ANHYSTERETIC MAGNETOSTRICTIVE EFFECTS IN IRON, NICKEL AND COBALT

By Paul McCorkle

Abstract

(1) *Effect of tension on the intensity of magnetization.* This is a continuation of previous work,[1] using the same specimens of iron, nickel and specially pure cobalt. In order to eliminate the effect of hysteresis, use was made of an alternating field of 1500 cycles, superposed at suitable intervals. Use of this field led to a convenient method of compensating for the earth's field. In the case of iron, with a weak field (0.85 gauss), the first effect of tension in a freshly annealed specimen is an increase to a maximum, but successive cycles of loading caused this initial increase to disappear. For a field of 1.55 gauss the effect was a decrease from the start, the effect increasing more rapidly than the tension and being considerably greater than when hysteresis was not eliminated. In the cases of nickel and cobalt the effect is a steady decrease which in both cases increased less rapidly than the tension. The elimination of hysteresis greatly increased the effect in nickel (0.85 to 7.7 gauss) but not in cobalt (18 and 57 gauss). (2) *Effect of a longitudinal field on the length of specimen under tension* of 7.6×10^7 dynes/cm^2 was an increase in the case of iron, a decrease in the case of nickel. In both cases, elimination of hysteresis increased the effect for fields below 15 gauss. The effect for cobalt was too small to measure. The thermodynamic relation between the two effects $(\partial I/\partial F)_H=(\partial L/\partial H)_F$, where F is the tension, is not satisfied by the results obtained. Until the irregularities and discrepancies between different specimens are eliminated, agreement is hardly to be expected.

In a previous paper[1] results were given for various magnetostrictive effects in iron, nickel and a specimen of especially pure annealed cobalt wire. As a continuation of this work, a study was made of the effect of tension upon the intensity of magnetization in the same specimens. A survey of the work of other investigators on this effect emphasizes the important role which hysteresis plays in making the results complex. Ewing,[2] studying the effect of tension on intensity of magnetization in iron and nickel, found that for the initial loadings in the case of iron the results are very peculiar, but that after several repetitions of loading and unloading, a condition is reached called cyclic in which there is more regularity. There is still, however, marked evidence of the effect of hysteresis. His results showed that nickel was influenced less by hysteresis than iron. The effect of tension on the intensity of magnetization has been investigated by many other workers, but perhaps the most

[1] McCorkle, Phys. Rev. **22**, 272 (1923)

[2] Ewing, Magnetic Induction in Iron and other Metals.

careful study was made by Honda and Terada.[3] In no case so far as is known has any attempt previously been made to eliminate hysteresis completely in such experiments.

Various investigators have devised methods of reducing hysteresis in connection with magnetization experiments. These methods consist

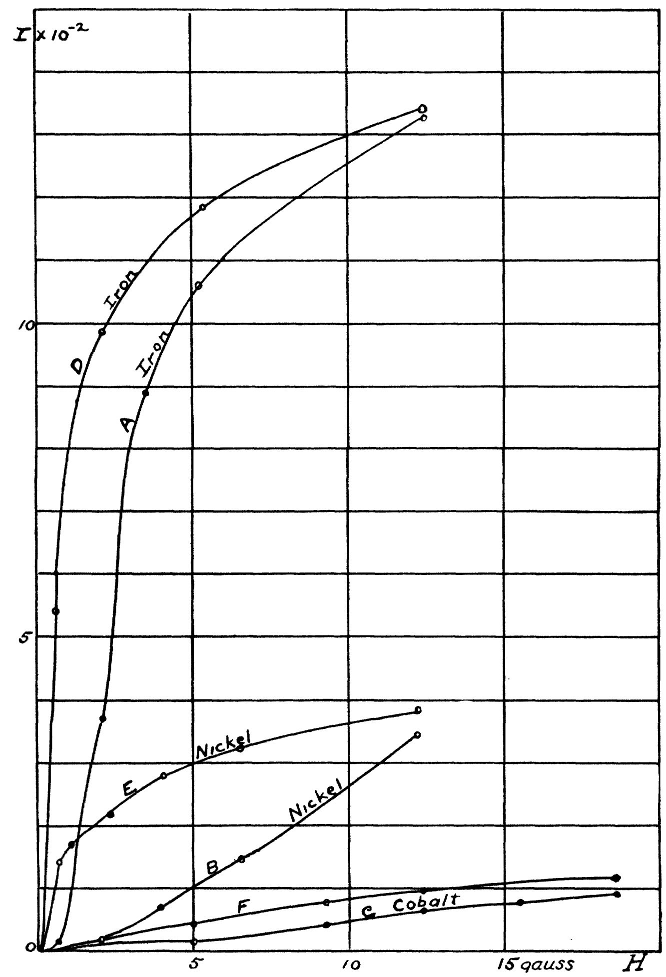

Fig. 1. Intensity of magnetization as a function of field H. Curves A, B, C; with hysteresis. Curves D, E, F; with no hysteresis.

