

# Effect of Twist on the Magnetization of Nickel and Iron.

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Plate XXVII.

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The present paper is a continuation of one published some time ago under the title 'Combined effects of torsion and longitudinal stress on the magnetization of nickel.'\* The results there described were only for a single specimen of nickel, and moreover the range of twist to which the wire under examination was subjected was always the same, namely,  $\pm 4.5$  per cm. length of the twisted wire. The main facts established in that paper were as follows:—

When the nickel wire is twisted in a constant magnetizing field, the magnetization curve obtained during torsion and detorsion undergoes a gradual transformation as the amount of longitudinal stress acting on the wire is increased. Under low tensions, the magnetization increases on twisting, and decreases on untwisting. The nature of the hysteresis is such that the ascending branch of the curve is always above the descending branch, and the curve is quite symmetrical on both sides of zero twisting. On increasing the longitudinal stress, the magnetization curve becomes gradually deformed, while at the same time, there is great decrease of magnetization. Eventually when the loading reaches a certain value, one end of the wire acquires

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\* See this Journal Vol. II. pg. 283.

reversed polarity, and the curve which was double looped transforms into a single looped curve.

Now the question naturally suggests itself, can this curious phenomenon of the reversal of polarity as well as other remarkable characteristics in the magnetization of nickel be still observed in wires taken from different sources, and also for different angles of twist? The objects of the experiments now to be described are to fill in these gaps, and also to extend the investigation to the case of iron.

The method of procedure was exactly the same as in the former experiments. The intensity of magnetization was measured by the direct magnetometric method from the amounts of deflection of a magnetometer mirror. The wire was placed vertically within a solenoidal coil, and its upper end was magnetic east of the magnetometer mirror. A constant magnetic field was maintained within the solenoid; and as the wire was subjected to the given cyclic twisting, the deflections on the magnetometer scale were noted. The twist was applied by means of the twisting apparatus described in the former paper. The effects were examined for two specimens of nickel wire obtained from different manufacturers. They were of different diameters, being 0.86 mm. and 1 mm. thick respectively. The latter was the one used in earlier experiments. Each wire studied was first annealed by gently passing it over the flame of a spirit lamp three or four times.

As the object of the investigation was merely to examine the changes of magnetization, I have not thought it necessary to reduce the observed readings to absolute units; and consequently the numbers given are simply in terms of the scale unit. The reversal of polarity and other accompanying changes are so complicated that I have examined only a few particular cases, and most of the experi-

ments for nickel were performed under low tensions. The effects of torsion on magnetization are much simpler for iron than for nickel, yet in both there exists quite a curious change in the hysteresis as will appear hereafter.

### Effect of Twist on the Magnetization of Nickel.

The effect of cyclic twisting on the magnetization of nickel wire is itself a function of the magnetizing field and of the range of twisting, and passes through a distinct gradation of changes as this range is gradually increased. For small twists these changes are marked by many peculiar and interesting characteristics; and most of my experiments are limited to cases in which the twist is not very large. To examine the effect of longitudinal stress on the magnetization for each range of twist and for each magnetic field would be a matter of immense labour. I have therefore examined only a few cases in which the load was varied, and have noted some of the general features.

*Changes of magnetization for the twist of  $\pm 0^{\circ}86$ .*—The smallest amount of twist producing changes in magnetization, which could be measured with certainty, was about 0.9 per cm. A nickel wire, 0.43 mm. in radius and 35 cms. long, was well annealed, and placed in position, the longitudinal stress acting being only the weight of the small twisting rod and the brass wire connecting this rod to the lower extremity of the nickel wire.

The first experiment was performed in a field of 0.34 (C.G.S. electro-magnetic unit). The wire was twisted through  $\pm 30^{\circ}$  ( $0^{\circ}86$  per cm.) on both sides of the initial unstrained position. After the changes in magnetization became cyclic, the following readings of the deflections were taken.

