THE BARKHAUSEN EFFECT

By E. P. T. Tyndall

Abstract

Barkhausen effect for silicon steel.—In a typical experiment a strip of silicon (4.2%) steel, after having been carried through several hysteresis cycles and brought to a steep part of the *B-H* curve, was subjected to a magnetic field which was increased in a continuous manner by 0.13 gauss in 2 sec. To obtain a record of the discontinuities in magnetization, the specimen was surrounded by a small search coil connected through an amplifier to a moving coil oscillograph. The *oscillograph records* show many almost instantaneous deflections with a random distribution both as to time of occurrence and as to magnitude, each followed by an approximately exponential return to zero. The duration of an impulse depends probably on eddy currents in the specimen. A rough time constant of 3×10^{-5} sec. is computed for a 4% silicon steel wire, 1 mm in diameter. The apparatus was calibrated by means of artificial impulses of the same type. Assuming each impulse is due to a sudden saturation of a small portion of the material, the change in magnetic moment of this portion is found to vary from .001 to .008 e.m.u.; the average change .003 is sufficient to saturate a volume of 1.7×10^{-6} cc. This volume, while comparable with that of a crystal grain in the particular case described, was found not to depend upon grain size in any marked degree in other experiments. The results favor the suggestion of Barkhausen that magnetic materials magnetize discontinuously, but leave open the question as to what determines the size and shape of the portions which suddenly change.

Introduction

THE discontinuities in the magnetization of iron and other magnetic materials have been investigated by Barkhausen,[1] Van der Pol,[2] Gerlach and Lertes,[3] Weiss and Ribaud,[4] Zschiesche,[5] and S. R. Williams.[6] Barkhausen and Van der Pol consider the effect as due to the sudden reorientation of groups or chains of molecular magnets, possibly all the magnets in a single crystal turning simultaneously. The latter has published pictures of the discontinuities as recorded by a fluxmeter and by a string galvanometer. Gerlach and Lertes, and Zschiesche placed the specimen in a solenoid which was then rotated at an arbitrary rate between the poles of an electromagnet. The amplified and rectified

[1] H. Barkhausen, Phys. Zeits. **20,** 401 (1919)
[2] B. Van der Pol, Proc. Acad. Amst. **23,** 637, (1921); **23,** 980 (1922)
[3] W. Gerlach and P. Lertes, Zeits. f. Phys. **4,** 383 (1921)
[4] P. Weiss and G. Ribaud, Jour. de Phys. (6) **3,** 74 (1922)
[5] K. Zschiesche, Zeits. f. Phys. **11,** 201 (1922)
[6] S. R. Williams, Phys. Rev. (2) **22,** 526 (1923)

current from the solenoid as measured by a galvanometer is defined by them as the "effect." Various experiments led them to the conclusion that the effect is dependent on magneto-striction and not primarily on discontinuities in magnetization. Williams has recently obtained oscillograms of the effect using a telephone receiver as an oscillograph. All observers seem agreed that the effect takes place only where the *B-H* curve for the material is steep. Preliminary work in this laboratory showed that the effect as measured by the noise in a telephone receiver is roughly proportional to the slope of the *B-H* curve. Iron dust, loose or compressed, gave a negligible effect. The work reported here was undertaken to test the hypothesis that the phenomenon is due to the magnetization of single crystals and to obtain a more detailed picture of it than has yet been presented. Most of the work has been done on one specimen, though enough observations have been made on others to give confidence in the generality of the results.

The discontinuities in magnetization are best measured by the induced voltages in electrical circuits, magnetometer methods being unsuited to the proper analysis of the effects. In an attempt to record the discontinuities separately and with as little distortion as possible various methods have been tried. The first instrument used was the oscillograph tube developed in this laboratory by J. B. Johnson.[7] This gave visual evidence of the discontinuities but it was at once apparent that photographs could not be taken quickly enough to follow the changes in a single event. Later a moving coil oscillograph of the ordinary type[8] was used and found more satisfactory.

