an approximation that the shape of the wave is independent of velocity in the experimental range and remains constant in the limit as $v \rightarrow 0$. It may then be possible to make a first order calculation of magnetic field arising from eddy currents for low velocity and assume that this remains valid at the highest velocities measured. The proportionality of peak voltage to velocity and the approximate shape constancy found by experiment themselves strongly suggest that first order effects are the important ones.

Let us tentatively assume that Fig. 13 indicates the nature of a discontinuity travelling from right to left with magnetization reversing from positive to negative. Both unchanged and reversed portions of the medium present north poles to the wave front with the result that it is a surface of magnetic charge of pole strength m per unit area, m being given by

$$m = \Delta I dy/dx \tag{9}$$

where y is the depth of the discontinuity below the wire surface at a distance x back from the front edge. This distribution of magnetism, supposed stationary, gives rise to an almost radial magnetic field from the discontinuity surface outward. An approximate calculation of this field can be made on the assumption that $y \propto x$. For the 100 cm discontinuity in the 0.038 cm wire with ΔI equal to 3240, Eq. (9) gives

$$m \sim 3240 \times 0.019/100 = 0.62$$

whence the radial field near the front edge is

$$H_r = 4\pi m = 8 \text{ gauss}.$$

A field of this magnitude would not allow the elements which are completing their reversal to align themselves axially, but a little consideration will show that their deviation from axial alignment need be very little in order to annihilate the internal poles. Referring to Fig. 14 showing the discontinuity FF' travelling with velocity v, it is readily seen that if the intensity of I_2 in the reversed domains forms the same angle with FF' as the original intensity I_1, there is no pole development in the wire. The angle β, being twice α, will thus be about $2 \times 0.019/100 = 3.8 \times 10^{-4}$ radians which is a negligible deviation from perfect alignment. Finally, this deviated I_2 can be joined to the axial I_2 which is supposed to exist when the discontinuity has completely passed with a discrepancy only of the order of $(3.8 \times 10^{-4})^2$.

In this representation the reversal of intensity occurs within a distance equal to the thickness of a domain, but it is also possible to picture the transition as being much less abrupt. The one condition to be fulfilled, established by the requirement that no internal poles develop, is that the intensity of magnetization be solenoidal throughout the wire, or, mathematically, that $\nabla\cdot I=0$. This means, of course, that we can imagine tubes of intensity drawn in the wire and that all poles develop on the surface. A little consideration

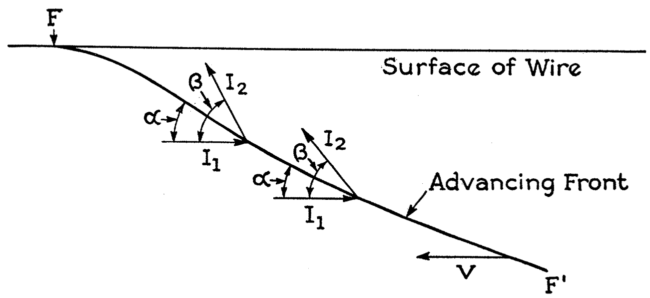


Fig. 14. Compensation of internal poles.

shows that this surface distribution of pole strength is given by the oscillograms. Fig. 15a shows two possible configurations of intensity tubes for an iron-nickel strip with idealized surface distribution. Only half the strip is shown. As represented, the tubes are of equal strength and therefore terminate at the surface in equal poles as given by equal partial areas under the

