DISCONTINUTIES OF MAGNETIZATION IN IRON AND NICKEL

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(Received June 29, 1929)

Abstract

Discontinuities of magnetization.—These have been observed in iron and nickel and recorded photographically. The number corresponding to a given small change of magnetizing force has been determined for different speeds of magnetization. For high speeds there appear to be more and smaller discontinuities as the speed is slightly reduced. If the speed is greatly reduced, however, there are fewer discontinuities in ordinary specimens than for high speeds. The length of the portion of material associated with each discontinuity is estimated to be 2 or 3 mm; the volume is of the order 10^{-7} cm^3.

A method for determining the hysteresis loop of very small specimens.—The specimen, on an elastic support, is mounted on the axis of a solenoid and its deflection measured with a microscope when currents of varying magnitude flow through the solenoid. For a small piece of nickel wire it is found that the loop is made up of a few discontinuities separated by uniform changes of magnetization.

Theory.—It is suggested that in different portions of the material different magnetostrictive effects may occur. Thus strains are set up which, when relieved discontinuously, produce the jumps of induction.

It WAS discovered by Barkhausen[1] that when iron is magnetized by a steadily varying field the magnetization may change discontinuously. Since Barkenhausen's discovery the phenomenon has been extensively investigated. As yet, however, there appears to be some disagreement as to the explanation of these discontinuities. Tyndall[2] considers that there is little justification for the theory advocated by Gerlach and Lertes[3] and by Zschiesche,[4] a theory which makes the effect depend on magneto-striction. On the other hand McKeehan's theory[5] of the relation between strain and magnetization seems well adapted to explain certain phases of the Barkhausen effect.

The writers have made determinations of the dependence of the number of discontinuities on the rapidity of change of the magnetizing force in iron and nickel; also, by varying the size of the specimen an estimate has been made of the length of the portion of the material which is involved in one of the discontinuities.

[1] H. Barkhausen, Phys. Zeits. **20,** 401 (1919).
[2] E. P. T. Tyndall, Phys. Rev. **24,** 439 (1924).
[3] W. Gerlach and P. Lertes, Zeits. f. Physik **4,** 383 (1921).
[4] K. Zschiesche, Zeits. f. Physik **11,** 201 (1922).
[5] L. W. McKeehan, Jour. Frank Inst. **202,** 737 (1926).

Apparatus

The specimen was placed in a small coil of fine wire, which for many of the experiments had 2200 turns, was 0.5 cm long, and had a maximum diameter of 1.0 cm. The e.m.f. induced in this coil by the jumps of magnetization was amplified by a three stage amplifier, the first two units of which were resistance coupled, the last, transformer coupled. The output terminals of the amplifier were connected to a sensitive telephone receiver. The diaphragm of this receiver was coupled to a tiny mirror mounted between needle points, the coupling bar and the mirror being made very light so as to minimize inertia effects. The image of a straight edge was reflected from this mirror through the slit of a light-tight box on to a moving picture film. When the film was unrolled past the slit a record of the Barkhausen discontinuities was thus obtained. A time scale was obtained by focusing the image of a lamp filament on the edge of the film. When a small permanent magnet was in its vicinity the filament vibrated with the frequency of the 60 cycle current through it.

The magnetizing field was produced by a solenoid in which was placed the specimen in the pick-up coil. A resistance in series with the solenoid

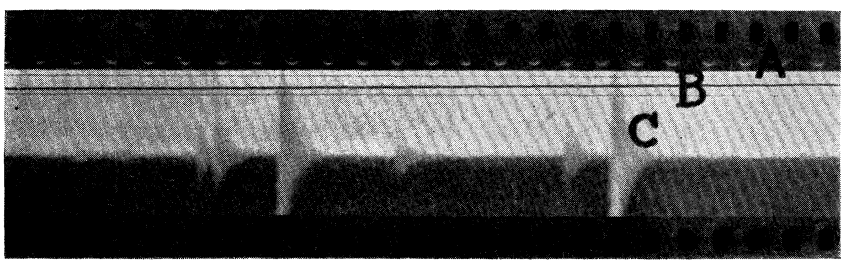

Fig. 1. Barkhausen discontinuities in nickel.

could be made to vary uniformly by means of thermal control. This resistance—a nickel wire—was placed inside an electric heater which cooled with comparative slowness after the current was cut off. More rapid cooling was obtained by use of an air jet.

The value of the magnetizing current was measured with a milliammeter. To the needle of this milliammeter a light aluminum wire was fixed vertically so as to pass across the horizontal slit of the film box when current traversed the instrument. Two fine wires across this slit served as reference lines. The milliammeter readings being known for coincidences of the needle wire with each of the reference wires, intermediate values of the current could be determined from the film record.

