DISCONTINUOUS CHANGES IN LENGTH ACCOMPANYING THE BARKHAUSEN EFFECT IN NICKEL

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Abstract

A heterodyne beat method is described by means of which displacements as small as $9\text{x}10^{-9}$ cm may be measured. When a nickel wire, 1.96 cm long and 0.01 cm in diameter, is subjected to a steadily changing magnetic field there is evidence of a sudden length change at the instant of a Barkhausen discontinuity of magnetization. For a nickel wire 2 cm long and 0.002 cm in diameter these sudden length changes were larger and could easily be measured. They were associated with every Barkhausen jump observed in the specimen. The largest one measured was $4.7\text{x}10^{-7}$ cm. Calculations based on the measurements of these magnetostrictive jumps give $3.7\text{x}10^{-7}$ cc. for the minimum value of the volume of the element which suffers the jumps. Reasons are advanced for believing that the sudden change in intensity of magnetization of this volume element cannot be less than 40 units nor more than 330. A qualitative theory of the phenomenon is given.

When a ferromagnetic substance is magnetized by a field which changes continuously it is found that a part at least of the resulting change in intensity of magnetization takes place in sudden discontinuous jumps. This Barkhausen effect is usually observed by means of the induced voltages in a coil surrounding the specimen. Ferromagnetic substances also undergo a change of length when magnetized. There appears to be a very close relation between the magnetostrictive effect and the Barkhausen effect. One phenomenon has so far not been observed in a substance without the other, and both are affected by heat treatment and by mechanical strain.

It seemed probable therefore, that the discontinuities of magnetization should be accompanied by discontinuous changes in length of the specimen. This conclusion follows directly from one interpretation of McKeehan's[1] theory of atomic magnetostriction and is also in agreement with a theory of the Barkhausen effect which has been discussed by one of the authors.[2] In the experiments to be described a very sensitive and quick acting apparatus has been constructed and sudden changes in the length of a nickel wire have been observed to occur simultaneously with the Barkhausen discontinuities.

Apparatus

The heterodyne beat method of measuring small capacity changes or small displacements is used. The apparatus, shown diagrammatically in Fig. 1, is a modification of that previously used by one of the authors.[3] Oscillator A

[1] L. W. McKeehan, Jour. Frank. Inst. **202**, 737 (1926).
[2] C. W. Heaps and J. Taylor, Phys. Rev. **34**, 937 (1929).
[3] A. B. Bryan, Phys. Rev. **34**, 615 (1929).

is maintained at 1819 k.c. by a quartz crystal. Oscillator B, employing a shield grid tube, is the same as in the previous work except that different condensers are used. C_1 is a calibrated General Radio precision air condenser and is used for purposes of adjustment and calibration. C is a small condenser with two circular horizontal plates 2 cm in diameter. The top plate is supported by a 2 cm length of the nickel wire to be examined. It is steadied and vibrations are damped out by three short sections of rubber cut from ordinary rubber bands, arranged to press downward at three points on its upper surface. The lower plate is provided with a screw adjustment so that the spacing between the plates can be made very small. C is mounted near the center of the large solenoid S_1, which is 15.7 cm long and has an inner diameter of 5.9 cm. The winding of S_1 and the leads to it are completely inclosed in a grounded copper shield. A field strength of 74.5 gauss per ampere is obtained.

Detector D includes a small loop antenna, a detector and a two stage amplifier. The radio frequency oscillations from A and B are picked up by D and the audible beat note between them is impressed on the telephone

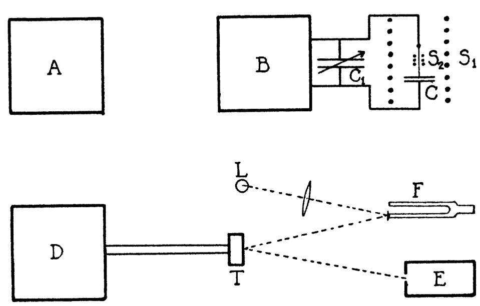


Fig. 1. Diagram of apparatus.