Experimental Method

The circuit used in obtaining oscillograms of the effect is shown in Fig. 1. Changes in magnetization are produced by passing current through either of two single-layer solenoids S_1 and S_2, each 80 cm long and 2.5 cm in diameter, wound in parallel on a glass tube. The search coil S_3 is a multiple-layer solenoid of 10,000 turns, 2.5 cm long and 2.2 cm in outside diameter. The specimen is a straight wire or flat strip longer than the search coil and supported at the center of the magnetizing coils S_1 and S_2. The voltage generated in S_3 by sudden changes in magnetization of the specimen is amplified by the amplifier A, the output of which goes to the oscillograph (Vibrator No. 2). The circuit connected to S_1 is used to carry the specimen through several magnetizing cycles

[7] J. B. Johnson, Jour. Opt. Soc. Am. and R.S.I. **6,** 701 (1922)
[8] General Electric Company Oscillograph, Type EM Form C.

before taking an exposure. The specimen can thus be brought to any desired point in the cycle. The experimental change in magnetization is then effected by closing the filament circuit of the vacuum tube V. As the temperature of the filament rises the current through S_2 grows continuously and almost linearly with time, thus giving a smooth variation of magnetizing field. This current is recorded on the oscillograph (Vibrator No. 1). A time scale is given by a 60-cycle alternating current (Vibrator No. 3). No transformers are used in the amplifier circuit, the coupling being by means of resistance (100,000 ohms) and capacity (0.1 mf). A "V" tube[9] is used in each of the first three stages; in the fourth are two "L" tubes,[10] connected in parallel. The space current (20×10^{-3} amp.) from the last stage passes directly through the oscillograph vibrator. An

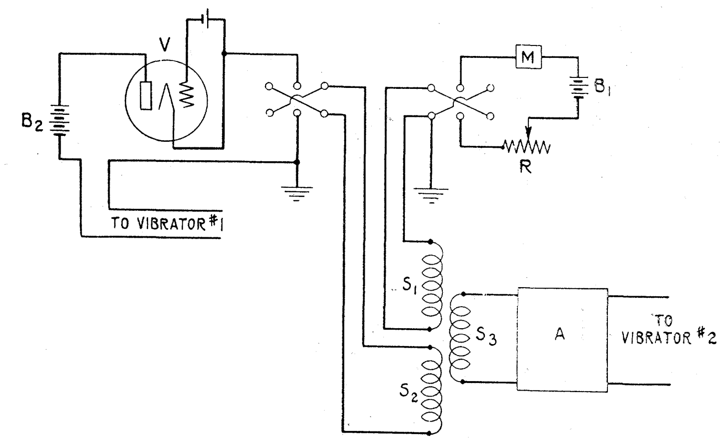


Fig. 1. Diagram of apparatus for recording Barkhausen effect.

amplifier of this type is comparatively free from distortion. The effect on the records due to amplifier and oscillograph characteristics is discussed below.

Before taking an oscillogram the specimen is taken about ten times around a hysteresis loop wide enough to ensure nearly complete saturation at either end, and so brought to some desired point, usually that corresponding to zero current in solenoid S_1. The magnetizing field thus produced is not quite zero since the vertical component of the earth's field is not neutralized. The light is then screened from vibrators No. 2 and No. 3 and the zero position of vibrator No. 1 marked on the film during one rotation of the drum. After these preliminaries the oscillogram is taken at once to minimize the disturbing effects of stray magnetizing

[9] Western Electric Company, 102-DW
[10] Western Electric Company, 216-A

fields. The exposure is made just after closing the filament circuit of the auxilliary vacuum tube V. To simplify the comparison of records two standard rates of the oscillograph drum were chosen. In the slower case the closing of the key in the filament circuit of V also opens the shutter of the oscillograph by means of a relay. The picture thus obtained shows the process from the beginning nearly to the end, lasting about two seconds. In the faster records the vacuum tube filament is lighted and after a suitable short interval the shutter is opened. A record at this rate covers half a second or less and a more detailed picture is given of a small part of the process.

