THE HALL EFFECT IN PERMALLOY

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Abstract

The Hall effect has been studied in three permalloys, the composition being 84, 81 and 78 percent nickel with the remaining part iron. The observed transverse electromotive forces are unsymmetrical for the two opposite directions of the magnetic field. This dissymmetry arises from an unsymmetrical change of resistance in the transverse magnetic field. Since this change of resistance is a complex function of the magnetic field, this dissymmetry is also a complex function of the magnetic field. In each of these alloys the Hall effect is at first positive as in iron but reverses its direction and becomes negative as in nickel for sufficiently large magnetic fields. For magnetic fields less than about 11,000 gauss an increase in the concentration of iron increases the Hall effect. With an increase in the concentration of iron the maximum in the curve showing the Hall electromotive force as a function of the magnetic field shifts toward greater magnetic fields. The greater the concentration of iron, the larger is the magnetic field at which a reversal in the direction of the Hall electromotive force takes place.

Each of the Hall effect curves can be resolved into two component curves, one negative, the other positive. The negative component is a straight line, with a slope which is nearly the same for each alloy. This negative component may be attributed to the action of the magnetic field on the so-called free electrons. The positive component has the form of the corresponding curve for iron or nickel. The magnitude of this component increases with an increase in the concentration of the iron. The positive component may be attributed to the orientation of the elementary magnets by the transverse magnetic field.

THE fact that the sign of the Hall effect may be either positive or negative is of much importance in any theoretical interpretation of this effect. The classical electron theories of metallic conduction[1] indicate that the sign of this effect should be negative as in bismuth. The recent theory of Sommerfeld[2] amounts to a modification of the classical theory with no further consideration of the question of the sign of the effect. In alloys of bismuth and tin,[3] in alloys of bismuth and lead[4] and in certain specimens of bismuth in the form of single crystals[5] the Hall effect is negative for values of the magnetic field less than a certain critical value and positive for magnetic fields greater than that value. This reversal is also without explanation. Since the Hall effect is positive in iron and negative in nickel, there is some interest in examining it in binary alloys of these two metals, especially permalloys which have unusual magnetic properties.

[1] O. W. Richardson, Electron Theory of Matter, 434 (1914).
[2] A. Sommerfeld, Zeits. f. Physik **47**, 43 (1928).
[3] A. V. Ettingshausen and W. Nernst, Ann. d. Physik [3] **33**, 474 (1888).
[4] A. W. Smith, Phys. Rev. [2] **10**, 358 (1917).
[5] J. Becquerel, Comptes rendus 154, 1795, (1912).

Experimental Method

Specimens of three permalloys with different concentrations of iron and nickel were made available through the kindness of Professor L. W. McKeehan at that time with the Bell Telephone Laboratories. One of these alloys contained 84 percent nickel and 16 percent iron; another 81 percent nickel and 19 percent iron; the other 78 percent nickel and 22 percent iron. The specimens were originally in the form of thin sheets which had not been annealed. From these sheets rectangular plates were prepared for the investigation. Some of these plates were cut with the direction of the longer axis of the plate coinciding with the direction in which the sheet had passed through the rolls and some of them were cut so that the direction of the flow of current was at right angles to the direction in which the plate had been rolled. Plates of different thickness and sizes were prepared and the Hall effect was examined in these plates before and after annealing at 1000° C for 4 hours. The plates were approximately 0.04 cm or 0.003 cm in thickness.

The method of making the observations was essentially that used by one of the authors[6] in previous investigations of the Hall effect in metals and alloys. Data on the Hall electromotive force were obtained by measuring this electromotive force for a number of magnetic fields when the magnetic field remained fixed in direction without reversal. A similar series of observations was then made on the same plate with the magnetic field in the reversed direction. The algebraic mean of the observed electromotive force for a particular magnetic field gives the Hall electromotive forces for that field and is equal to one half the electromotive force which would be set up in the plate by the reversal of the magnetic field. The reason for paying especial attention to this method of procedure arose out of the fact that there was a marked dissymmetry in the magnitude of the observed transverse electromotive force for each direction of the magnetic field separately. Care was taken that residual magnetism in the plate was not responsible for the dissymmetry. The Hall electromotive force for unit current and unit thickness of plate was calculated from the familiar equation,

$$E = RHI/d$$

where E and I are measured in absolute units and d in centimeters.