receiver T. A small mirror attached to T thus vibrates with the frequency of the beat note between A and B. A beam of light from lamp L, is reflected first from a mirror attached to one prong of a 300 cycle electrically driven tuning fork F. It is then reflected from the mirror attached to T and finally falls on a strip of motion picture film in camera E. The film moves downward while both mirrors are arranged to vibrate the beam of light in a horizontal plane. When the fork and heterodyne beat frequencies are about the same the combined motions of the two mirrors thus produce a sort of "photographic" beat as shown in Fig. 2. The frequency of this photographic beat is equal to the difference of the two component frequencies. When the field of S_1 produces magnetostriction in the nickel wire the capacity of C changes and there is a resulting change in the frequency of oscillator B, of the heterodyne note and of the photographic beat.

A time scale is obtained by focusing an image of the filament of an ordinary lamp on one edge of the film. The lamp carries 60 cycle alternating current and the filament vibrates with this frequency when a permanent magnet is brought near. This arrangement is not shown in Fig. 1.

The nickel wire passes through a small bakelite spool on which solenoid S_2 is wound. This solenoid is 0.65 cm in length and 1.58 cm in outside diameter and has 3960 turns. It is connected through a three stage amplifier to a second telephone receiver carrying a mirror. Light reflected from this mirror produces the third trace on the film, in this case a straight line which is broken when the sudden Barkhausen change in magnetization of the nickel wire induces a voltage in S_2. None of this equipment except S_2 is shown in Fig. 1.

Suitable rheostats are used in series with S_1 to control the magnetizing current. A spiral of fine nickel wire is also connected in series with S_1. This spiral may be heated by means of a nichrome heating coil which surrounds it, the resulting resistance change producing a slow continuous variation of current over a small range. The rheostats are so adjusted that this continuous change takes place over a range in which the Barkhausen discontinuities are largest.

Theory of the Measurements

Let the parallel plate condenser C have capacity C, area A, and plate distance d. Then $C=A/4\pi d$ and if d changes by a small amount δd we get $\delta d=-(A/4\pi C^2)\delta C$ where δC is the corresponding change in C.

Let n_0 be the frequency and C_0 the total capacity of oscillating circuit B. Then if we assume that $n^2{}_0$ is inversely proportional to C_0 it may easily be shown that a decrease δC_0 in C_0 will produce an increase δn in n_0 such that

$$\delta C_0 = C_0\left[1-\left(\frac{n_0}{n_0+\delta n}\right)^2\right] \tag{1}$$

or

$$\delta C_0 = 2C_0\delta n/n_0 \tag{2}$$

for small changes. The only change in C_0 is that produced by the nickel wire in raising or lowering the upper plate of condenser C. Thus $\delta C_0=\delta C$ and we get

$$\delta d = -AC_0\delta n/(2\pi C^2 n_0). \tag{3}$$

In this equation δd is of course the desired change in length of the supporting nickel wire. All the quantities on the right may be easily determined. The area of A of the circular condenser plate as calculated directly from its measured diameter is 3.14 cm^2. The value of n_0 differs by a negligible amount from the known frequency of the quartz crystal used and may be taken as 1819 kilocycles. The other three quantities are found as follows:

(1). Determination of C_0.—A wavemeter is used to measure n_0. Then a known large change in C_0 is produced by means of the calibrated variable condenser C_1 and the frequency $(n_0+\delta n)$ is again measured. These readings and Eq. (1) give C_0. The mean of several determinations is $C_0=597.4$ cm.
(2). Determination of C. The reading of C_1 is noted when A and B are tuned to the same frequency. Then C is disconnected and B again tuned to the fre-

quency of A by adjusting C_1. The increase of C_1 required for the retuning gives the value of C to be 41.2 cm.

