A COMPARISON OF THE LONGITUDINAL AND TRANSVERSE JOULE MAGNETOSTRICTIVE EFFECTS IN THE SAME SPECIMENS OF STEEL AND NICKEL.

BY S. R. WILLIAMS.

THE interesting discovery made by Joule[1] that a rod of iron would change its length when subjected to a longitudinal magnetic field led to his investigation of the effect of a transverse field upon the length of a piece of iron. In order to get a transverse field imposed upon an elongated specimen of iron, Joule sent an electric current through an insulated wire inside of an iron pipe. The circular magnetic field about the wire in the pipe produced a field normal to the length of the pipe whose change in longitudinal dimension was to be measured. The primary object of this latter investigation by Joule was to discover whether or no volume changes occurred when the iron was magnetized. Joule had no facilities for obtaining high field strengths, hence his results show that in the longitudinal effect only an elongation occurred and in the transverse only a shortening. From this relation he concluded that there was no change in volume.

It is to Bidwell[2] that we owe the extension of our knowledge of the effect of strong longitudinal magnetic fields on iron rods, viz., an elongation for weak fields and a contraction for strong in which for the latter there were certain field strengths which made the specimen shorter than in its virgin state. The question therefore arises as to whether the transverse field produces opposite effects to those of the longitudinal for all field strengths, *i. e.*, will the transverse effect be an elongation, for strong fields in the case of iron?

In 1894, Bidwell[3] contributed two short articles bearing upon the longitudinal and transverse effects which occur in iron rings when they are magnetized. Since the appearance of the papers by Joule and Bidwell, little or no additional work has been done on this subject. Because this subject has an important bearing upon a working hypothesis of magnetization which the author has used with considerable success in

[1] Joule, Phil. Mag., p. 76, Vol. 30, 1847.
[2] Bidwell, Proc. Roy. Soc., 1885–1890. See Trans. Roy. Soc. also.
[3] Bidwell, Proc. Roy. Soc., 1894.

other magnetic phenomena, it seemed desirable to compare these two effects of magnetization in the same specimens of ferro-magnetic substances. The hypothesis, on which the writer has been working, indicates that qualitatively there should be this reversal for all field strengths in all ferro-magnetic substances, and since the work of Bidwell did not attempt specifically to compare these two effects, but to determine volume changes due to magnetization, it seemed not out of place to present some results which have been obtained upon this subject. Bidwell used toroids in the investigation of the changes in length due to longitudinal and transverse fields. One advantage of the toroid is that, since there are no free poles developed, there is no demagnetizing field, and hence the magnetizing force is the same as the magnetic field which would exist inside of the magnetizing coil without an iron core. There is, however, a practical objection to this form in that every sample of ferro-magnetic substance to be tested requires winding with a magnetizing coil and since this must be done by hand the process is one which consumes a great deal of time. Bidwell's work is limited to two specimens of iron, one in the annealed and the other in the unannealed state. So far as the author knows this has been the extent of comparative work done on these two effects.

In the experiments described below, measurements of changes in dimensions were made upon two specimens of steel and two of nickel, the transverse effect in nickel being measured with considerable difficulty. I wish here to express my thanks to Mr. Paul Weeks, one of our advanced students, for the help and skill in carrying out the measurements.

Methods.

There seem to be two ways of comparing these two magnetostrictive effects. Let A, B, C, D, Fig. 1, represent the cross-section of a cube of steel to which has been applied a magnetic field, H, in the direction indicated. Obviously if the change in length of AC is measured as the field, H, is varied, we have the ordinary longitudinal Joule effect, whereas if DB or the length normal to the page is measured we have the transverse Joule effect. This is the method which Bidwell used in measuring the two effects, *i. e.*, keeping the direction of the magnetic field fixed he measured the variations of two dimensions at right angles to each other, one of which was parallel to the field applied.

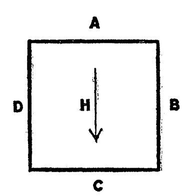

Fig. 1.

The other method is to apply the field, H, as indicated and measure changes in AC, then apply the field parallel to DB and again measure AC.

In this case the dimension whose change in length was measured has been the same and the field has been applied in two directions at right angles to each other, one of which was parallel to the dimension whose variation was measured.