Results

Figure 1 gives a typical set of results for an unannealed plate of a permalloy containing 84 percent nickel and 16 percent iron. Curve I is for the magnetic field in one direction and Curve II is for the magnetic field in the opposite direction. For magnetic fields less than about 13,000 gauss the observed electromotive forces are in the same direction for the two directions of the magnetic field. Curve III is obtained by taking the algebraic mean of the electromotive forces for the two directions of each of the magnetic fields and plotting this mean against the corresponding magnetic field. This curve there-

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

fore shows the true Hall electromotive forces set up in the plate by the magnetic field, without the distortion due to the dissymmetry of the electromotive forces. It is to be noted that the Hall electromotive force rises to a maximum at about 5,000 gauss, reverses its direction at about 11,000 gauss and that for fields greater than about 11,000gauss there is a linear relation between

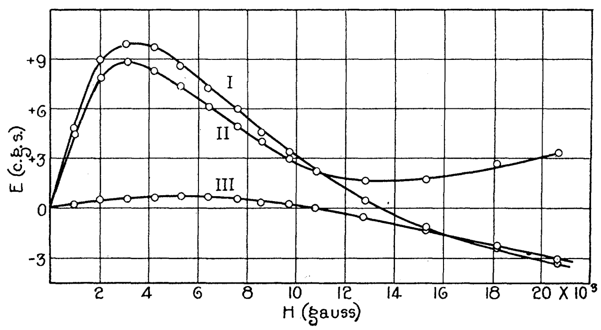

Fig. 1. Hall effect in unannealed permalloy, 84 percent nickel and 16 percent iron; Curve I for magnetic field in one direction; Curve II for magnetic field in opposite direction; Curve III algebraic mean of Curve I and Curve II.

the Hall electromotive force and the magnetic field. For magnetic fields less than about 11,000 gauss the Hall effect in this plate is positive as in iron. For fields greater than 11,000 it is negative as in nickel.

Similar observations were made on a number of other samples of the permalloy of this composition. These plates differed in length, width and thickness. Some were annealed and others were unannealed. The dissymmetry of the effect varies from plate to plate but the mean curve representing the Hall

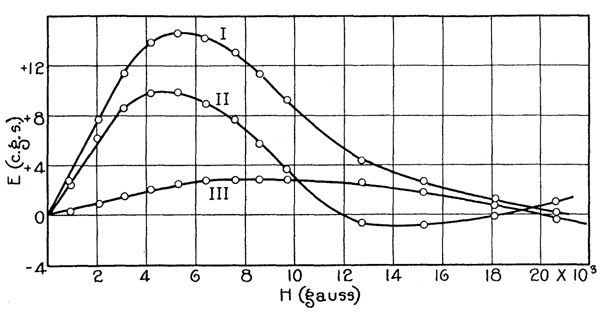

Fig. 2. Hall effect in unannealed permalloy, 81 percent nickel and 19 percent iron; Curve I for magnetic field in one direction; Curve II for magnetic field in opposite direction; Curve III algebraic mean of Curve I and Curve II.

electromotive force is essentially the same in all cases. Variations from plate to plate were not more than might be expected to arise from minor changes in composition or other physical characteristics of the plate.

Figure 2 gives similar data for a specimen of permalloy containing 81 percent nickel and 19 percent iron. Here again the dissymmetry is quite marked.

Curve I for the magnetic field in one direction lies for the most part on the same side of the axis as Curve II for the magnetic field in the opposite direction. The algebraic means of these electromotive forces for each value of the magnetic field are plotted as Curve III which is a measure of the Hall effect. It will be observed that the direction of the effect in this alloy is the same as in iron and that the Hall electromotive force rises to a maximum at about 10,000 gauss and reverses its direction at about 20,000 gauss. Similar results were obtained for the other specimens of this alloy. The dimensions of the plate, the heat treatment and other physical characteristics change the magnitude of the electromotive forces for a particular value of the magnetic field when the field is in a given direction. However, Curve I and Curve II are changed in such a way that the resultant Curve III is essentially unchanged. Hence the observed Hall electromotive forces in the different plates may differ