(3). *Determination of* δn. Let n_A, n_B, and n_F be the frequencies of oscillator A, oscillator B, and the fork F, respectively. For simplicity assume $n_B > n_A$ and $(n_B - n_A) > n_F$. Then $(n_B - n_A)$ is the frequency of the heterodyne beat note between the two radio frequency oscillators and $(n_B - n_A - n_F)$ is the frequency of the photographic beat between this heterodyne note and the fork, as observed on the film. n_A and n_F remain constant. A decrease δd in the length of the nickel wire produces an increase δn in n_B and the frequency of the photographic beat increases to $(n_B - n_A - n_F + \delta n)$. Let $T = 1/(n_B - n_A - n_F)$ and $T' = 1/(n_B - n_A - n_F + \delta n)$ be the periods of the photographic beat before and after the change δd occurs, respectively. Then $\delta n = (T - T')/(TT')$. The periods T and T' are readily obtained from the film by means of the time scale. Obviously some care is necessary to determine whether an observed δn corresponds to an increase or a decrease in the length of the nickel wire.

To get an estimate of the smallest change in length which can be detected assume that $T = 1$ second and that a change in T of 10% can be observed. These conditions are obtained fairly easily. In this case $\delta n = 0.1$ cycle per sec. approximately,and from Eq. (3) $\delta d = 9.7 \times 10^{-9}$ cm. A higher sensitivity is obtained for larger values of T.

It should be mentioned that with this extremely high sensitivity there is always a gradual change in the beat frequency because of unavoidable temperature changes. Vibrations are perhaps an even more serious source of trouble. The condenser C was mounted on sponge rubber, a basement room was chosen for the experiment and records were taken at night; nevertheless seismic disturbances and a temperature drift were always in evidence. The sensitivity could no doubt be considerably increased by further efforts to eliminate these two disturbing factors.

Results

The first specimen was a nickel wire 0.01 cm in diameter and 1.96 cm long. The photographic record showed several Barkhausen discontinuities. A curve was drawn with the period of the photographic beat plotted against time. Since the magnetizing current varied continuously with the time the curve indicated how the length of the wire varied as the field changed continuously. It was found that the smooth course of the curve showed breaks at two of the points where Barkhausen impulses occurred. However, since these breaks were only a little larger than the apparent discontinuities due to experimental error it was felt that the evidence was not entirely conclusive.

Accordingly a new nickel wire 0.002 cm in diameter and 1.98 cm long was prepared by immersing a larger wire for a short time in nitric acid. With a fine wire it was thought that the volume which gives the Barkhausen discontinuity by its magnetization change would be a larger percentage of the whole wire and would thus produce a proportionally larger effect on the gross magnetostriction of the specimen. The results seemed to justify this idea. The magnetizing field was decreased from a large negative value to zero and then increased to a positive value of 18.6 gauss. A further slow increase to 26.1 gauss was then produced with the hot wire arrangement previously described and the photographic records were taken during this slow increase. There were usually one large Barkhausen impulse and two smaller ones in this region. Fig. 2 shows one of the three photographic records taken of the large impulse. The break at A shows the time of arrival of the impulse. The length BC, as measured on the time scale F, shows the period T of the photographic beat before the arrival of the impulse to be (70.2/60) sec. and the length DE shows the period T' after the impulse to be (10.5/60) sec. Hence $\delta n = (T-T')/(TT') = 4.85$, and from Eq. (3) the change δd in the length of the wire is found to be 4.7×10^{-7} cm. The change in this case was a contraction, showing that the intensity of magnetization had passed through its zero value and was increasing.