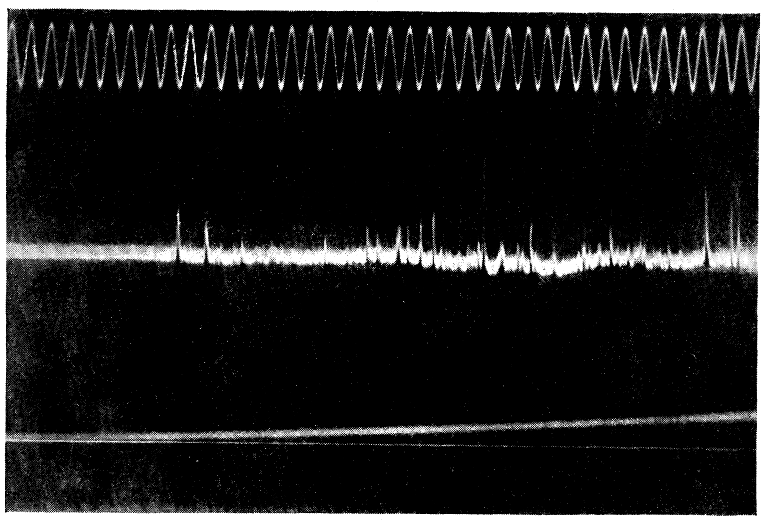


Fig. 2. A record taken at the slower rate.

Data and Discussion

A portion of a typical film, taken at the slower rate, is shown in Fig. 2. This record was obtained with a strip of silicon steel (4.2%) 0.043 cm $\times$ 0.178 cm $\times$ 17.8 cm which had been annealed in vacuum for 11 hours at 900°C and had then had a further heat treatment, also in vacuum, of 30 min. at 1200°C. The average linear dimension of the grains as measured on etched areas is about 1.5×10^{-2} cm. The record of Fig. 2 shows well the discontinuities in the process of magnetization. The amplified curve is approximately the derivative of the B-H curve for the specimen. It shows that a portion of the B-H curve consists of short straight lines parallel to the B axis and H axis alternately.

It might be expected that consecutive experiments under identical conditions would give superposable oscillograms, the magnitude and order of the impulses being completely determined by the initial state of magnetization. In no case, however, was it possible to obtain two identical records, even though many successive films were compared, in which the specimen had been left undisturbed in position and had been brought to the same state through identical preliminary magnetizing cycles.

A study of the occurrence and magnitude of the discontinuities was made. Five successive records like that of Fig. 2 were analyzed. The change in the magnetizing field was 0.130 gauss and the change in the induction corresponding thereto was about 2000. This increment was divided into intervals 0.005 gauss long and the number of impulses in each interval recorded. A count was then made of the number of intervals containing 0, 1, 2, 3 etc. impulses. These data are graphically presented in Fig. 3. The ordinate of any point is the number of field intervals

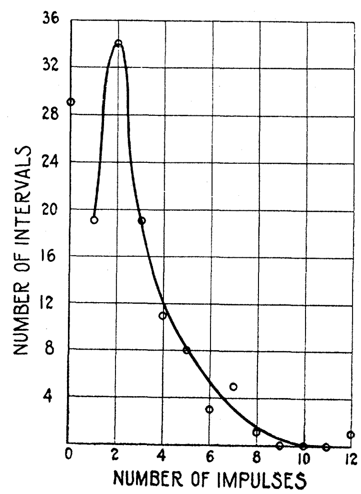


Fig. 3. Distribution among equal field intervals of discontinuities in magnetization.

containing the number of impulses shown by the abscissa. The graph shows that this distribution is a random one, except for the excess of intervals containing no impulse, most of which occur at the beginning of the record. It is thought that this results from the unavoidable fluctuations in magnetizing field between the end of the preliminary treatments and the beginning of the exposure. In Fig. 4 is plotted the distribution of the impulses as to magnitude. The ordinate of any point is the number of impulses having a magnitude (simply the deflection in cm measured on the film) of the size given by the corresponding abscissa. This distribution also appears to be a random one.