Twist (positive).	Deflections.	Twist (negative).	Deflections.
0°	112.5	0°	109.5
10	107.4	10	110.4
20	110.1	20	120.0
30	121.1	30	132.4
20	117.9	20	128.8
10	113.0	10	122.2
0	109.5	0	113.7

The examination of the curve (Fig. 1, Plate XXVII.) will shew that on twisting the wire in the positive direction, there is a slight diminution of magnetization till the angle of twist amounts to about  $10^\circ$ , then the magnetization gradually increases up to  $30^\circ$ . On untwisting, the magnetization diminishes, but at a somewhat slower rate than it had just been increasing, so that the return curve lies above the other until the wire is nearly all untwisted. The same things happen during negative twisting and untwisting. Thus in the present instance, the course of the change of magnetization is quite different from what was obtained in my former experiments under like circumstances. There I found that when the nickel wire was twisted  $\pm 4.5$  per cm., the magnetization rose gradually till the maximum twist was reached, but on untwisting diminished at a somewhat quicker rate than it had just been increasing, so that the return curve lay below the other.\*

*Reversal of hysteresis.*—Comparing these two experiments, we find that there is true lagging or hysteresis in magnetization when the

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\* In my former paper, I spoke of Fig. 5 (Pl. XVI.) as being exactly the reverse of Thomson's curve for iron, but I was mistaken; had the course of the curve been as for the twist of 0.86, it would have been so, but not otherwise.

Compare also Professor Wiedemann's curve (Fig. 4) in his paper *Magnetische Untersuchungen* (Wied. Ann, Bd. XXVII, 1886).

range of twist is small, but that when the range is large there is a 'priming' in magnetization rather than a lagging.\* Now we are quite warranted in using the word hysteresis in both senses, just as acceleration in dynamics includes retardation. We may speak of positive and negative hysteresis; and express the phenomenon just described as a reversal of hysteresis, occurring probably at some twist intermediate to the two just named. How this reversal of hysteresis is affected by various conditions such as the quality of nickel, the strength of the magnetizing force, the amount of twist, &c., is a very obvious matter for investigation.

*Effect in stronger fields.*—With the same wire and other conditions being the same, the field was taken stronger and stronger. Very similar effects were obtained as may be seen from Fig. 2, which corresponds to a field  $\mathfrak{H}=11.9$ . In Fig. 3, however, a change begins to shew itself. The field is now 13.8, and the particular wire examined was a new piece cut from the same specimen. It will be noticed that the range of change is much diminished, but that the character of the hysteresis is still the same as before. When the strength of the magnetizing force is increased to 18.7 units, the magnetization curve (Fig. 4) wears quite a different aspect. On first twisting, the magnetization diminishes as in the former cases, but it never passes a minimum, although the rate of fall becomes very slow towards the limit of twist. On untwisting, there is gradual increase of magnetization, but it is always smaller for the same angle of twist, than it was during the operation of twisting. Thus there is hysteresis in the proper sense of the word. Further twisting in the opposite direction produces a similar succession of changes, although the curve is not quite symmetrical about the line

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\* I was not aware, until my own experiments were all completed, that this phenomenon had been observed by Mr. Imagawa. See the preceding paper, by Dr. Knott.

of zero twist. The curve of magnetization for stronger fields (Fig. 5) are similar to the aboves, the range of the change of magnetization becoming apparently greater as the magnetizing field is increased.

*Reversal of polarity for the twist of  $\pm 0.86^\circ$ .*—The next wire used was taken from the same specimen as before. A weight of 5 kgs. ( $881 \text{ kg. cm}^{-2}$ ) was strung to the end of the brass wire attached to the lower extremity of the nickel wire. After the wire was brought to the cyclic condition by repeated torsion and detorsion in a field of 0.34 unit, the following deflections were taken.

Twist (positive).	Deflections.	Twist (negative).	Deflections.
0	11	0	10
10	2	10	19.5
20	— 8	20	29
30	—17	30	41
20	— 9	20	33
10	0.6	10	23
0	10	0	11.5

These readings shew that, in the given field, the amount of longitudinal stress was sufficient to produce the phenomenon of reversed polarity. The magnetization curve (Fig. 6) when compared with the corresponding curve for the twist of  $\pm 4.5^\circ$  again indicates how the changes of magnetization differ in these two cases. In former experiments, there was always increase of magnetization on first twisting, and decrease on untwisting, the hysteresis being negative. In the present instance, there is steady decrease of magnetization during positive twisting, and increase during untwisting. Besides, as the twist at either extremity begins to be undone, the magnetization lags behind, so that the hysteresis is positive.