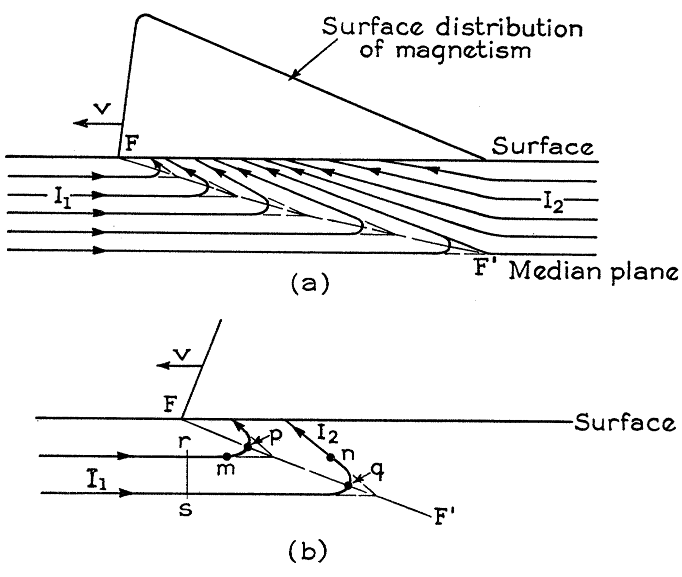


Fig. 15. a. Possible configuration of lines of intensity in a strip. b. Detail of reversal region.

distribution-of-magnetism curve. I_1 can join I_2 either via the sharp dashed bend or via the smooth curve. The former corresponds to Fig. 14, the latter to a more gradual transition.

The interesting feature of this transition is that it cannot occur as a uniform progression. Referring to Fig. 15b, which gives the detail of Fig. 15a, it is seen that such a progression would mean a continually increasing rotation of I from domain to domain in going from m to n. This in turn would require that the intensity of all domains along pq be parallel. Now it is evident that a tube of intensity expands between rs and pq, both of which represent surfaces normal to the tube. Since I is solenoidal, I at pq must be less than I at rs, which is incompatible with detailed parallelism of the domains. But if we abandon the idea of uniform progression and suppose that as the reversal region mn begins to traverse any small volume (large compared to a domain) certain of the domains scattered throughout it reverse before others, then no such inconsistency arises.

The representation of the discontinuity just given has only been recently devised and no calculation of the fields arising from eddy currents in the neighborhood of the front edge has been made. It seems quite possible, however, that they may be comparable with $H-H_0$. In that case we shall have reached the simple viewpoint that the excess magnetic field over H_0 is just that necessary to overcome the opposing eddy current field.

The velocity would thus be dependent upon the surface magnetization in the neighborhood of the wave front, the length λ of the discontinuity is in turn the product of this velocity and the calculable penetration time δt. Both λ and ΔI, as well as a, then fix the average pole strength of the surface. But what in turn establishes the surface distribution of magnetism? That must probably await a detailed solution.

9. The Effect of Inhomogeneities in the Wire

Magnetic inhomogeneities. The magnetic and mechanical uniformity of the wire is of utmost importance with respect to large Barkhausen discontinuities. The importance of the first factor has been pointed out by Preisach in the experiment in which he varied the limits of the hysteresis cycle. We now look at it from a new viewpoint reached through our knowledge concerning the propagation. In all the preceding experiments the cycle of magnetization was carried as far as ± 34.5 gauss. Later we performed an experiment somewhat similar to Preisach's. In successive cycles the positive field strength limit was decreased as indicated in Fig. 16. On the negative side the limit was always at 34.5 gauss. We note that reduction of the maximum field on the positive side reduces both starting field and the magnetization change at the succeeding jump. In the limiting case, if the maximum positive field used is that required to cause the jump, the succeeding negative starting field is little less than the critical field for this wire.

The explanation for this lies in the following. The usually small change in induction which occurs after a large discontinuity is irreversible and contains smaller Barkhausen discontinuities. Thus in not carrying the cycle to saturation on the positive side, we have failed to turn a number of elementary magnets into the positive direction. These particles set up fields in the negative direction and thus act as nuclei where a discontinuity may start. The bigger such a nucleus is, i.e., the higher the field it produces, the lower the starting field which we have to apply in order to start propagation. We should expect