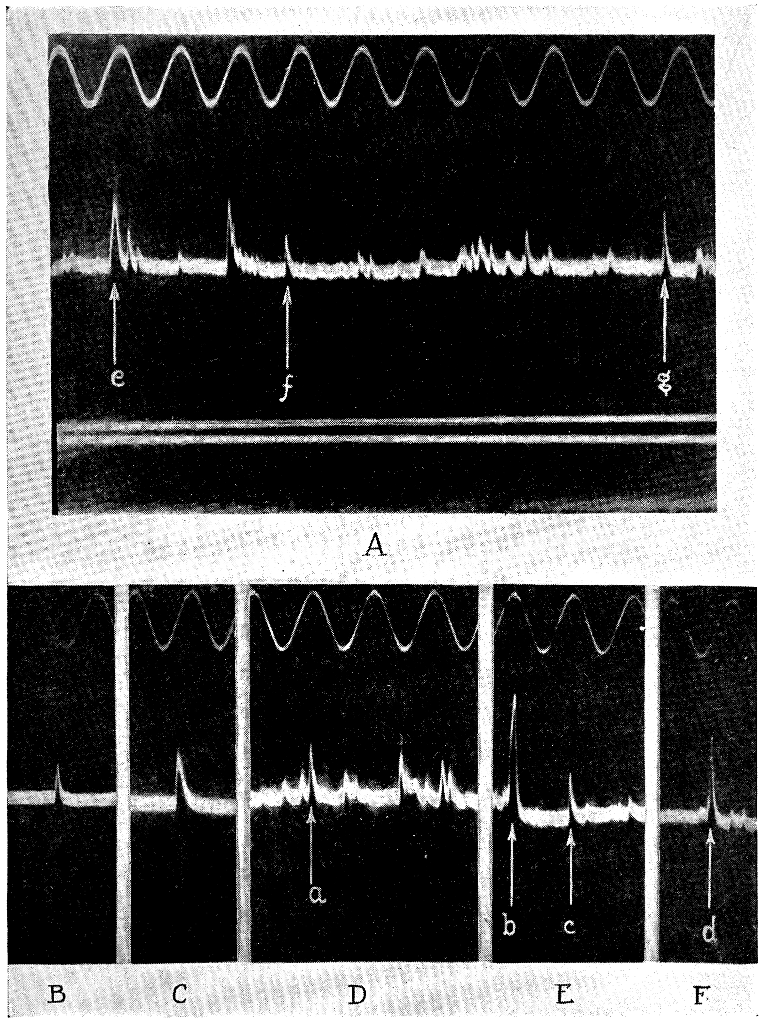


Fig. 5. Records taken at the faster rate.
A. Change in H 0.022 gauss. Measured impulses e,f,g.
B. Artificial impulse, $\tau=0.1\times10^{-3}$ sec.
C. Artificial impulse, $\tau=1.45\times10^{-3}$ sec.
D, E, F. Measured impulses a,b,c,d.

In a record of the second kind described above each impulse consists of an almost instantaneous deflection followed by an approximately exponential return to zero. Part of one such record is shown in Fig. 5A. Oscillograms taken with fresh damping fluid show higher and sharper peaks, corresponding to the lower value of damping factor thus obtained.

To calibrate the amplifier artificial impulses were similarly recorded by the arrangement shown in Fig. 6. The search coil S_3, and the amplifier circuit are as before, there being, however, no specimen in S_3. In the circuit with S_2 are now an inductometer (L_3, r_3), resistance r_4, and milli-

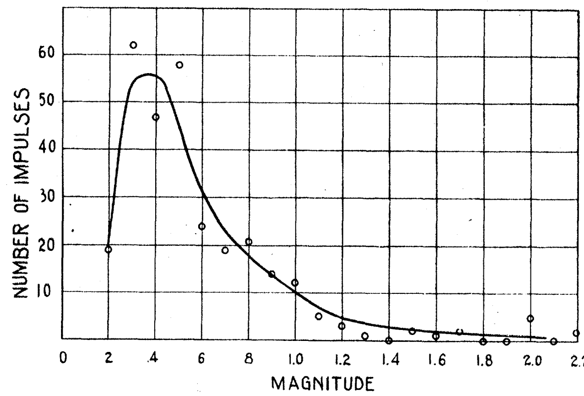


Fig. 4. Distribution in magnitude of discontinuities in magnetization.

ammeter M. By adjusting the ratio of r_4 to R and the value of L_3 it is possible to establish a current of a chosen magnitude in the circuit in which S_2 is included and to adjust the time constant of this circuit as desired. The equation for this current is given by

$$i = I(1 - \epsilon^{-t/\tau}) \tag{1}$$

in which

$$\tau = (L_2 + L_3)/(r_2 + r_3 + r_4) \ . \tag{2}$$

In these expressions I is the steady state current with the key K closed and τ is the time constant. The voltage induced in the search coil S_3, is

$$e = M di/dt = (MI/\tau)\epsilon^{-t/\tau} \tag{3}$$

where M is the mutual inductance of S_2 and S_3. It is an amplified picture of this voltage which is recorded on the film as a function of the time. Its initial value and the area under the curve are given by

$$\epsilon_m = MI/\tau \quad \text{and} \quad \int_0^\infty e dt = MI \ .$$

Oscillograms showing two such impulses are shown in Fig. 5B, 5C. Table I gives results of measurements on such artificial impulses, the deflection h, and the area under the curve A, being the quantities measured from the oscillograms.

