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Interaction Between Longitudinal Current and Flux in a Nickel Bar

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It was found that reversing the current through the nickel alters the change of magnetism both when it is abruptly established and when it is abruptly stopped. In the sixteen different cycles considered, invariably a current flowing with the flux opposed magnetization, while a current flowing against the flux favored magnetization. A thorough analysis of the numerical data shows that in addition to the well-known "shock effect" equivalent to a mechanical jar, there is another effect which is reversed by reversing the direction of the current with reference to the flux. This effect apparently is not due to the circular flux set up by the current nor to any dissymmetry in the bar, but instead appears to be some kind of action between the current itself and the flux. This hypothesis was strengthened by a supplementary experiment showing that the resistance of a nickel bar is decreased when it is strongly magnetized by an alternating field.

INTRODUCTION

THE apparatus used in this investigation was identical with that used by Dr. Doolittle and myself in our experiments with residual magnetism in iron.[1] In our published article the various circuits and coils have been fully described[1] and only a brief recapitulation is given here. The sample to be tested was a short cylinder of nickel, kindly donated by the International Nickel Company. It was cored and slotted, so that its section is like a thick and nearly closed letter C. The purpose of the slot was to eliminate as far as practicable the circular flux set up by the longitudinal current through the bar. The sample was placed on the axis and at the center of a long solenoid in which a current of about two amperes sets up a strong magnetizing field. Surrounding the solenoid is a coil of many turns of fine wire connected to a ballistic galvanometer. The magnetizing current could be either made or broken abruptly by means of a switch, or gradually by moving sliders along the coils of three drum rheostats in series, thus varying the current from 0.0004 to 1.8 amperes in a few seconds.

The longitudinal current, to be here denoted simply by I, was always made or broken abruptly, and its effect, as Dr. Doolittle and I had previously observed, was equivalent to a mechanical shock causing a sudden increase or decrease in the bar's magnetism according to circumstances. This change in flux caused the galvanometer to deflect by an amount dependent on the violence of the mechanical blow or on the magnitude of the longitudinal current, and of course on the magnetic condition of the sample.

PROCEDURE

In the present investigation the value of I was always two amperes, and the magnetizing current was always brought, either quickly or slowly, to a final maximum very close to 1.8 amperes. The procedure involved carrying the nickel cylinder through a quasi-hysteresis cycle, and observing the deflections of the galvanometer at the vertical ends of the cycle as shown in Fig. 1. As these deflections are proportional to the change in flux caused by making or breaking I, they alone are quoted in what follows which is only concerned with relative values.

Sixteen cycles were examined, each of which may be represented qualitatively by one of the diagrams in Fig. 1. In (a), the nickel cylinder was magnetized following a curve similar to a typical $B-H$ curve from a to b, while the current I was flowing through it. At b, I was stopped. This caused an increase in magnetism bringing the flux abruptly to c which may be regarded as the normal condition for that field intensity. The field was then decreased to d when I was re-established and the condition at a was recovered by a decrease of flux proportional to da. The increase from b to c and the decrease from d to a indicate a hysteretic lag which always occurs in

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[1] H. A. Perkins and H. D. Doolittle, Phys. Rev. 60, 811–817 (1941).

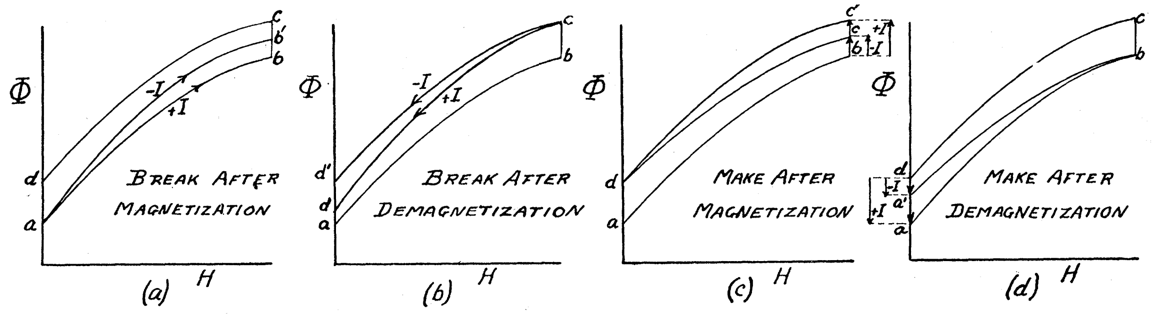

FIG. 1.

nickel, because the property of "overshooting the mark" previously found in Norway iron[1] does not exist with nickel or cast iron.