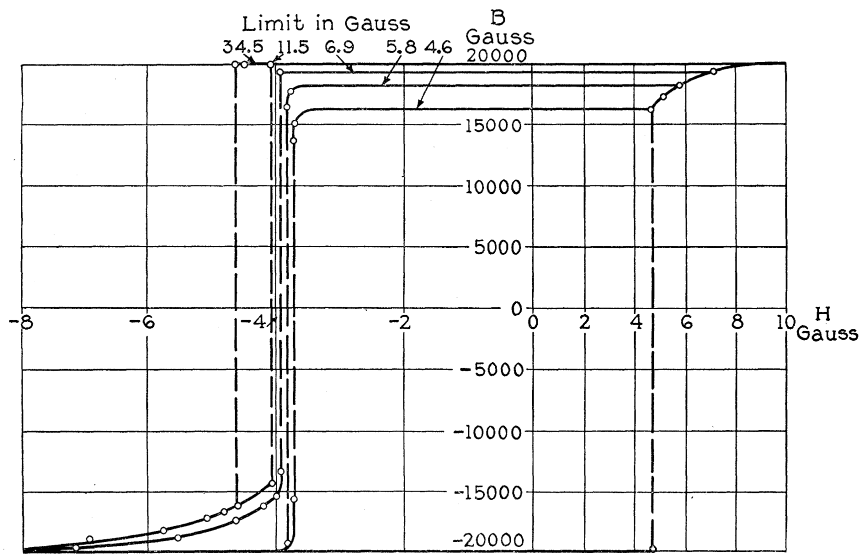


Fig. 16. Effect of varying one limit of the hysteresis loop. Wire of 0.038 cm diameter from ingot No. 32, 15 percent Ni-Fe.

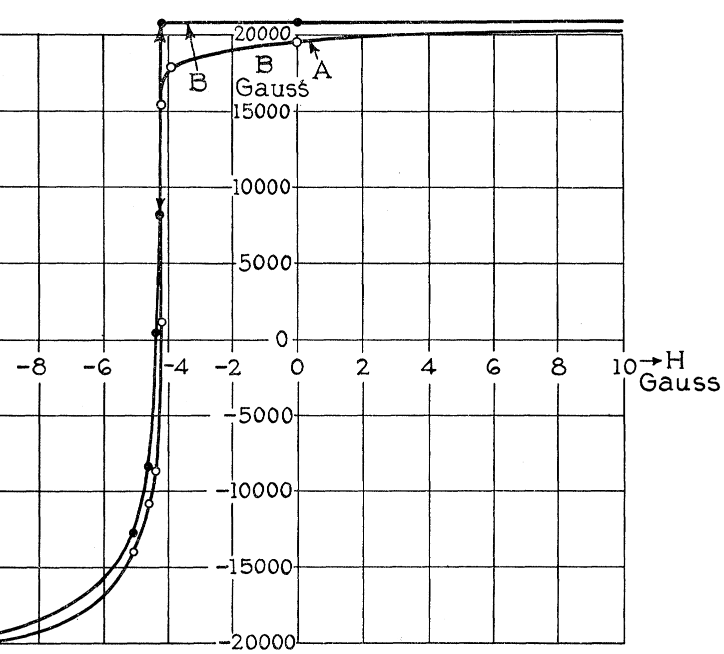


Fig. 17. Influence of a bend in the wire. A. Apparent hysteresis loop of the bent portion. B. Hysteresis loop of unbent portion.

that the starting field could never be less than the critical field, since we found this to be the lower field limit for propagation. In experiment this expectation was not quite confirmed since the lowest observed starting field in some cases was lower than the critical field. But the deviation in no case amounted to more than a few percent.

Mechanical inhomogeneities. In a special case the range of field strength, within which propagation could be observed in a 14 percent Ni-Fe wire of 0.038 cm diameter and under 62 kg/mm^2 tension was found to be 4.25 to 4.65 gauss. This wire was bent in its middle to a semicircle of 2.5 mm radius (the wire being strained far beyond its elastic limit in doing this), was then straightened out again and was finally put under the same tension as before. After this treatment the starting field coincided with the critical field at 4.25 gauss so that propagation could not be obtained. This behavior can be explained by the fact that the bent part has a magnetization curve different from the rest of the wire as shown by curves A and B of Fig. 17. Curve A was taken in the usual way with a search coil placed at the bent portion of the wire. The hysteresis curve so obtained gives a change of induction just below the starting field which is even less than the actual because of the flux leakage arising from the shortness of the bent portion. Thus when the critical field of the normal wire is reached, a considerable part of the bent portion has already changed magnetization and again those elementary particles, which point in the field direction, act as nuclei to start propagation.