The values of the ratio e_m/h are interesting in that they show how the amplifier and oscillograph distort a very sudden voltage impulse, the maximum value being cut down while the rate of return is diminished. If there were no distortion the ratio e_m/h would be constant. In spite of the distortion, however, the system is a competent integrator, for, as the

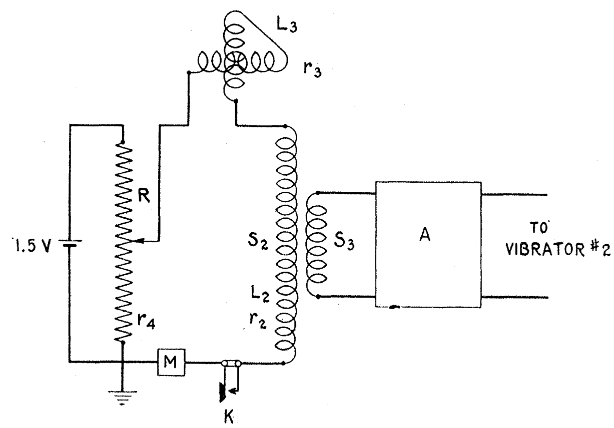


Fig. 6. Diagram of apparatus for producing and recording artificial impulses.

last column shows, $\int edt/A$ is approximately constant for values of τ down to 10^{-4} seconds. It is moreover considered constant for values of τ less than 10^{-4} seconds, as it was later checked experimentally to $\tau=10^{-5}$

TABLE I

τ	e_m	$\int edt$	h	A	e_m/h	$\int edt/A$
($\times 10^{-3}$)	($\times 10^{-3}$)	($\times 10^{-3}$)		($\times 10^{-3}$)	($\times 10^{-3}$)	($\times 10^{-3}$)
0.1 sec.	2.93Volts	0.293	0.75 cm	0.64	3.9	0.46
0.1	6.30	0.630	0.78	0.97	8.1	0.65
0.2	3.21	0.648	0.90	0.65	3.6	1.00
0.2	6.25	1.25	1.33	1.26	4.7	0.99
0.2	1.53	0.31	0.55	0.635	2.8	0.49
0.2	3.97	0.80	1.02	1.30	3.9	0.62
0.28	8.16	2.28	2.13	3.55	3.83	0.64
0.3	3.11	0.923	1.17	1.64	2.66	0.56
0.41	2.85	1.17	1.58	1.94	1.8	0.60
0.60	1.80	1.08	1.17	1.64	1.5	0.66
0.62	3.68	2.28	1.86	3.12	2.0	0.73
0.63	1.79	1.13	1.60	2.42	1.1	0.47
1.45	0.764	1.11	1.01	1.78	0.76	0.62
					Average	0.652

seconds, there being no considerable change in $\int edt/A$ between $\tau=10^{-3}$ and $\tau=10^{-5}$ seconds. These data are not included in the table as they were taken after replacement of the damping fluid in the oscillograph, which changed the actual value of $\int edt/A$ for any value of τ.

