Discontinuities of Resistance Associated with the Barkhausen Effect

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A nickel wire, under bending stress, shows a large discontinuity of magnetization. The resistance of such a wire has been examined with a sensitive Kelvin double bridge and a jump of magnetoresistance of magnitude $dR/R = 6.35 \times 10^{-5}$ has been found associated with the magnetization jump. The negative results of Steinberg and Miroschnischenko are explained as being due to insufficient sensitivity of their apparatus. It is suggested that the resistance jump is due to small rotations of the saturated magnetization of small elements of the material, these rotations being due to alterations of the Lorentz field by reversals of magnetization in neighboring elements.

WHEN a ferromagnetic body is subjected to a magnetizing force which changes smoothly and continuously its intensity of magnetization may exhibit sudden jumps called Barkhausen discontinuities. The electrical resistance of the body will, in general, also vary when its magnetization changes, but up to the present no jumps of resistance have been found to occur when the Barkhausen discontinuities occur. From a study of the way in which magnetoresistance varies with magnetization W. Gerlach[1] concludes that the irreversible discontinuities of magnetism are without influence on the electrical resistance. Recently Steinberg and Miroschnischenko[2] have performed an experiment expressly designed to detect these resistance jumps. They report that in a nickel-iron alloy showing large discontinuities of magnetization no sudden changes of resistance could be detected.

The writer[3] recently advanced reasons for believing that these resistance jumps should exist but did not offer adequate experimental evidence in support of this view. This experimental evidence has now been secured.

Experimental Method

The specimen was a wire of commercial nickel 15 cm long and 0.0096 cm in diameter. The wire was annealed in a Bunsen flame, stretched beyond the elastic limit, bent into a circular coil of about 2.3 cm diameter, and then thrust into a fine, straight, capillary glass tube. Under these conditions nickel shows a single large magnetic discontinuity when the specimen is being demagnetized. A search coil around the tube was connected to an amplifier and loudspeaker for the detection of the discontinuity. The wire was now inserted in a solenoid and connected so as to form one arm of a sensitive Wheatstone bridge. When the solenoid current was brought smoothly and continuously to a certain value (by the use of a slider on a long straight resistance wire) a jump of magnetization was indicated by a single sharp noise in the loudspeaker. Simultaneously the galvanometer of the bridge was suddenly deflected several centimeters. The mean of a number of observations gave 3.2×10^{-5} as the decrease of resistance per ohm associated with the magnetic discontinuity.

In view of the negative results of Steinberg and Miroschnischenko a more careful test seemed in order. With a Wheatstone bridge the Peltier effect at the junctions of the nickel wire causes temperature differences which introduce a thermoelectromotive force in the circuit. Since the thermoelectric power of nickel is affected by magnetization there seemed to be a possibility that jumps of thermoelectric power were being observed instead of jumps of resistance.

[1] W. Gerlach, Ann. d. Physik **12**, 894 (1932).

[2] D. Steinberg and F. Miroschnischenko, Phys. Zeits. d. Sow. **3**, 602 (1933).

[3] C. W. Heaps, Phys. Rev. **43**, 763, 945 (1933). The desirability of an experiment of the type described in this paper was suggested by K. Sixtus, of the General Electric Company. The writer wishes to acknowledge here the helpful criticism received from Dr. Sixtus in connection with previous papers.

To obviate this uncertainty a special type of Kelvin double bridge was constructed as follows. Another nickel wire similar to the first was prepared but it was several cm longer. The ends of this wire projected out of the capillary tube and out of the solenoid. The ends of two copper wires were soldered to each end of a 15 cm segment in the center of the nickel wire. (This segment was held straight by a 15 cm capillary tube.) These copper wires led to the galvanometer circuit of the double bridge. Resistances of the entire bridge were adjusted so that the current flowing from the nickel wire into these copper leads was the same at both junctions. The resistance measured by the bridge is the resistance of the segment between the copper leads, and any change of thermoelectric power of nickel with respect to copper will not affect the measurement under these conditions.

The 15 cm segment of nickel had a resistance of 2.09 ohms. The bridge was balanced by adjusting shunts across this segment. The galvanometer was of the four-coil, astatic-needle type provided with a triple iron shield. The sensitivity of the bridge was such that a value of dR/R as small as 4×10^{-7} would produce a deflection of 1 mm. (Here dR= change in resistance R of the nickel segment.) Actually, because of temperature changes the galvanometer was subject to a slow, steady drift of perhaps 3 or 4 cm per minute, so that the above sensitivity was not realized practically.