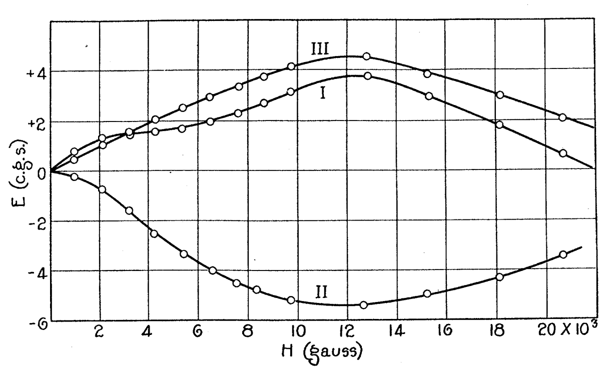

Fig. 3. Hall effect in unannealed permalloy, 78 percent nickel and 22 percent iron; Curve I for magnetic field in one direction; Curve II for magnetic field in opposite direction; Curve III algebraic mean of Curve I and Curve II.

somewhat in magnitude but are always represented by a curve similar to Curve III.

Figure 3 gives the results on an unannealed sample of permalloy containing 78 percent nickel and 22 percent iron. An examination of the Hall effect in other plates of this same composition gave results essentially equivalent to those shown in Fig. 3, showing that the Hall effect in this alloy is essentially independent of the dimensions of the plate, its heat treatment, etc. It will be seen from this figure that Curve I and Curve II giving the Hall electromotive force for the two directions of the magnetic field lie on opposite sides of the horizontal axis. There is in this case also some dissymmetry in the effect since the curves are not identical. Curve III which is obtained by taking the mean of the ordinates of the other two curves for each magnetic field shows the Hall electromotive forces as a function of the magnetic field. This curve rises to a maximum when the magnetic field is about 12,000 gauss. After this magnetic field is exceeded the Hall electromotive force decreases. For fields used in this investigation there is never an actual reversal of the effect but there is a clear indication that at still higher fields there would be a reversal. The direction of the effect is always positive as in iron.

Dissymmetry

The dissymmetry of the Hall effect in bismuth was attributed by Lebret[7] and van Everdingen[8] to an unsymmetrical change of resistance. The same explanation will account for the dissymmetry observed in the alloys of bismuth and tin and in the alloys of bismuth and lead. Reasons for an unsymmetrical change of resistance in a transverse magnetic field in the case of alloys of iron and nickel are quite evident. Webster[9] has shown that the change of resistance of iron in a transverse magnetic field depends upon the orientation of the crystal axis with respect to both the direction of the current and the magnetic field. Similar results have been obtained by Kaya[10] on the change of resistance of nickel in a transverse magnetic field. The change of resistance may be either positive or negative and it is a complex function of the magnetic field. From these results it is evident that the change of resistance produced by a transverse magnetic field in a solid solution of iron and nickel would depend in a complex way on the intensity of the magnetic field, on the orientation of the crystals with respect to the current and the magnetic field and on the concentration of the iron and nickel in the solution. The concentration of the iron and nickel in the alloy is probably not entirely uniform and the orientation of the crystals is certainly not uniform over the entire surface of the plate. Hence the change of resistance produced in one part of the plate by the transverse magnetic field would not necessarily be the same as that produced in another part of it and this variation of the change of resistance from one part of the plate to another would cause a change in the direction of the flow of current in the plate. This change in direction of the flow of current would be independent of the direction of the magnetic field and hence it would not be reversed by a reversal of the magnetic field. The algebraic addition of the transverse electromotive force produced by this change in the direction of the flow of current and the true Hall electromotive force would account for the observed dissymmetry. Since the unsymmetrical change of resistance varies with the intensity of the magnetic field, the dissymmetry of the Hall effect will also vary with the intensity of the magnetic field.

Reversal of the Hall Electromotive Force

From Fig. 4 it is evident that an increase in the concentration of iron in the alloy, increases the Hall electromotive force for lower magnetic fields and causes the maximum in the curve to occur at higher magnetic fields. It is also evident that the field at which a reversal in the direction of the electromotive force takes place, increases with an increase in the concentration of iron in the alloy.