Another example of the same type of phenomenon is the fact that hand-drawn wires have starting fields which lie only slightly above the critical field. The irregularity of hand drawing undoubtedly creates "weak nuclei" just as the bending did. Since a low starting field makes it impossible to measure the higher speeds of propagation, machine drawn wires were used in all experiments.

In all but one early experiment the wire projected from both ends of the magnetizing coil so that it extended into regions of comparatively low field strength. In that experiment, however, a short wire terminating within the homogeneous part of the field was used. This wire was clamped to copper wires with brass fastenings and was put under tension. The ends of the wire where it was clamped were not under the same strain as the middle part. Accordingly they did not have rectangular hysteresis loops and acted as weak nuclei.

From these experiments we can conclude that the upper limit of the propagation range is fixed by the non-homogeneity of the wire. The greatest range observed extended from 3.20 to 4.75 gauss in the case of a 14 percent Ni-Fe wire under combined tension and torsion. To the higher field value there corresponded a velocity of 40,000 cm sec^{-1}, which is the highest one measured so far.

10. Torsion

Preisach obtained great discontinuities in magnetization also when he applied torsion to a wire. In this case, too, we found that the magnetization propagated in the same way as in the case of tension. We also observed a parallel shift of the velocity field lines to the left for increased twist in the range between 8 and 20 percent Ni-Fe, but we obtained much greater variations with respect to slope than in the case of tension. Fig. 18 taken for a 0.038 cm, 25 percent Ni-Fe wire shows this behavior very clearly. For this particular wire it made a great difference whether the twist was applied clockwise or counter-clockwise and if tension was added still another slope was found. All these curves were perfectly reproducible which shows that the