The solenoid was 15 cm long and had an internal diameter of 5.5 cm, so that its field was not very uniform. A current of 1 ampere produced a field of 105.5 oersteds at its center. The specimen was supported axially in the solenoid and was packed in cotton to secure thermal insulation.

With this apparatus the magnetic discontinuity was found to produce a galvanometer deflection of almost 200 mm. The mean of ten trials gave a value of $dR/R=6.35\times10^{-5}$, the separate values all lying between 6.07×10^{-5} and 6.51×10^{-5}.

In Fig. 1 a part of the right half of a magnetoresistance hysteresis cycle is shown. The upper curve was obtained as follows. A field of 1000 oersteds, applied to saturate the nickel, was quickly reduced to a specified value and the bridge balanced. The field was then brought to zero and a new balance secured. The resistance change indicated by the two different bridge settings was plotted in Fig. 1 as dR/R for the specified field. The lower branch of Fig. 1 was obtained as follows. The nickel was saturated by the field of 1000 oersteds, the field was made zero and the bridge balanced, a small reverse field of specified magnitude was applied and the bridge again balanced. The resistance change indicated by the two bridge settings was then plotted as dR/R for the specified field.

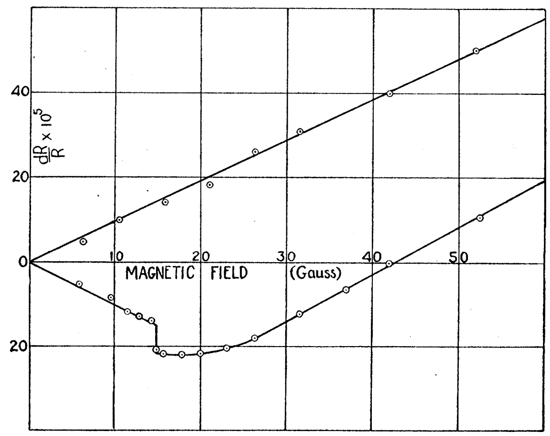

FIG. 1. Part of the right half of a magnetoresistance hysteresis loop of strained nickel. The abscissae should be multiplied by 10/14.7 if comparison is made with Fig. 2.

This method of procedure is necessary to secure accuracy when there is a temperature drift; the result is that Fig. 1 shows a value of $dR/R=0$ in zero magnetic field, although actually residual magnetism has left the wire with a higher resistance than it has when unmagnetized. The negative values of dR/R are therefore not to be interpreted as a decrease of resistance produced by magnetization. The two branches of Fig. 1 join together, within the limits of experimental error, at about 600 oersteds.

Fig. 2 shows the magnetic hysteresis loop of this specimen of nickel, still in the strained condition inside the capillary tube. An astatic magnetometer similar to that of Bozorth[4] was used. The magnetizing solenoid was here 30 cm long so that the field was quite uniform. The magnetic discontinuity occurred in Fig. 2 at a

[4] R. M. Bozorth, J.O.S.A. and R.S.I. **10**, 591 (1925).

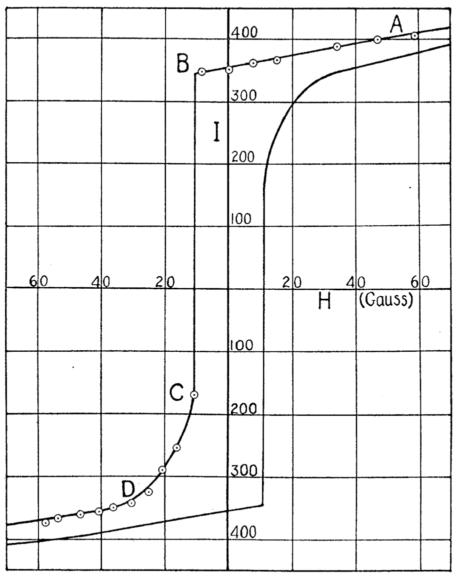

FIG. 2. Magnetic hysteresis loop of strained nickel. The right-hand branch is drawn in by symmetry.

demagnetizing field slightly greater than 10 oersteds, while in Fig. 1 the discontinuity of resistance is at 14.7 oersteds. The discrepancy is due to the fact that the solenoid of Fig. 1 did not give a very uniform field, and the field plotted is the maximum at the center. It was also observed that the demagnetizing field at the jump varied slightly with different trials, possibly because of temperature differences affecting the state of strain of the specimen.