Figure 1 shows a short sample of a record taken with nickel. The time scale is at A; the heavy line under B gives the position of the milliammeter needle. The distance between the two fine lines corresponds to 2 milliamperes. The total current through the solenoid was so chosen as to bring the specimen to the steep part of the hysteresis loop.

Each Barkhausen impulse gave a sharp crack in the telephone receiver and a characteristic record C on the film. The diaphragm and mirror system oscillated with its natural frequency for a short time after each impulse, but the frequency was so high that the oscillations were not clearly separated in the record. Thus a single impulse produced a record of quite appreciable length as shown, but there was no difficulty in detecting the existence of two impulses very close together as occurred in some instances.

Discussion of Results

Counts were made of the number of discontinuities in nickel when a given field change occurred in different times. Table I gives some results obtained for two separate sets of observations.

Table I. *n = total number of impulses, N = number of large impulses.*

	Time (Sec.)	n	N
I	3.5	77	29
	4.33	84	11
II	1.45	56	25
	2.44	80	20

It appears from this table that decreasing the speed of change of the magnetizing field increases the total number of discontinuities, but decreases the number of large discontinuities. Intercomparison of sets I and II is not allowable because of changed experimental conditions.

Because of the small differences appearing in the table it was felt that corroborative evidence was necessary before definite conclusions could be drawn. Supplementary experiments were therefore performed. A nickel wire specimen was drawn down to a small diameter and a short piece stuck in the pick-up coil with wax. A permanent magnet mounted on a carrier driven by a screw was used to produce induction changes and the discontinuities were detected and counted by the sound in a loud speaker which replaced the receiver oscillograph.

For a soft iron wire 0.447 cm long and 0.005 cm in diameter 46 distinct impulses were counted when the part of the hysteresis loop corresponding to ACD of Fig. 2 was traversed in 2 minutes, and only 29 when the time was 10 minutes. A second trial gave 43 and 24 for these two times. For a nickel wire of length 0.284 cm and diameter 0.010 cm 2 impulses were observed for a time of 10 minutes and 9 for a time of about 10 seconds. Along the part of the loop corresponding to AB of Fig. 2 and using the same iron wire, a slow speed gave only two or three impulses; a high speed gave an initial rustling noise followed by about 10 impulses.

The interpretation of the data seems to be as follows. As the speed is decreased the impulses become more numerous but on the average they are of smaller magnitude. For very slow speeds a great number of impulses become so small as to produce no observable effect. Only the few remaining large impulses can then be counted. This interpretation agrees with the observations made by Pfaffenberger.[6] Using different times, of the order of a few seconds, Pfaffenberger found for the same field-change more jumps of magnetization for the long times; the sum of the amplitudes of all the jumps, however, appeared to be the same for the different speeds. Low enough speeds were not used to eliminate any of the jumps.

The physical condition of the wire seems to influence the phenomenon to a considerable extent. We have examined a nickel specimen, 0.004 cm in diameter and 0.19 cm long, which had been annealed, stretched to the breaking point, bent and straightened, and have found only two discontinuities of magnetization along the curve *ACD*, Fig. 2. The clicks of these two impulses were heard very clearly in the loud speaker, whether the field change occurred in half a second or in 2 minutes. For this specimen the speed of field-change did not influence the phenomenon.

An estimate of the volume of the material involved in a single discontinuity may be made as follows. Assume that each jump of magnetization is produced by a limited portion of the material changing its intensity of magnetization from one value to another. When the last nickel specimen mentioned above suffered complete reversal of magnetization two discontinuities were observed. If the discontinuities were associated with different coherent elements of about the same size (the impulses appeared equally loud) the volume of the coherent element could not be greater than half the volume of the specimen, or 2.3×10^{-7} cm^3. The maximum length of the coherent element would of course be the length of the specimen, 0.19 cm.

The method by which the magnetization of this nickel specimen was reversed influenced the number of discontinuities. If the field was kept constant in magnitude at the specimen but rotated in direction, five impulses of diminished strength were counted instead of two. If each of these impulses corresponded to changes of magnetization of separate equal coherent elements the volume of each of the latter would be 9×10^{-8} cm^3. A lower limit to the length of a coherent element in the nickel wire would be the length of the shortest specimen exhibiting discontinuities. We have observed one of these discontinuities in a nickel wire 0.1 cm long, but for shorter wires the effect could not be detected.

For a soft iron wire the minimum length in which discontinuities could be observed was 0.2 cm. Calculating the volume of a coherent element by the method used above for nickel, and for the specimen giving 46 impulses in 2 minutes, we get 1.9×10^{-7} cm^3. In silicon steel Tyndall calculated by a different method this volume to be 1.7×10^{-6} cm^3. Pfaffenberger, also by a different method, estimated the length of a coherent element in steel to be 0.3 cm. The differences in the various estimates are no more than might be expected, since specimens of different structural character were used in the respective measurements.