Both methods are open to question, but the latter seemed to have fewer objections than the first, particularly for specimens whose ratio of length to diameter was several hundred. If the first method is pursued the aeolotropic condition of the material will certainly produce a coefficient of change of length different in one direction from that in the other, consequently the comparison of the two changes cannot be made quantitatively. On the other hand when the field is applied in two different directions the aeolotropic nature of rolled and drawn metals prevents the securing of similar fields, as we should have for quantitative comparative tests. The latter method is most readily applied to specimens in long rod or tube form. It seemed, therefore, that conditions most nearly alike in these two effects could be secured when the direction of the field was varied and the direction of the dimension to be measured was kept the same. In other words no absolute comparative tests can be made of these two magnetostrictive effects unless one has a perfectly homogeneous specimen with which to work. So far as the author knows no such samples are obtainable. The author has started work to see what can be done in cast specimens. This study is therefore concerned with a qualitative comparison of the two magnetostrictive effects in the same specimen.

The first specimen of steel was a piece of water pipe, 30.74 cm. long, and whose inner and outer diameters were 10.20 and 11.35 cm. respectively. The wire was wound about it in the form of a toroid, Fig. 2, but not placed directly in contact with the steel so as to restrict the expansion of the cylinder. This was accomplished by winding the insulated wire about a wooden framework which consisted essentially of two wooden rings, R, R, held apart by small brass rods not shown in the figure. The windings were of No. 13, double cotton covered, copper wire, B. & S. gauge, making three hundred turns in all. The value of the circular field was calculated from the equation,

$$H_c = \frac{2nI}{10r},$$

where n indicates the number of turns, I the current in amperes, and r equals 10.77 cm., the mean radius of the iron cylinder.

The change in length of the cylinder was measured by means of the displacement of interference bands produced by the light reflected from the two glass surfaces, g, g, shown in Fig. 2. Light from a sodium flame, S, was reflected by the mirror, M, down to the optical surfaces of g, g and thence reflected back by nearly the same path to an observing micrometer microscope. This optical device for measuring the change in length could be used without disturbing the system both in the longitudinal and transverse effects. The method of observing the displacement of the bands was to locate the position of one band with a fixed cross-wire in the micrometer eye-piece and then set the movable cross-wire about where the band would come when the field was applied. After a trial or two the distance between the movable and fixed cross-wires would represent with considerable accuracy the displacement of the band. Knowing the width of the band it was possible to determine the amount of the change in length of the steel cylinder. This method of measuring the shift did not require the magnetizing current to be left on for any length of time and consequently heat effects were minimized.

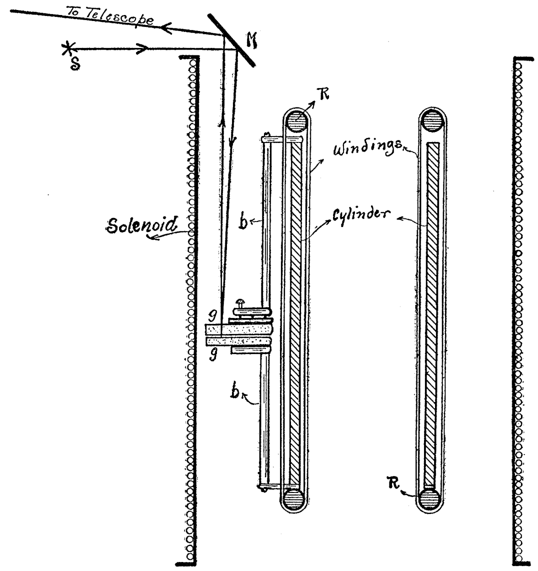

Fig. 2.

The change in length was measured as the field was increased from zero upward, with several makes and breaks of the circuit for each field strength measured. Successive sets of readings were taken in this way and the mean results are plotted in Curve 2, Fig. 3. Demagnetization by reversals occurred after each series of readings.

The longitudinal effect was obtained by placing a solenoid of a large cross-section around the toroid as shown in Fig. 2. The axis of the toroid coincided with that of the solenoid. The ends of the cylinder were 11.5 cm. back from the ends of the solenoid. The current both for the toroid and the solenoid was supplied by a storage battery. The measurement of the change in length due to the longitudinal field was

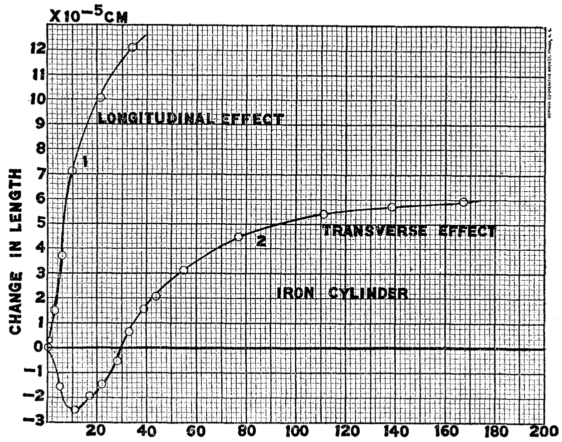

Fig. 3.

carried out in exactly the same way as for the transverse field. The results are shown in Curve 1, Fig. 3, after making corrections for the end effects of the solenoid and the demagnetizing effect of the cylinder itself.

