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Mono-Crystal Barkhausen Effects in Rotating Fields

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The directions of Barkhausen effects in a single crystal disk of silicon steel, held stationary in a magnetic field rotating slowly in the plane of the disk, have been determined. Search coils at right angles picked up impulses proportional to selected rectangular components of the changes in magnetization. Measurements on an oscillographic record were made at two values of magnetization, 190 and 100. Values of the angle ϕ between the change in magnetization ΔI and the corresponding variation in the applied field, $(dH/dt)\Delta t$ were determined for various positions of the applied field relative to the crystallographic axes. The normal to the disk made angles of 30°, 60°, 90° with these axes. For these low values of magnetization the effects are mainly transverse with respect to H (and therefore nearly parallel to dH/dt) and are more nearly transverse for the greater value of magnetization. The average value of ϕ is about 20° (ΔI lagging dH/dt) for the lower value of I and is less than 5° for the higher value. The average magnetization apparently lags the applied field and makes a small angle with it. The direction and frequency of effects seemed unaffected by changing the direction of H in the plane of the disk, so that no dependence upon the crystallographic directions of I, H or dH/dt have been established.

INTRODUCTION

A GREAT deal of experimental evidence relating to discontinuous changes in magnetization has been presented since the discovery of the Barkhausen effect.[1] Data have been obtained concerning the effect in various materials, the size of the volume element, or rather the magnitude of the change in magnetic moment, the relation between mechanical strain and effect and the relation between the effect and the slope of the magnetization curve or hysteresis loop. Various methods have been employed for the detection of the discontinuities principal among which are, the measurement of the noise from a telephone receiver, the measurement of the average current output from an amplifier by means of a galvanometer, and the measurement of the instantaneous current output from an amplifier by means of an oscillograph. All but the most recent studies have concerned themselves wholly with the changes in magnetization which take place in the direction of the applied field. Recently Bozorth and Dillinger[2] and Bozorth[3] have studied in addition the change in magnetization occurring in a direction at right angles to the applied field. It is recognized that a knowledge of this so-called transverse effect may give additional information as to the nature of processes occurring in the elementary domains.

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[1] H. Barkhausen, Phys. Zeits. **20**, 401 (1919).

[2] R. M. Bozorth, and J. F. Dillinger, Phys. Rev. [2] **38**, 192 (1931); **41**, 345 (1932).

[3] R. M. Bozorth, Phys. Rev. [2] **39**, 353 (1932).

In the present investigation a single crystal of silicon steel was employed as a test specimen. An apparatus was devised so that an indication of the longitudinal and transverse components of the change in magnetization arising from one and the same discontinuity could be obtained. As a means of causing the effect a uniformly rotating field was employed, the specimen being held stationary. It was felt that an investigation along these lines would give some insight as to the transverse effect, relate the direction of the change in magnetization with the position of the exciting field and disclose any dependence of the direction of the change in magnetization upon the crystallographic directions of $\boldsymbol{I}$, $\boldsymbol{H}$ and $d\boldsymbol{H}/dt$. It seemed likely that a better indication of the actual phenomena taking place could be had by obtaining the ratio of the change in magnetization along the field and at right angles to the field corresponding to each individual discontinuity and then averaging this ratio, rather than considering the ratio of the average longitudinal component to the average transverse component.

The Apparatus

The apparatus devised to give the information desired consists essentially of the main exciting field and the search coils, the amplifiers, and the oscillograph. Fig. 1 illustrates the essential features of the effect producing mechanism. Here A is the field-producing coil consisting of 65 turns of 9 A. W. gauge (diameter 0.289 cm) double cotton covered wire. The winding is excited from a storage battery source of supply and produces a field of strength 4.8 gauss per ampere directed in the plane of the crystal. The main field is electrically driven through reduction pulleys and the worm and wheel B. Throughout the course of the investigation the rate of rotation of the field was 1 revolution in 5.63 minutes. This low rate was found to be necessary in order to secure sufficient resolution between successive discontinuities. To pick up two mutually perpendicular components of magnetization due to a single discontinuity it was necessary to employ two search coils mounted at right angles to each other. These coils are indicated in the diagram as C and D, referred to herein as the outer and inner coils, respectively. The outer coil consists of 12,000 turns of 44 A. W. gauge (diameter 0.0051 cm) enameled wire wound in two sections. The inner coil consists of 11,000 turns of 44 A. W. gauge enameled wire also wound in two sections. The sections of each individual coil are connected in series so that the induced e.m.f.'s will be ad-