These experiments sufficiently prove that the reversal of polarity

takes place in different specimens of nickel, and also for different amounts of twist. The curve representing the changes of magnetization when the polarity suffers reversal is, as already noticed, single looped, whereas we get double looped curves in cases where there is no reversal of polarity, that is, in cases in which the longitudinal stress is sufficiently weak. Hence in the present case we should expect that, by gradually increasing the magnetizing force, until the longitudinal stress of 5 kgs. weight is insufficient to cause reversal of polarity, we shall be able to transform single looped into double looped curves. The experiment when made fulfilled the expectation, as may be seen from Fig. 7. Here the field is 5.0 units; the curve has ceased to dip below the zero line so that the polarity is not reversed. At the same time, the curve, though unsymmetrical with respect to the line of zero twisting, turns out to be double looped. On further increasing the field the two loops become more and more symmetrical (see Fig. 8). Thus the question as to whether a given curve will be single looped or double looped seems to depend on the existence or non-existence of the phenomenon of the reversal of polarity. What has been stated in my earlier paper with respect to the form of the magnetization curve for the twist of  $\pm 4^\circ.5$  per cm. is also applicable for that of  $\pm 0^\circ.86$  per cm. There is, however, a remarkable difference in the change of magnetization which may be expressed by saying that there is reversal of hysteresis between these two different twists.

*Reversal of hysteresis for the twists of  $\pm 1^\circ.5$  and  $\pm 1^\circ.3$ .*—In the next series of experiments, the twists were taken larger. A wire 40 cms. long and 1 mm. thick was set in various magnetizing fields, and twisted through a total range of  $\pm 60^\circ$  or through a twist of  $\pm 1^\circ.5$  per cm. The only longitudinal stress acting was the weight of the twisting rod and the brass wire attached to the end of the

nickel wire. Out of the many curves obtained in this series, I give only three, those namely which correspond to fields of 2.8, 15.3, 21.1 units respectively. The first two curves (Fig. 9 and Fig. 10) have the same characteristics as those obtained for nickel twisted through  $\pm 0^\circ.86$  per cm. There is still true lagging on untwisting. But the third curve (Fig. 11) for  $\mathfrak{S}=21.1$  is not similar to the corresponding curves represented in Fig. 7 and Fig. 8. The curve in its general form is like those obtained for smaller twists, but the nature of the hysteresis has been changed. The hysteresis which has been positive for the two former curves becomes negative for this strength of the magnetizing force. The magnetization diminishes on twisting till the extreme limit of torsion is attained, and on untwisting it gradually increases. If the magnetization had tended to lag behind, as was found to be the case for the smaller twist, the return curve would have been the lower. But this is no more the case; the curve on untwisting passes above that of twisting, and thus there must have been reversal of hysteresis for this strength of the magnetizing force. It is at once apparent that the strength of the magnetizing field is one of the principal factors affecting the phenomenon of the reversal of hysteresis.

In order to investigate this change more thoroughly, a new wire was taken from the same bundle, and examined in fields  $\mathfrak{S}=16$  (Fig. 12) and  $\mathfrak{S}=20.8$  (Fig. 13). The former curve shows that there is decrease of magnetization up to a certain amount of twist, but on further twisting there is increase. This increase, however, is so small that it is barely sufficient to attain the original intensity even at the extreme limit of twist. On untwisting, the magnetization gradually diminishes but increases again, passing through a minimum value before the wire is completely brought back to its initial position. This peculiarity of a minimum on untwisting had never been



noticed before for the smaller twists. On increasing the field to 20.8 units, another change takes place in the magnetization curve. The points of minimum magnetization on both twisting and untwisting have vanished altogether, the magnetic intensity always diminishing in the former, while it increases in the latter. At the same time, the original double looped curve becomes contorted, and the going and returning curves cross each other. But as soon as this stage is past, the increase of magnetizing force makes the four loops of the magnetization curve collapse into two, and hereafter the curve wears the general aspect as shown in Fig. 11.

