NOVEMBER, 1928 *PHYSICAL REVIEW* *VOLUME 32*

HALL EFFECT AND MAGNETIC INDUCTION IN A BAR OF ELECTROLYTIC IRON

BY EMERSON M. PUGH

ABSTRACT

The Hall effect was measured in a bar of electrolytic iron in contrast to the usual method of measuring it in thin sheets of the material. Direct measurements were taken at the same time of the magnetic induction B and of the Hall e.m.f. E.

The E-*vs.*-B curve is a straight line up to $B=12{,}000$ gauss where its slope starts to decrease. The curve of permeability-*vs.*-B has its maximum at this same value of B. Measurements taken at points on a "hysteresis loop" indicate that E is also proportional to B when the magnetizing force has been removed and only the residual B remains. The Hall coefficient for this bar is found to be only 20 percent lower than that found by A. W. Smith for electrolytic iron, if in its calculation the value of B is substituted for H in the usual formula.

INTRODUCTION

MEASUREMENTS of the Hall effect in different materials have shown that if the current in the material is kept constant, the Hall e.m.f. varies linearly with the magnetic induction in non-magnetic substances. In magnetic substances, however, the ratio of the Hall e.m.f. to the magnetic induction is constant only for values of the induction below a certain point, which is sometimes called the "saturation point." Above this point the ratio decreases.

This breaking of the curve away from a straight line was thought to occur when the substance was magnetically saturated, but this had not been verified since no experiments had been performed in which the B-*vs*-H curve and the Hall effect were investigated in the same piece of material. The reason that this had not been done is obvious when we consider that the best shape of material for measuring the Hall e.m.f. is a very thin sheet in which it would be quite difficult to investigate the magnetization curve.

The fact that many experimenters[1] have found large variations in the Hall coefficient for extremely thin sheets, and that W. van B. Roberts[2] found a Hall coefficient in his cylinder of bismuth which was only 1/3 of the value generally found for bismuth suggested there might be a much different value for the coefficient in a bar from that usually found for iron in thin sheets. The measurement of the Hall coefficient for a bar of iron was accordingly undertaken. The dimensions of this bar were 2.005 cm by 1.050 cm by 11 cm. It was forged out of electrolytic iron to which 0.2 percent of manganese was added to make it forgeable. The bar was then carefully machined and filed to the dimensions given. The iron was prepared and forged by the Westinghouse Research Laboratories. Although this particular sample was not analysed, another sample prepared in the same

---

[1] J. C. Steinberg, Phys. Rev. **21,** 22 (1923).

[2] W. van B. Roberts, Phys. Rev. **24,** 532 (1924).

way, except that no manganese was added, contained less than 0.06 percent of all impurities.

Method of Measurement

(a) *Magnetization curve.* Since a bar of iron was used, the usual method of determining the *B-vs-H* curve could be employed. The bar was placed in a magnetic circuit with a search coil wrapped around it near the center. The search coil was connected in series with a ballistic galvanometer and the secondary of a standardizing air-core solenoid. This made the determination of the absolute values of magnetic induction quite simple. Readings on the bar were made by reversing a given magnetizing current after the bar had been first completely demagnetized. No attempt was made to obtain the absolute value of the magnetic field strength H, and so a quantity proportional to the permeability was calculated by dividing the magnetic induction by the magnetizing current. However, since the balance of the magnetic circuit consisted of nearly pure soft iron of much larger cross-section than the bar under test, the true field H in the bar could be considered proportional to the magnetizing current without appreciable error.

(b) *Current density.* Measuring the Hall e.m.f. presented more difficulties. It was necessary to produce current densities comparable to those used by other investigators in their thin sheets and to have them perpendicular to the magnetic induction. Reference to Fig. 1 will show how this was accomplished. A current of 50 to 100 amperes from a storage battery was passed through the bar by means of the electrodes M, M', E, E'. By increasing the current through the outside electrodes, E, E', it was possible to make the lines 1-2-3 and 4-5-6 equipotentials, and thus insure sensibly uniform parallel lines of flow between the middle electrodes M, M'. To test for these equipotentials, one terminal of a galvanometer was connected to a fixed position on the iron bar and the other terminal was touched successively to the points 1, 2, 3, 4, 5, 6. The lengths of the leads to electrodes E, E' were adjusted until the readings taken at points 1, 2, 3 were equal to each other, as were also those taken at 4, 5, 6. After the final adjustment, the variation in either group of readings was less than 1 percent of the difference in readings between points 2 and 5. Therefore, neither of the lines 1-2-3 and 4-5-6 varied from equipotential lines by more than 1 percent of the potential difference between them, and the error in the current density at point O between M and M', calculated by assuming the current to flow in parallel lines between M and M', was no greater than 2 percent. Correction was made, of course, for the width of the slots between M and E.