It should be noted that Figs. 1 are misleading in one respect. They exaggerate the deflection of the galvanometer at the two ends of the cycle. Although these "throws" were often over 100 scale divisions, the reading that would have been produced by the abrupt magnetization or demagnetization of the cylinder would have run to a thousand or more. An accurate drawing of such a cycle would show two curved lines very close together.

Another point to be noted is the absolute necessity of going through each cycle four or five times before any readings are made, in order to get the nickel accustomed to the regime. Nickel, and iron even more so, have amazing memories, and it takes considerable treatment to make them forget their immediate past. Taking this precaution, a given cycle in the case of nickel could be repeated again and again, or recovered later on with surprising consistency. Unfortunately Norway iron did not behave so well, although some of the same effects as with nickel were observable.

The sixteen cycles were obtained from the various possible combinations of the following factors. The magnetizing field may be established or discontinued either abruptly or slowly. The current may be flowing while the flux is increasing and not flowing while it is decreasing, or flowing during decreasing flux and not flowing during increasing flux. It may also flow during both processes or not flow during either except at the ends of the cycle where a momentary opening or closing of the switch is needed to obtain the galvanometer throw indicating the change of flux. As there are two such abrupt changes for each cycle, indicated by *bc* and *da* in Figs. 1, the 16 cycles give 32 different readings of the galvanometer. Then by reversing I, we obtain 32 more making a total of 64 distinct observations. Each of these observations was the average of four similar readings which never varied more than about seven percent from the average and generally very much less.

As a result of a careful study of the 64 different cases observed, it was found that, without exception, in stopping the longitudinal current I after magnetization, or in starting it after demagnetization, the galvanometer throw is greater when I is with the flux (denoted by $+I$) than when it is against it (denoted by $-I$). In starting I after magnetization or stopping it after demagnetization, the galvanometer throw is less when I is positive, and greater when it is negative. The meaning of these differences may be understood by referring to Figs. 1. In (a) the deflection due to the flux change $b'c$ when $-I$ flowed during magnetization is less than that due to bc when $+I$ was flowing. Thus $-I$ favored the growth of the flux while $+I$ held it back to the lower point b.

Figure 1(b) shows what happens at the other end of the cycle when I flowed during the process of demagnetization. When the current is with the flux ($+I$) the curve descends to d, while with $-I$ it only goes to d'. Thus there is more residual magnetism when the current is against the flux than when it is with it. So here again $-I$ favors the magnetic state as compared to $+I$ which presumably opposes it.

Figures 1(c) and (d) illustrate abruptly starting I at the two ends of the cycle. In (c) starting $-I$ causes the larger throw (b to c') indicating a

TABLE I. Results for eight different cases.

	Reading when I flows in nickel		Relative decrease of deflection when I is reversed	Reading when I flows in axial wire		Relative decrease of deflection when I is reversed
Procedure	$+I$	$-I$		$+I$	$-I$	
1. Break after slow magnetization	+64	+50	22%	+66	+64	3%
2. Make after slow magnetization	+51	+58	12%	+59	+64	8%
3. Break after quick magnetization	+43	+34	21%	+54	+51	6%
4. Make after quick magnetization	+31	+40	23%	+49	+54	9%
5. Break after slow demagnetization	−100	−140	29%	−113	−120	6%
6. Make after slow demagnetization	−146	−105	28%	−120	−112	7%
7. Break after quick demagnetization	−23	−49	53%	−47	−45	4%
8. Make after quick demagnetization	−51	−25	51%	−48	−48	0%

greater increase of magnetism than that caused by starting $+I$ which carries the flux only to c. In (d) starting $-I$ after demagnetization brings the flux from d to a', while starting $+I$ brings it to a. But a' indicates more residual magnetism than a, so in this fourth case also, $-I$ favors the magnetic state while $+I$ tends to diminish it.