*Diminution of magnetization by twisting in strong magnetizing fields.—*

The fact that the magnetization diminishes instead of rising when twisted in high magnetizing fields, can be explained from the nature of the curves of magnetization for different twists. In my former paper,\* it was shown that beyond a certain strength of the field, the susceptibility of the twisted wire diminishes more rapidly than that of the untwisted, so that the magnetic intensity is in general smaller for the twisted than for the untwisted. Thus we should be led to expect a diminution of magnetization on twisting, and increase on untwisting, and the curve will have the appearance as in Figs. 7, 8, and 11. But this does not throw any light on the reason for the change of sign of hysteresis between the cases represented by Figs. 10 and 11.

*Reversal of hysteresis occurs in lower magnetizing fields as the twist is taken larger.—*The preceding experiments for the twist of  $1^{\circ}.5$  led me to suspect that the strength of the magnetizing force as well as the amount of twist formed a chief cause of the reversal of hysteresis, and is not due to the difference in nickel. To test this, a thin wire 35 cms. long was twisted through  $\pm 1^{\circ}.7$  per cm. The curve (Fig.

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\* Magnetization and retentiveness of nickel wire under combined torsional and longitudinal stresses. This Journal, Vol. II.

14) obtained in  $\mathfrak{H}=0.34$  shews that the nature of hysteresis is similar to the two former results for smaller twists and is the reverse of that for the twist of  $\pm 4^{\circ}.5$  per cm. But in the stronger field of  $\mathfrak{H}=2.4$ , the amount of hysteresis was greatly diminished as may be seen from the curve shewn in Fig. 15. For  $\mathfrak{H}=5.1$ , the deflections were as follows:—

Twist (positive).	Deflections.	Twist (negative).	Deflections.
0°	422	0°	426
10	452	10	444
20	483	20	473
30	503	30	497
40	515	40	512
50	522	50	519
60	527	60	524
50	521	50	518
40	512	40	508
30	497	30	492
20	474	20	466
10	441	10	435
0	426	0	422

The curve as plotted in Fig. 16 shews what change has taken place. There is increase of magnetization on twisting till the extreme limit of torsion is attained. On untwisting there is diminution, and, for the corresponding angles of twist, the intensity of magnetization is always less than on twisting. In other words, the magnetization has no tendency to lag behind on untwisting, but rather the contrary. There is negative hysteresis for this particular combination of twist and magnetizing force. In fact the nature of hysteresis is similar to that for the twist of  $\pm 4^{\circ}.5$ , but reverse to any so far obtained for smaller twists in low magnetizing fields. As the magnetizing field is increased, the same order of things comes in, and the course of the

magnetization curve is opposite to what holds in weak fields for the same angle of twist, as will be seen from Fig. 17. These experiments sufficiently prove that the reversal of hysteresis not only depends on the amount of twist, but also on the strength of the magnetizing field, the phenomenon appearing in lower and lower magnetizing fields as the twist is taken greater and greater.

The above statement is confirmed by further experiments made with 1 mm. wire, the range of twist amounting to  $\pm 2^\circ$ . The curve (Fig. 18) for  $\xi=0.34$  has the course usual for small twists, so that there is true lagging on untwisting. But when the field strength is increased to 7.3 units (see Fig. 19), the going curve lies above the returning curve, and thus the hysteresis turns out to be negative. Thus for this amount of twist, the magnetizing force was sufficient to cause the reversal.