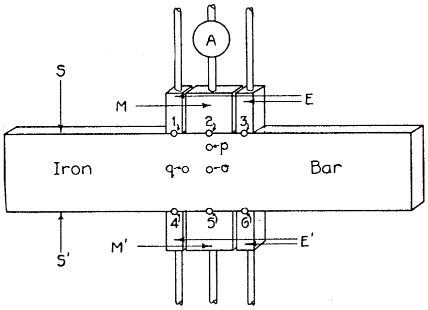

Fig. 1. Electrodes soldered in place to produce high uniform current density in iron bar.

(c) *Hall e.m.f.* The Hall e.m.f. was measured by means of a Wolff Thermokraftfrei Potentiometer and a Leeds and Northrup High Sensitivity galvanometer. The combination was capable of reading to 10^{-8} volts. Connections to the iron bar were made by means of two electrolytic iron contact screws which were pressed against opposite sides of the bar at point O. To test the accuracy of the current density adjustment described in (b) some readings were also made at points p and q. Since the Hall e.m.f. readings taken at these points fall on the same curve as those taken at O, the current was assumed to be uniform in this space.

The current between the electrodes and the magnetizing current were both allowed to become steady before readings were taken. Then the potential difference between the contact screws was measured. The magnetizing current was then reversed and the potential difference was measured again. The difference between these two potentiometer readings was twice the Hall e.m.f. No corrections were necessary for *IR* drops or thermoelectromotive forces since these would not change with the reversal of the magnetization. *This process was repeated many times, and at each reversal of the magnetizing current, the throw of the ballistic galvanometer was read, so, the Hall e.m.f. and the magnetic induction were both measured at the same time.* See Table I.

TABLE I. *Sample data giving Hall e.m.f. and magnetic induction.*

Magnetic induction $=(59.56-47.07)\ 789=9850$ gauss
Hall e.m.f. $=287.6/2=143.8$ volts$\times 10^8$

	Ballistic galvanometer readings (cm)		Potentiometer readings (volts$\times 10^8$)		Differences (volts$\times 10^8$)
1		47.1		974	
2	59.6		1262		288
3		47.0		974	287
4	59.7		1260		286
5		47.05		974	289
6	59.5		1266		287
7		47.1		983	285
8	59.6		1270		287
9		47.05		982	283
10	59.5		1260		286
11		47.05		965	290
12	59.5		1250		292
13		47.05		951	286
14	59.5		1223		286
15		47.1		923	290
16	59.6		1203		291
17				901	288
18			1175		288
19				872	
Ave.	59.56	47.07			287.6

(d) *Corrections.* All values plotted on the curve in Fig. 2 have been corrected to a current density of 24.7 amps. per cm^2 and to a temperature of 26°C. For the temperature correction, a coefficient of 1.36 percent per °C, given by A. W. Smith[3] was used. This coefficient may not be very ac-

---

[3] A. W. Smith, Phys. Rev. **30**, 1 (1910).

curate for the iron used, but the important points were all taken so close to 26°C that the correction was negligible.

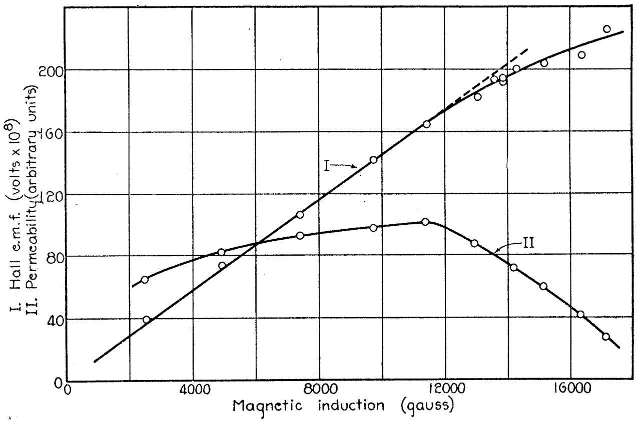

Fig. 2. Curves showing Hall e.m.f. and permeability in bar of electrolytic iron.