[7] A. Lebret, Com. Phys. Lab. Univ. of Leiden, No. **19,** 17 (1895).
[8] E. van Everdingen, Com. Phys. Lab. Univ. Leiden, No. **26,** 10 (1896)
[9] W. L. Webster, Proc. Roy. Soc. **A114,** 611 (1927).
[10] S. Kaya, Sci. Reports, Tohoku Imp. University **17,** 1027 (1928).

Each of the curves representing the Hall electromotive force as a function of the magnetic field can be resolved into two component curves. Fig. 5 shows these component curves for the alloy containing 84 percent nickel and 16 percent iron; Fig. 6 for the alloy containing 81 percent nickel and 19 percent iron and Fig. 7 for the alloy containing 78 percent nickel and 22 percent iron. One of these curves is a straight line indicating that one component of the Hall electromotive force is proportional to the magnetic field. This part of the net electromotive force is negative, that is, it has the same direction as the Hall electromotive force in bismuth. The other component has the

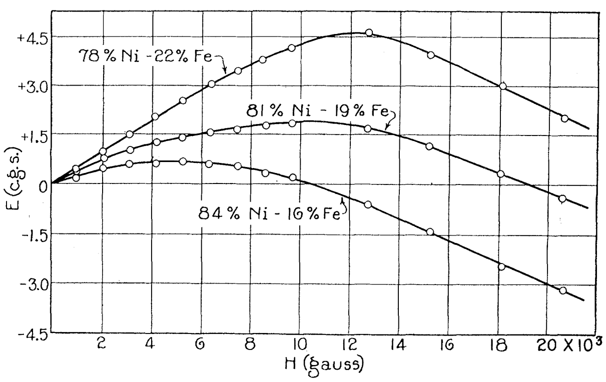

Fig. 4. Comparison of Hall effect in three permalloys of different compositions.

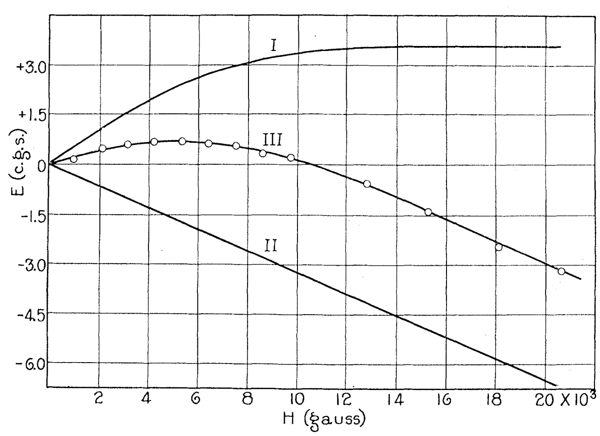

Fig. 5. Resolution of Hall effect into two components for alloy containing 84 percent nickel and 16 percent iron.

form of the curve showing the Hall electromotive force in iron or nickel as a function of the magnetic field. At first there is almost a linear relation between this part of the Hall electromotive force and the magnetic field but with further increase of the magnetic field the curve becomes parallel to the horizontal axis along which the magnetic fields are plotted. The curve showing the observed Hall electromotive force as a function of the magnetic field is obtained by taking the algebraic sum of the ordinates of the two component curves and plotting these ordinates against the corresponding abcissae.

The resolution of these Hall effect curves into two parts shows that the observed Hall effect in these alloys may be considered as made up of a positive

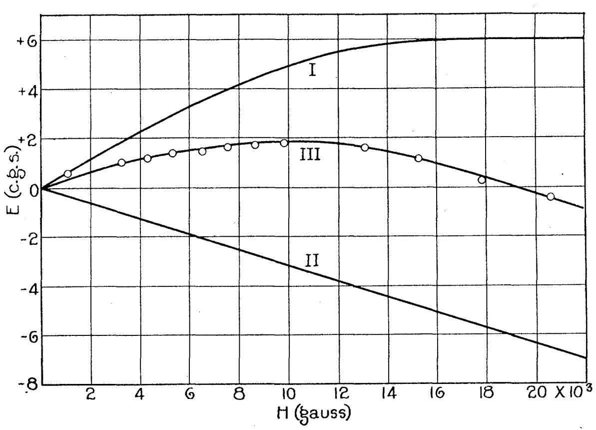

Fig. 6. Resolution of Hall effect into two components for alloy containing 81 percent nickel and 19 percent iron.