[6] J. Pfaffenberger, Ann. d. Physik **87**, 737 (1928).

THE HYSTERESIS LOOP FOR A SMALL SPECIMEN

The fact that for one small specimen of nickel only two large discontinuities were observed during reversal of magnetization suggested that the character of the hysteresis loop might be different from that of larger specimens. Accordingly the following method was devised for determining the nature of the loop for very small specimens.

The specimen in the form of a short fine wire was stuck with wax horizontally across the end of a fine vertical quartz rod. The mounting for the lower end of this rod was contained in a glass tube full of oil. The specimen was thus supported several mm above the surface of the oil, but vibrations were critically damped. A horizontal solenoid of length 7.7 cm was now placed with one end close to the specimen, the latter being on the axis of the solenoid. When a current flowed through the solenoid a force was exerted on the specimen and its deflection from the normal position was measured with a microscope, for which 1 scale division $=0.00247$ cm.

The force on the specimen is given by $F=IVdH/dx$, where $I=$intensity of magnetization, $V=$volume of the specimen and dH/dx is the field gradient at the specimen along the axis of the solenoid. We have, however, $dH/dx=2\pi nir^2(a^2+r^2)^{-3/2}$, where $n=$number of turns per cm of the solenoid, $r=$radius of the solenoid, $i=$the current, and $a=$distance of specimen from end of solenoid. The field at the specimen is given by $H=2\pi ni\left\{(a^2+r^2)^{1/2}-a\right\}(a^2+r^2)^{-1/2}$. We may thus write $F=AHI$, where $A=Vr^2\left\{(a^2+r^2)^{1/2}-a\right\}^{-1}(a^2+r^2)^{-1}$.

If the deflection D is small so that a is approximately constant, D will be proportional to the product IH. Thus D/H will be proportional to I. Also, H is proportional to i.

The following values of the above quantities were used: $a=1.2$ cm, $n=44.1$, $r=2.90$ cm. The specimen was a nickel wire of length 0.13 cm and diameter 0.0065 cm, which had been stretched, bent, and then straightened. The current i could be varied smoothly and continuously by means of a sliding contact on a long resistance wire in the solenoid circuit. This contact was mounted on a small car which could be pulled smoothly along between two tracks by means of a long string.

Figure 2 gives the form of the loop for the nickel specimen. The time required to traverse half the loop was about 10 minutes. The curve is not accurate for large values of the field because the deflections in that case caused an appreciable change in a. Three Barkhausen discontinuities were observed. They showed up clearly in the microscope as sudden jumps of the specimen, and are indicated by the arrows in Fig. 2.

It appears from this curve that the observable discontinuities do not account for the complete reversal of magnetization of the specimen. In fact, two of the discontinuities of Fig. 2 have occurred before the specimen as a whole has reversed magnetization. Except for the jumps indicated on the curve the motion of the specimen was smooth and steady,—agreeing with the observations made by the inductive method on the small piece of nickel, in which only distinct clicks were heard with no doubtful sounds between.

Supplementary Observations

Several observations of an incidental nature were made during the course of the experiments.

1. For a thin iron wire, as its length is decreased the number of discontinuities decreases along the part of the curve corresponding to *ACD* of Fig. 2. Along *AB* the discontinuities are more easily observed for a short specimen than for a long one of the same diameter. They also appear more pronounced in magnitude as *A* is neared. It is obvious that the demagnetization factor is of importance in connection with this phenomenon.

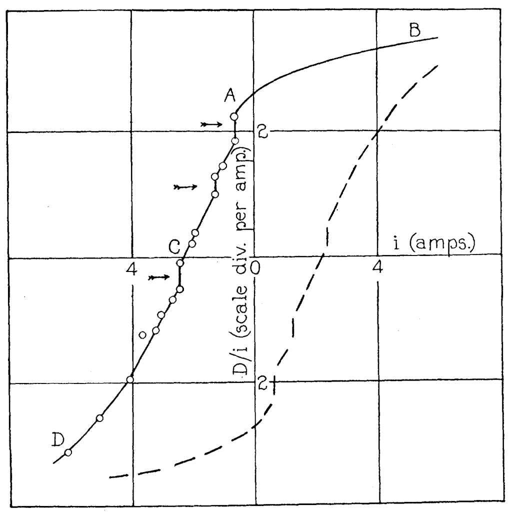

Fig. 2. Hysteresis in nickel. The broken line is drawn from symmetry considerations. Experimental points along *AB* are omitted because they were somewhat scattered, thus creating an impression of discontinuities which did not really exist.

2. When a nickel wire is annealed the discontinuities are small and frequent as in soft iron. If the wire is stretched beyond the elastic limit the effect may be made almost inappreciable; if a single bend is now put in the wire and then removed a relatively few loud clear impulses are heard in the loud speaker of the amplifying system. These observations agree with those of Forrer,[7] and show that internal strains strongly influence the Barkhausen effect.