From oscillograms of the effect taken at the faster rate some speculations concerning the magnitude of the change in magnetic moment producing a sudden voltage impulse may be made. Impulses of various sizes, all from the same specimen previously described and with zero current in S_1, Fig. 1, were studied. Some of these are shown in Fig. 5 already referred to. The time constant of any of these impulses is by inspection not more than 10^{-3} seconds and may be very much less. Since it has been shown that the area under the curve of the amplified voltage is practically independent of the time constant of the voltage impulse, an estimate may be made of the total change in magnetization corresponding to any impulse without knowing the time required for the change. It will merely be assumed that a change in magnetization of a small portion of the material takes place in a short space of time. The portion of material will be considered as a dipole whose magnetic moment changes suddenly from one value to another. Let M be the variable magnetic moment of the dipole and consider it situated at the center of the short solenoid S_3, Fig. 1. It is then very easy to show that the area under the curve for the voltage induced in such a solenoid when M changes from 0 to M is

$$\int edt = \frac{2\eta Mn}{10^8\sqrt{a^2+R^2}} \text{ (volts–sec.)}$$

where n is the number of turns on the solenoid S_3, a is half its length in cm, and R is the mean radius of the multiple layer winding. Some objection may be made to the assumptions that have been made but until more is known of the mechanism of magnetization they do not seem unreasonable. The dipole has been considered as surrounded by nonmagnetic material. This assumption, however, does not seem so arbitrary when it is remembered that it is evident from the records that the rest of the material does not greatly change its magnetization when one small portion does. That a sudden change in magnetization might set up eddy currents in the surrounding material which would modify the observable effect, is quite possible, and will be discussed later.

For a given Barkhausen impulse the $\int edt$ may be determined from the area by the calibration factor derived in Table I. The experimental data on a series of impulses, shown in Table II, have been interpreted on the basis of the analysis given above. The letters a to g designate the impulses shown on Figs. 5. For simplicity the area under each deflection has been approximated to that of a triangle whose base b is the time during which the vibrator is deflected from the zero position.

TABLE II

Impulse	b	h	Area	$\int edt$	M
	$(\times 10^{-3})$				$(\times 10^{-3})$
a	2.16 sec.	1.00 cm	1.08	0.71	1.5 e.m.u.
b	2.43	2.15	2.61	1.70	3.6
c	1.69	0.95	0.80	0.52	1.1
d	2.60	1.62	2.10	1.37	2.9
e	3.04	1.28	1.95	1.27	2.7
f	1.59	0.65	0.52	0.34	0.72
g	1.85	1.10	1.02	0.67	1.4
h	2.58	1.20	1.55	1.01	2.1
i	1.98	0.72	0.71	0.46	0.97
j	1.52	0.70	0.53	0.35	7.3
k	1.06	1.05	0.56	0.37	7.7
				Average	2.9

Discussion of Results

Assuming that a small volume v of the material is magnetized to saturation to produce each of the changes in magnetic moment given in Table II, the average value of v is given by

$$v = M/\sigma \ .$$

Putting σ, the intensity of magnetization at saturation, equal to 1700 gives

$$v = 1.7 \times 10^{-6} \text{cm}^3 \ ,$$

and

$$v^{1/3} = 1.2 \times 10^{-2} \text{cm} \ .$$

Although this is not far from the average linear dimension of the grains in the specimen, it is not to be concluded that the grains become magnetized as units. Experiments to be quoted below will make this clear. However the change in magnetization arises, the order of magnitude of the change has been estimated on the basis of somewhat speculative assumptions.

It will be interesting to compare the result with that obtained by another experimenter. Van der Pol assumes groups of elementary magnets in long filaments and computes that the change in flux corresponding to one discontinuity is 0.33 lines. On the same assumption the average magnetic moment shown in Table II would correspond to a change in flux of 0.14×10^{-2} lines. Van der Pol used a different material and a different method and it is not surprising that the results should differ. An experiment was performed to determine whether the filaments which he describes existed in the specimen here studied. Two identical search coils, one of which was that previously used, were placed end to end over the specimen and substituted in the measuring circuit for the single coil S_3, Fig. 1. Connections were such that a change in magnetization of given sign would cause oppositely directed voltage impulses in the two coils. The record showed deflections on both sides of the zero line, similar in type and approximately equal in number and magnitude to those obtained with a single search coil, clearly indicating that few changes in magnetic moment affected both coils. This was taken to mean that this sample differed from that studied by Van der Pol in having few long filaments or at least in having few that became magnetized as units. The result of this experiment justifies the assumption that the magnetic element may be treated as a dipole.

