Propagation of Large Barkhausen Discontinuities. II

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A new formula for the penetration time of large Barkhausen discontinuities is given which is based on definite assumptions regarding the condition for magnetic reversal. In order to bring this formula into agreement with experimental results, it must be modified by the introduction of a length of 0.035 cm of unknown origin. The modified formula agrees well with the results observed for wires of various diameters, a strip, for various impressed fields, tensions and torsions, and for variations of jump magnitude and electrical resistivity. The behavior of the discontinuity in a 15 percent NiFe wire relative to heat treatment was investigated. Changes in critical (minimum propagating) and coercive fields were indicative of the internal state of strain in the wire. The presence of cold-work strains appears to be necessary for the occurrence of the jump but the addition of strains arising from cooling through the γ-α transformation reduces the tendency to form the large discontinuity. Propagation was observed at temperatures up to 350°C. With increasing temperature the slope A of the v-H curves increased. At the same time the range between the critical field and the field at which propagation starts spontaneously at some point in the wire decreased. Etching the surface of a wire also increased A and decreased propagation range. Cracks appearing in the wire surface indicated that the release of surface strains may well have been responsible. It was established that neither the removal of material nor the absorption of hydrogen were the cause.

I. Introduction

The earlier work which has already been reported upon under the same title and in two additional notices[2,3] has been continued and extended. Some phases of the new material will be discussed in the present paper and additional results will be published shortly.

As a considerable number of symbols denoting various magnetic fields are required we list them here: H, longitudinal main field impressed on the wire; H_0, critical field, minimum longitudinal field for propagation; $\Delta H = H - H_0$, excess field; H_s, starting field, minimum value of H which initiates propagation in the wire; H_e, eddy current field; H_p, field arising from the magnetic pole distribution; H_m, total field at a point; and H_c, coercive force, used in place of H_0 when the large discontinuity is absent.

II. Revised Formula for the Penetration Time

1. Old formula

In **I** we have shown that one has to distinguish between the propagation in two different directions: A propagation into the wire, which depends on

[1] K. J. Sixtus and L. Tonks, Phys. Rev. **37**, 930 (1931). This paper will be referred to as **I** in the text. On page 932 a was erroneously defined as the wire diameter. Throughout **I** and here also a is the radius of the wire.
[2] K. J. Sixtus and L. Tonks, Phys. Rev. **39**, 357 (1932).
[3] I. Langmuir and K. J. Sixtus, Phys. Rev. **38**, 2072 (1931).

eddy currents arising in the material, and a propagation in the longitudinal direction, depending, we believed, on conditions in the surface of the wire. The propagation into the wire requires a time interval δt which we have called the penetration time. The approximate calculation made in **I** gave values one-fourth of those found experimentally in a 0.038 cm diameter wire. We shall here give the derivation of Eq. (8A)[2] previously stated without proof. In the interim an independent derivation[4] has appeared which is, however, less satisfactory for our purpose.

2. Basic assumptions

Any exact calculation of this time must take the actual manner of penetration into consideration. The hypothesis adopted is that stated in **I**, p. 947, with the additional assumption, already implicit in **I**, Eq. (7), that magnetization reverses when the total field H_m at a point in the discontinuity exceeds the critical field H_0, and that it reverses so rapidly that the eddy currents generated reduce H_m to H_0 at every instant. This, in turn, implies that the discontinuity is of infinitesimal thickness, but the results of the calculation will be valid to the extent that this thickness is small compared to the diameter of the wire.

For clarity, we shall call the portion of the wire already traversed by the discontinuity, and which has therefore changed magnetization, the *saturated phase*, the unchanged portion, the *antisaturated phase*. Thus the moving discontinuity can be looked upon as a propagating phase boundary.

3. Calculation of eddy current field

Denoting distance along the wire and in the direction of propagation by x, and representing the shape of the phase boundary by the unknown function, $R=R(x)$, our first problem is to set up this function.

The change in flux in a cross section of the wire during the time dt is $2\pi R dR\cdot 4\pi\Delta I$, where $4\pi\Delta I$ is the change in induction between the two phases. The line integral of e.m.f., E, around the wire at a radial distance $r>R$ is thus

$$2\pi r E = (8\pi^2 R\Delta I/c)dR/dt \tag{1}$$

(of course, for $r<R$, $E=0$). By introducing the longitudinal velocity of propagation $v(=dx/dt)$ and using R' for dR/dx this becomes

$$E = 4\pi v R R'\Delta I/rc. \tag{2}$$

Since the current density I is E/ρ, the total circular current per cm length of wire is

$$\int_R^a E dr/\rho = (4\pi v R R'\Delta I/\rho c)\ln(a/R) \tag{3}$$

where a is the radius of the wire.

[4] W. Wolman and H. Kaden, Zeits. f. techn. Physik **13**, 330 (1932).

This eddy current, in turn, gives rise to a magnetic field H_e at R which is given by

$$H_e = -(16\pi^2 v\Delta I/\rho c^2)RR'\ln(a/R) \tag{4}$$

the negative sign indicating that H_e is in opposition to H, the impressed field.

4. Field relations and shape of phase boundary

It is readily seen that H, H_e, and the field H_p arising from the magnetic poles created in the reversal all contribute to H_m, so that

$$H_m = H + H_e + H_p. \tag{5}$$

It will be shown later that in the propagating wave it is justifiable to neglect H_p because the poles are distributed over such a great length of the wire. The application in Eq. (5) of the fundamental assumption that $H_m = H_0$ leads to the appearance of the quantity $H - H_0$ in the equation, a quantity which will be called the "excess field" and will be denoted by ΔH. Then eliminating H_e with Eq. (4) gives

$$RR'\ln(a/R) = (\Delta H \rho c^2)/(16\pi^2 v\Delta I) \tag{6}$$

as the differential equation of the boundary. Integration gives

$$R^2[\ln(a^2/R^2) + 1] = (\Delta H\rho c^2 x)/(4\pi^2 v\Delta I) \tag{7}$$

the integration constant being chosen so that the discontinuity intersects the axis at $x=0$. The length, λ, of the discontinuity is then the value of x when $R=a$.