*Form of the curve when the reversal is about to take place.*—One important point still remains to be investigated. We must examine what form the curve takes just as the reversal of hysteresis is about to occur. I had the satisfaction of obtaining the desired curve by subjecting the wire to a twist of  $\pm 2^\circ.5$  per cm. under the action of the vertical component of the terrestrial magnetic force. The curve just on point of reversal (see Fig. 20) is no more double looped, but becomes more complex. Examining the changes of magnetization, we notice that on twisting, there is always increase of magnetization till the extreme limit of twist is reached, while on untwisting, the curve, instead of going below the former path, goes above it for a certain distance but before returning to the line of zero twisting, crosses the course taken in going, and finally passes below it. Thus the curve is four looped. The appearance of four loops marks the transition in the nature of hysteresis, and any further increase of the magnetizing field produces reversal of hysteresis, the curve becoming

again double looped as in Fig. 21.

*Curves for large twists.*—When the range of twist is increased to  $3^\circ$  or  $4^\circ$  per cm., a reversal of hysteresis by increasing the magnetizing force is not obtained. The curves are generally of the same character as those already described for the twist of  $4^\circ.5$ . Even for such large twists as  $9^\circ$  or  $10^\circ$  (see Fig. 22 and Fig. 23) the above remark holds true, the hysteresis being such that the going always passes above the returning curve. To give detailed description on this point would be merely repeating the earlier paper, and I feel no need of entering into the discussion of the results for these twists.

*Effect of twist in strong magnetizing fields.*—Another thing which calls for remark is the behaviour of nickel in strong magnetizing fields, during cyclic twistings. It was already noticed for the twist of  $\pm 1^\circ.5$ , how the magnetization diminishes on twisting, and increases on untwisting and how a particular complexity in the curve precedes the transference into such a state. The same curve of transition is also observed when the amount of twist is so large that the reversal of hysteresis takes place in a low magnetizing field. This is well exemplified in Fig. 24, which was obtained for  $\xi=20.8$  with a thicker wire twisted  $\pm 2^\circ$  per cm. But owing to the reversal of hysteresis, the course of the curve is different as the comparison of Figs. 13 and 24 will shew. The general character of the magnetization curve in strong magnetizing field, during cyclic changes of torsion, is shewn in Fig. 25, which is given as a type of such curves. It was obtained with a wire of 0.43 mm. radius in a field of 24.7. There is constant decrease of magnetization during twisting, and increase during untwisting up to a certain angle of twist, where it reaches a maximum. It then diminishes, and returns to its former value when the wire is brought to the initial position of zero twisting. The intensity of magnetization is always greater during untwisting than

during twisting. It will be afterwards shown that the curve is analogous to that of iron subjected to large twists.

*Reversal of polarity for different twists.*—With regard to the reversal of polarity for different amounts of twists, another set of experiments was performed with a thin wire for a twist of  $\pm 1^\circ.7$  per cm. On loading the wire with a weight of 5 kgs., the longitudinal stress was sufficient to produce the reversal of polarity when placed in the field  $\mathfrak{H}=0.34$ . The magnetization curve thus obtained is represented in Fig. 26. This curve is single looped, and has the same characteristic as those obtained for the twist of  $\pm 4^\circ.5$  in weak magnetizing fields under high tensions. The hysteresis in the present case is negative, and is opposite to that for the twist of  $\pm 0^\circ.86$ . (Compare Fig. 6 and Fig. 26). The difference of hysteresis for these two twists must be due to the difference of twist. To test this more fully, a new wire was placed in the same condition as before with regard to the longitudinal stress and the strength of the magnetizing field, and subjected to two different twists of  $\pm 1^\circ.2$  and  $\pm 1^\circ.4$  respectively. The curve obtained from the former was similar to that for  $\pm 0^\circ.9$ , while the one given by the latter agreed with that for  $\pm 1^\circ.7$ . Thus, for the above longitudinal stress and  $\mathfrak{H}=0.34$ , the reversal of hysteresis must take place between the twists of  $\pm 1^\circ.2$  and  $\pm 1^\circ.4$ . This result indicates that the hysteresis is influenced by the difference of twist although the wire is subjected to high tensions.