To test the effect of grain size on the phenomenon a strip of the same silicon (4.2%) steel sheet was vacuum annealed at about 1300°C for 30 minutes. This produced large grains, extending through the thickness of the strip. A specimen 4.3 cm × 0.238 cm × 0.043 cm was sawed from the portion where the grains were largest. About half this strip consists of one large grain. Another grain is about half as large, and altogether there cannot be more than twenty-five grains. That such large grains really represent single crystals was shown by examining the etching pits, which were alike over any one grain, and was checked by making a Laue photograph.[11] The records taken with this specimen do not differ more from those taken with the specimen first described than is to be expected in view of its shortness and consequent smaller change of induction for a given increment of magnetizing field. The impulses occur in the same random manner and are of about the same general intensity and number as before. A single grain, therefore, can hardly be conceived of as changing its magnetization as a unit.

If a dipole be instantaneously created in the interior of a conducting mass, the sudden growth of the magnetic field will set up eddy currents. The field of these currents will oppose the growing field of the dipole. A solenoid surrounding such a system would have a voltage pulse generated in it, consisting of an instantaneous rise to a finite maximum (initial) value and a gradual decay. The time of decay would depend on the time constant of the eddy current circuit. A paper by Wwedensky[12] enables a rough approximation of the time of the decay of the Barkhausen impulses to be made. Wwedensky considers an infinite cylinder of magnetic material, whose permeability is constant, subjected to the influence of a

[11] By Dr. R. M. Bozorth of these laboratories.

[12] B. Wwedensky, Ann. der Phys. (4) **64,** 609 (1921)

longitudinal magnetic field whose intensity changes instantaneously to a higher or lower value. He obtains an expression for the reduced mean flux through the cylinder as a function of time. Defining a sort of rough time constant as the time, τ', for the growing flux to reach $(1-1/\epsilon)$th of its final value, and using Wwedensky's expression, a silicon steel wire of 0.05 cm radius (permeability 400, conductivity 0.02×10^{-3} e.m.u.) has $\tau'=3\times10^{-5}$ sec. A lower value of permeability or smaller radius would give a smaller value of τ'.

The impulses of Table II were produced in a strip only 0.043 cm thick and the corresponding value of τ' although not directly calculable may be 10^{-5} sec. or even less. An attempt was made to detect the effect of eddy currents by comparing records taken with two specimens of silicon (3%) steel using fresh damping fluid in the oscillograph. One specimen was a wire 0.16 cm in diameter; the other was a tape 0.30 cm wide and 0.048 cm thick. Under these experimental conditions it was observed that the impulses were somewhat broadened in the case of the wire. The time constant of the deflection as measured on the oscillograph did not in either case differ much from 10^{-4} sec. The energy dissipated by such transient eddy currents is to be considered inseparable from the process of magnetization and not, like that dissipated by the eddy currents ordinarily considered, a function of the frequency of alternating magnetizing fields. There should, therefore, be a difference between the energy loss in low frequency magnetization as measured by calorimetric methods and that measured by plotting stationary values of induction and magnetizing field, in addition to the difference ascribable to eddy currents of the same frequency as the magnetizing field.

Conclusion

The above results favor the theory advanced by Barkhausen and upheld by Van der Pol that magnetic materials magnetize discontinuously, but do not substantiate the belief that each discontinuity is due to a single crystal. What determines the selection, number, and grouping of atoms which may at any time form a simultaneously magnetizable unit, and what determines the order of response of such units to an externally applied field, are not apparent, nor can any conclusion be drawn as to whether a given unit magnetizes to saturation in one jump or in several. That there should be any continuous variation of magnetization between the discontinuities seems unlikely. The apparently smooth parts of the curve observed by Van der Pol with the fluxmeter can be considered as regions in which a large number of small discontinuities occur, that is, the phenomenon can be regarded as too fine-grained for the method of observation. Little justification has been found for the theory proposed by Gerlach and Lertes and supported by Zschiesche. Their adoption of a complicated and somewhat obscure explanation depends mainly on their failure to detect an effect in iron powder and divided iron bars. With iron powder of the sort here examined even saturation of individual grains would give discontinuities too small and too numerous to give effects measurable either by their method or by that here described. It seems best to adopt the simpler notion that for some reason, limited portions of the material magnetize by jumps, either partially or to saturation, and to leave open the question of what determines the size and shape of these portions in various materials and in various specimens of the same material which have undergone different treatments. The identification of these individuals and a better understanding of their behavior would give microscopic detail to pictures of the mechanism of magnetization.