5. Penetration time

Noting that

$$\lambda/v = \delta t \tag{8}$$

Eq. (7) gives

$$\begin{aligned} \delta t &= 4\pi^2 a^2\Delta I/\rho c^2\Delta H \\ &= 3.94 \times 10^{-8} a^2\Delta I/\rho\Delta H \end{aligned} \tag{9}$$

in practical units. Thus the exact definition of the discontinuity under our assumptions doubles the numerical factor in **I**, Eq. (8), thereby reducing the discrepancy between $\delta t_{\text{exp.}}$ and $\delta t_{\text{calc.}}$ which is noted in **I**, Table I, column 7, from the factor 4 to the factor 2. In the case of a strip the corresponding formula is

$$\delta t_{\text{strip}} = 7.88 \times 10^{-8} b^2\Delta I/\rho\Delta H \tag{10}$$

where b is the half-thickness.

The derivation of these equations was based on the assumption that the surface of magnetic discontinuity makes only a small angle with the axis, but a plot of Eq. (7), as given in Fig. 1, shows that the discontinuity is perpendicular to the axis both at the axis and at the surface of the wire. Other considerations must apply in these two regions. At most, however, the exceptional districts include less than one percent of the discontinuity, so that Eqs. (9) and (10) may reasonably be expected to be valid.

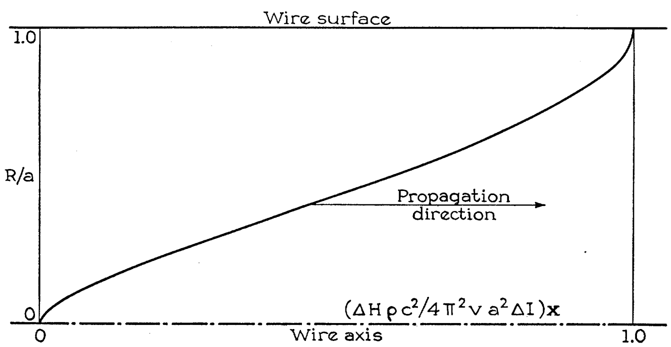

Fig. 1. Theoretical shape of the boundary in a wire.

6. Test of formula and empirical modification

For the further testing of these formulas a new series of oscillograms were taken covering variations in a, ΔI, and ρ. The procedure is described in **I**, page 944. It immediately appeared that δt was proportional to a rather than a^2, the missing power of a being replaced by an empirical constant which in an earlier note[2] was given as 0.031 cm. A more complete and critical examination of the data leads, however, to the present slightly higher value, 0.035 cm. Accordingly, Eq. (9) was changed to

$$\delta t_{\text{wire}} = 3.94 \times 10^{-8} \times 0.035\ a\Delta I/\rho\Delta H. \tag{11}$$

The results of applying this modified equation to a series of 15 percent NiFe wires under both tension and torsion are shown in Table I. No systematic variation of $\delta t_{\text{calc.}}/\delta t_{\text{exp.}}$ is evident. Only the torsion case, subdivision 3, shows a marked general deviation from unity. It is remarkable and doubtless significant that the empirical length of 0.035 cm determined by tension experiments should apply even this well to a case where the strains are so different. The fact that the jump is only 50 percent of the double saturation value appears, in the light of later results,[4,5] to arise from a transverse component in the reversal as well as from a probable absence of reversal near the axis where the shearing strain approaches zero. The former case is covered by the theoretical formula, but in the latter the necessary correction would reduce the calculated time, thus making the discrepancy worse. This case certainly demonstrates, however, that three- to four-fold changes in ΔI are accompanied by only a 20 percent difference between formula and experiment.

The theoretical formula for a strip was modified in exactly the same way as the wire formula, that is, to

$$\delta t_{\text{strip}} = 7.88 \times 10^{-8} \times 0.035\ b\Delta I/\rho\Delta H. \tag{12}$$

[4,5] See also R. M. Bozorth and J. F. Dillinger, Phys. Rev. **41**, 345 (1932).

Subdivision 6 shows that this semi-empirical formula applies. In addition it should be noted that this is an extreme case in that b is less by half than the smallest wire radius.

TABLE I. *Experimental and calculated times of penetration in 15 percent NiFe wire and ribbon under tension or torsion.* Wire No. 37; resistivity, $\rho=31\times10^{-6}$ ω cm.