The next point to be examined is how the double looped curve is transformed into a single loop when the opposite polarity is about to appear. This interesting point was examined by increasing the strength of the magnetizing force. For  $\mathfrak{H}=2.5$  and  $\tau=\pm 1^\circ.7$ , the opposite magnetism is completely effaced, while at the same time the curve (Fig. 27) becomes double looped. Although the loop formed during positive twisting is very thin, it is quite certain that the

curve becomes double looped simultaneously with the vanishing of the opposite polarity. The newly formed loop gradually widens as the magnetizing force is further increased, as will be seen from Fig. 28. The experiments made for the twists of  $\pm 0.86$ ,  $\pm 1.7$ ,  $\pm 4.5$  all show that the cyclic curve of magnetization is gradually transformed from a double looped to a single looped curve, when the wire begins to shew opposite polarity.

Large twists applied to nickel do not seem to affect the phenomenon of reversal of polarity. After observing the changes in magnetization as shown in Fig. 22, I loaded the wire with 1 kgrm. weight. The longitudinal stress thus applied was already sufficient to cause the reversal of polarity and the curve as shown in Fig. 29 was obtained. It is single looped and similar in character to those observed for the twist of  $\pm 4.5$ . The results thus far obtained by varying the amount of twist from  $\pm 0.86$  to  $\pm 9^\circ$  per cm. prove that the phenomenon of the reversal of polarity always takes place however the twist may vary, provided sufficient longitudinal stress be applied. To examine more particularly into these intricate relations between twist, longitudinal stress, and magnetization would mean an amount of labour, which the importance of the subject hardly seems to merit.

### **Effect of Twist on the Magnetization of Iron.**

This subject was first investigated by Sir William Thomson, and the experiments to be described are to a great extent merely a repetition of his. The effect of twist on the magnetization of iron is not of so complex a character as it is in the case of nickel. In iron, the effect of the longitudinal stress combined with twist does not produce any reversal of polarity, nor are the changes of hysteresis so intricate as in nickel. But when the twist exceeds a certain limit,

there is the same curious reversal in the hysteresis.

*Repetition of Thomson's experiments.*—I shall first of all describe some of the curves obtained for small amounts of twist, being merely a repetition of Thomson's experiments. An iron wire 0.66 mm. thick and 40 cms. long was well annealed by means of a spirit lamp, and arranged in the same way as the nickel wires had been. The wire was then twisted through  $180^\circ$  in both directions, the strength of the magnetizing field being kept constant. The curves thus obtained during cyclic changes of torsion are shown in Figs. 30 and 31. The former was obtained under weak longitudinal stress in the magnetizing field  $\mathfrak{H}=2.9$ . The latter is plotted from observations made in the same field, the longitudinal stress amounting to 1800 kgrms. per sq. cm.

The effect thus produced by twisting iron is not so complex as for nickel, and the change in magnetization is but a small fraction of the whole. The curves obtained under various loads are nearly all similar in shape, and for the most part agree with those given by Thomson.

New experiments were made by using a wire of the same length taken from the same specimen, and twisting it through  $\pm 360^\circ$  ( $\pm 9^\circ$  per cm.). The curves thus obtained in different magnetizing fields are plotted in Figs. 32, 33, 34. The hysteresis in these magnetization curves is such that in the returning branch the curve is lower than in the going branch. The comparison of curves subjected to twists of  $\pm 4.5$  and  $\pm 9^\circ$  will shew that everything remains the same except in a single point. As the twist is increased, the ascending and the descending branches of the curve tend gradually to approach towards each other, although the hysteresis has the same sign in both cases. Thus the amount of hysteresis in iron is affected by different twists, while the increase of the magnetizing force seems to cause no

essential change. If the twist be still more increased, two cases are quite possible; either the going and the returning branches of the curve will continually tend to approach, or the going will ultimately lie below the returning branch, so that reversal of hysteresis will declare itself.

*Reversal of hysteresis.*—To solve this question, a wire 27 cms. long and 0.66 mm. thick was treated in the usual way, and twisted through  $\pm 360^\circ$ . The twist thus applied was very large and amounted to  $13^\circ\frac{1}{3}$  per cm. After a number of twistings and untwistings, the following readings of deflections were taken for  $\zeta = 2.9$ .