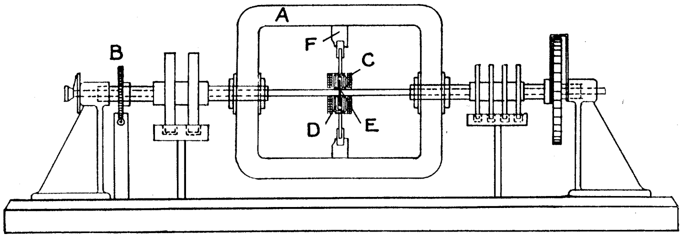

Fig. 1. Side view of mechanism.

ditive. The coils were wound on specially constructed Bakelite forms so arranged that the inner coil could be slipped out of the outer coil and the crystal disk *E* inserted. The coil holder *F* maintains the coils with 90° between their axes and permits shifting of the arrangement relative to the field coil.

In order to obtain measurable impulses it was necessary to amplify the outputs from each search coil. Fig. 2 is a wiring diagram of the amplifiers employed. It was found advisable to use an output transformer in the last stage to increase the output current to a value which would actuate the oscillograph. The value of the coupling resistances, coupling condensers and by pass condensers are given below in Table I. Considerable difficulty was met with in securing the high amplification necessary, consistent with good stability. In order to eliminate feed back, extreme care was taken in the wiring of the amplifiers. Each individual stage of both amplifiers was separately shielded. The input leads from the search coils and the output leads to the oscillograph were also separately shielded. Further, to eliminate disturbances of an electromagnetic origin, the entire apparatus was placed in a large copper box. The search coils and main field were, in addition, separately shielded. The effect of sound vibration was almost wholly eliminated by using non-microphonic tubes and by suspending the amplifiers from rubber tubing which served to damp out the vibrations.

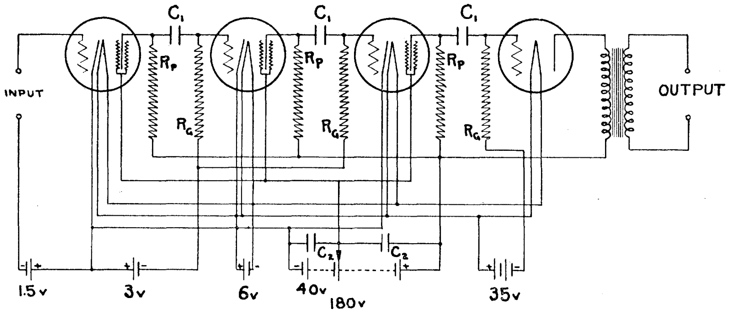

Fig. 2. Wiring diagram of one amplifier.

TABLE I.

	1st	2nd	3rd	4th
R_g	—	50,000	750,000	250,000
R_p	25,000	100,000	50,000	—
C_1	—	0.1	0.1	0.1
$C_2=4$ mfd				

The oscillograph used was a G. E. Type PM-12-A 1 two element instrument. The sensitivity of the elements was 0.7 m.a. per millimeter.

The specimen employed in the experiments was a disk one inch (2.54 cm) in diameter and 0.018 inch (0.0457 cm) thick cut from a single crystal of silicon steel grown by W. E. Ruder of the General Electric Laboratories. Precautions were taken in the cutting to minimize the effect of strain as much as possible. The analysis of the steel used is as follows:

C	Mn	P	S	Si
0.05	0.15	0.038	0.026	3.24.

X-ray analyses showed the specimen to be a single crystal and determined the direction of the cubic axes relative to an indicating mark ruled on the crystal. These directions are indicated in the diagram of Fig. 3.

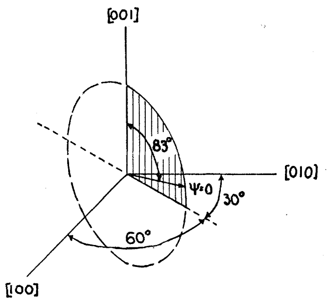

Fig. 3. Relation of cubic crystal axes to plane of disk and fiducial line thereon.