Osc. No.	ΔH oersted	ΔI e.m.u.	v cm/sec.	δt, millisec. exp.	δt, millisec. calc.	$\delta t_{calc.}/\delta t_{exp.}$	λ cm
	1. Diameter, $2a=0.0533$ cm; tension, 71 kg mm^{-2}; $H_0=1.40$ oersted						
124	0.21	2960	2500	18.5	16.7	0.90	47
123	0.44	3040	6000	8.0	8.2	1.02	48
122	0.67	3060	10000	5.0	5.5	1.10	50
	2. Diameter, $2a=0.038$ cm; tension, 77 kg mm^{-2}; $H_0=2.07$ oersted						
109	0.11	2320	2100	11.4	18.0	1.57	24
118	0.47	3170	8800	6.2	5.7	0.92	59
111	0.69	3210	13800	3.8	3.9	1.02	52
107	1.04	3260	21600	2.3	2.6	1.14	50
	3. Diameter, $2a=0.038$ cm; torsion, 4 turns/80 cm; $H_0=2.49$ oersted						
120	0.16	830	3000	5.6	4.4	0.78	17
119	0.39	1030	8000	2.9	2.3	0.79	23
	4. Diameter, $2a=0.026$ cm; tension, 85 kg mm^{-2}; $H_0=3.49$ oersted						
104	0.31	3170	6500	6.2	6.0	0.96	41
105	0.66	3280	15000	2.8	2.9	1.03	42
	5. Diameter, $2a=0.013$ cm; tension, 158 kg mm^{-2}; $H_0=5.93$ oersted						
133	0.39	1600	7400	1.6	1.20	0.75	12
134	0.63	3150	11600	2.1	1.45	0.69	24
132	0.87	3320	15800	1.2	1.10	0.92	19
135	0.97	3320	17800	0.9	0.97	1.08	16
131	1.21	3320	22000	0.75	0.78	1.04	17
	6. Strip, 0.0071×0.0685; tension, 85 kg mm^{-2}; $H_0=3.80$ oersted						
127[b]	0.35	2450	4600	3.0	2.20	0.73	14
127[a]	0.47	2920	5800	2.4	1.95	0.81	14
126	0.81	3130	9800	1.5	1.24	0.83	15
125	1.39	3130	19600	(1.2)*	0.70	(0.58)	(24)

* Uncertain because of the shortness of the time interval.

7. Further tests of formula

Table I, as remarked, covers experiments in which ΔI shows some variation from one test to the next. A greater range was embraced by using wires of different compositions. These wires showed, in addition, marked differences in resistivity, the 39 percent Ni-Fe having 71×10^{-6} ω cm and the 90 percent Ni-Fe having 13.5×10^{-6} ω cm. The 39 percent alloy lies in a range where it is difficult to obtain large discontinuities. After quite a number of trials it was found that combined torsion and tension were required to give large enough jumps to work with. The 90 percent alloy lies in a range where tension reduces the size of discontinuities. Accordingly torsion alone was used in this case.

The results are exhibited in Tables II and III. Although there are deviations from unity in column 7 of each table, these show no correlation with

TABLE II. *Experimental and calculated times of penetration in 39 percent NiFe wire under combined tension and torsion.* Wire No. 26; resistivity, $\rho = 71\times10^{-6}$ ω cm; diameter, $2a = 0.0388$ cm; torsion, 15 turns; tension 30.5 kg/mm²; $H_0 = 8.36$ oersted.

Osc. No.	ΔH oersted	ΔI e.m.u.	v cm/sec.	δt, millisec. exp.	calc.	$\delta t_{calc.}/\delta t_{exp.}$	λ cm
255	0.24	690	4300	1.40	1.08	0.77	6.0
254	0.36	728	6400	0.80	0.76	0.95	5.1
253	0.48	765	8700	0.75	0.60	0.80	6.5
252	0.61	803	11400	0.60	0.50	0.83	6.8
256	0.74	820	14000	0.50	0.42	0.84	7.0

A vibrator with natural frequency 5000 cycles/sec. was used for these oscillograms.

TABLE III. *Experimental and calculated times of penetration in a 90 percent NiFe wire under torsion.* Wire No. 6a; resistivity $\rho = 13.5\times10^{-6}$ ω cm; diameter, $2a = 0.0386$ cm; torsion, 5 turns; $H_0 = 4.02$ oersted.

Osc. No.	ΔH oersted	ΔI e.m.u.	v cm/sec.	δt, millisec. exp.	calc.	$\delta t_{calc.}/\delta t_{exp.}$	λ cm
209	0.46	460	1000	1.82	1.97	1.08	1.8
206, 213, 214	0.58	500	1300	1.96	1.70	0.87	2.5
202, 205, 208, 211	0.80	520	1900	1.60	1.28	0.80	3.0
215	1.04	550	2800	1.21	1.04	0.86	3.4
204, 210	1.15	550	3400	1.28	0.94	0.74	4.4

variations in any of the listed quantities. In this connection it must also be borne in mind that there is some indefiniteness in interpreting the oscillograms of the discontinuity which yield the values of δt, particularly in the lower velocity cases. The general shape of the trace is that of an isosceles triangle with the sides curving into the zero line. The time occupied by the curved portion in relation to the velocity of propagation represents roughly the distance along the wire that one should expect the effects of an advancing (and receding) magnetic change to reach ahead (and persist behind) when the actual size of the search coil is taken into account. Thus the search coil had an outer radius of 1 cm and an axial thickness of 0.6 cm and the distances found from the oscillograms were about 1 cm.

8. Significance of empirical constant

It is interesting to observe that the special constant, 0.035 cm, appearing in Eqs. (10) and (11), lies in the neighborhood of the radius above which propagation does not occur. For example, as mentioned in **I** in connection with Fig. 9, the 0.071 cm diameter wire showed propagation but only with decreasing jump magnitude, and other tests on larger wires have also failed to show propagation without decrement. What significance, if any, is to be attached to this coincidence is not known.

III. Annealed Wires

1. Introduction

It was thought that the effect on the magnetic properties of the material of annealing at different temperatures might give more information regarding the influence of various factors, such as inhomogeneous strains and crystal orientation. Such tests have already been reported by Preisach.[5] Practically all of the measurements in this and the following section were made on 15 percent NiFe (Ingot No. 37) so that unless otherwise stated all results and conclusions apply to this alone. The exact percentage composition of this wire by weight as determined by chemical analysis was: Ni, 14.75; Mn, 0.11; C, 0.02; P, 0.02; S, 0.016; Si, trace; Fe, remainder.

