Transient Electric Currents produced by twisting Magnetized Iron, Steel, and Nickel Wires

by

Hantarō Nagaoka.

With Plates XXIX, XXX.

The existence of a transient electric current when a magnetized iron wire is suddenly twisted was first noticed by Matteucci.* The same subject was afterwards investigated by Professor Ewing,† who examined especially the hysteresis in circular magnetization, when the direction of the magnetizing force was suddenly reversed. He considers the transient current thus developed as an induction current due to aeolotropic magnetic susceptibility produced in the iron wire by twisting. He also found that the transient current in the twisted wire, produced by reversing the magnetizing current reaches a maximum at a certain strength of the magnetizing force; and that when the field is made greater the current is gradually weakened, but it never changes its direction. I was led to investigate the subject with the aim of tracing some connection between this transient current in nickel and the reversal of polarity in nickel wire in a steady field,‡ when it is under the combined action of torsional and longitudinal stresses. Preliminary experiments were made during the Summer of 1888. My experiments were conducted

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* *Annales de Chimie et de Physique*, 1858; or Wiedemann's *Elektricität*, Bd. III.

† *Proc. R. S.* Vol. 36, 1884.

‡ See my previous paper on the combined effect of torsion and longitudinal stress on the magnetization of nickel wire; this *Journal* Vol. II, or *Phil. Mag.* Feb. 1889.

in a manner slightly different from that of Professor Ewing. The wire was suddenly twisted in the magnetizing field, and the quantity of the current thereby produced was measured by means of a ballistic galvanometer. In this way, I found that the direction of the transient current in nickel is opposite to that in iron. Nothing corresponding to the peculiar reversal of polarity was, however, observed. In addition to this, I found that the current in both iron and nickel reaches a maximum for a certain moderate strength of the magnetizing field. In iron, under a constant longitudinal field, there was also a definite angle of twist which gave a maximum current, but in nickel the current always increased with the increase of twist. The fact that the current in nickel is opposite to that in iron has also been independently discovered by Herr L. Zehnder.* The above experiments of mine are published in Philosophical Magazine for January 1890. Resuming the investigation more recently, I examined the transient current in iron, steel, and nickel, either by twisting the wire suddenly, or by reversing the direction of the magnetizing force after the wire had been twisted. Also wires of different diameters were examined.

Fig. 1.

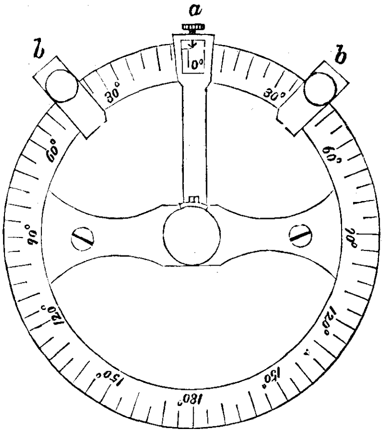
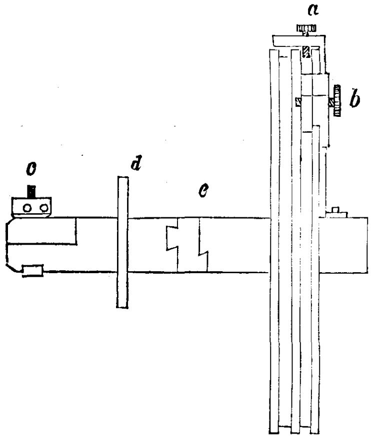


Fig. 2.



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* Wiedemann's *Annalen*, Bd. 38. p. 68, 1889.

The twisting apparatus consisted of a graduated circle provided with a small twisting arm (*a*), which can be clamped in any position. (See Fig. 1). A stout brass axis passed through the centre of the circle, and the twisting arm was firmly fixed to it. Round the rim of the graduated circle, two grooves were cut. In one of these, two clamps (*b*) (*b*) were made to slide. These clamps were capable of being fixed in any desired position by means of screws, and served to stop the motion of the twisting arm at the desired angle of twist when the wire was suddenly twisted. The clamp and the grooves are shewn in Fig. 2, which represents the lateral view of the twisting apparatus.

The magnetized wire could not of course be near the galvanometer; and being under the necessity of working alone, I was compelled to use some device for effecting the twist at a distance. For this purpose, two strings were attached to the twisting arm, and made to slide in opposite directions. The strings after passing the groove were made to slide on two pulleys fixed on the table, on which the whole apparatus rested. The axes of these two pulleys were parallel and their planes perpendicular to the face of the circle. The distance between them was equal to the diameter of the circle, and they were fixed in such a position that the strings on leaving the groove and passing down to the pulleys were both vertical. The two clamps (*b*) (*b*) being adjusted so as to stop the twisting arm at the desired positions, the wire was twisted in either direction by simply pulling the proper string. In fact, the mechanism was similar to that of the rudder of a ship.

The wire under examination had its one end clamped to the extremity (*c*) of the axis of the graduated circle, being held in position by pressure sustained by a small nut (*c*), as sufficiently indicated in Fig. 2. Between the clamp and the graduated circle a projecting rim of circular shape was attached. This dipped in a mercury cup placed underneath, and was in connection with one of the terminals of the galvanometer coil. In order to avoid any induction current that might arise from the sudden motion of the twisting arm and its appendages, that extremity of the axis which served to clamp the wire and lead the current to the galvanometer was insulated, from the rest of the axis and the graduated circle, by a piece of wood (*e*).

The other end of the wire was clamped somewhat similarly on a piece of thick brass plate of rectangular shape, of which the front view is shown in Fig. 3. It was provided with two V shaped projections (*b*) (*b*), which could slide smoothly on V grooves cut in a brass stand as shown in Fig. 4. The metal plate was prevented from turning over when the wire was twisted, by means of two hooks (*c*) (*c*), which slid in two grooves (*c′*) (*c′*) cut on the lateral sides of the stand. This groove arrangement was necessary when the effect of longitudinal stress was to be studied. The longitudinal stress was applied by hanging a pan of weights to the end of a flexible string which was fastened to the clamping plate and passed over a pulley fixed to the table. The plate was connected with the other terminal of the galvanometer.

Fig. 3.

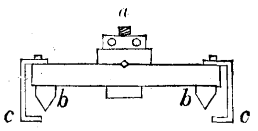
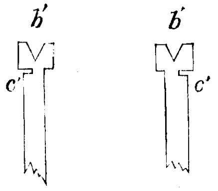


Fig. 4.



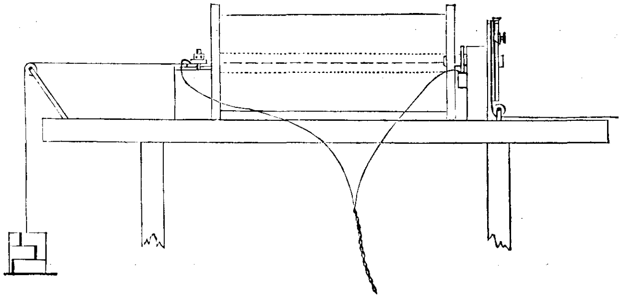
The wire to be examined was always well straightened and carefully annealed. When the wire was to be renewed, precaution was taken to cut it always from the same bundle for differences of material necessarily produces difference in the transient current. The wire was clamped while the pointer of the twisting arm was at zero of the graduated circle. Two clamps were previously fixed on both sides of the twisting arm such that when the wire was twisted in either direction, the arm should stop at the required angle of twist on either side of the initial position of no torsion. The wire was twisted between two extreme limits of twist by pulling the strings attached to the twisting arm in the way before mentioned. When the wire was first twisted, the deflection of the galvanometer magnet was generally large, but after repeated twistings and untwistings, the current settled to its ultimate value, and the reading was then noted.

The coil of the low resistance ballistic galvanometer was wound in 20 layers of thick copper wire. It had a resistance of 0.28 ohm. In the core of the coil, a heavy magnet was suspended and the first swing was read by the deflection of a spot of light reflected from a mirror placed outside the coil, but rigidly connected with the magnet. The suspension was similar to that of the ballistic galvanometer made by Siemens and Halske. Since the logarithmic decrement of the vibrating magnet was very small, no correction arising from it was thought necessary, so that the amount of current in the arbitrary scale was taken to be equal to the reading of the first swing. As the moment of the galvanometer magnet is liable to changes especially when the momentary currents are passed through the galvanometer coil, the galvanometer was gauged from time to time by means of an earth inductor.

The magnetizing coil was wound in six layers. The coil was placed on a table due magnetic east and west, and at a distance of nearly 5 metres from the ballistic galvanometer. It was 25 cm. long, and had a resistance of 1.3 ohm. The magnetizing field due to a current of one ampere was 35.5 C. G. S. units. The current was derived from 16 Daniell cells, and its strength was measured by means of a Thomson Graded Galvanometer. For obtaining strong magnetizing forces, a large coil wound in 12 layers was used with a sufficient number of Bunsen cells.

The arrangement of the coil and the twisting apparatus is shewn in Fig. 5.

Fig. 5.



Transient Current in Iron and Steel.

The transient current produced by twisting an iron wire placed in a magnetizing field has already been studied to a small extent. The results of this earlier investigation have been given in the paper referred to above. The method used in the experiments now to be discussed was different from the earlier method ; and in addition, wires of various thickness were examined. The present results are, however, essentially the same, although there are many features which passed unnoticed in the earlier and less detailed experiments.

I shall first of all describe the experiment in the varying magnetizing field, the wire being, in each successive field, twisted to and fro through a given constant angle.

Most of the experiments were made on a soft iron wire, 1.24 mm. thick and 27 cm. long. The wire was carefully annealed, and deprived of residual magnetism by heating it red hot as it lay in a position perpendicular to the magnetic meridian. This precaution is always necessary, for if there remain but a small quantity of residual magnetism, a transient electric current will be produced, when it is twisted even in zero magnetic field. In fact, one can test whether the wire is completely deprived of magnetism or not, simply by twisting it with its length placed due magnetic east and west, and observing if there exist any transient current or not. The wire thus prepared was placed within the magnetizing solenoid, and suddenly twisted through an angle of 15°. It was then twisted back through zero to an equal angle of twist on the opposite side of zero. The total twisting was therefore through an angle of 30°, namely, $+15°-(-15°)$. This twisting I denote as on previous occasions, by $\pm 15°$; and generally the twisting $\pm\theta$ means a twisting to and fro through an angular range 2θ about the original position of no twist. Generally the transient current did not settle to a constant value until the wire was twisted several times between the two extreme limits of twist. For each of a series of gradually increasing values of the magnetizing force, the transient current produced by one sudden twisting from limit to limit was measured on the ballistic galvanometer after the system had through repeated to and fro twistings reached a steady cyclic condition. The following are the values in successive fields :—

Magnetizing force.	Transient Current.*
0.7	12
1.7	26
3.2	34
4.5	36
5.8	35
7.5	34
9.8	32
14.6	27
22.0	21
29.0	17
36.7	15

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* One scale division corresponds to 1.1×10^{-6} Coulomb.