RESEARCH LABORATORIES OF THE
AMERICAN TELEPHONE AND TELEGRAPH COMPANY
AND THE WESTERN ELECTRIC COMPANY, INCORPORATED.
April 21, 1924.

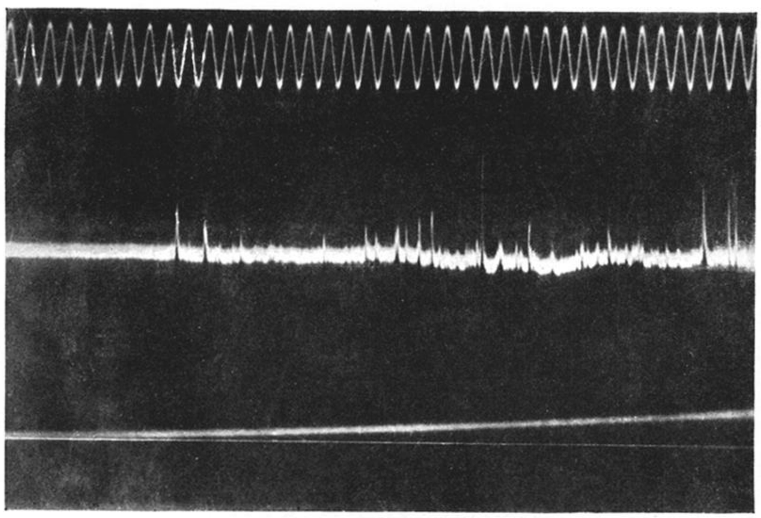
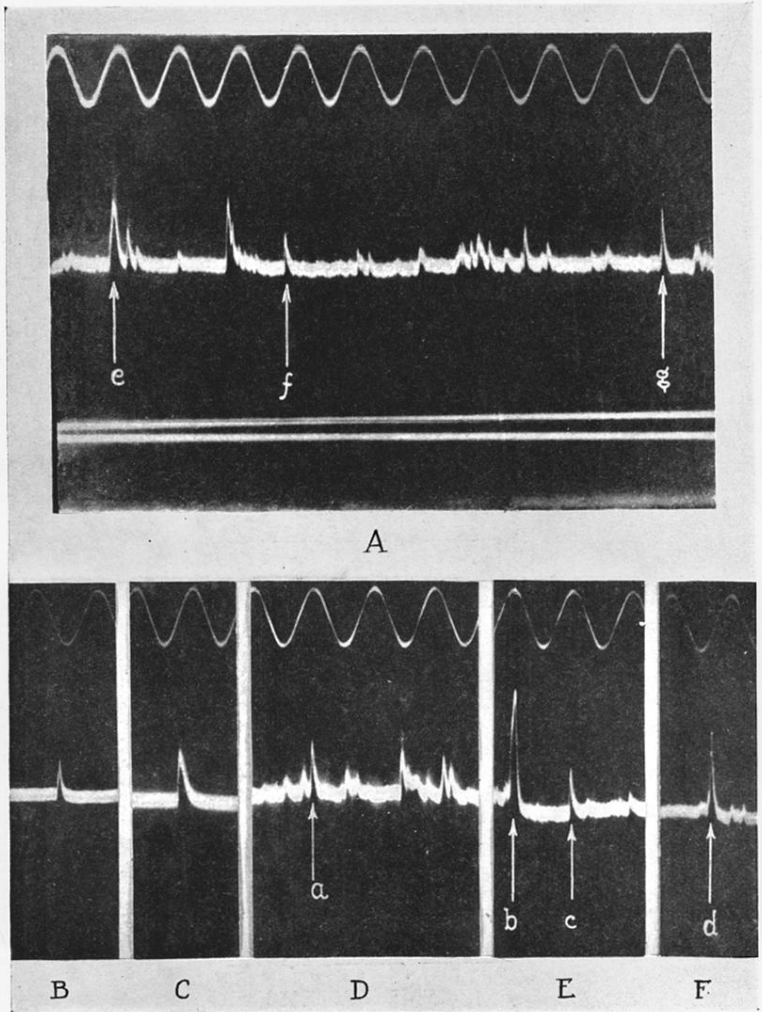


Fig. 2. A record taken at the slower rate.



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