Although many different heat treatments have been tried, we shall only describe the results obtained on a series of wires heated for 10 hours in hydrogen at 400°, 600°, 800° and 1250°C, since these exhibit the important phenomena very clearly. Using the equilibrium diagram and with the help of x-ray spectrograms and photomicrographs we shall attempt to explain these observations. The transformation points for the alloy of 15 percent Ni-Fe were taken from the extensive report of Peschard[6] which furnished the main basis for the diagram published in the National Metals Handbook (p. 608). In a 15 percent alloy with very pure constituents the transformation from α- to γ-phase occurs between 570° and 670° in heating, whereas in cooling the change from γ to α structure occurs between 300° and 140°C. In a rough test it was found that the α-γ transformation in the present wire began as low as 450°C. The difference between this value and the one found by Peschard can be ascribed to impurities.

The original wire had undergone a severe cold working as it had been drawn cold from 0.080 to 0.038 cm diameter and had, accordingly, a fibrous structure with very fine crystal grains whose boundaries, even with a magnification of 1500, could not be recognized. X-ray spectrograms showed the well-known orienting effect of cold working. In the center portion of the wire one could observe a preferred crystal orientation of the (110) axis parallel to the wire axis; but near the surface to a depth of about $\frac{2}{3}$ of the radius there was random crystal orientation.

2. Properties of annealed wires

The changes in the magnetic properties of the wire after annealing are given in Figs. 2 and 3. Annealing at 400°C, below the transformation range, caused a marked reduction of coercive force and critical field for all tensions, and the large discontinuity appeared at a lower tension than before. The x-ray pattern did not differ from the one obtained with the original wire.

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

[6] Peschard, Rev. de Met. **22,** 490 (1925).

Obviously, the only effect of annealing in this case was the release of internal strains, a result well known in connection with the reduction of coercive force of ferromagnetic materials.

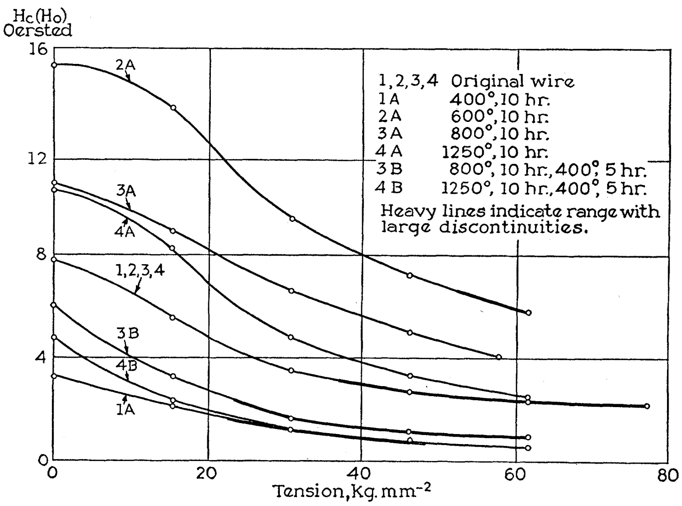

Fig. 2. Effect of annealing on coercive force H_c or critical field H_0.

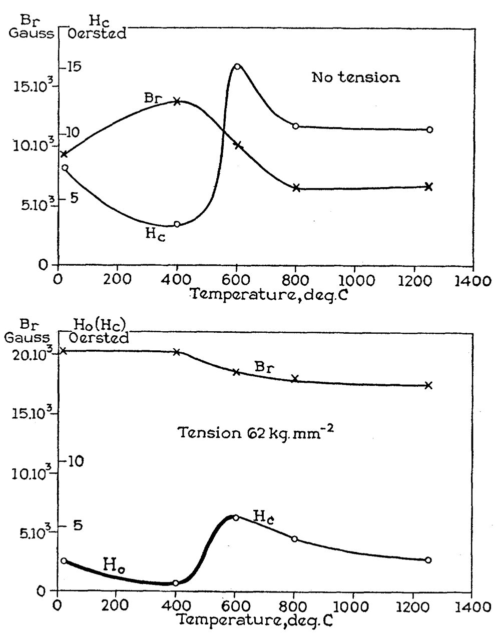

Fig. 3. Remanence and coercive force (or critical field).

After the anneal at 600°C, where the wire had at least partly undergone the α-γ transformation, H_0 and H_c had been increased many fold, and a discontinuity could only be obtained with very high tension. At the same time the remanence had decreased. Again the x-ray analysis showed no change in crystal orientation, and besides gave no indication of the presence of the γ-phase.

We therefore have to conclude that the increase in H_0 or H_c, as the case may be, is not due to a variation in crystal orientation nor to the presence of the γ-phase. Presumably the wire shows persisting effects of the transformation between γ- and α-phase, even though the sample was cooled slowly with the furnace. These observations are consistent with the view that large inhomogeneous strains are present whose suppression to an extent sufficient to align the preferred directions of the elementary districts requires large applied tension.

The 800° wire showed increased H_c, and photomicrographs revealed a certain grain growth of the crystals, while there was no apparent change in crystal orientation as seen from the x-ray spectrograms. No large discontinuities could be obtained in this wire. In a wire with only 2 hours anneal a 50 percent discontinuity was observed for high tension (72 kg mm^{-2}).

The 1250° wire, having high H_c and no discontinuities, had lost its fibrous structure entirely. It had recrystallized and new crystals of 0.01 to 0.05 cm linear dimensions had formed. In the center portion preferred crystal orientation was still noticeable, although it was less pronounced than before.