part as in iron and a negative part as in a metal like gold or silver. The positive part just as in iron approaches a limiting value for sufficiently large magnetic fields and thus behaves like the Hall effect in iron or nickel. The negative part on the other hand is a linear function of the magnetic field and is thus

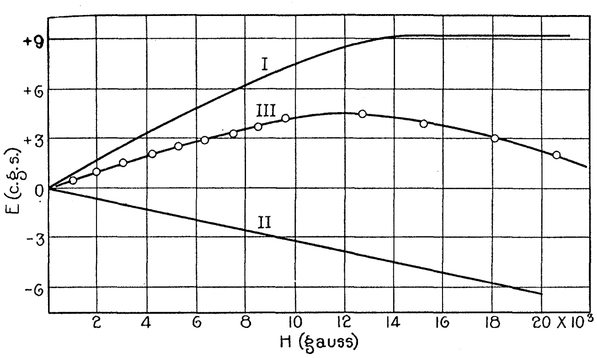

Fig. 7. Resolution of Hall effect into two components for alloy containing 78 percent nickel and 22 percent iron.

similar to the Hall effect in such elements as copper, gold or silver. This component of the effect may be explained as being produced by the direct action of the magnetic field on the so-called free electrons just as the Hall effect in gold and silver is explained on the basis of the deflection of the free electrons by the magnetic field. The positive component curve which resembles the corresponding curve for nickel and iron is probably caused by the orientation of the elementary magnets in the transverse magnetization of the plate. When all the elementary magnets have been oriented in the direction of the magnetic field, the electromotive force arising from this cause remains constant as the magnetic field is further increased.

It is noted that the slopes of the linear curves for each of these alloys is essentially the same, indicating that the effect of the magnetic field on the free electrons is essentially the same in each case and nearly independent of the concentration of the iron and nickel in the alloy. Moreover the slope of these linear curves has the order of magnitude of the slopes of the corresponding curves for one of the non-magnetic elements like gold, silver or copper. Hence since the slope of the curves for copper, silver and gold gives a measure of the effect of the magnetic field on the free electrons in them and since the negative component curves for these alloys have essentially the same slope as the corresponding curve for copper, gold and silver, it would seem that the effect of the transverse magnetic field on the free electrons is of the right order of magnitude to account quantitatively for the slopes of these linear negative component curves. Furthermore theories of the Hall effect based on electronic theories of metallic conduction ordinarily lead to the conclusion that the Hall constant is the same in all non-magnetic elements. For example the Hall constant for non-magnetic elements like copper, gold, or silver is given by the expression,

$$R = 3\pi/(8\epsilon \cdot n)$$

on the classical theory and by

$$R = 1/(\epsilon \cdot n)$$

in Sommerfeld's theory where ϵ is the electronic charge and n the number of electrons per unit volume. These expressions indicated that the Hall constant is independent of the nature of the metal and depends only on the electronic charge and the density of the electrons in the metal.

An examination of the positive components of the Hall effect curves for these alloys shows that the magnitude of the positive component for a particular field becomes greater when the concentration of the iron in the alloy is increased. The curve for the alloy containing 78 percent nickel and 22 percent iron lies above the curve for the alloy containing 81 percent nickel and 19 percent iron and the curve for the alloy containing 84 percent nickel and 16 percent iron. This fact has the effect of causing the Hall effect curve for the alloy containing the greatest percentage of nickel to cross the horizontal axis before the curve for the alloy containing a greater percentage of the iron and a less percentage of nickel. If the positive components of these Hall effect curves can be attributed to structural changes in these alloys, it would seem that the additional structural changes noted when the content of iron increases indicates that the higher magnetic moment per unit atom of the iron is more effective in producing structural changes than the smaller magnetic moment per unit atom of nickel.