The average differences expressed in galvanometer scale divisions between the effects of $+I$ and $-I$ for the four cases just described and based on all 64 observations are as follows:

1. Break after magnetization: 12 mm due to bb', Fig. 1(a);
2. Break after demagnetization: 33 mm due to dd', Fig. 1(b);
3. Make after magnetization: 8 mm due to cc', Fig. 1(c);
4. Make after demagnetization: 34 mm due to aa', Fig. 1(d).

It is evident that the phenomenon is much more pronounced after demagnetization than after magnetization. This is to be expected, because as we approach saturation the magnetic state becomes increasingly rigid. Also the relative changes of flux are found to be larger after quick than after slow demagnetization, although the actual changes involved are smaller, because quick demagnetization results in a smaller residual flux than when the magnetism is gradually reduced.

In Table I are listed eight essentially different cases. Each of the galvanometer throws indicated under $+I$ or $-I$ is the average obtained from four different cycles. These four values agree fairly well among themselves, especially after demagnetization, which shows that an individual case is not much influenced by the rest of the cycle.

DISCUSSION OF RESULTS

It will be seen that after magnetization the deflection is listed as positive to indicate an increase of flux, while the negative sign after demagnetization indicates a decrease as would be expected. The first two columns of figures are those already discussed. The other values for an axial current will be explained later. The column indicating the relative change due to a reversal of I shows that in some cases the change is very marked and is never less than 12 percent. This effect can be explained by supposing two major effects, A and B, and a third minor one, C. The first of these, A, is the well-known "shock effect" which alters the magnetization as a result of a mechanical jar or a sudden rush of current, independent of its direction. The second, "B effect," accounts for the change of deflection when I is reversed. It is this phenomenon with which the present discussion is chiefly concerned, and it is apparently not accounted for by classical electromagnetic theory.

The C effect is due to the action of the circular flux set up in the bar by the current flowing through it. This circular flux might be supposed to explain the effect of reversing I, but it was shown to be much too small to account for the magnitude of the observed phenomena. A crucial test proving this fact was made as follows. Instead of sending I through the nickel, it was carried in a wire along the axis of the cored cylinder. Thus only two effects were possible, namely, shock and the interaction between the circular flux set up by the axial current and the longitudinal flux in the bar. This interaction, in spite of the slot, designed to minimize circular flux, must also occur to some extent when the current flows through the metal. But calculation, as stated in the earlier article,[1] shows that the circular flux is 2.5 times as large when the current is axial, so we should now expect it to assume some importance. Thus though the shock effect must be independent of the direction of I, the influence of the circular flux should result in somewhat different galvanometer throws when I is reversed.

The results obtained with the axial current, keeping all other conditions the same as before, are given in the last three columns of Table I. It will be seen that the galvanometer throws are similar to those previously obtained. But, though of the same general magnitude, the lower value of the various pairs is now nearly equal to the higher values and the proportional decrease does not exceed 9 percent obtained in case number 4 as compared to 23 percent previously observed. It goes down practically to 0 percent as compared to 51 percent in case number 8. The differences caused by reversing I when it is axial are probably due to circular flux, but though observable in all but case number 8, it is relatively small, and since the axial current is 2.5 times as effective in setting up a circular flux as the current through the bar itself, we may be justified in dividing the percentages by that figure. Then the largest proportional change of 9 percent would be reduced to 3.6 percent as compared to 23 percent when the B effect as well as the C effect is present. Thus the C effect is shown to contribute something but not a great deal to the change of deflection brought about by reversing I.