Taking for abscissae the strengths of the magnetizing force, and for ordinates the corresponding transient currents, we get the curve (Plate XXIX, Fig I, Curve I) representing the relation between the two.

An examination of the curve will show the changes in the transient current as the strengths of the field is increased. The current at first increases nearly proportional to the increase of the magnetizing force. On passing the field of about 3 units, the increase takes place very slowly and ultimately reaches a maximum for $\mathfrak{H}= 4.5$ nearly. The current then gradually decreases, though at a slower rate than that at which it first increased. This rate of decrease becomes still slower as the field is further increased. The curve representing the relation between the transient current and the strength of the magnetizing force has thus two inflexional points, the one just before reaching the maximum, and the other after passing the maximum. From its similarity to the analogous feature in the curve of magnetization, I shall hereafter call the point at which the ratio of the transient current to the magnetizing force is greatest the 'Wendepunkt' of the transient current curve.

On increasing the angle of twisting to ±30°, and experimenting on a new piece of wire taken from the same bundle and treated in the same way as before, Curve II. Fig. I. was obtained. The examination of this curve shows the same characteristics as before. But the transient current has greatly increased for all strengths of the magnetizing field, while, at the same time, the maximum current occurs in a higher magnetizing field than in the former case. This takes place for $\mathfrak{H}=6$ nearly.

By increasing the twisting to ±60°, Curve III. was obtained. The changes wrought by this second doubling of the twisting were not nearly so great as in the first doubling from 15° to 30°. The general feature remaining the same as before, we notice a peculiar difference between the curves II. and III. At first the transient current increases for $\tau=\pm 60^\circ$ as the field is increased, but until the magnetizing force is about 5 C. G. S. units, the current is always smaller than that for the twisting of $\pm 30^\circ$. When $\mathfrak{H}=5$, the transient current attains the same value for these two different twists, and henceforth the current for the larger twisting acquires an ascendency over that for the smaller. The rate of decrease after passing the maximum is slower for the larger twist than for the smaller. The maximum point occurs in a still higher field, namely, $\mathfrak{H}=8$ nearly.

With the twist increased to $\pm 90^\circ$, the transient current curve (IV.) becomes still further transformed. What was noticed on comparing II. with III. applies equally well when we compare III. with IV. The curve in weak fields lies below that for $\tau=\pm 60^\circ$, but when $\mathfrak{H}$ exceeds 13, the former lies above the latter. In this case, however, the maximum current is less for the larger twisting.

From the comparison of these four curves, we may reasonably infer what would be the course of the curve when the angle of twisting is further increased. Evidently the transient current in weak magnetizing fields as well as the amount of maximum current will be smaller for high than for moderate angles of twist. After passing the maximum, the slope of the curve will become less steep, as the angle of twist is increased, so that the curve will necessarily cut all those having a greater maximum current, and ultimately lie above the corresponding branch of the curves for smaller twistings. At the same time, the strength of the magnetizing field corresponding to the maximum transient current will be increased as the twist is taken greater.

The effect of longitudinal stress on the transient current was also tried. It simply produced decrease of the current as I have already mentioned in my former paper.

Professor Ewing has remarked that the production of a transient current by twisting an iron wire in a magnetizing field is a natural consequence of Sir William Thomson's discovery that aeolotropic stress gives rise to aeolotropic magnetic susceptibility in iron. The stress on twisting the wire is equivalent to compression and stretching along lines perpendicular to the radius, and inclined at 45° to the normal plane section. The susceptibility along the lines of compression is different from that in the direction of stretching. The consequence is that the lines of induction originally parallel to the axis of the wire are changed into helices which are inclined toward the direction of the relatively increased magnetic susceptibility. These considerations lead to the conclusion that in nickel, the direction of the current is determined by that of compression while in iron it is determined by that of stretching. Thus the direction of the transient current in iron and nickel should be in opposite directions, and in fact this was found to be the case.

It may, however, be doubted whether the effect of twisting is even approximately equivalent to compression in one direction and extension in the other. It is not at all improbable that twist gives rise to changes in the molecular configuration of the wire. As we are absolutely ignorant of the ultimate structure and arrangement of the molecules, nothing definite can be stated. But if there is any change produced among the polarized molecules of the magnetized wire, it is quite probable that the displacement of the molecules will give rise to changes in the transient current, which will be quite inexplicable in terms of aeolotropic susceptibility as generally assumed. Although such aeolotropy may be one of the chief causes of the transient current, yet other causes may exist whose effects can not be neglected. In fact, I have reason to believe that aeolotropy does not sufficiently explain all the phenomena observed in iron and nickel, as will be described afterwards.

Considering the results of the preceding experiments, one naturally asks, why does the transient current flow in the direction above specified and why does it reach a maximum? Supposing that aeolotropy is the only cause of the transient current, the increase of the current would mean a greater magnetic induction in the direction of stretching than in the direction of compression. The susceptibility of the stretched iron is greater and that of the compressed iron is less than that of iron in an unstrained state, up to a certain critical value of the field. Thus the helices representing the lines of induction would be inclined toward the direction of stretching, and the current must be constantly on the increase until at a certain field the difference of magnetic induction in these two directions begins to diminish. Reasoning in this way, we may explain the general feature of the curve in the following manner.

The amount of compression as well as that of stretching remaining constant throughout the course of experiment, increase of the magnetizing field produces a greater increase of the circular component of the lines of induction in the direction of stretching, than in the direction of compression. The difference in the circular components of magnetization at last reaches a maximum for a certain strength of the magnetizing force. This critical strength of the magnetizing force depends upon the amount of compression and of stretching. In the wire tried above, the position of the maximum is gradually shifted into higher field as the compression as well as stretching is increased, but at the same time, the current does not increase proportionally. There is a certain maximum twisting for which the difference of circular lines of induction in the direction of compression and of stretching reaches the maximum. This seems to occur for the twisting of about ±60° in the wire discussed, that is, a twist per cm. length of ±2.°2. When once the maximum difference in the circular lines of induction is reached, the susceptibility in the direction of compression and of stretching gradually tend to equality, so that in strong magnetizing field, the current becomes very small. Subjecting the wire to higher degrees of compression and of stretching makes the difference of susceptibility in strong fields greater, although the maximum difference of susceptibility becomes less after a certain amount of stress is exceeded. Thus it will be seen that the existence of a maximum transient current bears a close relation to the Villari critical point and an analogous point in compressed iron.

Another set of experiments was tried by the following method. Instead of twisting the wire always through the same angle while the magnetizing field was varied the latter was kept constant, while the wire was twisted through angles of twist of gradually increasing amount. For each successive value of twist, the transient

	Curve I.	Curve II.	Curve III.	Curve IV.
τ	$\mathfrak{H}=2.4$	$\mathfrak{H}=5.3$	$\mathfrak{H}=20.7$	$\mathfrak{H}=58.2$
5°	8	3	—	—
10°	33	16	12	5
15°	46	34	24	—
20°	51	46	33	14
30°	55	56	44	19
40°	54	58	53	24
50°	52	59	55	27
60°	51	58	57	29
70°	51	57	58	30
80°	50	57	58	31
90°	50	56	57	31

current was obtained and measured exactly as in the previous set of experiments. The wires used in these experiments were in all cases taken from the same bundle, and had a diameter of 1.24 mm. The accompanying table gives the currents in the arbitrary scale unit.

These readings are plotted in Fig. II. (Plate XXIX.), in which the abscissa gives the angle of twisting and the ordinate the corresponding transient current.

In general characteristics all these curves strongly resemble each other. The transient current increases at first very rapidly. Ultimately the current attains its maximum value, and thereafter it begins to decrease very slowly. The general feature of the curves obtained by varying the amount of twisting does not differ much from those obtained by varying the magnetizing force. Each of the curves obtained in both sets of experiments has a maximum point; namely, that corresponding to a particular twist in a constant magnetizing field, or that corresponding to a particular field when the amount of twisting is kept the same. In the latter case, the magnetizing field that gives the maximum current is greater for greater twistings, while in the former the twist giving the maximum current is greater in the stronger field. Although it is difficult to find the particular angle of twisting for which the current attains its maximum value, it can be approximately estimated from the curves plotted in Fig. II. Thus the angles of torsion giving maximum transient currents in different strengths of the magnetizing field come out as follows:—

$\mathfrak{H}$	τ
2.3	±30°
5.3	±50°
20.7	±76°
58.2	±90° (about)

The increase of the angle of torsion giving maximum transient current with the strength of the magnetizing force is thus apparent. We see a strong analogy between the magnetizing force giving maximum current when the twisting is kept constant, and the angle of twisting producing maximum current when the magnetizing force is kept constant; the increase in the one produces increase in the other.

When the wire is subjected to longitudinal stress, the transient current is greatly diminished, while the maximum point occurs for larger twists than in the case of the unstretched wire. In $\mathfrak{H}=2.4$, the maximum current occurs for the twist of ±30° when the wire is unloaded; when it is loaded with 4 kg. weight, it occurs at about ±36°, and when the load is increased to 8 kg., it takes place at about ±42° as will be seen from the curves V. and VI. For $\mathfrak{H}=5.3$, the angle of torsion giving the maximum transient current is ±50° when the wire is unstrained, but becomes greater than ±90° when the wire is loaded with 8 kg.

If we suppose the development of the transient current to be entirely due to the aeolotropic magnetic susceptibility caused by twisting the wire, the transient current in the present set of experiments must depend upon the difference of susceptibilities along the lines of compression, and the lines of stretching. Taking this as the basis of our reasoning, let us examine what these curves giving the relation between the current and the amount of twisting indicate. The difference of magnetic susceptibilities along lines perpendicular to the radius and inclined at 45° to the normal plane section of the wire increases at first as the wire is subjected to greater twistings. This difference, however, attains a maximum value. Hereafter the susceptibilities along these two lines gradually tend to equality though very slowly as the twisting is taken greater.