for the most part in superposing various alternating and oscillatory fields upon the magnetizing field. Maurain[4] made a careful comparative study of the efficacy of the various fields and found that the type of field

[3] Honda and Terada, Phil. Mag. **14,** 65 (1907)
[4] Maurain, Jour. de Phys. **3,** 417 (1904)

to be used depended largely upon the type of specimen to be studied. If the Ewing magnetometer method of measuring the intensity of magnetization is used, one of the most satisfactory methods for the elimination of hysteresis is to apply an alternating field after each step in the magnetizing process. The procedure is to apply a magnetizing field of small value and follow with the alternating field, varying its amplitude from zero to a maximum and back to zero. The result of applying this field is to cause a sudden jump in the intensity of magnetization to a new value. (Fig. 1.) In the case of iron the effect is very pronounced, a near approach to saturation being reached in very small fields.

The solenoid used in the experiments consisted of a brass cylinder with three concentric windings. The innermost one was used for the magnetizing current, the middle one for the alternating current and the outer one for the current used to neutralize the vertical component of the earth's field. The solenoid was sufficiently long so that the field was practically uniform over the length of the specimens, 23 cm. A Ewing magnetometer was used to measure the intensity of magnetization. The specimens were the same as used in the previous work.[1]

The method just described accidentally provided a very convenient method for the compensation of the vertical component of the earth's field inside the solenoid, which is usually a troublesome process. In order to neutralize the earth's magnetic field, the zero position of the magnetometer needle was determined and a wire or thin rod of iron or nickel was hung in the center of the solenoid. This produced a deflection, due partly to the magnetization caused by the earth's field and partly to residual magnetism in the specimen. The alternating field was now varied from zero to about 15 gauss and back to zero. The result was a large deflection of the needle of the magnetometer because of the fact that the alternating field had greatly increased the intensity of magnetization of the specimen. A small compensating field was now applied in the proper winding and the alternating field again applied. If the compensating field was in the right direction the deflection was smaller than before. A few repetitions of the process brought the needle back to the zero position. The method had the great advantage that it could be used at any time without disturbing the adjustments and was also very sensitive.

In attempting to use this method for reducing hysteresis in connection with the study of the effect of tension on intensity of magnetization, several difficulties are at once met. An alternating field of ordinary frequency disturbs the magnetometer needle to some extent, and in consequence the small variations due to the change of intensity of magnetization when the specimen is under tension may be partly masked. Another difficulty is the heating due to the eddy currents in the specimen, which becomes more troublesome the higher the frequency used. Various frequencies were tried and it was found that a 1500 cycle current which was available in the laboratory was quite satisfactory in all respects. By means of a combination of water and slide wire resistances, the current could be varied rapidly and continuously to very low values, a very essential feature. In order to investigate the possibility of heating, a test was made with a thermocouple, and it was found that the temperature change was quite small. In view of the fact that susceptibility varies very little with small variations in room temperature, no especial precautions were taken to keep the temperature accurately constant.