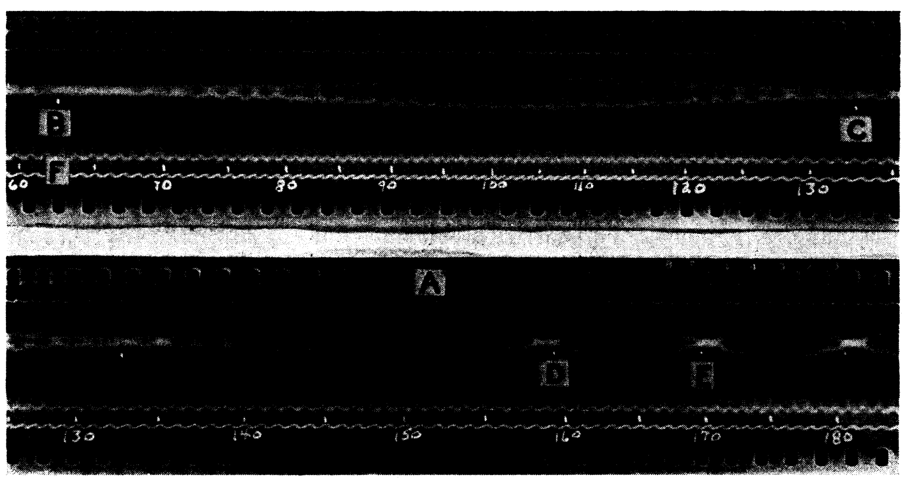


Fig. 2. Photographic record of frequency change. The lower record is a continutation of the upper with slight overlapping.

The two other records, taken in the same way, give values of 2.95×10^{-7} cm and 3.6×10^{-7} cm for this quantity. The three determinations thus give an average δd of 3.75×10^{-7} cm. The large impulse did not always occur at exactly the same magnetizing field value and it is probably not to be expected that the three determinations should be in exact agreement. Numerous additional visual observations with this same specimen showed that every Barkhausen impulse heard was invariably accompanied by a simultaneous sudden change in length of the wire.

Discussion of Results

A qualitative theory of the Barkhausen effect to which the present experiments lend support has previously been proposed.[2] This theory ascribes the effect to the presence of stresses in the specimen. To be specific, assume that there is one small volume element in the interior of the nickel specimen which is initially under tension. The two effects of tension on nickel are to produce a decrease in magnetic permeability and a relatively larger increase in the magnetostrictive contraction for a given intensity of magnetization.[4] Consequently, when the specimen is magnetized the volume element under consideration will contract more than the surrounding material in spite of its abnormally low intensity of magnetization and the initial tension will increase until eventually there is some sort of slipping or rearrangement of the material and the tension is partially or completely released. This release causes a measurable change in length of the specimen only when the cross sectional area of the volume element is an appreciable part of that of the whole specimen. The sudden length change should thus be more prominent in fine wires, as has been observed in the present work. The release of tension also causes a sudden increase in the permeability and the intensity of magnetization of the volume element. Thus we get the Barkhausen effect. This increase in intensity of magnetization will in turn produce a secondary change in the field acting on all other parts of the specimen and in their intensities of magnetization and lengths, but this secondary effect is probably negligibly small.

The following calculation, based on the above conception of the Barkhausen effect, may be considered as a rough approximation. Assume that the volume element which has produced the experimentally observed effects has a length L parallel to the axis of the wire and a uniform cross sectional area a. Let δI be the sudden change in the intensity of magnetization I for the volume element and δL be the accompanying change in L which would result if the element were not restrained by the material around it. The actual length change, which may be identified with the observed δd, may reasonably be taken equal to $\delta L(a/a_0)$, where a_0 is the area of cross section of the whole wire. Ewing's[5] I vs H curve and an unpublished $\delta L/L$ vs H curve obtained by the present writers together give $\delta L/(L\delta I) = 9.5\times 10^{-9}$ for hard drawn nickel, the value being taken at a point on the hystersis loop where $H = 20$ gauss and is increasing. The Barkhausen jumps for which δd was measured were near this point on the hysteresis loop. Then, assuming the magnetic similarity of the three samples of hard drawn nickel involved, the value $\delta L/L\delta I = 9.5\times 10^{-9}$ may be taken as correct for the volume element considered. Replacing δL by $a_0\delta d/a$, and using the experimentally found values for δd and a_0, we get $aL\delta I = 1.24\times 10^{-4}$. Here aL is the volume V of the volume element. The exact value of V cannot be obtained because δI is unknown. However, the maximum value of δI may be taken to be 330, this being the approximate saturation value of I for nickel. The corresponding