Now let us analyze the susceptibilities along the directions of stretching and of compression separately. We know that the susceptibility increases with loading, but when the wire is stretched beyond a certain limit, the susceptibility does not increase any more, and begins to decrease. Although the stretching and compression caused by twisting the wire varies at different distances from the axis of the wire, yet on the whole the increase of twisting necessarily gives rise to increased susceptibility in the direction of stretching until the critical value of stress is reached. It is well known that this critical point occurs with smaller amounts of pulling stress as the magnetizing force is increased. The consequence is that by twisting the wire in strong magnetizing fields, the wire acquires the maximum susceptibility in the direction of stretching for smaller amounts of twisting. Accordingly if stretching was the only stress acting in producing the circular lines of induction which produces the transient current, we should expect to obtain the maximum current at smaller twistings as the magnetizing force is taken greater.

This is contrary to the observed fact, which is that the twisting corresponding to the maximum current is increased with the strength of the magnetizing force. Thus the effect of compression must play an important part in changing the amount of the transient current.

Unfortunately we have not many experimental data on this subject, so full and detailed as those we have on the Villari critical point. According to the experiments of Ewing and Low*, the effect of compression in altering the susceptibility of iron has a certain similarity to the effect of stretching; and there is a similar reversal corresponding to that of Villari. Under constant compressional stress, the curve of magnetization for compressed iron lies below that for the unstrained, in weak magnetizing fields. In strong magnetizing fields, the former acquires greater susceptibility, and the curve lies above the latter. I do not know of any experiment establishing the relation between susceptibility and the compressional stress, when either the magnetizing force or the amount of compression is made to vary. Without these data, it is difficult to examine the effect on the transient current either by varying the magnetizing force or by varying the amount of twisting.

The fact that compression reduces the susceptibility of iron in weak fields shows why the transient current increases with increase of twist. So long as the magnetizing force does not exceed a certain limit, the susceptibility diminishes in the direction of compression, while it increases in the direction of stretching provided the Villari critical point is not exceeded. Thus the circular component of the lines of magnetic induction is constantly increasing as the twisting is increased and will therefore give rise to an increasing transient current. The increase of current will take place so long as the difference of susceptibilities in these two directions do not diminish. Observation shows that the maximum transient current occurs for larger twistings as the magnetizing force is taken greater. Since the stretching stress giving the maximum susceptibility becomes smaller as the magnetization of the wire is increased, it seems that compression

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* *Phil. Mag.* 1888.

produces greater diminution of susceptibility as the magnetizing field is taken greater. But consistently with the existence of a point similar to the Villari reversal, and the diminution of magnetization in weak fields, we should find increase of susceptibility in the direction of compression when the magnetizing field is taken sufficiently great. Of course, the increase of susceptibility in a given field will take place only within a certain limit of compressional stress, beyond which there is decrease. If this is really the case, the increase of susceptibility in the direction of stretching must always be greater than the increase in the direction of compression however great the magnetizing field is taken, for otherwise there would be reversal of the direction of current.

Now examining the results of Professor Ewing on the magnetization of soft iron wire, I find that the increase of susceptibility by loading is very small, when the field strength is over 10 units. It is not thus improbable that when the field is taken sufficiently great, the increase of susceptibility in the direction of compression exceeds that in the direction of stretching, so that the current is reversed. But this is quite contrary to the results of the present experiments. On this account, it seems that twisting the wire does not give rise to simple compression and extension along lines inclined at 45° to the normal plane section of the wire and perpendicular to the radius. The molecular arrangement of the wire must also be affected and give rise to additional changes in the transient current, which cannot be ascribed to aeolotropy alone.

In the experiments so far described, the wire was always twisted in the magnetizing field between two extreme limits of twist. In the experiments now to be described, the wire after being twisted repeatedly to and fro, was kept in position at either extremity of the range of twist, and the external magnetizing field was then suddenly reversed in direction. This was done by means of a rocker commutator placed in circuit with the magnetizing solenoid. With the wire kept steadily twisted either on the right or left hand side of the initial position of no torsion after repeated to and fro twistings, a magnetizing force was applied. On reversing the direction of the magnetizing force a momentary current passed through the galvanometer coil. In general the deflection of the galvanometer magnet settled to a constant value after numerous reversals, upon which the swing of the galvanometer magnet corresponding to a reversal was noted. The wire was then twisted in the opposite direction, and after numerous reversals of the magnetizing force, the deflection of the galvanometer magnet was again noted. The mean of these two readings was taken as a measure of the transient current. It should be noted that the direction of the transient current is reversed when either the twist is reversed or the direction of current reversal is changed.

The first set of experiments made in this way was by varying the magnetizing force, the amount of twist remaining constant. The iron wire used was 1.24 mm. thick and 27 cm. long. Instead of giving the observed numbers, I refer to curves plotted in Fig. III. (Plate XXIX.) These show at a glance the relation between the current and the magnetizing force for different amounts of twist. These curves were obtained for the following different angles of torsion.

Curve I for the twist of ± 5°,
,, II ,, ,, ,, ,, ± 15°,
,, III ,, ,, ,, ,, ± 30°,
,, IV ,, ,, ,, ,, ± 60°,
,, V ,, ,, ,, ,, ±120°.

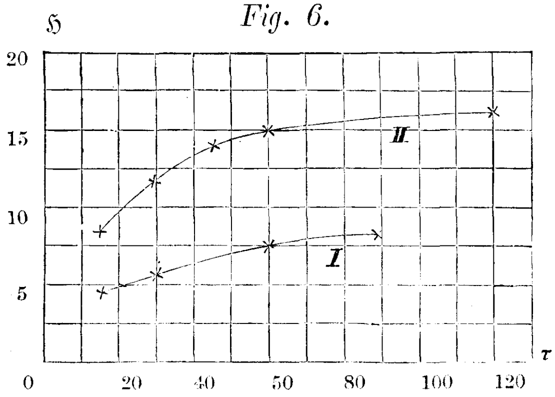
The general feature of all these curves are similar to those obtained by twisting the wire through a given angle in different magnetizing fields. The transient current increases on the application of an increasing magnetizing force, at first rapidly; but ultimately the current attains a maximum value. Thereafter it begins to decrease very slowly as the magnetizing force is increased. The transient current in weak field is smaller for large than for moderate twists, but after reaching the maximum, the rate of decrease becomes slower as the twist is taken greater. The consequence is that the curves for larger twists cut the curves for the smaller in a particular magnetizing field. This is well exemplified in the three curves III, IV, and V.

The magnetizing field corresponding to the maximum transient current becomes greater as the amount of twist is increased. The following numbers give the strengths of the magnetizing force corresponding to the maximum transient current.

Angle of torsion.	$\mathfrak{H}$
± 5°	6
± 15°	9
± 30°	12
± 60°	16
±120°	17

The magnetizing field corresponding to the maximum transient current is, however, nearly twice as great when the field is reversed with constant twist than when the twist is suddenly reversed with constant field. The accompanying figure gives the relation between the magnetizing force corresponding to the maximum transient

Fig. 6.



current and the angle of torsion. I. is for the method of sudden twisting, while II. is for the method of sudden reversal.

In the preliminary investigation on this subject, I have already noticed the fact that the magnetizing field giving the maximum transient current by sudden twisting is less than that obtained by Professor Ewing by the method of reversal. I then thought the discrepancy to be probably due to difference of procedure. On experimenting in these two ways with the same wire, I now find that the difference in the position of the maximum is certainly due to the difference in the method. But it seems inexplicable why this should be so, unless the ultimate causes of the transient current are known.

Corresponding to the experiments made by twisting the wire through different ranges in constant magnetizing fields, another set of experiments was tried by reversing the direction of the magnetizing force for different amounts of steady twist. Curves showing the relation between the transient current and the amount of twist are given in Fig. IV. These curves were obtained for the following different strengths of the field.

Curve I for $\mathfrak{H}=1.6$
,, II ,, $\mathfrak{H}=5.2$
,, III ,, $\mathfrak{H}=8.3$
,, IV ,, $\mathfrak{H}=13.0$
,, V ,, $\mathfrak{H}=51.8$
,, VI ,, $\mathfrak{H}=5.1$ (loaded 4 kg.)

Curve VII $\mathfrak{H}=9.6$ (loaded 4 kg.)
,, VIII $\mathfrak{H}=5.5$ (,, 8 ,,).

These curves, in their chief characteristics, all resemble those obtained by the application of sudden twisting. As the angle of twist is increased, the transient ourrent due to reversal increases at first very rapidly, but ultimately it reaches a maximum whence it begins to decrease slowly. For strong values of the reversing field, the current is small for small twists, but as the twist increases, it ultimately cuts the curves for smaller magnetizing force. Thus the rate of decrease of the current for greater twists becomes smaller as the field is increased. So far everything is similar to the results obtained with sudden twisting.

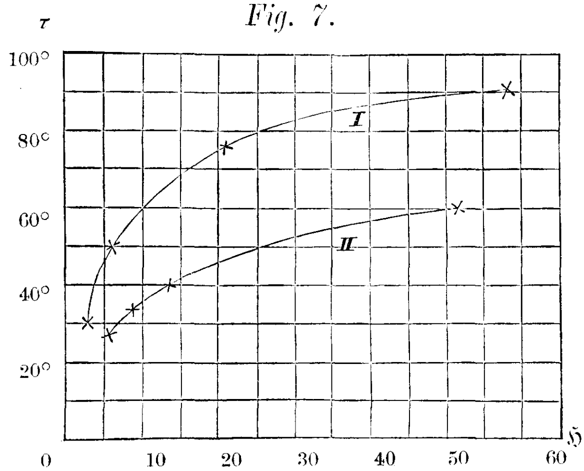
In the curves given in Fig. IV., we again notice the shifting of maximum point to places of greater twist as the magnetizing force is taken greater, as will be seen from the following table.

$\pm\mathfrak{H}$	Twist corresponding to maximum current.
5.2	27°
8.3	31°
13.0	40°
51.8	60°

The twist corresponding to the maximum transient current, whether that is due to reversal of field or to sudden twisting, has a similar relation to the magnetizing force. As the field is increased, the angle of torsion corresponding to the maximum current becomes correspondingly great; but, for the same strength of the magnetizing field, the twist corresponding to the maximum current when the field is reversed is smaller than the twisting of the same name, which for steady field gives the maximum current. Of course the angle of torsion in these two cases is not strictly comparable, the strain caused by twist or by twisting being somewhat different.