Both the 800° and the 1250° wire were tempered for 5 hours at 400°C. This treatment reduced their H_c (see Fig. 2) nearly to the value of the original 400° wire, but only in the 800° wire was the discontinuity restored. The effect on H_c is consistent with the view, expressed above, that intense strains were set up during the γ-α transformation which were relieved by subsequent tempering below the transformation temperature. The recrystallization of the 1250° wire, i.e., the formation of large crystals with new orientations in this case, is accompanied by the complete disappearance of the jump, and the release of strains by tempering cannot bring it back.

In all the wires tested the slope A of the v-H curves was only slightly affected by the heat treatment with no apparent tendency to either increase or decrease. The variations which were found were no larger than those already observed in unannealed wires (**I**, Fig. 9), lying for different wires under various tensions between 19,000 and 32,000 cm $sec.^{-1}$ $oersted^{-1}$.

3. Theory

It is difficult to formulate any approximately complete explanation of these effects. One conclusion does seem possible, however, and that is that uniform crystal orientation is not necessary for the occurrence of the jump. Too small a fraction of the wire cross section shows partial orientation compared to the complete reversal of the whole wire which is often observed. Secondly, experiments have been made[7] which show that the preferred direction dominating the discontinuity can be in the surface layers where no uniform crystal orientation exists, and this direction coincides with a principal strain axis which can make any angle up to 45° with the wire axis.

The following not quite satisfactory hypothesis for the response of the

NiFe wire to heat treatment is offered in the absence of complete and convincing data: The type of strain distribution introduced by cold working is necessary for the occurrence of the jump. A possible explanation for the relationship between strain and critical field is offered by the ideas of Bloch.[8] On his view it is the presence of local variations in strain which establishes magnetic barriers and thereby leads to Barkhausen discontinuities. Annealing at 400°C reduces the strains, with a consequent decrease in H_c (H_0). Annealing at 800°C does not eliminate them completely even though the α-γ transformation range has been traversed, but on the return from this temperature the γ-α change introduces widely dispersed strains of a different type which tend to obliterate the jump. When this treatment is carried on for 10 hours, the jump is actually eliminated. Subsequent heating at 400° has no additional effect on the cold-work strains, but does decrease the transformation strains so that the jump reappears. Finally, a 10-hour 1250° anneal does eliminate the cold-work strains to such a degree that no jump can be found subsequently.

4. Special experiments

A few special cases remain which should be mentioned. The wire, which apparently had the smallest internal strains as judged by its decreased hardness and the fact that it had the smallest H_c (H_0) observed so far for any

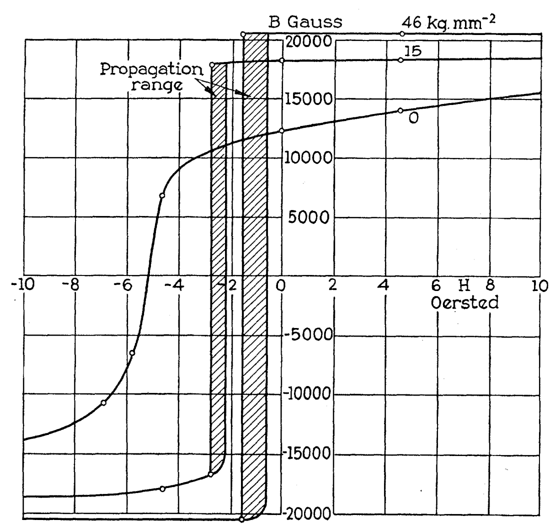

Fig. 4. Hysteresis loops under different tensions for wire annealed at 800° for 1 hr., then at 400° for 6 hrs.

given tension, had been heated for 1 hour at 800°C and subsequently for 6 hours at 400°. Besides it gave a large discontinuity with an extremely low applied tension (approximately 10 kg mm^{-2}). The hysteresis loops for various tensions are given in Fig. 4.

[7] L. Tonks and K. J. Sixtus, Phys. Rev. **41,** 539 (1932).

[8] F. Bloch, Zeits. f. Physik **74,** 332 (1932).

All the wires so far mentioned were annealed without tension. In one experiment a wire was annealed under a tension of 82 kg mm^{-2} for one hour at 300°C. It showed very nearly the same variation of H_0 with tension as a wire given the same heat treatment without tension.

A soft permalloy wire (78.5 percent NiFe, annealed for 1 hour at 900°) gave no jump when tension was applied, but after it had been stretched plastically by about 1 percent of its length, the same tension produced a large discontinuity in its hysteresis loop. Both the soft and the deformed wire had a slight preferred crystal orientation at the center and to about the same degree. The theory formulated above is consistent with this behavior if we assume that the strains introduced by stretching are of the same nature as those caused by drawing or rolling.

A 35 Ni, 20 Fe, 45 Ni perminvar wire showed an anomalous behavior for which no explanation can at present be offered. This wire had been annealed at 1000°C for 1 hour and was extremely soft. It is known[9] that under these conditions a large jump occurs with no applied tension. Its v-H curves were taken over a considerable range of H and their slopes were found to be nearly equal to those of Ni under torsion. When tension or torsion was applied, the discontinuity diminished, and if these stresses were sufficiently large, the phenomenon disappeared completely. An x-ray spectrogram showed the crystal structure to be of the face-centered cubic type.