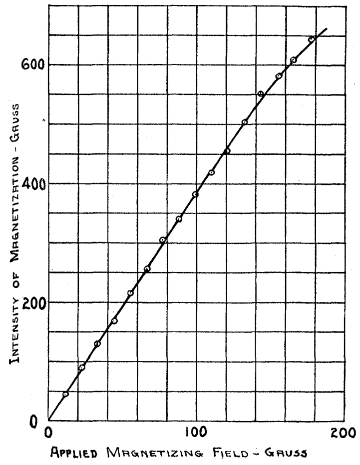

Fig. 4. Relation between magnetization and applied magnetizing field.

A curve showing the relation between the field strength of the main field and the intensity of magnetization is plotted as Fig. 4. The curve was obtained by suspending the disk by means of a fiber in a uniform magnetic field. The disk was then set into oscillation and the period of the system determined at various field strengths. Measurements of the effect were made at two values of I, 190 and 100, corresponding to a main field current of 10 amperes and 5 amperes, respectively.

Method of Procedure

In taking observations the crystal was placed in position in the apparatus so that the indicating mark on it was perpendicular to the base of the apparatus. The main field was then excited from a storage battery source of supply. With the amplifiers in operation the field was slowly rotated at a uniform rate. The rotation of the field caused the appearance of Barkhausen discontinuities, the effect of which could be viewed or photographed by means of the oscillograph. The crystal position was maintained fixed during the course of the measurements. The positions of the field are designated by the angle ψ which is the angle between the field vector and the mark on the crystal. The positions of the search coils relative to the field are designated by means of the angle θ which is the angle between the field vector and the axis of the inner coil.

With the field is a given position, e.g., $\psi=0$ and the search coils at the position $\theta=0$, a photograph is taken of the discontinuities affecting each coil. With the field in the same position, i.e., $\psi=0$ photographs are taken for values of θ from $\theta=0°$ to $\theta=90°$ at 10° intervals. The above process is repeated for values of ψ from $\psi=0$ to $\psi=180°$. Photographs have been taken in the manner outlined above for a main field current of 10 amperes corresponding to an intensity of magnetization of 190 gauss. Another run was taken at a field current of 5 amperes corresponding to an induction of 100 gauss. Here the search coils were always maintained at a position $\theta=45°$ with respect to the field.

The change in magnetization taking place when a discontinuity occurs is proportional to the area under the corresponding curve traced out by the oscillograph. The areas corresponding to each discontinuity were obtained by considering the impulse to be triangular in shape and measuring the base and altitude of the triangle. From these measurements the ratio of the change in magnetization in the outer coil to the change in magnetization in the inner coil can be obtained for the various values of ψ and θ. Curves of this ratio plotted as a function of θ are then obtained corresponding to various values of ψ. In order that these curves have any significance it is necessary that the over-all amplification of both the outer and inner coil circuits be the same in magnitude. The amplifiers employed were matched as closely as possible and the outer coil wound with more turns than the inner coil in order to compensate for the relatively smaller efficiency of the outer coil. Adjustment of the over-all amplification of both circuits was then made by comparing the ratio of the impulses at $\theta=0°$ and $\theta=90°$. If the over-all amplification is f_o for the outer coil circuit and f_i for the inner coil circuit we have

$$f_i/f_o = [(A_i/A_o)_{90}/(A_o/A_i)_0]^{1/2}.$$

Here $(A_o/A_i)_0$ is the ratio of the impulses in the outer and inner coil circuits at $\theta=0°$ and $(A_o/A_i)_{90}$ is the same ratio at $\theta=90°$.

From the data obtained in the manner outlined above the ratio of the change in magnetization along the field and perpendicular to the field may be determined. From this information the angle ϕ which the change in magnetization makes with $(d\mathbf{H}/dt)$ may be determined. These data can be averaged for the various positions of the field and a curve of average ϕ plotted as a function of ψ.

RESULTS AND DISCUSSION

The results of the investigation are contained in curves of which Fig. 5 is typical and in the curves of Fig. 6. In Fig. 6, curve 1 is for a field current of 10 amperes while curve 2 is for a field current of 5 amperes.