The difference between the two will be seem from the accompanying figure, in which the abscissa gives the magnetizing force and the ordinate represents the twist or twisting corresponding to the maximum transient current. Curve I. is for the method of sudden twisting while II. is for the method of reversal.

Fig. 7.



If we compare Figs. 6 and 7, we notice that in the latter I. is above II. while in the former II. is above I. This at first sight seems paradoxical, but we see that one is a natural consequence of the other. We saw that for the same angle of torsion, a greater magnetizing force must be applied to make the current attain its maximum strength by the method of reversal than by sudden twisting. Thus it would follow that to make the current reach its maximum value in a given magnetizing field by the former method the amount of twist must be less than the corresponding angle given by the method of sudden twisting. On this account II. lies below I. in Fig. 7.

The strain at any point by twisting the wire depends on the distance of the point from the axis of the wire. All parts of the normal section which are at equal distances from the axis of the wire will be equally strained. Evidently the outer part of the wire must suffer the greater strain. With the same angle of torsion, the strain must be greater in the thick wire than in the thin. Had the wire been in the form of a thin tube, it would be easy to see how the change in the transient current takes place when the diameter is made to vary. Inside the cylindrical wire, the strain is different in different places, and it is not at all easy to see how the transient current will be altered with the thickness of the wire.

To find how this alteration takes place, wires of different thickness were examined by the method of reversal. These wires were 0.88 mm., 1.24 mm., 1.54 mm., and 2.00 mm. thick respectively. In each case the wire was twisted through 60° in either direction, and the transient current produced in these different specimens by reversing the direction of the magnetizing force was measured. The following table gives the readings.*

$r=0.44$ (Fig. V, Curve I.)		$r=0.62$ (Fig. V, Curve II.)	
$\mathfrak{H}$	Transient Current.	$\mathfrak{H}$	Transient Current.
3.4	4	1.4	2
6.6	18	3.4	17
11.0	27	6.3	43
16.4	29	9.4	54
21.0	28	13.5	61
24.3	27	16.4	60
28.9	26	20.9	60
37.3	23	29.0	56
		37.4	50

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* In subsequent experiments, one scale division corresponds to 2.1×10^{-6} Coulomb.

$r=0.77$ (Fig. V, Curve III.)		$r=1.00$ (Fig. V, Curve IV.)	
$\mathfrak{H}$	Transient Current.	$\mathfrak{H}$	Transient Current.
1.4	2	1.4	1
4.1	19	4.5	5
6.3	44	7.2	21
9.6	59	10.6	47
12.3	67	13.6	63
16.7	72	16.4	75
21.7	73	20.5	84
24.9	72	28.2	90.5
30.5	69	36.7	90.3
37.0	67		

These readings are plotted in Fig. V. The general appearance of the curve remains the same as was already noticed, but there is gradual transformation of the curve as the thickness of the wire increases. The transient current produced in wires of different thickness varies with the strength of the magnetizing force. In every case, there is an increase of the transient current when the magnetizing force is first increased. The current, however, attains a maximum, and then begins to diminish slowly as in the case of the wire 1.24 mm. thick. With thick wires, the current increases very slowly in weak magnetizing fields, so that the curves for thick wires intersect those for the thin. This effect is very well marked in the thickest wire used. Curve IV. lies below all the rest of the curve so long as the magnetizing force is not great. In all cases, the maximum transient current is greater as the wire becomes thicker. Thus increasing the diameter of the wire has, to some extent, a similar effect to that produced by increasing the twist in a wire of the same diameter.

When we examine the variation of the maximum position, we notice another feature analogous to that produced by increasing the angle of twist in the same wire. As the diameter of the wire increases, the maximum point is shifted into stronger fields. The following table gives the magnetizing force corresponding to the maximum transient current in wires of different thickness.

For $r=0.44$ $\mathfrak{H}=14$,
,, $r=0.62$ $\mathfrak{H}=16$,
,, $r=0.77$ $\mathfrak{H}=22$,
,, $r=1.00$ $\mathfrak{H}=30$.

The wires used in the above experiment were of ordinary soft iron. If the quality of iron be different, the transient current curve is somewhat changed. Thus, with a wire of 0.91 mm. radius specially drawn from Swedish iron, the transient current was greater than that obtained with the thickest wire used in the above experiment. The course of the curve is shown in Curve V. Fig. V. In addition to this, the maximum position corresponds to a weaker magnetizing field than it would have done had the wire been of ordinary soft iron. The general feature of the curve, however, does not seem to be greatly affected by the difference in quality.

Another set of experiments was performed by varying the angle of twist while the reversing field was kept constant in magnitude. The wires were taken from the same specimens as used in the above experiments. The magnetizing force was in all cases equal to 19.7. The following table gives the readings, which are plotted in Fig. VI.

	$r=0.44$ (Curve I.)	$r=0.62$ (Curve II.)	$r=0.77$ (Curve III.)	$r=1.00$ (Curve IV.)
τ	Trans. Cur.	Trans. Cur.	Trans. Cur.	Trans. Cur.
5°	8	—	25	32
10°	18	26	47	56
20°	33	48	71	72
30°	42	56	82	88
40°	45	58	88	89
50°	48	60.5	87	84
60°	49.0	61.3	82	80
70°	49.3	60.5	80	78
80°	49.0	59	—	
90°	48	58	77	
120°	46	56	76	

The curves plotted in Fig. VI. have the same appearance as those obtained in similar experiments, by the method of reversal, with wires of the same thickness. For small angles of twist, the current increases very rapidly, but as the twist is further increased, the current attains its maximum value whence it begins to decrease slowly. Examining each curve separately we see that the transient current does not increase in simple proportion to the thickness of the wire. On the contrary, the curves obtained for the wire $r=1.00$ cuts that for $r=0.77$ when the twist exceeds 40°. But it follows by no means that the transient current for the thick wire cannot attain still higher values. Looking at Fig. V, we see that $\mathfrak{H}=19.7$ is a little above the point where the curve for $r=1.00$ crosses the curve for

$r=0.77$. For the latter, it is near the field giving the maximum transient current. Had the field been stronger, the curve for the thick wire would have lain far above that for the thin wire.

In the preceding experiment, we found that the maximum point of the curve was shifted into stronger fields as the radius of the wire was increased. This shews that if the magnetizing field be kept constant, a large amount of twist must be applied to the thin wire in order to produce the maximum current. The angle of twist corresponding to the maximum current as found from the present set of experiments are as follows:—

For $r=1.00$,	angle of twist corresponding to max. cur.	$=36°$
,, $=0.77$,	,,	44°
,, $=0.62$,	,,	60°
,, $=0.44$,	,,	72°.

Thus the angle of twist at which the maximum current occurs becomes greater as the radius of the wire becomes smaller.

Professor Ewing* in discussing the apparent discrepancy in the direction of the transient current as obtained by him and by Matteucci attributes it to the fact that in Matteucci's experiments, the amount of twist as well as the magnetization of the iron bar were so great that the Villari critical point had been passed. Unfortunately Matteucci's experiments were performed at a time when the current was not measured in units now in general use. It is now impossible to know the exact value of his magnetizing field; but it is no doubt true, since the iron bars examined by him, were over 5 mm. thick, that the pull and push produced by twisting were very great; and judging from the number of Grove cells he used, the magnetizing field must have been strong. According to the experiments of Professor Ewing, the Villari critical point comes earlier with strong than with weak stresses. Thus it is quite probable that in Matteucci's

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* *Proc. R. S.*, 1884.

experiments, the critical point may have been passed. But Professor Ewing in discussing the transient current as due to aeolotropic magnetic susceptibility takes the pulling stress only into account, and completely ignores the effect in the direction of compression. As I have already pointed out, compression must play an important part in changing the amount of the transient current. It is the difference of magnetization in the directions of compression and of stretching that gives rise to the transient current, if the phenomena is entirely due to aeolotropic susceptibility. Thus, although the Villari critical point has been passed, the current may flow in the same direction so long as the corresponding compressional stress produces greater decrease of susceptibility than in the direction of stretching. Again the current can reverse its sign even when the Villari critical point has not been passed, provided compression produces greater increase in the magnetism of the iron wire examined. The scantiness of experimental data in this branch of research does not admit us to draw any definite conclusion on the subject under discussion. To see whether the application of very large twist reverses the direction of the transient current, I had recourse to direct experiment rather than to mere reasoning on scanty resources. With this object in view, I subjected an iron wire 1.54 mm. thick, and 27 cm. long to fore and back twistings through an angle of 360°. The twist thus applied amounted to 13° per cm., and must correspond to great compressional and stretching stresses. On reversing the magnetizing current and observing the transient current, it was found that the direction was always the same and determined by the direction of stretching; nor did the current due to this large twist show any notable decrease as compared with currents due to smaller twists as the comparison of the following readings with the same wire for smaller twists will show.

$\mathfrak{H}$	Trans. Cur.
2.0	3
5.7	39
8.9	52
13.0	57
17.3	57.5
19.7	57.5
23.0	57
27.2	56
29.7	54

To study the effect of longitudinal tension upon the current, loads of 4 and 8 kg. were successively applied, and the reading of the galvanometer magnet measured by reversing the magnetizing force. The effect of loading was simply to reduce the current by a small amount, and the representative curves were not greatly altered.

The above result leads me to suspect that possibly Matteucci made a mistake in determining the direction of the current in relation to the twist and field, always in such experiments somewhat of a confusing matter. The main difference between the experiments of Matteucci and those of later investigators lay in the thickness of the bar or wire. Matteucci used mostly an iron bar 6.5 mm. thick, while in the present investigation, the thickest wire experimented on had a diameter of only 2 mm. Accordingly, I determined to repeat the experiment of Matteucci with a soft iron bar 5.6 mm. thick and 28 cm. long. This was tested both by sudden twisting and by reversing the direction of the magnetizing force. The arrangement for twisting the bar was different from the one described above. It was twisted by means of a lever, into the details of which I need not here enter.

The sudden twisting of the bar produced a large amount of transient current, but the direction of the current was always the same as with wires of smaller diameter. The only difference noticed by twisting the wire was the quantity of the current developed. Nothing differed from the results hitherto described. Professor Ewing has suggested that the twist applied by Matteucci was already beyond the critical value, since the bar was very thick, and that consequently the current must have changed its direction. In the above experiment the bar was twisted through 90° (3° per cm.). This greatly exceeds the twist applied by Matteucci, his limit being 20° in a bar 60 cm. long, or only $\frac{1}{3}$° per cm. We cannot therefore explain the supposed discrepancy in the direction of the transient current as the result of a large twist.