Results

(a) *Hall e.m.f. and permeability.* It will be seen from the curves in Fig. 2 that the Hall e.m.f. increased linearly with the magnetic induction up to approximately 12,000 gauss. It will also be noticed that the permeability curve reaches its maximum at approximately the same point, namely 12,000 gauss. Therefore, the condition of the iron which causes the break from linear relation in the Hall effect is apparently the same as that which causes maximum permeability.

(b) *Hall coefficient.* The Hall coefficient R for this bar at 26°C was calculated from the formula[4] $E = RBib$ using the slope of the straight line part of the curve in Fig. 2 for the ratio E/B. Its value was 0.0055 c.g.s. electro-magnetic units, and the error is less than 3 percent. A. W. Smith[3] found a value of 0.0066 c.g.s. e.m.u. for a sheet of electrolytic iron which he measured in 1910. Since the value of the coefficient has been shown to be greatly influenced by the size of the crystals in the material and by slight impurities, the difference between these two values is not surprising. If, however, the value of H had been used in the calculation instead of B, the coefficient would not be constant, and its value would be increased several thousand fold. This would place its value above that for bismuth.

---

[4] It should be noticed (Fig. 2) that the Hall e.m.f. is plotted against magnetic induction B rather than field strength H. In all previous experiments on the Hall effect the field strength was measured in the space outside the thin sheet of material, which obviously gave the induction inside the sheet. Most investigators have recognized this fact, but it is the belief of the author that the use of H in the generally accepted formula $E = RHI/t$ has been misleading to many and should be replaced by B. The author believes that the formula should be written $E = RBib$ since the effect depends primarily upon the current density i rather than the total current I. Here $i = I/bt$, where b is the width of the strip in the direction in which the Hall e.m.f. is measured.

(c) *Hysteresis loop.* A set of measurements was made when the iron was taken through a number of complete hysteresis loops by closing the magnetizing circuit first in one direction, then opening it, then closing it in the opposite direction, and then opening it again. Each time the magnetizing current was made or broken, the throw of the ballistic galvanometer was read and a potentiometer reading was taken. From these readings, four points on the hysteresis loop were plotted, and the corresponding values of Hall e.m.f. were plotted upon the same sheet. The resulting curve for the Hall e.m.f. was another hysteresis loop which was proportional to the first, within the limits of observational error. The accuracy of these readings was little better than 10 percent on account of the difficulty in keeping conditions constant during the time required for completing each loop, but the results show quite definitely that there is a Hall effect due to the residual magnetization of the iron.

Conclusions

In the present work a method has been devised to measure both the Hall e.m.f. and the magnetic induction in the same piece of material at the same time. It is shown (Fig. 2) that in the specimen of electrolytic iron used the maximum on the permeability curve and the break from the straight line on the Hall e.m.f. curve occur at the same value of magnetic induction. It is also shown that a Hall e.m.f. occurs due to residual magnetism which is approximately the same as that due to a corresponding induction on the normal magnetization curve. The Hall coefficient was found to agree within 20 percent of that given by A. W. Smith[3] in 1910 for electrolytic iron. This discrepancy might easily be accounted for by differences in purity or in treatment of the two samples of iron.

The following conclusions can then be drawn for this specimen of electrolytic iron:

(a) The linear relation between the Hall e.m.f. and the magnetic induction breaks down where the permeability reaches its maximum value.

(b) A Hall e.m.f. is produced by the residual magnetism which is approximately the same as that produced by a corresponding value of magnetic induction on the normal magnetization curve.

(c) The Hall coefficient is of the same order of magnitude in the bar as in the thin sheets providing the value of B be used in the calculation instead of the value of H.

The author wishes to thank Dr. J. J. Weigle and Professor A. G. Worthing for their valuable suggestions and criticisms. He also wishes to acknowledge his indebtedness to the members of the Physics Department of Carnegie Institute of Technology and to the Westinghouse Research Laboratories for furnishing the iron bar.

University of Pittsburgh and Carnegie Institute of Technology,
Pittsburgh, Pennsylvania,
July 23, 1927.