The data indicate that changes in magnetization sometimes occur which give a component in a direction opposite to the applied field. This result is in apparent contradiction with expectation in that it seemingly involves a change in magnetization for which there is an increase of the potential energy. However, Bozorth[3] points out that in all probability the volume element undergoing a change is exceedingly small, approximating 10^{-9} cm^3. It seems reasonable to suppose that the actuating field causing a Barkhausen discontinuity is the field in the immediate vicinity of the volume element which subsequently undergoes a change. This field is the resultant of the externally applied field and the field due to all other surrounding elements. With this supposition the discontinuity may give a longitudinal component in an opposite direction to the applied field and still give a component in the direction of the actuating field in its immediate vicinity. From the curves of average ϕ-*vs.*-ψ we see that the average change in magnetization involves a transverse component which has a direction always in the direction of the increment of the applied field. Changes in magnetization involving a transverse impulse opposite to this would give values of ϕ greater than 90°. One is led to the conclusion from these results that the average direction of magnetization always lags the direction of the applied field. The data indicate that, for these low values of magnetization and for the particular crystal in question, the change in magnetization has a large component transverse to the

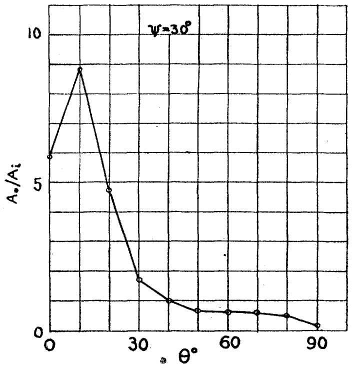

Fig. 5. Relation between ratio (A_o/A_i) of impulses in outer and inner search coils to the search coil setting θ for a single value of ψ. Magnetizing current 10 amperes; A_o/A_i has been corrected for inequality of amplifiers.

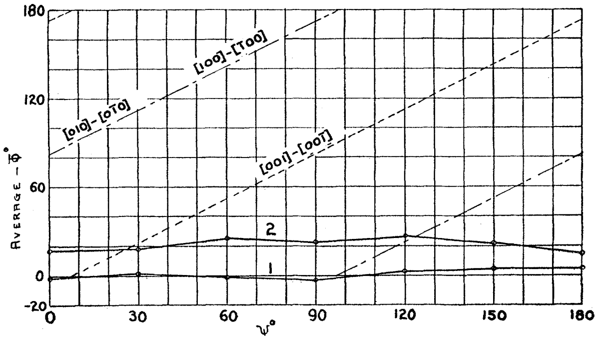

Fig. 6. Relation between mean ϕ and ψ for two magnetizing currents. Curve marked 1 for 10 amperes, curve marked 2 for 5 amperes.

applied field. The average angle ϕ appears to decrease as the field strength is increased. This apparently indicates that the angle between the average magnetization and the applied field is small at large values of magnetization. When saturation is reached the average intensity of magnetization should be directed along the applied field.

It will be interesting to consider the data in light of the possible modes of change in magnetization as indicated by the recent theoretical considerations of Akulov.[4] On the basis of energies involved Akulov concludes that the changes in magnetization which occur are most probable when these changes occur between pairs of the six [100] directions in a crystal. The theory further indicates that two possible modes of change must be considered in attempting to explain experimental results. The first is the so-called *Umklappungprozess* in which the magnetization vector of a small single magnetized region reverses its direction but retains its absolute value unchanged. A change of this type is that in which the change is from the [100] direction to the [$\bar{1}$00] direction. The second mode of change is the so-called *Drehprozess* in which the magnetization vector turns through 90° but again suffers no change in absolute value. An example of this type would be a change from the [100] direction to the [010] direction. The first type of change involves smaller energies than the second and occurs for lower values of magnetization. At the low values of magnetization at which our experiment was performed it is more probable that changes of the first type would occur. Changes of this type are illustrated by the diagonal lines of Fig. 6. As is seen, there occur regions in the interval $\psi = 0$ to $\psi = 180°$ for which the expected impulses are of the longitudinal type. The actually observed curves indicate that impulses occur which are transverse in character.

If one considers the distortion of the lattice due to mechanical strains as the guiding factor a similar variation of ϕ with ψ would result as was found in connection with Akulov's theory. On Becker's theory[5] one would have to conclude from the experimental data that the distorted regions travel with the applied field in order to account for the small deviations in the average angle ϕ between $\psi = 0$ and $\psi = 180°$. This is contrary to Becker's postulate that the strains are nearly independent of the condition of magnetization.

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[4] N. S. Akulov, Zeits. f. Physik **67**, 794 (1931).

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