IV. Propagation at Elevated Temperatures

1. Experimental procedure

In order to extend the propagation measurements to higher temperatures, the set-up comprising the wire, the main coil, the two search coils and the adding coil had to be placed into a furnace. This was accomplished in the following way:

On the middle part of a Nonex capillary tube (120 cm in length, 0.15 cm in inside, and 0.5 cm in outside diameter) two search coils (each 0.6 cm long with 500 turns of 0.0075 cm diameter enameled copper wire) were wound at a distance of 20 cm from each other. Beyond one of them and 15 cm away, 10 turns of enameled copper wire (of 0.05 cm diameter) were wound to serve as an adding coil. The glass tube and coils fitted into an alundum tube (of 1.6 cm outside diameter) on which the coil to give the main field was directly wound. This coil consisted of 1200 turns of 0.05 cm diameter enameled copper wire in a single layer occupying a length of 67 cm, thus having a constant of 22.5 oersteds/amp. All the coils and leads were covered by a cement of waterglass and flint, which protected the copper from too rapid oxidation in the temperature range used.

Both tubes were placed in an electric furnace which had an equal temperature zone about 70 cm long. A copper-copnic thermocouple in the furnace was used to determine this temperature. The wire was inserted in the capillary tube and put under tension by an arrangement similar to the one used before.

[9] H. Kühlewein, Wiss. Veröff. Siemens-konz., **10** (2), 72 (1931).

The leads to the different coils were brought out at both ends of the furnace. During the measurements the heating current was turned off in order to avoid any possible influence of its magnetic field. In that interval the temperature of the furnace fell at most 20°. This comparatively small change did not affect the results.

All supports, etc., were made of brass as it had been noticed that iron parts, even if only slightly magnetized, disturbed the homogeneity of the field sufficiently to result in low starting fields. The velocity measurements were taken in as short a time as possible to avoid large changes in temperature. Since the tension was maintained by a spring, the flow occurring at the higher temperatures reduced this stress and constant readjustment was necessary to keep it constant. These measurements have led to several general observations.

2. Variation in H_0

Figs. 5 and 6 show a typical family of v-H curves for a fresh wire when heated to 300°C and cooled to room temperature again. One feature is that the critical field decreased markedly as the wire was heated for the first time, but with decreasing temperature H_0 remained practically constant at a value

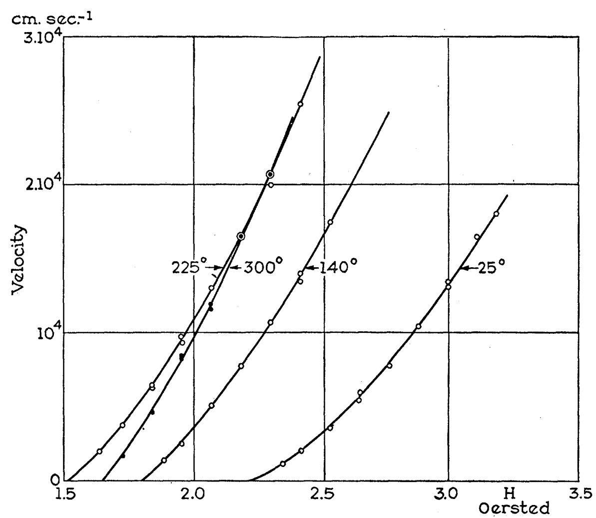

Fig. 5. v-H curves for increasing temperature with a tension of 77 kg mm^{-2}.

somewhat above the minimum reached during the heating. Fig. 7 shows this behavior for a wire at two different tensions. Subsequent heat cycles in which the maximum original temperature was not exceeded only retraced the first cooling curve. The explanation given in the present section III applies here. The permanent, if partial, relief of internal strains leads one to expect that the only effect of subsequent heating and cooling would be of the same character as the usual change in coercive force with temperature. A rough estimate from the curve for annealed Fe[10] puts the expected reduction in the

[10] Handbuch der Physik, **15**, p. 194.

neighborhood of 25 percent for a 300-degree rise in temperature, while actually almost no change with temperature was observed. We were, of course,

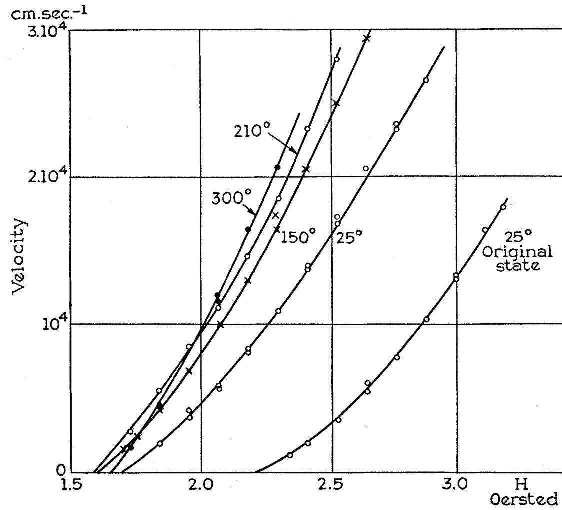

Fig. 6. v-H curves for decreasing temperature with a tension of 77 kg mm^{-2}.

dealing with a wire still having high internal strains and these, together with the uniform applied tension, may easily cause this very different behavior.

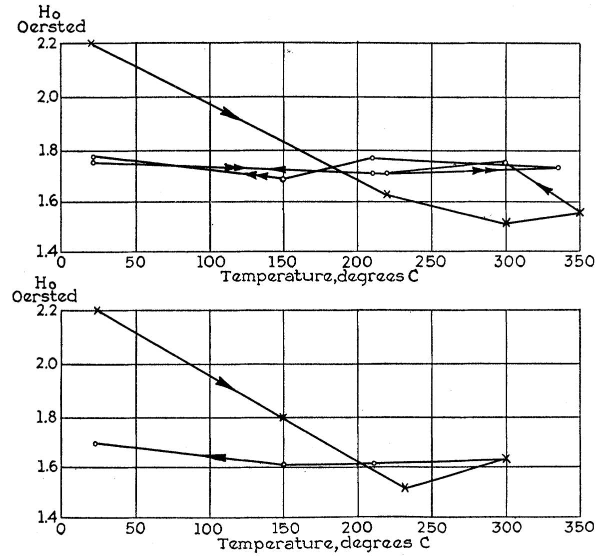

Fig. 7. Effect of temperature on H_0. Tension: 62 kg mm^{-2} for upper curve, 77 kg mm^{-2} for lower curve.