Twist (positive).	Deflections.	Twist (negative).	Deflections.
0°	487.2	0°	489.8
40	481.7	40	484.0
80	476.8	80	479.3
120	473.4	120	476.0
160	470.0	160	472.2
200	467.2	200	469.8
240	464.1	240	467.0
280	462.0	280	464.8
320	459.9	320	462.9
360	457.3	360	460.8
320	460.0	320	463.3
280	463.8	280	467.0
240	469.2	240	472.0
200	476.8	160	478.7
160	487.5	120	489.6
120	497.6	120	499.7
80	500.7	80	502.4
40	495.9	40	496.8
0	489.8	0	490.9



By examining the curve (Fig. 35) we see that on twisting the wire, there is constant decrease of magnetization, while on untwisting, the magnetization rises steadily till it reaches a maximum, after which it returns to its original value at the initial position of zero twisting. Thus in the returning branch the curve is no more lower than in the going branch, so that the course of the magnetization curve is opposite to that for the twists smaller than and up to  $\pm 9^\circ.0$ . As was already noticed in nickel, there is also reversal of hysteresis in iron. So far as my experiments go, the strength of the field or the amount of longitudinal stress does not seem to produce any remarkable variation on hysteresis, as the curves (Fig. 36, 37, 38) will shew.

It is thus established that the hysteresis in iron becomes reversed when the range of twist exceeds a certain limit. This must evidently lie between the twists of  $\pm 9^\circ$  and  $\pm 13^\circ \frac{1}{2}$  per cm. But it is not easy to determine the exact critical twist, even by experimenting for twists intermediate between the two. For a twist of  $12^\circ$  per cm. the difference between the going and returning branches of the curve diminishes to a certain extent as will be seen from Fig. 39. For a twist of  $10^\circ.4$  (Fig. 40) the two branches of the curve are separated by a still smaller interval; but still the former lies below the latter, so that the hysteresis is opposite in character to that for the twist of  $9^\circ$  per cm. Judging from these experiments, it can safely be inferred that the curious phenomenon of the reversal of hysteresis in iron takes place when the range of twist amounts to about  $\pm 10^\circ$  per cm.

*Comparison of results for iron and nickel.*—Comparing these results for iron with those obtained for nickel, we find some analogy between the two. As was formerly remarked, the changes in magnetization in nickel due to cyclic twistings are opposite in character to those of iron. But when the amount of twist as well as the

strength of the magnetizing force is varied, we find gradual transformations taking place. The magnetization curves in nickel for small twists and weak longitudinal stresses are opposite in character to those in iron for moderate twists. When the twist in nickel exceeds  $1^{\circ}.5$  per cm., and the magnetizing force is sufficiently strong, the magnetization curve loses its opposite character to that of iron under moderate twists, and acquires a form similar to that for iron subject to very large twist, as the comparison of Figs. 25 and 39 shews.

*Summary.*—I shall in conclusion summarise the results obtained in the present experiment.