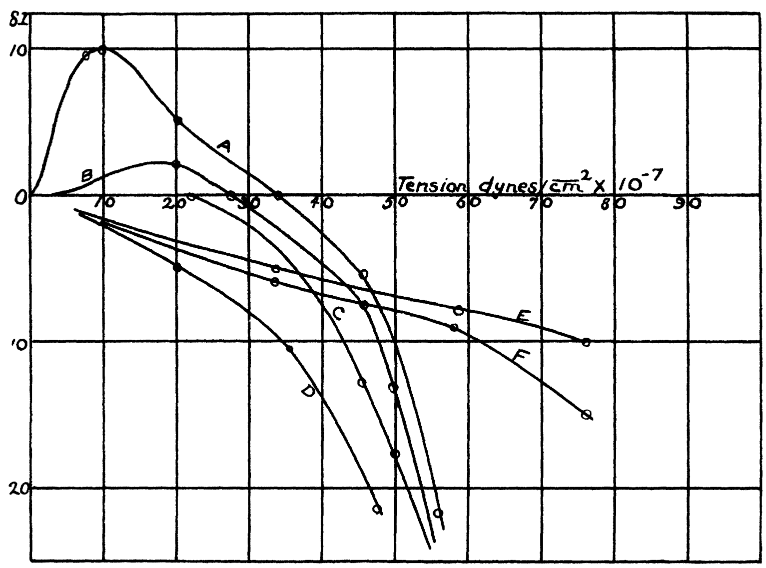

Fig. 2. Change of magnetization of iron due to tension in a field H. For curves A, B, C, $H=0.85$ gauss. For curves D and E, $H=1.55$ gauss. For curve F, $H=2.94$ gauss. Hysteresis eliminated for curves A, B, C and D only.

Effect of Tension on Intensity of Magnetization

An iron specimen was hung in the center of the solenoid, the earth's field was carefully neutralized, and a small magnetizing field (0.85 gauss) was applied. A load of one kilogram was hung on the specimen, and the alternating field varied from zero to 15 gauss and back to zero. The deflection being read, a new load was added and the process repeated. After sufficient loadings, keeping always below the elastic limit of the material, the loads were removed in the same manner. It was found that hysteresis had practically disappeared, the descending curve coinciding with the ascending one at practically all points. In a few cases mechanical oscillations were superposed to remove the last traces of hysteresis. Determinations could only be made at low fields because of the large deflection of the magnetometer. Moreover the measurements at high fields are not important in this work because hysteresis is not a factor there. It was found (Fig. 2 curve A) that for a field of 0.85 gauss the effect of tension on a freshly annealed iron specimen was an initial increase in the intensity of magnetization to a maximum, a reversal, and finally a large decrease as the load was increased. As the process was repeated many times, it was noted that the initial increase began to disappear (curve B). The specimen was now re-annealed and upon test the initial increase reappeared. After about 40 cycles of loading this increase again disappeared (curve C). Evidently the cyclic state of the specimen determines whether an initial increase in the intensity of magnetization will occur.

With a field value of 1.55 gauss there was probably no increase in the intensity of magnetization (curve D). If any existed it was too small for observation.

Determinations were also made for fields of 1.55 gauss (curve E) and of 2.94 gauss (curve F), in which hysteresis was not eliminated. Comparison of curves D and E shows clearly the effect of eliminating hysteresis.

No explanation is offered for the shape of the curves which are concave downward. The general character of all the curves is the same. Any attempt to trace the curve further was prevented by the necessity of keeping the load well under the elastic limit of the specimen.

The study of this specimen of iron may help to explain the complex curves of Ewing. If the superposition of the a.c. field was stopped at an early stage of the loading process and the loads applied without further eliminating hysteresis, the iron appeared to be in a state of extreme instability. The needle of the magnetometer wandered about in such a manner as to indicate that rapid variations were taking place in the structure of the specimen. If the alternating field was now reapplied, the cyclic condition reappeared, and on additional loading the results were the same as in the previous determinations.

In the case of nickel the elimination of hysteresis increases the magnitude of the change in the intensity of magnetization caused by tension for all values of the tension and of the impressed magnetic field. Two sets of curves (Fig. 3) have been drawn to show the result of eliminating hysteresis.

It is of interest to compare the results of Honda and Terada[3] with those of this article. This comparison was made by determining from Fig. 1 the value of the intensity of magnetization corresponding to the magnetic field value for curves D, E, F, of Fig. 3, and for curve C of Fig. 2. The results of Honda and Terada were compiled for the same values of the intensity of magnetization and tension. Some interpolation was necessary to get corresponding values but the shape of the curves seemed to justify this proceeding. In the case of iron the agreement was only fair