3. The mechanical Barkhausen effect—obtained by twisting or stretching a wire passed through the pick-up coil—was observed in iron and annealed nickel, but not in unannealed nickel. This effect almost disappears if the specimen is magnetized to saturation.

4. Certain natural crystals of magnetite, usually dark in color and with bright, well developed cleavage planes, show discontinuities of magnetization.

[7] R. Forrer, Comptes Rendus **180**, 1253 (1925).

Other specimens, usually with rounded corners and uneven faces, do not. A hematite crystal showed a pronounced effect.

5. A hard steel ball of fine homogeneous structure showed no discontinuities.

CONCLUSIONS

Our experiments indicate that in nickel which had not been annealed certain parts of the magnetization curve consist of sudden changes separated by uniform changes. A small specimen has been found to show several distinct discontinuities of considerable magnitude. Sudden changes other than these could not be detected. Yet these observed discontinuities can account for only a small part of the magnetization curve. If the remaining part of the curve is made up of a series of jumps then these jumps must be very numerous and of a different order of magnitude from those observed.

R. M. Bozorth[8] states that he has found a considerable part of the hysteresis loop to be accounted for completely by the discontinuities, substantially all of which he could detect. Our results disagree with those of Bozorth. As no details of Bozorth's experiments are published the cause of the discrepancy is not evident. It may possibly be associated with differences in the sizes or character of the specimens, or in the differences of speeds of magnetization. Bozorth also states that "the apparent large differences in the effect in various materials, and in the same material in different forms, are due to the different rates of decay of eddy-currents in them." We do not believe that the pronounced change in the effect which we have observed when an annealed and stretched nickel wire is given a single sharp bend and then straightened can be due to a changed rate of decay of eddy-currents.

A suggested explanation of the discontinuities of magnetization is as follows. In the magnetic material there are inhomogeneities, either of a chemical or physical nature. For example, certain portions of the material may be subjected to a strained condition differing from that of the rest of the material. As the magnetizing force increases the intensity of magnetization of the strained element will vary in a different way from that of the rest of the material, and thus the condition of strain, because of magnetostriction, will change with the field. Eventually the mechanical equilibrium between the specified portion and the surrounding material will become unstable and slip will occur at the boundary of the element. The strain condition is thus suddenly changed, and owing to the reciprocal relation between strain and magnetization the intensity of magnetization of the element will suddenly change also.

A very similar process would result if the small element, instead of being in a strained condition initially, were of slightly different chemical constitution from the rest of the material. Its magnetization and magnetrostriction would then vary in a different way from that of the rest of the material,

[8] R. M. Bozorth, Phys. Rev. **33**, 636 (1929).

strains would be set up, and slip might eventually occur at the natural boundary o' the element.

On this view of the phenomenon we see why a sing'e bend in a fine nickel wire, which has been annealed and stretched, can cause the discontinuities to appear more pronounced and fewer in number. The stretching of the wire is found to make the discontinuities very small. The stretching probably introduces a filament structure parallel to the length of the wire, and these filaments may not be tightly enough coherent to produce appreciable strain when they suffer magnetostriction of different amounts. It is also possible that there may be little difference in the initial strain condition of the filaments. A bend in the wire would limit the magnetostriction of different filaments in different ways. It would tend to prevent an individual filament from moving freely with respect to its neighbors. Thus interior strains would be set up and large discontinuities of magnetization result.

A very slow change of magnetizing force would allow time for readjustment of internal strains, perhaps by plastic flow or relatively more frequent slip at boundary surfaces. The discontinuities would thus be fewer; or being more numerous because of smaller slips, their magnitudes would be smaller.

The entire hysteresis loop, on this theory, would not be made up of a series of sudden changes; continuous changes would be possible while strain is building up in a small element. Our experiments indicate that such a structure for the loop is probable.

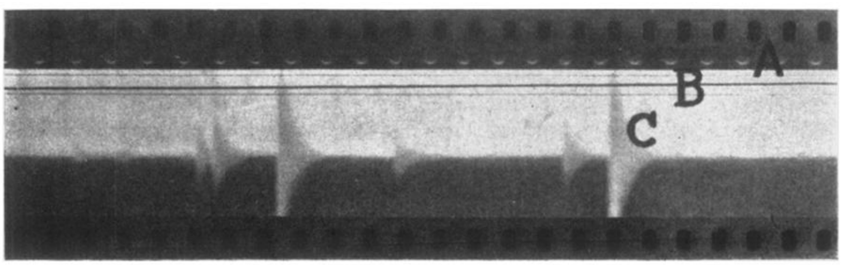

Fig. 1. Barkhausen discontinuities in nickel.