To shew the similarity of the effect obtained with the bar to that obtained with the thin wire, I give the following readings taken in various magnetizing fields by the method of reversal.

$\pm\mathfrak{H}$	Trans. Cur. for $\tau = 30°$	$\pm\mathfrak{H}$	Trans. Cur. for $\tau = 60°$
3.0	20	2.9	20
6.1	72	5.6	66
9.8	138	8.6	116
12.5	177	11.8	160
16.4	209	15.3	194
21.0	233	18.9	219
24.3	238	22.7	236
30.9	240	27.1	239.5
38.1	234	32.6	239.8
45.4	216	38.8	235
69.4	169	61.4	195
78.9	148	74.8	174

The observations recorded by Matteucci are very few in number. He gives only four galvanometer readings for each experiment. In spite of the scantiness of his data, we can see in a general way what form his transient current curves will have. In all cases, the transient current increases at first with the number of cells used, but always decreases when 10 cells are used. This shows that the transient current curve will have a maximum point, and must be similar in form to those obtained in the experiments described above. From this we may also estimate roughly the strengths of the magnetizing field used by Matteucci. These facts indicate that the direction of the current as stated by Matteucci, if not an accidental mistake, must be due to some other cause than that suggested by Professor Ewing.

The transient current developed in twisted steel wires was examined by the method of reversal, as was done for iron. The wire was twisted through ±60°, and the strength of the magnetizing force gradually increased. The direction of the magnetizing current was reversed, and the reading of the galvanometer magnet was noted. Two specimens of steel wires were examined. The one had a diameter of 1.28 mm., and the other 1.50 mm. Plotting the readings on the galvanometer scale, Fig. VII. was obtained. The current increases as the magnetizing force is increased. Ultimately it reaches a maximum, and then gradually begins to diminish. The transient current flows in the same direction as in iron. The only differences, which will be apparent at a glance, are the comparative smallness of the current and the higher magnetizing force corresponding to the maximum transient current. For wires of nearly the same thickness, the transient current in steel does not amount to more than a fourth part of that in iron. On the other hand, the maximum current in steel occurs in a stronger magnetizing field than in iron, as the comparison of the curves represented in Figs. V. and VII. will show.

With varying twists in a constant field of 20 C. G. S. units, Curves I., II., III. in Fig. VIII. were obtained with three specimens of steel wires of different gauge. Their diameters were 1.26 mm., 1.50 mm., and 1.82 mm. respectively. The readings are as follows:—

	$r=0.63$ (Curve I.)	$r=0.75$ (Curve II.)	$r=0.91$ (Curve III.)
τ	Trans. Cur.	Trans. Cur.	Trans. Cur.
5°	1	—	—
10°	3	5	9
20°	7	11	14
30°	10	14	19.5
40°	15	17.8	21.3
50°	16.5	18.3	20
60°	16.8	17.0	18.5
70°	15.8	16	18.0
80°	15.0	15	
90°	14.3		

In these three curves, we notice the same characteristics as have been already noticed in similar experiments with iron. There is a certain angle of twist for which the transient current is a maximum. This angle of twist varies with the thickness of the wire, and is smaller for the thick than for the thin wire. Thus the currents in iron and steel are in every respect similar, except in the amount of the transient current developed and the position of the maximum current.

When soft iron or nickel wire is twisted it immediately acquires a large permanent set, and would in no case return to the initial position of no torsion. In steel, the limit of elasticity is very great compared with soft iron or nickel. Whenever the steel wire is twisted and afterwards released, the wire almost always returns to its former position although the amount of twist is considerable. The smallness of the current in steel indicates that the stress produced by twist has a smaller effect in steel than in iron. The principal point of difference in these two substances is at the same time attended with a difference in the permanent set acquired by the twisted wires. These facts suggest that there exist certain intimate relations between the transient current and the limit of elasticity.

Transient Current in Nickel.

As I have already remarked, the present investigation originated in searching if the transient current does not show any peculiarity in the magnetized nickel wire, which has undergone the reversal of polarity by the combined action of torsion and longitudinal stress. With this object in view, the transient current produced by twisting the nickel wire was examined under different longitudinal stresses, the strength of the magnetizing field being made to vary. No peculiarity occurring simultaneously with the reversal of polarity was observed. A more minute study was then instituted, in which the nickel wires were subjected to the same treatment as the iron and steel wires.

The arrangement for twisting the wire, and the method of measuring the transient current, were exactly the same as in the experiment with iron, so that the further description of the process will be unnecessary here.

Two specimens of nickel wires were specially examined. The one was 0.5 mm., and the other 0.43 mm. in radius. The wire was carefully annealed, and deprived of residual magnetism by heating it red hot. This precaution was especially necessary with the nickel wire, for if there remained but a small quantity of the residual magnetism, quite a large amount of transient current was produced. As in the case of iron, the current did not attain its ultimate value until the wire was subjected to many back and fore twistings. The following table gives the reading of the swing of the ballistic galvanometer magnet, obtained by twisting the wire 1 mm. thick and 27 cm. long, through different angles, while the magnetizing force was made to vary.

$\tau = \pm 30°$		$\tau = \pm 45°$		$\tau = \pm 60°$		$\tau = \pm 90°$	
$\mathfrak{H}$	Trans. Cur.	$\mathfrak{H}$	Trans. Cur.	$\mathfrak{H}$	Trans. Cur.	$\mathfrak{H}$	Trans. Cur.
3.9	67.5	2.3	69.6	1.2	63.3	0.6	60.0
6.7	70.8	4.4	74.6	3.8	75.8	2.0	73.6
10.1	71.7	8.5	75.9	7.1	78.6	4.5	76.7
14.1	73.1	13.3	77.3	9.3	79.8	7.2	79.0
17.0	73.6	21.0	77.1	13.9	79.8	9.4	79.8
23.6	73.6	30.2	76.9	21.1	78.6	13.6	80.5
32.3	72.5	48.5	75.5	39.6	78.2	16.5	80.5
53.7	70.0			54.1	77.1	23.0	79.8
65.5	68.9					28.6	79.7
						30.8	79.0

These readings express the quantity of transient current in the same scale unit as used formerly in similar experiments with the iron wire of 0.62 mm. radius. These readings are plotted against the corresponding magnetizing force in Plate XXX. Fig. IX. Curves I., II., III., IV. Two dotted curves V. and VI. were obtained from experiments made on thin nickel.

The above table shows that the rate of increase of the current when the magnetizing force is first applied is enormous. The curve rises nearly perpendicular to the axis of $\mathfrak{H}$. This rapid increase, however, takes place only within a small range of the magnetizing force. After a certain strength of field is reached, which in the above experiment does not exceed 5 units, the curve reaches the wendepunkt. After passing this point, the curve rises very little, the current remaining of nearly the same strength within a pretty large range of the magnetizing field. There is, however, a maximum, as will be seen by examining the readings. But as the decrease of the current after as well as its increase before the maximum is reached takes place very slowly, it is difficult to know the exact strength of the magnetizing force corresponding to the maximum. The curve representing the transient current is somewhat similar to the curves of magnetization of twisted nickel wire, with the difference that in the latter there is no maximum point.

The examination of these curves shews that there is no great variation of current with the difference of the angle of twist, so that among the four curves taken with 1 mm. wire, we notice only small displacement of curves for larger twistings. Nevertheless, the current is sensibly smaller for the smaller twistings. Nothing definite can be said as to any change of the magnetizing force corresponding to the maximum transient current as the twist is increased. One thing, however, is quite certain—the magnetizing field corresponding to the maximum transient current is generally greater in nickel than in iron.

Another remarkable difference in the currents produced in iron and in nickel is the oppositeness of the direction of the transient current. The direction of the current in iron is from the north to the south pole when the wire is twisted right-handedly, whereas in nickel it is from the south to the north pole. If we consider the current as the effect of aeolotropic stress produced by twisting, the current in nickel is determined by the direction of the spiral of compression. Sir William Thomson described these phenomena in the following language.*

"To avoid circumlocutions suppose the iron or nickel wire to be vertical, and the magnetizing current to be in the opposite direction to that of the motions of the hands of a watch held with its face up. The undisturbed magnetization is downwards. Now suppose a right-handed twist to be given to the wire. Its elongational spiral is right-handed, and its contractional spiral is left-handed. If the substance is iron, the lines of magnetization become left-handed spirals; if nickel, right-handed. Now a downward current, in the downwardly magnetized wire, would, by the superposition of circular magnetization in the direction opposite to that of the hands of a watch, cause the lines of magnetization to become left-handed spirals. Hence the sudden right-handed twist induces in iron a current upwards, in nickel a current downwards. Thus we have the following simple specification for the directions of the induced longitudinal currents in the two substances, without reference to "up" and "down."

"From any point, P, on the surface of the wire draw samewards parallels to the current in the nearest part of the magnetizing solenoid, and to the direction of the induced longitudinal current. Draw a helix through P making an acute angle with each of these lines. This helix is of same name as the elongational helix for iron, and as the contractional helix for nickel."

Another set of experiments was tried by twisting the nickel wire in a constant magnetizing field, different amounts of twist being taken in succession. The results are shown graphically in Fig. X.

For the wire of 0.5 mm. radius:—

Curve I. for $\mathfrak{H} = 5.0$

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* See note to my former paper, *Phil. Mag.*, Jan. 1890.

Curve II. for $\mathfrak{H}= 9.8$
„ III. „ „ $=10.5$ (loaded 5 kg.)
„ IV. „ „ $= 9.8$ (loaded 8 kg.)

For the wire of 0.43 mm. radius:—

Curve V. for $\mathfrak{H}=32.8$
„ VI. „ „ $= 9.9$ (loaded 8 kg.)

For wires under no longitudinal stress, the current increases as the twist is increased. The rate of increase is at first very rapid, but the curves always show a wendepunkt beyond which the increase takes place only very slowly, up to the greatest amount of twist applied in the present experiment. The current increases with the twisting for all strengths of the magnetizing force, but in all cases the increase of the current beyond a certain angle of twist takes place so slowly that the curve seems to be nearly parallel to the horizontal axis.