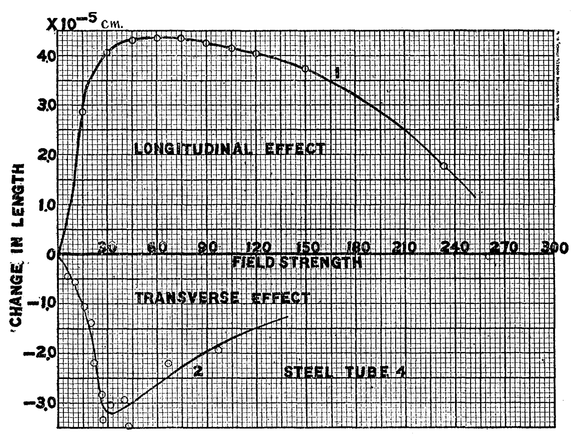

Fig. 4.

The solenoid had a length of 53.7 cm. and an average diameter of 28.74 cm. There were six layers with a total number of 1,466 turns.

The next specimen tested was a steel tube 80 cm. long and 0.297 cm.

in mean radius. This is known as tube 4 in previous investigations.[1] The device for measuring the changes in length due to the longitudinal and transverse fields was the same as used in former work. The transverse field was obtained by passing a current through only a few turns of insulated wire inside of the tube and consequently not very large fields could be obtained. The results are shown in Curves 1 and 2, Fig. 4.

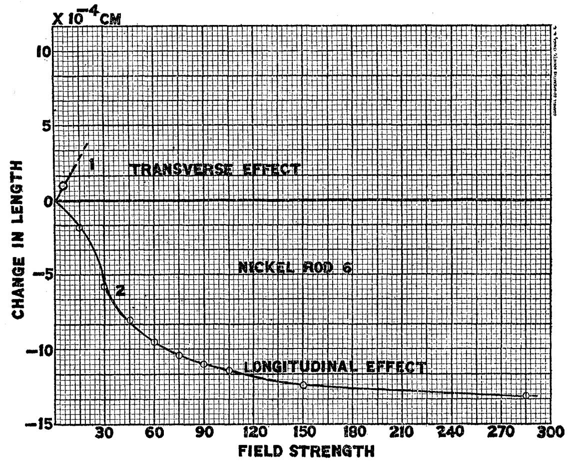

Fig. 5.

For the two specimens of nickel which were tried, much more difficulty was encountered in measuring the change in length for the transverse field than was experienced with the steel samples. This was due to the sensitiveness of nickel for heat effects. Curves are shown for only one specimen as the two were similar. For the few field strengths which could be measured only an increase in length was found which is the reverse of that for the longitudinal field (Fig. 5).

Discussion of Results.

Roughly, the curves seem to indicate this reversal of effect when the longitudinal and transverse fields are applied. The results obtained from the long specimen (80 cm.) seem the most trustworthy. The large demagnetizing factor for the short steel tube decreased the effective value of H, the field of the solenoid, to so large an extent that large field values could not be obtained for comparison. The values for the demagnetizing factors used were obtained from equations given by Ewing[2] and applied to a hollow cylinder, just as one would to a solid cylinder. This was done because Grotrian[3] has shown that for fields which do not attain

[1] Phys. Rev., p. 261, Fig. 7, Vol. 34, 1912.

[2] Ewing, Magn. Induc. 3d ed., p. 25.

[3] Grotrian, Annal. der Physik, Vol. 52, p. 735, Vol. 54, p. 452.

values giving a saturated condition the demagnetizing factors of solid and hollow cylinders are practically the same. As to the reversal of effects, suppose one had a homogeneous specimen of a ferro-magnetic substance and assumed that the turning of the elementary magnets was the cause of the changes in length; then if the elementary magnet had the form of an oblate spheroid it would be easy to see why the application of a transverse field produced the reversed effect to that brought about by the longitudinal field. I have indicated this possibility in a former paper.[1] If the curves shown there for the single elementary magnet held for the group, then qualitatively the longitudinal and transverse effects should be the reverse of each other; but as pointed out, the aeolotropic condition of the specimen precludes any exact relation occurring in ferro-magnetic substances in drawn and rolled samples.