DISCUSSION

It appears that Steinberg and Miroschnischenko did not observe discontinuities of resistance because their apparatus was not sensitive enough. They state that a resistance change of 33×10^{-6} ohm produced a galvanometer deflection of 1 mm. They do not give the resistance of their specimen, which was a wire 70 cm long, 0.038 cm in diameter, composed of 15 percent Ni and 85 percent Fe. Assuming the specific resistance to be 30×10^{-6}, as found by Yensen for this alloy, the resistance is calculated to be 1.8 ohms. The value of dR/R producing a deflection of 1 mm is thus 18×10^{-6}. With a discontinuity of the size shown in Fig. 1, therefore, the apparatus of the Russian physicists would give a sudden galvanometer jump of about 3.5 mm. If the galvanometer were not quick in action, and if there were a slight temperature drift, such a small jump could hardly be detected.

There is also, of course, a possibility that in the matter of resistance jumps an iron-nickel alloy under tension does not behave like nickel under bending stress. From the standpoint of theory, however, it is not easy to see why the alloy should have no resistance jumps when the nickel exhibits them so decisively.

A comparison of Figs. 1 and 2 brings out certain points of interest. While the intensity of magnetization is decreasing along AB in Fig. 2 a decrease of about 65 in I produces a decrease of 58×10^{-5} in dR/R. At the jump BC a change in I of 500 produces a $dR/R=6.3\times10^{-5}$. Where I is increasing continuously from C to D, changing by 155, the change in dR/R is practically negligible, but as I begins to show signs of saturation the dR/R begins to show a more rapid rate of increase.

Apparently small resistance change is associated with steep parts of the hysteresis loop. It is precisely this characteristic which led Gerlach to suppose that magnetic discontinuities did not produce resistance discontinuities, inasmuch as magnetic discontinuities are largely confined to steep parts of the loop.

The current theories of magnetism assume a ferromagnetic body to consist of small elements magnetized to a saturation intensity I_0. The body as a whole is unmagnetized when the I_0 vectors of the small elements are oriented at random. An external field may magnetize the body by (A) sudden reversals of the directions of those I_0 vectors which oppose the external field, (B) rotation of the I_0 vectors into directions which more nearly agree with that of the applied field. Process B is reversible, A is irreversible. Discontinuities of magnetization are supposed to be due to process A.

It appears that process A is not the only one involved in the magnetic discontinuities. From principles of symmetry process A cannot be supposed to produce resistance changes. Neither could it produce magnetostriction changes. Since both resistance changes and length changes[5]

[5] C. W. Heaps and A. B. Bryan, Phys. Rev. 36, 326 (1930).

appear in conjunction with magnetic discontinuities we must assume other processes than A to be operative.

It seems probable that when the I_0 vector of one element reverses, the local magnetic field in which a certain specified neighboring element finds itself is changed. This field is the sum of the external field and the Lorentz field of neighboring doublets. The change of the Lorentz field due to sudden reversals of nearby doublets can cause a rotation of type B in the specified element. This rotation, possibly through only a small angle, can cause a change of length and a change of resistance. (This conclusion follows from the fact that magnetostriction and magnetoresistance have quite different values depending upon whether they are measured along the direction of saturated intensity of magnetization or at right angles thereto.) According to this view the resistance jump of Fig. 1 is due to the summation over all elements of rotations of type B, these rotations being produced by sudden changes of the Lorentz fields of the elements. The sudden changes of the Lorentz fields are produced by reversals of type A which occur in neighboring elements.

It appears that these rotations of type B produced in this way are small, hence the magnetoresistance on the part of the hysteresis loop where discontinuities prevail—that is, on the steep parts—is small.[6]

A third type of change of I_0 has been suggested in which the vector suddenly swings through 90° in an unstrained cubic crystal. If the Barkhausen effect is due to this kind of process it could have magnetoresistance and magnetostriction associated with it inherently, and there would be no necessity of considering effects due to secondary rotations of neighboring elements. However, the small size of the resistance discontinuities would seem to be an objection to this theory.

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[6] The Editor of the *Physical Review* has pointed out that the resistance jump will probably become smaller as the magnitude of the magnetic discontinuity increases. This conclusion appears to be true because complete reversal in all domains would reverse the Lorentz fields as well as the magnetization of each element, and hence no change of resistance would occur.