When the nickel wire is loaded, the effect of increasing the angle of twist is somewhat different from what occurs under no longitudinal stress. The current reaches the maximum value at a certain angle of twist, and then begins to decrease as will be seen from curves III. and IV. With wires 0.86 mm. thick, no such maximum was noticed.

The stress produced by twisting the nickel wire is a combination of compression and stretching as in the case of iron. The magnetic susceptibility of nickel in the direction of contraction is always decreasing as the twist is increased, and that in the direction of compression is always increasing. Thus the component of circular magnetization will be in the direction of compression. Moreover the circular magnetization is always increasing as the amount of twist is made to increase. This increase, however, takes place very slowly beyond a certain angle of twist, for when the stretching and the compressional stresses are increased, the change in magnetization in both directions becomes very small. In fact, we should expect the transient current to increase with the twisting, and to have no maximum if the current be due simply to aeolotropy. The preceding experiments in constant magnetizing field show that this is really the case. On the other hand, when the magnetizing field is made to vary, the current reaches a maximum. Looked at from the point of view of aeolotropy, this would mean that the arithmetical sum of the increase of the magnetization in the direction of compression and the decrease of magnetization in the direction of stretching reaches a maximum value at a certain magnetizing field, a conclusion which agrees with the experiments of Ewing. Thus aeolotropic magnetic susceptibility in the directions of stretching and of compression not only explains the direction of the current, but also some of its general characteristics.

The transient current produced by reversing the direction of the magnetizing force was examined in the same manner as in the case of iron. With the wire kept twisted, the magnetizing force was reversed many times, and immediately thereafter, the reading of the first swing due to the next reversal was taken. This was done with a series of gradually increasing values of the magnetizing force. Out of numerous experiments, I give only five of the curves (Fig. XI) taken with the thick wire and four (Fig. XII) obtained with the thin.

For the thick wire:—

Curve I. for $\tau=\pm 30^\circ$
,, II. ,, $\tau=\pm 90^\circ$
,, III. ,, $\tau=\pm 180^\circ$
,, IV. ,, $\tau=\pm 60^\circ$ (loaded 4 kg.)
,, V. ,, $\tau=\pm 60^\circ$ (,, 8 kg.)

For the thin wire:—

Curve I. for $\tau = \pm\ 60^\circ$
„ II. „ $\tau = \pm 360^\circ$
„ III. „ $\tau = \pm\ 60^\circ$ (loaded 4 kg.)
„ IV. „ $\tau = \pm\ 60^\circ$ („ 8 kg.)

The principal features of all these curves are nearly the same in all cases, and resemble those for iron. The first application of the magnetizing force makes the current increase very rapidly. This increase, however, takes place only within a small range of the magnetizing force. The curve soon reaches the wendepunkt, and thereafter goes on rising very slowly. In the first two curves in Fig. XI. the magnetizing force was not sufficient to make the current reach its maximum value. In the third experiment for $\tau = \pm 180^\circ$, stronger magnetizing forces were applied, and then the existence of the maximum was demonstrated. The following are the readings.

$\mathfrak{H}$	Trans. Cur.
3.7	3.8
5.4	15.3
7.6	38.0
9.5	48.4
12.6	56.1
16.5	59.9
20.7	64.3
34.1	67.4
50.6	67.4
78.6	66.9

As was remarked before for iron wires, the maximum transient current produced by reversing the direction of the magnetizing force occurs for higher values of the magnetizing force than is the case when the wire is suddenly twisted in a steady field. The comparison of curve III. Fig. XI. with any one given in Fig. IX. will show that this must also be the case with nickel.

Another point of difference between these two methods is the difference in the position of the wendepunkt, and the initial form of the curve before reaching the wendepunkt. In the experiments made by sudden twisting, the wendepunkt occurs in weaker magnetizing fields as the twist is increased; but it is otherwise when the magnetizing force is reversed. In this case, the wendepunkt gradually shifts into higher regions of the magnetizing field. The first increase of the *twisting* transient current, as the magnetizing force is increased, takes place more rapidly for greater twistings; but when the direction of the magnetizing force is reversed, the same increase takes place more rapidly for the smaller twist. This fact is evident from the examination of the curves I., II., III. in Fig. IX. and I., II. in Fig. XI. The curve for $\tau = \pm 90^\circ$ lies at first below the curve for $\tau = \pm 30^\circ$, while the curve for $\tau = \pm 180^\circ$ lies, at the outset, below the curves for these other angles of twist.

When the wire is subjected to longitudinal stress, the curve undergoes a slight alteration. The initial part of the curve lies below the curve for the unloaded wire, but the current increases steadily, and finally reaches the wendepunkt, which occurs at a higher field than in the case of wires under no longitudinal stress. As the longitudinal stress is increased, the current becomes smaller in weak magnetizing fields, but it increases steadily with the increase of the magnetizing force so that the curve ultimately cuts the curve for no longitudinal stress. At the same time the wendepunkt of the curve is shifted into stronger fields. Similar results have been obtained for the twisting transient current.

In the experiment made by suddenly twisting the nickel wire, it was seen that with the angle of twist then applied, the current was always increasing as the twist was increased. This is in harmony with the view of aeolotropic magnetic susceptibility. In the experiments now to be described, the same series of experiments were performed by subjecting the twisted wire to reversals of the magnetizing forces. The results thus obtained are somewhat striking, and seem incapable of explanation in terms of aeolotropic magnetic susceptibility.

The experiment was tried in exactly the same way as for iron. Out of a number of experiments made in this way, I give the following, as showing the typical relation between the amount of twist and the transient current.

The following are the readings made with the thick wire; and the corresponding curves are shown in Fig. XIII.

	Curve I.	Curve II.	Curve III.
τ	$\mathfrak{H}=10.6$, w$=0$.	$\mathfrak{H}=4.5$, w$=5$ kg.	$\mathfrak{H}=9.8$, w$=5$ kg.
10°	—	3	16
20°	21	13	50
30°	44	27	68
40°	63	38	74
50°	65	44	77
60°	64	43	75
70°	62	37	72
80°	59	23	71
90°	57	2.3	69
100°	52	1	63
120°	44	0	56
140°	38	0	(150°) 47
180°	18		41
270°	7		
360°	3		
450°	2		
540°	1.5		

The following give the observations made with the thin wire.

	Curve IV.	Curve V.	Curve VI.
τ	$\mathfrak{H}=9.8$, W$=0$.	$\mathfrak{H}=5.0$, W$=5$.	$\mathfrak{H}=25.1$, W$=5$.
10°	25	2	30
20°	44	—	59
30°	52	19	66
40°	56	20.5	64
50°	56	6.5	63
60°	57	4.0	62
70°	56	—	61
80°	55	2.8	61
90°	54	—	60
120°	52	0.5	—
150°	50		58
180°	47		56
360°	30		50

On the first application of twist, the transient current increases with the angle of twist, but it soon reaches the wendepunkt and very quickly thereafter a maximum. The curve then dips, and the decrease of current with the increase of twist takes place nearly proportional to each other, so that the curve appears to be nearly straight. But there is another point of inflexion (not shown in the figure, but evident from the readings). Thence the curve dips very slowly, and ultimately becomes asymptotic to the line of no transient current. The current is very small when the twist is large, but from the course of the curve it is evident that further twistings will not reverse the direction of the current.

The curve undergoes great deformation when the wire is subjected to longitudinal stress, especially when the magnetizing force is weak. The initial rise of the current takes place in the same way as represented by curves obtained with unstrained wires. The curve after passing the maximum dips very rapidly describing a curve which is more curved than that for the unloaded wire. The current decreases very rapidly, so that it is soon reduced to a very small amount. Thus after the angle of torsion exceeds 90° or thereabouts, the deflection of the galvanometer magnet produced by reversing the direction of the magnetizing force is scarcely appreciable. On greatly increasing the twist, the transient current remains in the same state, so that it is quite probable that the current ultimately becomes vanishingly small when the twist is very great, but the direction of the current will never become reversed. Curves II. and V. show these features very distinctly.

It must not be supposed that a similar curious change takes place in the transient current whenever the wire is loaded. It is only in weak magnetizing fields that the changes above described take place. On examining the transient current in $\mathfrak{H}=10.6$ with the thick wire subjected to a longitudinal stress of 5 kg. weight, Curve III. was obtained. The course of the curve is slightly different from that obtained with the unloaded wire in $\mathfrak{H}=9.8$ (see Curve I.). The maximum point is present for nearly the same angle of twist, both for the loaded and for the unloaded wire. The curve dips after passing the maximum, but the course is nearly straight and not curved as in II. and V., so that the transient current will be appreciable unless the twist becomes very great.

According to the researches of Professor Ewing, longitudinal stress always decreases the magnetic susceptibility of nickel, while compression always increases it. If we resolve the torsional stress, as has already been done into extension and compression at right angles to the radius of the wire, and inclined at 45° to the plane section normal to the axis, the circular component of the lines of induction will be constantly on the increase as the twist is taken greater. If, then, we are to explain the transient current in terms of known changes of susceptibility in the directions of elongation and compression, we should expect the circular components of the lines of induction in the wire, and probably the transient current, to increase as the twist is increased. But in the experiments just described, there is a maximum which comes with a tolerably small amount of twist, and there is always decrease of current when the angle of twist becomes sufficiently great. These results on the transient current, and the change of susceptibility in the directions of compression and of stretching lead to contradictory conclusions. Thus it seems that the peculiarities of the transient current cannot be explained in terms of aeolotropic susceptibility, but some other causes must be acting in producing the peculiarity mentioned above.

In order to find how the transient current is affected by the thickness of the wire, four specimens of nickel wire were examined by the method of reversal. The angle of twist was in all cases equal to ±60°. The following table gives the readings;* the curves are shown in Fig. XIV.

$r=0.5$ (Curve I.)		$r=0.65$ (Curve II.)	
$\mathfrak{H}$	Trans. Cur.	$\mathfrak{H}$	Trans. Cur.
1.5	3	3.5	24
3.8	8	7.6	55
5.8	21	12.2	63
7.6	32	17.7	65
11.4	39	22.7	66
14.8	41	27.7	66.3
18.2	42.8	33.5	66.8
20.4	43.3	41.9	66.5
23.6	43.5	50.6	66
27.8	43.5	66.6	64
33.8	43.3	117.0	57.
44.9	42.8		

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* One scale division corresponds to 2.1×10^{-6} Coulomb.