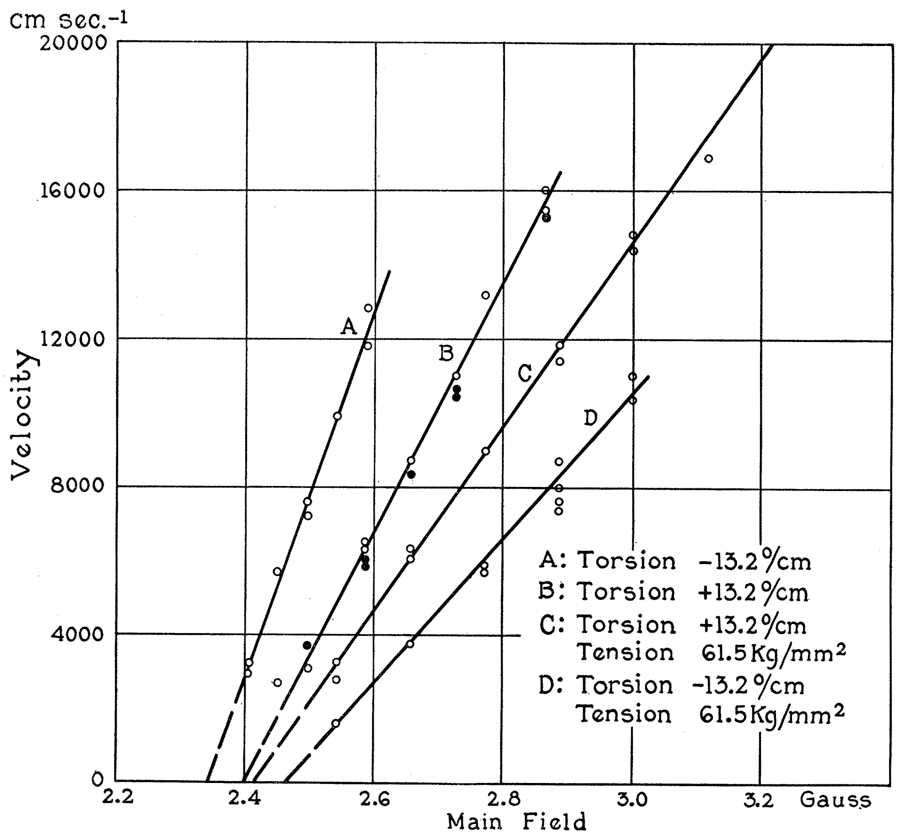


Fig. 18. Velocity-field curves for torsion and combined tension and torsion. Wire of 0.038 cm diameter from ingot No. 19, 25 percent Ni-Fe. The black dots represent check points.

strains were elastic. (The black dots in Fig. 18 were taken after the direction of applied torsion had been changed several times.) As another wire from the same lot did not exhibit this dependence of slope on direction of twist, it is probable that internal strains have an important influence on the slope in the case of torsion. More work on wires having different strain distributions has to be done before the observed effects can be explained.

The data for these cases are insufficient as yet for checking the application of Eq. (7).

11. Wires of Different Composition

Nickel iron wires of 3, 5, 8, 10, 12, 14, 15, 20, 25, 35, 40, 55, 60, 78, 80, 90 and 100 percent nickel content have been examined. We were able to obtain large discontinuities (i.e., of more than 80 percent of the double saturation value) with *tension* only in the ranges 8 to 25 percent and 55 to 78 percent.[10] From 5 percent down and from 80 percent up no large discontinuities could be observed and with 35 and 40 percent only small jumps of about 1/10 of the double saturation value appeared under tension. These jumps were very erratic and probably only included a short length of wire at a time so that velocity measurements with these compositions were impossible. Throughout the remainder of the range the v-H slope did not deviate much from an average value of 25000 cm sec^{-1} gauss^{-1}, but the effect of tension on the critical field varied profoundly. Between 8 and 20 and at 78 percent increasing tension reduced the critical field H_0, but at 55 and 60 percent it increased H_0. At 25 percent there was a pronounced reversal in the dependence of H_0 on tension. Up to a certain value of tension H_0 increased with increasing tension; after passing this value the critical field decreased again.

Torsion produced large discontinuities over the entire range between 8 and 100 percent Ni-Fe, and the great variations in v-H slope already mentioned as existing in the 8 to 20 percent interval were found to be present over this wider range, varying between the values 10^4 and 6×10^4 cm sec^{-1} gauss^{-1}. There were no simple relations between either composition or amount of twist and critical field. The v-H characteristics were occasionally curved, but no more frequently than in the case of tension.

No experiments have been carried out on the propagation in wires under an elastic bending force.

12. The Critical Field

Some of our experimental results allow comparison with a theory recently advanced by R. Becker[11] which has already been applied successfully to the case of nickel under tension.[12] Becker introduces the close and important relation between the magnetic and elastic state of materials by the assumption that the direction of magnetization in each Weiss domain is determined by the stress tensor in that domain in the absence of an external field. The theory enables him to derive hysteresis loops for these districts for different initial angles between magnetization and applied field.

For the limiting case of anti-parallelism between magnetization and field, this theory yields a rectangular hysteresis loop for which the coercive field is given by

$$H_C = 8SAI_m$$

[10] Preisach (p. 755) has already pointed out that the upper limit coincides with the composition at which magnetostriction and accordingly the effect of tension on magnetization change sign.

[11] R. Becker, Zeits. f. Physik **62**, 253 (1930).

[12] R. Becker and M. Kersten, Zeits. f. Physik **64**, 660 (1930).

where $S \sim 1$ is a factor calculated from magnetostriction, A is the elastic deformation of the domain and I_m is the saturation intensity of magnetization. With exact antiparallelism, however, the force couple exerted by the impressed field is zero, with the consequence that the domain may conceivably retain its position of unstable equilibrium even for values of H exceeding H_C. It is interesting that the Ni-Fe wire as a whole exhibits this behavior. On this basis the critical field H_0 is to be identified with the coercive field H_C, while the somewhat erratic starting field corresponds to the indeterminate field at which the equilibrium of the Weiss domain may be destroyed.