3. Variation in H_s

Comparing Fig. 5 with Fig. 6 we observe that the propagation range, $H_s - H_0$, was greater at any temperature for a wire heated previously to a higher temperature than for a fresh wire. The same result was found in section III at room temperature for wires annealed at 400°C. This indicates that the strain irregularities which gave rise to the weaker starting nuclei were eliminated by this low temperature heat treatment.

We further observe that $H_s - H_0$ decreased with increasing temperature. This probably arose from the increase in thermal energy which enhances the chance for the spontaneous formation of a nucleus at a particular field strength.

Above 350°C a new effect appeared. The starting field became so erratic that velocity measurements could not be made. The discontinuity frequently broke up into several part jumps in the same way that can occur at room temperature at small excess fields. The latter action is probably caused by local variations in H_0 which, at small values of ΔH, are comparable with or even exceed it, so that H does not exceed H_0 for every point in the wire. Thus portions of the wire are left unreversed until a larger main field is applied. In the present case, however, it is not possible to assign a reasonable cause for increased variability of H_0. The α-γ transformation does not change the saturation intensity appreciably below 450°C. It might still be supposed that highly localized portions of the alloy had transformed at 350°C, but, if the local forces were such as to cause the change 100° below the general transition, one should expect this γ-phase to persist even below the main γ-α transformation which begins at 300°. Actually, the wire when cooled to 300°C had regained in full its ability to propagate, so that this explanation is not convincing.

4. Variation of A

If Fig. 8 the variation with temperature of the slope A of the v-H curve is plotted. These results are taken from Figs. 5 and 6, from experiments with

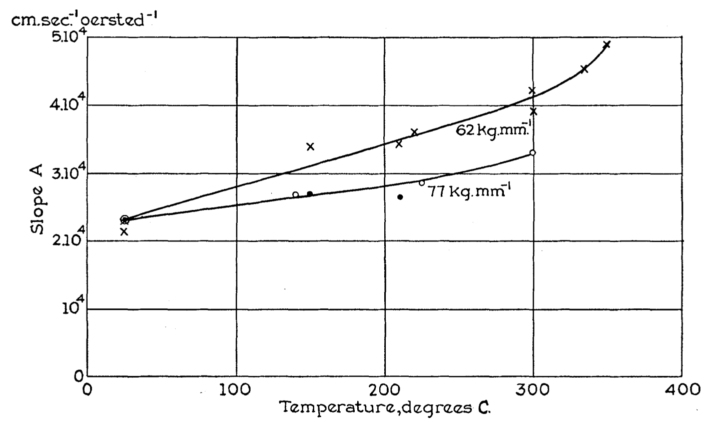

Fig. 8. Effect of temperature on slope A of v-H curves.

a wire under 77 kg/mm² tension, and from tests on a wire of different composition, namely 25 percent Ni, under a tension of 92 kg/mm². In those cases where the v-H curves were not straight lines, a tangent to these curves at

$v = 10^4$ cm sec.$^{-1}$ represented approximately the average slope of the curve and gave the value of A used in the diagram.

The increase in A shown by the figure might easily be caused by the increase in resistivity of the wire which amounts to about 90 percent from room temperature to 320°C for the 25 percent Ni wire. The factors, aside from the excess field, which determine v are not definitely known so that it is possible that resistance changes may affect it. On the other hand, we have noted in **I**, section II, that measurements at room temperature on wires of different compositions and hence of different resistivities gave values of A which showed no correlation with resistivity.

Another feature of the curves of Figs. 5 and 6 holds more hope for an explanation of the increase in A. It is the accompanying decrease in propagation range. Similar behavior was remarked in earlier experiments[2] where the point to point properties of a cold wire were investigated with the result that greater values of A were found at those places where the reversal could be started by the smaller adding fields. The minimum adding field is the least field which will start a reversal at a particular point. The starting field for the wire is the field which will just reverse the magnetization at that point where the minimum adding field is the least. Accordingly, it is permissible to assume that H_s is a rough measure of the average minimum adding field for the whole wire. The result is that both present and earlier observations record the same relation between slope and propagation range whether the variable factor is temperature or the local state of the wire.

The possibility of developing a theory relating slope to average minimum adding field seems very hopeful and the attempt to do this will be made in a later paper.

V. Etched Wires

1. Effect of etching

In our picture of the discontinuity, the velocity of propagation depends upon conditions at the wave front and hence at the surface of the wire. On this view it was expected that changes in the surface, such as caused by etching of the wires, would affect the propagation.

Wires of 15 percent NiFe (No. 37), 0.038 cm diameter were etched to various smaller diameters in a 15 percent solution of hydrochloric acid. This decreased the critical field for constant tension per unit area, an effect which presumably arises from the release of internal strains accompanying the removal of the outer layers of the wire.

In all cases the etching resulted in a marked increase in the v-H slope A amounting to 50 percent on the average. Even a reduction in diameter of as little as 5×10^{-4} cm had this effect. Fig. 9 shows a typical case. Subsequent polishing of etched wires with emery paper had erratic results, usually decreasing but sometimes increasing A. In the single case in which the etched and polished wire (0.0360 cm dia.) was drawn through a die (0.0355 cm dia.) there was a complete restoration of the original slope. Since the same stress was applied to the etched wires as to the unetched, the tension being adjusted to the reduction in cross section, the increase in A is not to be attributed to a change in applied stress. Besides, in unetched wires A is practically constant for wide variation in tension. Neither does the increase in A arise from the reduction in wire size, for it has been found that A is independent of diameter in unetched wires.