$r=0.84$ (Curve III.)		$r=1.00$ (Curve IV.)		$r=0.65$ (Curve V.) w=5 kg.	
$\mathfrak{H}$	Trans. Cur.	$\mathfrak{H}$	Trans. Cur.	$\mathfrak{H}$	Trans. Cur.
1.5	3	3.5	1	3.5	4
3.5	53	7.2	76	7.5	50
6.7	71	13.1	106	12.2	65
9.0	80	17.7	108	15.5	67
11.4	83	22.6	114	22.0	71
14.7	87	31.8	116	29.2	71.8
18.1	88	39.4	121	37.6	72.3
20.4	88	50.3	118	49.8	71
23.4	89	83.0	114	76.7	69.
27.8	89	125.1	108		
34.0	90				
45.6	88				

These curves for wires of different thickness, have all the same characteristics as already noticed. The current, after reaching the wendepunkt, increases so slowly that it is difficult to tell where the curve reaches a maximum. Nevertheless, as will be seen from the readings, the transient current for each of these wires does reach a maximum, which seems to occur at lower fields in the thinner wire. The curves for nickel are similar to those obtained with iron wires, the only points of difference between the two being the indistinctness of the maximum point in nickel and its occurence in higher fields. On stretching the wire longitudinally, the same effect as already described in similar experiment by the method of sudden twisting was obtained. In weak magnetizing fields, the current produced in the loaded wire is less than in the unloaded. But near the wendepunkt, the curve for the loaded wire passes above the unloaded, and beyond this point the current for the former becomes always greater than that for the latter. Moreover the maximum for the loaded wire takes place in stronger field than for the unloaded.

Corresponding to the above, another set of experiments was performed by the method of reversal, the strength of the field being kept equal to 19.7 throughout the course of experiment and the twists being varied. The following are the readings; the curves being shown in Fig. XV.

	r=0.5(Curve I.)	r=0.65(Curve II.)	r=0.84(Curve III.)	r=1.00(Curve IV.)
τ	Trans. Cur.	Trans. Cur.	Trans. Cur.	Trans. Cur.
5°	9	18	34	34
10°	16	34	51	62
20°	26	47	65	82
30°	30	52	71	85.0
40°	33	54	71	84.8
50°	33	54	69	83.8
60°	34	53	67.3	83
70°	34	52.5	67	82
80°	34	52.3	66.8	81
90°	34	—		
100°	33	51.8		
120°	33	51.		

The examination of these curves shows the increase of the transient current when the diameter of the wire becomes greater. As I have already noticed before, the transient current always reaches its maximum value for a certain angle of twist. The angle giving maximum current varies with the thickness of the wire. The thicker the wire, the smaller the amount of twist which is to be applied to make the current arrive at a maximum, as will be seen from the following:

for $r=0.50$ $\tau=70°$,
„ $r=0.65$ $\tau=45°$,
„ $r=0.84$ $\tau=36°$,
„ $r=1.00$ $\tau=30°$.

The curves also resemble those obtained in similar experiments with iron.

When the nickel wire is loaded and then subjected to varying twists, the curves of transient current present a peculiar aspect, especially when the field is weak. To test this for thick wires, experiments were performed with wires 1.68 mm. and 2.00 mm. thick respectively. The curves (see Fig. XVI.) thus obtained show the same characteristics as before noticed. After passing the maximum point, the decrease of the transient current takes place very rapidly. The current, a little while after, becomes insignificantly small, so that for large twists, it is insensible to the galvanometer. Thus the peculiarity seems not to be due to the thickness of the wire.

In my former paper, I had occasion to remark that the transient current curve resembles the curve of the Wiedemann effect. In the latter, the twist due to superposed circular and longitudinal magnetization of the wire increases at first with increase of the magnetizing force, but ultimately reaches a maximum. According to the researches of Professor Knott, the twist in nickel takes place in the opposite sense to that in iron, and the maximum twist in the former occurs in much higher magnetizing fields than in the latter. These facts are in every way similar to those observed in the transient current. Following the close analogy between the Wiedemann effect and the transient current, experiments were made in order to find if the similarity can be pushed even to very strong magnetizing fields. According to Mr. Bidwell, the Wiedemann effect in iron is reversed when the magnetizing force is sufficiently great. If the similarity exists, there should be a reversal in the direction of the transient current. With the strongest magnetizing current at my disposal ($\mathfrak{H}=500$) no reversal of the transient current was noticed. The analogy thus seems to fail in very strong magnetizing fields.

The following gives the summary of the results obtained in the present investigation.

1.—The transient current produced by suddenly twisting the iron wire, or by reversing the direction of the magnetizing force while the wire is held twisted, through a constant angle, increases as the field is increased, but after reaching a wendepunkt, it soon arrives at a maximum point, whence it begins to decrease slowly as the field is further increased.

2.—The rise of the transient current in gradually increasing fields is smaller for large than for moderate angles of twist, but in strong magnetizing fields, the current becomes greater as the twist is taken larger.

3.—The maximum point varies with the amount of twist, and occurs in higher fields as the twist is taken larger.

4.—The transient current in stretched iron wire is less than that in the unstretched.

5.—The transient current produced in a constant magnetizing field by varying the amount of twist increases at first with the increase of twist. The current, however, arrives at a maximum point, whence it begins to decrease slowly as the twist is increased.

6.—The initial rise of the transient current as the twist is increased is greater in weak than in strong fields.

7.—The maximum point varies with the strength of the magnetizing force, and occurs for larger twists as the field is stronger. The twist corresponding to the maximum current is smaller by the method of reversal than by sudden twisting.

8.—When the thickness of the wire is altered, the initial rise of the current with the increase of the magnetizing force is greater as the wire becomes thinner, but the maximum current and the magnetizing force giving the maximum current both increase with the thickness of the wire.

9.—When the twist is varied in a constant magnetizing field, the maximum point occurs for smaller twists as the thickness of the wire is increased.

10.—Everything with regard to the transient current in steel is similar to that in iron, with the exception, that the current is smaller, and the magnetizing force corresponding to the maximum current is stronger, than those observed in iron wires of the same thickness.

11.—The transient current produced by twisting nickel wire, or by reversing the direction of the magnetizing force is opposite in direction to that in iron. The wire being twisted into a right-handed screw, the current in nickel flows from the south to the north pole.

12.—The transient current produced by twisting, or by reversing the direction of the magnetizing force while the wire is held twisted, soon arrives at a wendepunkt, beyond which the increase takes place very slowly, and ultimately attains a maximum. The decrease with further increase of the magnetizing force is very slow. The wendepunkt, for the same angle of torsion, comes sooner by sudden twisting than by the method of reversal.

13.—The current in weak fields is smaller when the wire is loaded, but in strong fields the curve of transient current passes above that for the unloaded.

14.—With the magnetizing force constant, and the amount of twist variable, the transient current produced by sudden twisting always increases as the twisting is increased. The increase, however, takes place very slowly beyond a certain angle of twist.

15.—Everything being the same as in (14), the transient current produced by reversing the direction of the magnetizing force increases at first with the increase of twist, but it soon reaches a maximum. After this a slow decrease of the current takes place, and when the twist is very large, the current becomes very small.

16.—Loading the wire and proceeding in the same way as in (15), the current decreases rapidly after passing the maximum, and soon after becomes very small.

17.—When the thickness of the wire is different, the transient current is in general greater as the wire becomes thicker. The current in weak fields is smaller with the thick than with the thin. The maximum current occurs in higher magnetizing field as the thickness is increased.

18.—With the magnetizing force constant, and the amount of twist variable, the maximum current occurs for smaller twists as the wire becomes thicker.

PLATE XXIX.

Plate XXIX.

Fig. I.—Obtained by twisting iron wire ($r = 0.62$) in varying magnetizing fields.

Curve I. for $\tau = \pm 15^\circ$; Curve II. for $\tau = \pm 30^\circ$;
„ III. „ $\tau = \pm 60^\circ$; „ IV. „ $\tau = \pm 90^\circ$.

Fig. II.—Obtained by twisting iron wire ($r = 0.62$), τ being variable.

Curve I. for $\mathfrak{H} = 2.3$; Curve II. for $\mathfrak{H} = 5.3$;
„ III. „ $\mathfrak{H} = 20.7$; „ IV. „ $\mathfrak{H} = 58.2$;
„ V. „ $\mathfrak{H} = 2.4, w = 4$ kg.; „ VI. „ $\mathfrak{H} = 2.4, w = 8$ kg.;
„ VII. „ $\mathfrak{H} = 5.3, w = 8$ kg.

Fig. III.—Obtained by reversing the direction of the magnetizing force with iron wire ($r = 0.62$), $\mathfrak{H}$ being variable.

Curve I. for $\tau = \pm 5^\circ$; Curve II. for $\tau = \pm 15^\circ$;
„ III. „ $\tau = \pm 30^\circ$; „ IV. „ $\tau = \pm 60^\circ$;
„ V. „ $\tau = \pm 120^\circ$.

Fig. IV.—Obtained by reversal with iron wire ($r = 0.62$), τ being variable.

Curve I. for $\mathfrak{H} = \pm 1.6$; Curve II. for $\mathfrak{H} = \pm 5.2$;
„ III. „ $\mathfrak{H} = \pm 8.2$; „ IV. „ $\mathfrak{H} = \pm 13.0$;
„ V. „ $\mathfrak{H} = \pm 51.8$; „ VI. „ $\mathfrak{H} = \pm 5.1, w = 4$ kg.
„ VII. „ $\mathfrak{H} = \pm 9.6$; „ VIII. „ $\mathfrak{H} = \pm 5.5, w = 8$ kg.

Fig. V.—Obtained by reversal for $\tau = \pm 60^\circ$ with different wires, $\mathfrak{H}$ being variable.

Curve I. for $r = 0.44$; Curve II. for $r = 0.62$;
„ III. „ $r = 0.77$; „ IV. „ $r = 1.00$;
„ V. „ $r = 0.91$, (Swedish iron).

Fig. VI.—Obtained by reversal in $\mathfrak{H} = \pm 19.7$ with different wires, τ being variable.