As a matter of fact, the wire only approximates to a single Weiss domain, both because of the peaks evident in the oscillograms and because of the fact that for fields only slightly greater than H_0 the reversal of the wire is incomplete (as may be seen in Fig. 8), indicating that the coercive force for certain portions of the wire exceeds H_0. It is possible that the ΔI vs H curves in

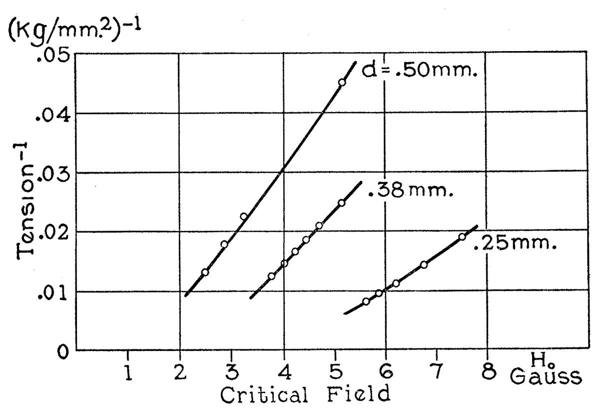


Fig. 19. Critical field for wires of different diameter. All Wires cold drawn from annealed wire 0.102 cm diameter from ingot No. 14, 14 percent Ni-Fe.

that figure give the proportion of the wire for which H exceeds the coercive field.

Becker's formula, when applied to our conditions, yields values more than 10 times higher than those observed by us and predicts in the case of iron and low nickel-iron alloys for which S is positive, an increase in H_C with increasing elastic deformation A. In our experiments with Ni-Fe wires of 8 to 20 percent nickel content, we observed just the opposite relation. This is shown clearly by Fig. 19 in which the reciprocal of tension is plotted vs. the critical field for different diameters. In a certain range of tensions we obtain almost a linear relation between $1/T$ and H_0! In his second article Becker recognizes this difficulty.

Fig. 19 allows of one other comparison with experiments made by Becker and Kersten. The critical fields obtained for wires of different diameter for the same stress are quite different. Since all wires were cold drawn from 0.102 cm, the explanation lies in the different amounts of cold working the wires have suffered. The more cold working, the greater are the internal strains, and the higher the coercive force. In their experiments with nickel wires Becker and Kersten are able to obliterate differences in internal strain conditions entirely by application of high tension and they can account for this satisfactorily by assuming that hard drawing produces only longitudinal strains in the wire whose influence disappears in the limiting case of high applied tension.

In our case, however, this does not occur, for even with tension near to the breaking point, the coercive forces are still considerably different for wires subjected to different amounts of cold working. This is illustrated by