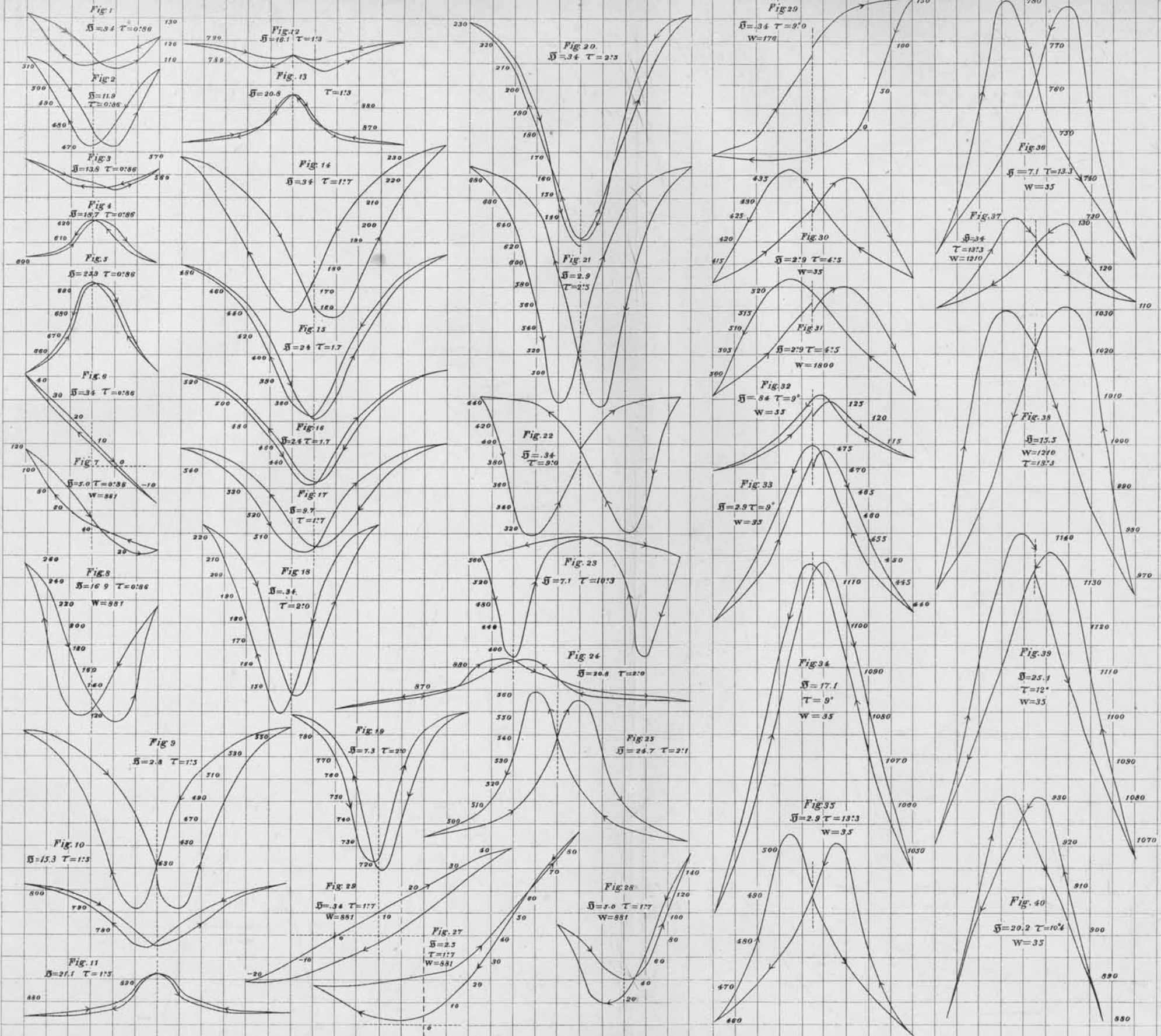
In nickel under feeble longitudinal stress, there is reversal of hysteresis when the range of twist is moderate. This phenomenon takes place in lower magnetizing fields as the twist is increased. When the amount of twist exceeds  $3^{\circ}$  per cm., nothing of this nature is observed. The reversal of polarity, on the contrary, is a phenomenon common to all twists, provided the longitudinal stress applied be sufficiently great.

In iron, so far as my experiments go, the magnetizing force does not alter the character of hysteresis, but reversal of hysteresis takes place when the twist exceeds  $10^{\circ}$  per cm., and the magnetization curve bears a close resemblance to that of nickel in strong magnetizing fields for moderate twists.

The effects of twist in iron and nickel, and especially in the latter, are so complicated that it is impossible to give anything like a true explanation coordinating all these facts. The magnetic qualities of these two metals with regard to stress are generally opposite. Not only do twist and longitudinal stress produce opposite effects in magnetization, but by twisting the wire in the magnetizing field we obtain transient currents in opposite directions for these two metals and

it can scarcely be doubted that these sets of phenomena are closely linked together. The occurrence of a *maximum* current for moderate amounts of twist and other peculiarities will be discussed in a future communication.





## ERRATA.

Error in Paging: Page Numbers 209-10 omitted by mistake.