[4] McKeehan states, reference 1, that, "In the case of nickel the resultant orientation of atomic magnetic axes across the axis of tension, which reduces the ease of magnetization along the axis of tension, will increase the magnetostriction (contraction)." Bidwell's experiments, however, (Proc. Roy. Soc. **A47,** 469, 1890) do not seem to agree with this statement unless large magnetic fields and small tensions are used.

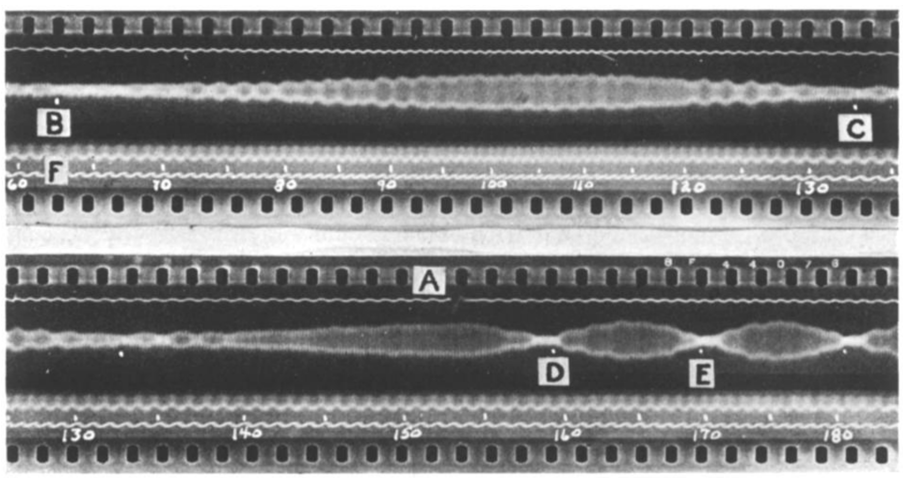
[5] J. A. Ewing, "Magnetic Induction in Iron," p. 87.

minimum V is 3.76×10^{-7} cc, which is roughly one sixteenth of the total volume of the specimen.

Bozorth and Dillinger[6] find that V varies over different parts of the hysteresis loop. Their value for the conditions of the present experiment is about 2×10^{-8} cc for annealed nickel, roughly a twentieth of the above found minimum value. However, they assume I to be a complete reversal from a saturation value in one direction to saturation in the other direction. With the same assumption in the present work the discrepancy between the two measurements is reduced to a factor of 10. This is not bad if we consider that the two determinations are widely different in character, that both are somewhat indirect, that the two specimens of nickel differ greatly in size and that one specimen is annealed and the other hard drawn. This last difference alone might account for the discrepancy since it is known that annealing reduces the Barkhausen effect.

The true δI is probably considerably less than the maximum of 330. An estimate may be made as follows. For a Barkhausen discontinuity to occur it is hard to see how the associated volume element could be greater than half the volume of the wire. Taking this value as a maximum for V the equation $V\delta I = 1.24 \times 10^{-4}$ gives $\delta I = 40$ as a minimum. The true δI is probably somewhere between the maximum of 330 and the minimum of 40, V having a corresponding intermediate value. The assumption of a complete reversal of the saturation value of I seems to be unwarranted. The length depends only on the magnitude of I and consequently it is difficult to see how a reversal, which involves no change in magnitude of I, could alone produce any permanent change in length, either the sudden δd of the present work or the gross magnetostriction as usually observed.

[6] Bozorth and Dillinger, Phys. Revs. **35**, 733 (1930).



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