Etching has a marked effect on the starting field. A wire having a propagation range of 1.07 oersteds before etching would, after a slight removal of

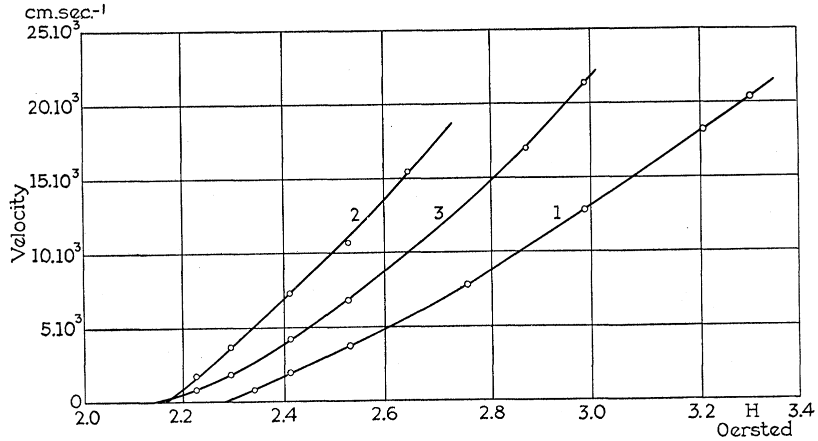

Fig. 9. v-H curves after etching and polishing of a wire. (1) Original wire; 0.0380 cm dia., tension of 77 kg mm^{-2}. (2) Wire after etching; 0.0375 cm, 75 kg mm^{-2}. (3) Etched wire after polishing; 0.0350 cm, 65 kg mm^{-2}.

surface material, show a reduction to 0.55 oersteds. If the wire was then polished, the range again increased with decreasing $v-H$ slope to 0.85 oersteds (see Fig. 9). Here again we have the same relation between propagation range and A which has been noted twice before. When the etching experiments were in progress neither this behavior nor its probable significance had been recognized. Still, the following conclusions reached in a rather exhaustive search in other directions furnish data which are fundamental to any complete explanation.

2. Surface effects and propagation

The etching changes the surface in several respects. They are absorption of hydrogen, roughening of the surface, and formation of cracks. It is well known that in etching iron or steel in HCl or H_2SO_4, large amounts of atomic hydrogen are taken up by the metal. But two experiments showed that this cannot be the explanation. First, heating the wire to 200°C for several hours to remove the hydrogen did not reduce the slope; second, etching in HNO_3 where no hydrogen is produced had the same effect on the slope as etching in HCl or H_2SO_4. On the other hand, there was no change in slope when the wire was used as cathode in the electrolysis of NaOH, where, presumably, large amounts of hydrogen were absorbed but the surface of the wire was not attacked. All these observations provided ample evidence that hydrogen was not responsible for the effects.

Under the microscope the surface of the wire looked smooth before the etching but appeared coarse afterwards. It was thought that roughening of the surface of a fresh wire with coarse emery paper would give the same magnetic effect, but the resulting variation from the normal value of A was within the normal range of variation.

One possibility of explanation remains. According to metallurgical references,[11] acid attacks the different crystal faces with different rapidity, and in some cases it dissolves the intergranular substance more quickly than the grains. This is especially true of materials with internal strains. This latter action may cause the formation of cracks in the material if high stresses across the notches formed by the acid are present.

Such fissures parallel in general to the wire axis were actually observed under the microscope on all the etched wires. Sometimes as many as five were found around the circumference at a given point along the wire. They were of several mm in length and of various widths averaging, as well as could be judged, 10^{-3} cm. It must be admitted that it is hard to understand how a crack of this width can open up as the result of the removal of only 2.5×10^{-4} cm of material. If these fissures had been the cavities which the photomicrographs show in the wire, they should also have been seen after polishing, but this was not the case. If the cracks arise from intense stresses, one should be able to prevent their formation by a preliminary annealing of the wire which is not so complete as to destroy the discontinuity. The attempt was made by heating a wire at 400°C for 10 hours. Its stiffness showed that it still contained internal strains, so that the appearance of etching cracks was not surprising. Even so, some annealing had occurred, for the heat treatment had reduced the coercive force from 7.8 to 3.3 oersteds. It may well be the release of surface strains made evident by the formation of cracks which reduces the starting field and increases A. Subsequent polishing would, on the other hand, reintroduce strains with contrary consequences.

3. Strips

A length of No. 37 wire of 0.024 cm diameter was cold rolled down to a strip 0.0076 cm thick and 0.071 cm wide. A portion cut from this was etched and it, like the wires, showed an increase in slope and a decrease in propagation range. The increase in A was, however, only 30 percent, which is considerably smaller than that found for wires. Under the microscope the etched strip showed no cracks but only a general roughness.

Two other samples cut from the same length of strip were reduced in thickness by polishing with emery paper. Erratic increases in slope up to 100 percent resulted but there was no correlation with propagation range apparent.

The taking and interpretation of the x-ray spectrograms used in studying the effect of heat treatment was done by Dr. W. P. Jesse of this laboratory to whom we express our thanks. Dr. I. Langmuir has, with his continued interest and suggestions, contributed essentially to this paper and also to the other papers on this same subject which are now in preparation.

[11] G. Tammann, *Lehrbuch der Metallographie*, 1920; Z. Jeffries and R. S. Archer, *The Science of Metals*, 1924.