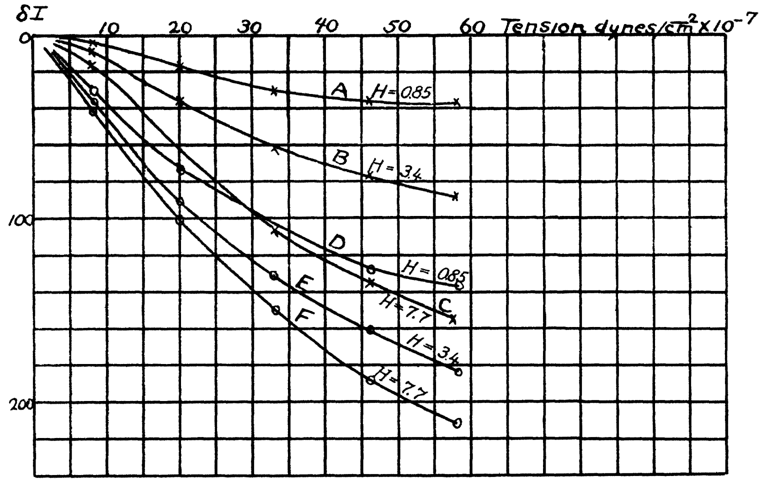

Fig. 3. Change of magnetization of nickel due to tension in a field H. Curves A, B, C; with hysteresis. Curves D, E, F; with no hysteresis. Curves A and D; $H=0.85$ gauss. Curves B and E; $H=3.4$ gauss. Curves C and F; $H=7.7$ gauss.

and the results are not shown. Some of the comparisons for nickel follow, for a tension of 5×10^8 dynes/cm².

	I	δI	H(gauss)
McCorkle	160	130	0.85
Honda and Terada	160	140	3.8
McCorkle	260	170	3.4
Honda and Terada	266	181	10.48
McCorkle	340	195	7.7
Honda and Terada	340	185	21.0

A possible explanation for this agreement in the values of δI is that in the low fields used, the change of the intensity of magnetization due to tension is a function of the intensity of magnetization rather than of the magnetic field. This deserves further study.

In the case of cobalt the elimination of hysteresis does not affect the change of intensity of magnetization as a function of the applied tension to a measurable extent. This is to be expected because of the small susceptibility of cobalt in low fields, and the small change of intensity of magnetization with elimination of hysteresis (Fig. 1). The curves (Fig. 4) give the result with hysteresis eliminated. No effect could be found with small magnetizing field values.

Change of Length with Longitudinal Magnetic Field

Because of the thermodynamic relation between change of intensity of magnetization with tension and change of length with magnetic field, it was of importance to study the change of length with hysteresis eliminated. The same alternating field was used. Before making determinations much time was spent in studying the heating effect and in devising ways to avoid it. It was found that nickel was extremely sensitive to

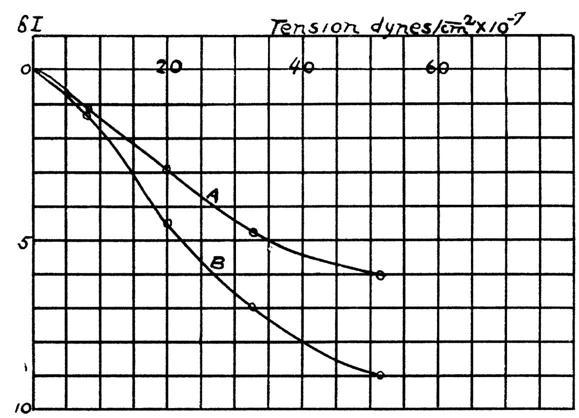

Fig. 4. Change of magnetization of cobalt due to tension in a field H. Curve A, $H=18.6$ gauss. Curve B, $H=57.3$ gauss. With no hysteresis.

eddy currents. However by making the time of application of the alternating field of the order of two seconds, the effect of change of temperature could not be detected by the highest magnification used in determining the change of length, about 85000. Unfortunately this short time may not completely eliminate hysteresis, but by far the greater part is removed as was shown by the previous experiment on the effect of tension on intensity of magnetization. Also inasmuch as the magnetic field produces a decrease in length in the case of nickel, and a rise in temperature would cause an increase in length, it is obvious that the observed change in length is not due to a rise in temperature of the specimen. In the case of iron the effect of eddy currents did not manifest itself so quickly and was not so troublesome where care was used.

The magnification device used to measure the change in length was a combination of a first class lever and an optical lever. The magnification of the first lever was 85, and that of the optical lever variable at will. All of the ordinary precautions were observed. The specimen was surrounded by a bath of water and was free from vibrations of mechanical origin. Readings were taken at night after traffic had ceased. The methods for varying the field were the same as in the previous paper.