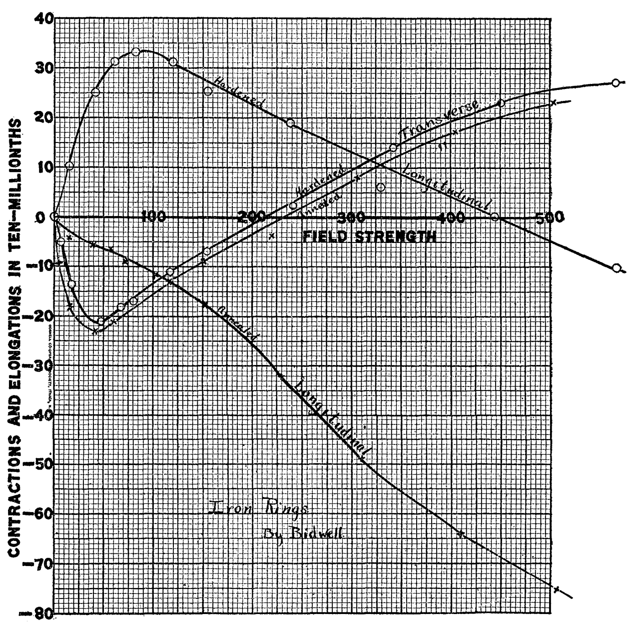

Fig. 6.

Bidwell[2] states that he had a specimen of iron which showed a contraction for all field strengths, and cites it as the only specimen which has yet been found showing this phenomenon. The author has found a specimen of steel which to all appearances showed the same phenomenon. Not until a much larger multiplying power of the device for indicating the change in length was used did it show a very small

[1] PHYS. REV., p. 40, Vol. 34, 1912.

[2] Bidwell, Proc. Roy. Soc., Vol. 56, 1894.

increase in length for weak fields. If this was the case with Bidwell's specimen then his work would be still more confirmatory of the reversibility of the two effects. His results are shown graphically in Fig. 6. Bidwell's specimens were very small while the rods and tubes used in my work were 80 cm. long and consequently gave an advantage for multiplying the effect.

As one studies the various theories of magnetism he is impressed with how little they have to say regarding magnetostrictive effects and yet if one should classify the various magnetic phenomena, the various magnetostrictive effects would make the major part of the phenomena. One is reminded of the words of Joule,[1] that "when we are able to answer some of the questions regarding magnetostrictive effects in a satisfactory manner we shall probably have a much more complete acquaintance with the real nature of magnetism than we at present possess."

Summary.

1. The results show a qualitative reversal of the two effects as the planetesimal hypothesis would indicate.

2. An exact quantitative reversal is not to be expected for several reasons: (*a*) non-homogeneity of the specimens, (*b*) in the transverse field there is not a uniform magnetic field applied, varying inversely as the distance out from the center of the specimen when the specimen is a hollow cylinder and the current is conducted through an insulated wire inside of the cylinder. In case the specimen is a solid cylinder then the field varies inversely as the square[2] of the distance from the center because the current flows in the specimen itself as a conductor, (*c*) the elementary magnets affected by the longitudinal field will be different from those influenced by the transverse field.

3. This comparison of the two Joule magnetostrictive effects should, according to previous investigators, give some clue as to change of volume. Knott[3] was undoubtedly the first to show that magnetization is generally attended by considerable change in volume, but later investigators did not find a relation existing between different specimens for volume changes which they had found for changes in length. For instance, since iron elongates and nickel contracts for initial field strengths, one might expect a difference in behavior of volume changes. Such is not the case as pointed out by Nagaoka and Honda.[4] Both metals increase in volume by magnetization. From the standpoint of

[1] Joule, Phil. Mag., p. 76, Vol. 30, 1847.
[2] Northrop, Phys. Rev., Vol. 24, p. 479, 1907.
[3] Bidwell, Proc. Roy. Soc., vol. 56, 1894, p. 99.
[4] Nagaoka and Honda, Phil. Mag., Vol. 4, p. 71, 1902.

the planetesimal hypothesis, change in volume arises from the changed piling of the elementary magnets due to their orientation and there should be no particular relation between volume changes and the other magnetostrictive effects just as Nagaoka and Honda have shown.

4. This work points out why Berget[1] in working with a cylindrical bar measuring 5.2 cm. long and 1.95 cm. in diameter found that the length of the bar was still increasing at a field strength of 540 units. He neglected to take account of the demagnetizing factor which I have done in the case of specimen 1. The desirability of using long thin specimens in measuring the various magnetic effects is here again pointed out.

5. A complete theory of magnetism must explain the various magnetostrictive effects as well as the other magnetic phenomena.

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[1] Berget, Comp. Rend., p. 722, Nov. 7, 1892.