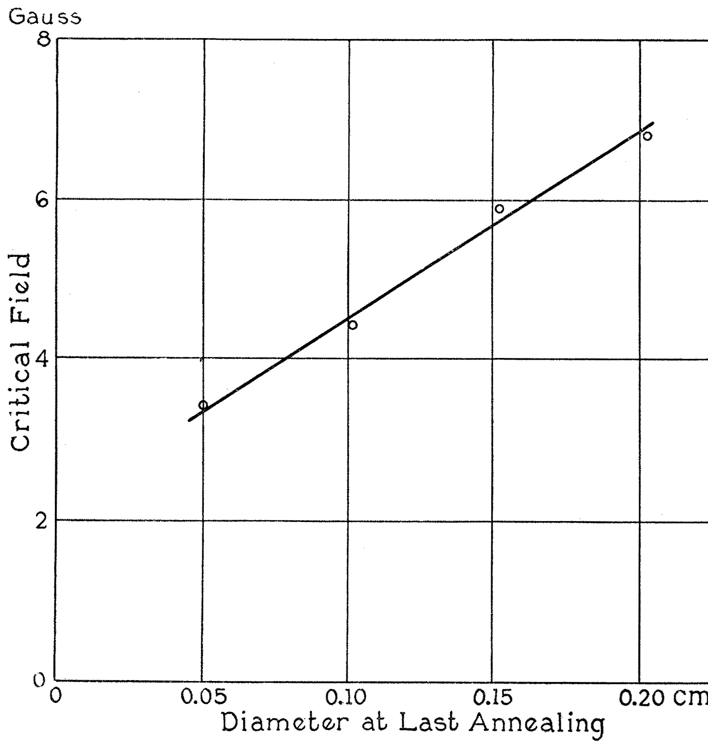
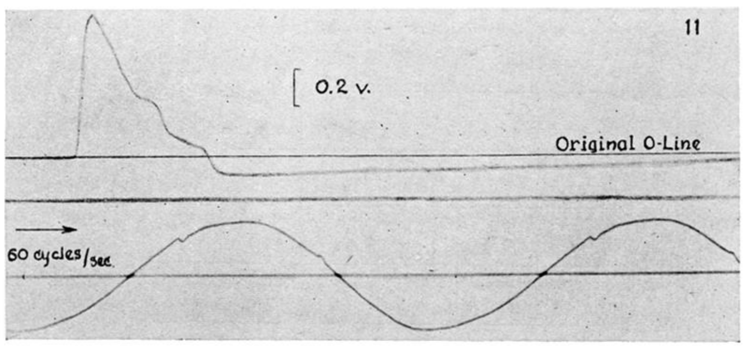


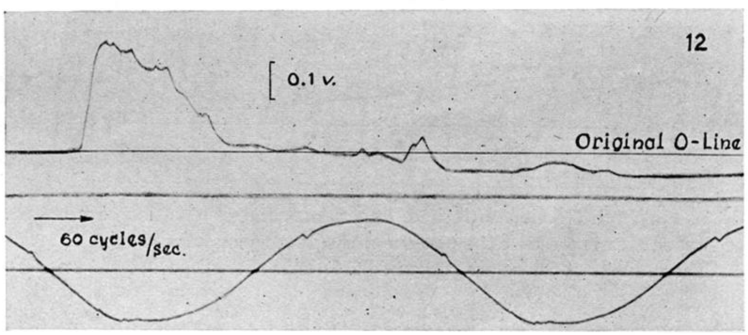
Fig. 20. Critical field at 62 kg/mm² tension for wires with different amounts of cold working. All wires of 0.038 cm diameter from ingot No. 22, 20 percent Ni-Fe.

Fig. 20 which shows the critical field for wires of 0.038 cm diameter annealed at the diameters shown and then cold-drawn. Even with 62 kg/mm² tension, the coercive force varies between 3.3 and 6.8 gauss. It may well be that radial and associated ring strains introduced by cold working play an important role in determining the coercive force. On the other hand, Becker and Kersten's results on stretched Ni wires where only continuous and reversible changes are present show that any radial strains can be neglected. Further investigation of propagation in thin strips may give additional information regarding the role of strains in this connection, as the strain structure is probably much simpler in rolled strips than in drawn wires.

Among the various possibilities which present themselves for extending this work we intend to refine the oscillographic method further and to use that method on different sized wires and strips and also on composite strips (strips with a surface layer only of Ni-Fe) with the hope of obtaining a more detailed picture of the magnetic discontinuity. We also intend to examine the effect of temperature change both on nucleus formation and propagation velocity.

We appreciate the interest which Professor R. Becker has shown in this work, and we wish to express our gratitude to Dr. I. Langmuir who, as we have said, not only foresaw the magnetic propagation, but has also given many suggestions and much advice.





Figs. 11 and 12. Amplified voltage induced in a 5000-turn search coil by the discontinuity. Velocities: Fig. 11, 17,000 cm sec^{-1} (see Table I, Osc. No. 29); Fig. 12, 7000 cm sec^{-1} (see Table I, Osc. No. 28).