The method of procedure was to determine first the time during which the alternating field could be used without causing an observable change of length. The earth's field being neutralized, the smallest value of the magnetizing field (1.2 gauss) was applied, and the change of length observed, if any. Another observer now applied the alternating field, and the change of length produced was noted. For the iron and nickel specimens this value of the magnetizing field gave no visible change of length, and the alternating field alone gave no change of length, but both fields together gave a definite result. This operation was repeated for various magnetizing fields and for different loads on the specimen.

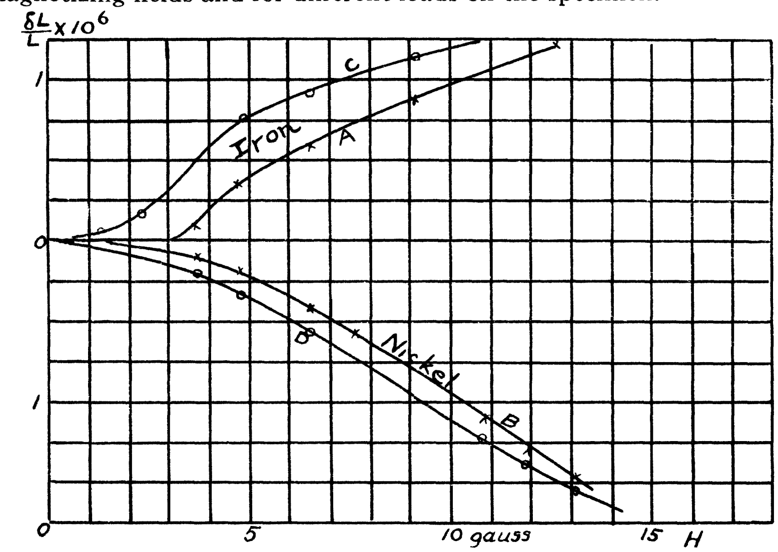

Fig. 5. Change of length with longitudinal field, for iron under a tension of 7.6×10^7 dynes/cm². Curves A and B; with hysteresis. Curves C and D; with no hysteresis.

In the case of iron and nickel the change of length for small fields was greater when the alternating field was used. However the maximum change of length was no greater when hysteresis was eliminated, the two curves (Fig. 5) intersecting at about 20 gauss. This would be expected because hysteresis is no longer a factor in fields of 20 gauss.

Repeating the cycle of operations on iron never produced any marked difference in the result. There was always a definite increase in the length with increase in the magnetizing field. In this respect the change of length caused by a magnetic field and the intensity of magnetization due to tension behave differently.

The change of length in cobalt could not be observed in the small fields used.

Theoretical Discussion

Consider a wire hung in a longitudinal magnetic field and acted upon by loads. Let F be the tension on the wire, L the length, I the intensity of magnetization and H the magnetic field. The elongation is due partly to F and partly to magnetostriction. If there is no hysteresis it follows from thermodynamical considerations[5] that $(\partial L/\partial H)F=(\partial I/\partial F)H$. Houstoun,[5] using data obtained by Honda, attempted to test this relation and found a qualitative agreement only. It was hoped that data obtained with hysteresis eliminated, a condition necessary for the correct use of the equation, might give better results.

In the case of iron, unfortunately, the data obtained depend to so great an extent upon the state of the specimen, as is shown in Fig. 2, that the curves for the two effects cannot be compared without some further knowledge as to the correct conditions for study. A comparison between these differential coefficients would therefore be of no value as a check for the theory.

In the case of nickel two comparisons will be given.

H (gauss)	F ($\times 10^7$ dynes/cm^2)	$(\partial I/\partial F)_H$ ($\times 10^{-7}$)	$(\partial L/\partial H)_F$ ($\times 10^{-7}$)
7.7	7.6	5.5	1
7.7	20	5.1	1

Several reasons may be offered as an explanation of the poor agreement shown. The accuracy of the measurements of the change of length in small fields is not great. Moreover the amount of the change of length seems to vary with different specimens for some unknown reason. A survey of results of other observers shows that some of their published data on the change of length would give a good agreement with the results here shown for the effect of tension on the intensity of magnetization. Other results give a far less satisfactory agreement. These variations must be reconciled before the thermodynamic relation can be completely tested. Cobalt gave insufficient data for checking the relation.

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October 7, 1924.

[5] Houstoun, Phil. Mag. **21,** 78 (1911)