ANALYSIS OF RESULTS

Since we are now justified in neglecting the relatively small C effect as an explanation of the observed phenomena, there remain the A and B effects to be considered. These may be separated as follows. The shock effect in nickel always involves an increased flux after magnetization and a decreased flux after demagnetization, for nickel, unlike Norway iron, shows no evidence of "overshooting the mark." This means that shock tends to carry the flux nearer to its final stable value. But the B effect tends to help or oppose this return to a stable state according to its direction, and whether or not reaching the stable state calls for an increase or decrease of magnetization. Thus if we call the change of flux caused by shock ΔA, and that caused by the B effect ΔB, we have $\Delta A+\Delta B=M$ when the effects are in the same sense, and $\Delta A-\Delta B=N$ when they are opposed. Thus $\Delta A=\frac{1}{2}(M+N)$ and $\Delta B=\frac{1}{2}(M-N)$. Applying this method to case number 7 (the most conspicuous one) we obtain from the galvanometer readings (proportional to ΔA and ΔB) $\Delta A=\frac{1}{2}(23+49)=36$ which is proportional to the shock effect, and $\Delta B=\frac{1}{2}(49-23)=13$ which represents the B effect caused by $+I$ flowing during the process of demagnetization. The same analysis applied to case number 3, for instance, gives $\Delta A=38.5$ and $\Delta B=4.5$. If this analysis is applied to the corresponding cases when the current is axial, we may separate the A and C effects. Thus case number 7 gives $\Delta A=46$ and $\Delta C=1$, while in case number 3 $\Delta A=52.5$ and $\Delta C=1.5$. These results seem to justify ignoring the effect of circular flux in estimating the B effect when the current flows through the bar, although strictly speaking the values 13 and 4.5 obtained above are partly due to C as well as B but with ΔC considerably smaller than 1 and 1.5 for reasons already mentioned. Aside from circular flux, other possible explanations of ΔB caused by reversing I are dissymmetry of the bar itself due to crystalline structure, and the effect of the magnetic field of the earth to which it was parallel. Both these were shown to be negligible by reversing the magnetizing current. When this is done, substantially the same values as before are recovered provided I is also reversed. Several cycles were carried through in this way, with practically the same galvanometer readings as before.

DISCUSSION OF RESULTS

To sum up the results, it seems safe to conclude that the B effect represents some apparently new kind of interaction between current and flux Φ, favoring Φ when it flows in the opposite direction and opposing Φ when in the same direction. Thus we may imagine a pure shock effect caused as by a mechanical jar tending toward magnetic stability with a bias due to B added to it or subtracted from it according to the direction of the current with respect to the flux. This effect exists in nickel, but to a much smaller degree, if at all, in a bar of Norway iron which was carefully examined with a view to detecting a possible alteration in the galvanometer deflection when I is reversed.

Finally the question naturally arises: Is there a reciprocal phenomenon? That is, if making or breaking a longitudinal current, aside from the effect of shock, alters the magnetic state of the iron, does a varying magnetic field alter the current? This would mean a change in the effective resistance of the bar. To test this possibility, bars of soft iron and of very pure nickel kindly donated by the International Nickel Company were wound with a double-layer solenoid and magnetized by an alternating current of 60 cycles. Their resistances both magnetized and demagnetized were measured in a Kelvin double bridge. The iron exhibited no observable change of resistance, but the resistance of the nickel was decreased by more than 0.6 percent when the field was applied, and remained at the lower value as long as the alternating current was flowing. There was of course a decided gradual increase of resistance caused by rising temperature, but during the short time needed to measure its new and smaller value, when the alternating field was applied, the rise due to higher temperature was much too small to obscure the phenomenon.

It has long been known that a steady longitudinal field raises the resistance of nickel measured in the same direction, that the relative increase, $\Delta R/R$, is unaltered by reversing the field, and that this magnetoresistance effect is associated with the still older phenomenon of magnetostriction.[2] But apparently the effect of a rapidly alternating field has not been examined, and it is certainly surprising to find that such a field *lowers* the resistance even more than it is increased by a steady field. This increase was also measured with similar excitation by the author and it was found to be between 0.5 and 0.6 percent instead of over 0.6 percent with an alternating current. In both cases the flux density was about 1900 gauss which was unnecessarily high, as the saturation flux density for this effect is of the order of 100 gauss.

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[2] L. W. McKeehan, Phys. Rev. **36**, 948 (1930).