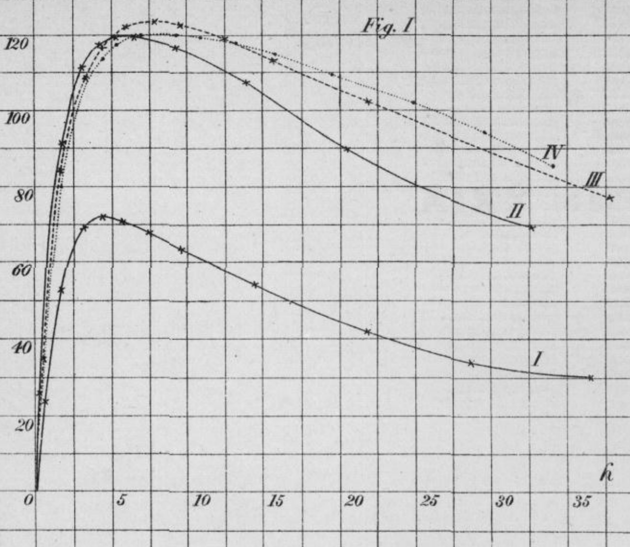
Curve I. for $r = 0.44$; Curve II. for $r = 0.62$;
„ III. „ $r = 0.77$; „ IV. for $r = 1.00$.

Fig. VII.—Obtained by reversal with steel wires, $\mathfrak{H}$ being variable.

Curve I. for $r = 0.63$, $\tau = \pm 60^\circ$; Curve II. for $r = 0.91$, $\tau = \pm 60^\circ$.

Fig. VIII.—Obtained by reversal with steel wires, τ being variable.

Curve I. for $r = 0.63, \mathfrak{H} = 19.7$; Curve II. for $r = 0.75, \mathfrak{H} = 19.7$;
„ III. „ $r = 0.91, \mathfrak{H} = 19.7$.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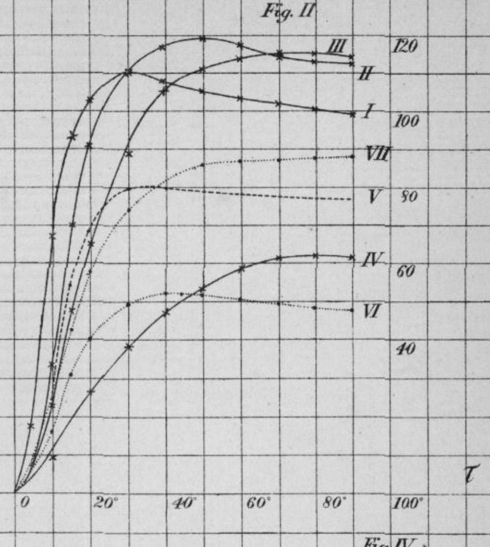
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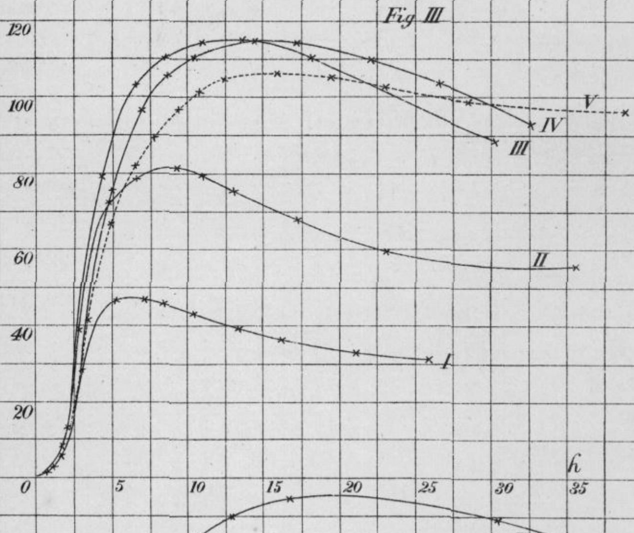
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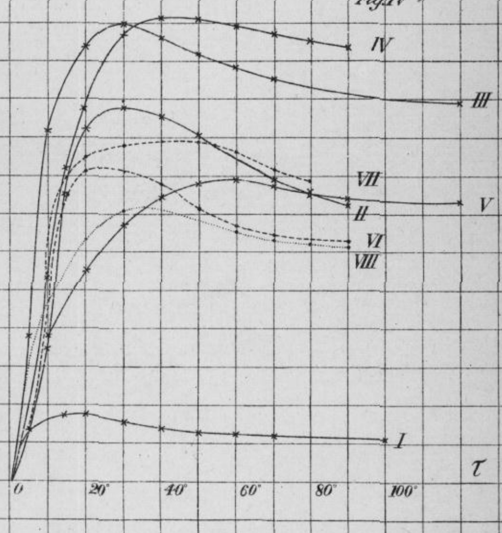
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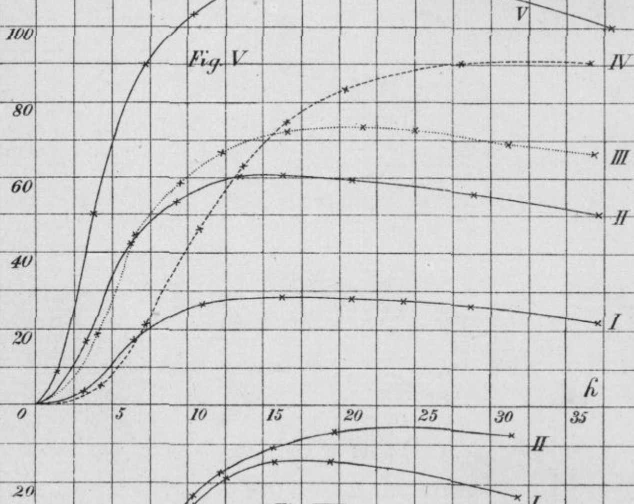
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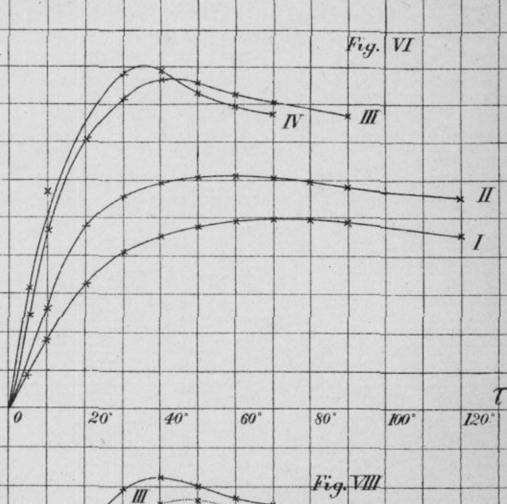
Fig. VI

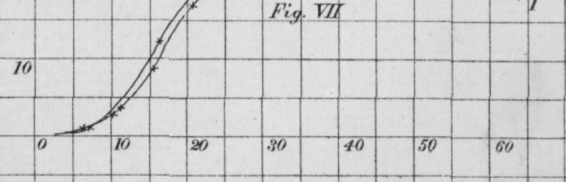
Fig. VII

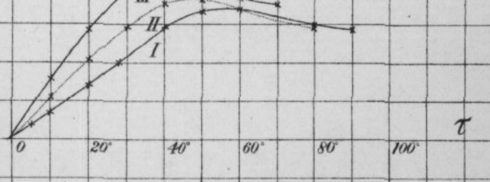
Fig. VIII

PLATE XXX.

Plate XXX.

Fig. IX.—Obtained by twisting nickel wires ($r = 0.50$) in varying magnetizing fields.

Curve I. for $\tau=\pm 30°$, $r=0.5$; Curve II. for $\tau=\pm 45°$, $r=0.5$;
„ III. „ $\tau=\pm 60°$, $r=0.5$; „ IV. for $\tau=\pm 90°$, $r=0.5$;
„ V. „ $\tau=\pm 60°$, $r=0.43$; „ VI. for $\tau=\pm 90°$, $r=0.43$.

Fig. X.—Obtained by twisting nickel wire, τ being variable.

Curve I. for $\mathfrak{H}=5.0, r=0.5$; Curve II. for $\mathfrak{H}=9.8, r=0.5,$
„ III. „ $\mathfrak{H}=10.5, r=0.5, w=5$; „ IV. „ $\mathfrak{H}=9.8, r=0.5, w=8$.
„ V. „ $\mathfrak{H}=32.8, r=0.43$; „ VI. „ $\mathfrak{H}=9.9, r=0.43, w=4$.

Fig. XI.—Obtained by reversing the direction of the magnetizing force, with nickel wire ($r = 0.5$), $\mathfrak{H}$ being variable.

Curve I. for $\tau=\pm 30°$; Curve II. for $\tau=\pm 90°$;
„ III. „ $\tau=\pm 180°$; „ IV. „ $\tau=\pm 60°$, $w=4$;
„ V. „ $\tau=\pm 60°$, $w=8$.

Fig. XII.—Obtained by reversing the direction of magnetizing force, with nickel wire ($r = 0.43$), $\mathfrak{H}$ being variable.

Curve I. for $\tau=\pm 60°$; Curve II. for $\tau=\pm 360°$;
„ III. „ $\tau=\pm 60°$, $w=4$; „ IV. for $\tau=\pm 60°$, $w=8$.

Fig. XIII.—Obtained by reversal with nickel wires ($r=0.5$ and $r=0.43$), τ being variable.

Curve I. for $\mathfrak{H}=\pm 10.6, r=0.5$; Curve II. for $\mathfrak{H}=\pm 4.5, r=0.5, w=5$;
„ III. „ $\mathfrak{H}=\pm 9.8, r=0.5, w=5$; „ IV. „ $\mathfrak{H}=\pm 9.8, r=0.43$;
„ V. „ $\mathfrak{H}=\pm 5.0, r=0.43, w=5$; „ VI. „ $\mathfrak{H}=\pm 25.1, r=0.43, w=5$.

Fig. XIV.—Obtained by reversal for $\tau=\pm 60°$, with nickel wires of different thickness, $\mathfrak{H}$ being variable.

Curve I. for $r=0.50$; Curve II. for $r=0.65$;
„ III. „ $r=0.84$; „ IV. „ $r=1.00$;
„ V. „ $r=0.65$, $w=5$.

Fig. XV.—Obtained by reversal in $\mathfrak{H}=\pm 19.7$, with nickel wires of different thickness, τ being variable.

Curve I. for $r=0.50$; Curve II. for $r=0.65$;
„ III. „ $r=0.84$; „ IV. „ $r=1.00$.

Fig. XVI.—Obtained by reversal, τ being variable.

Curve I. for $r=0.84, \mathfrak{H}=3.4, w=8$; Curve II. for $r=1.00, \mathfrak{H}=6.3, w=8$.

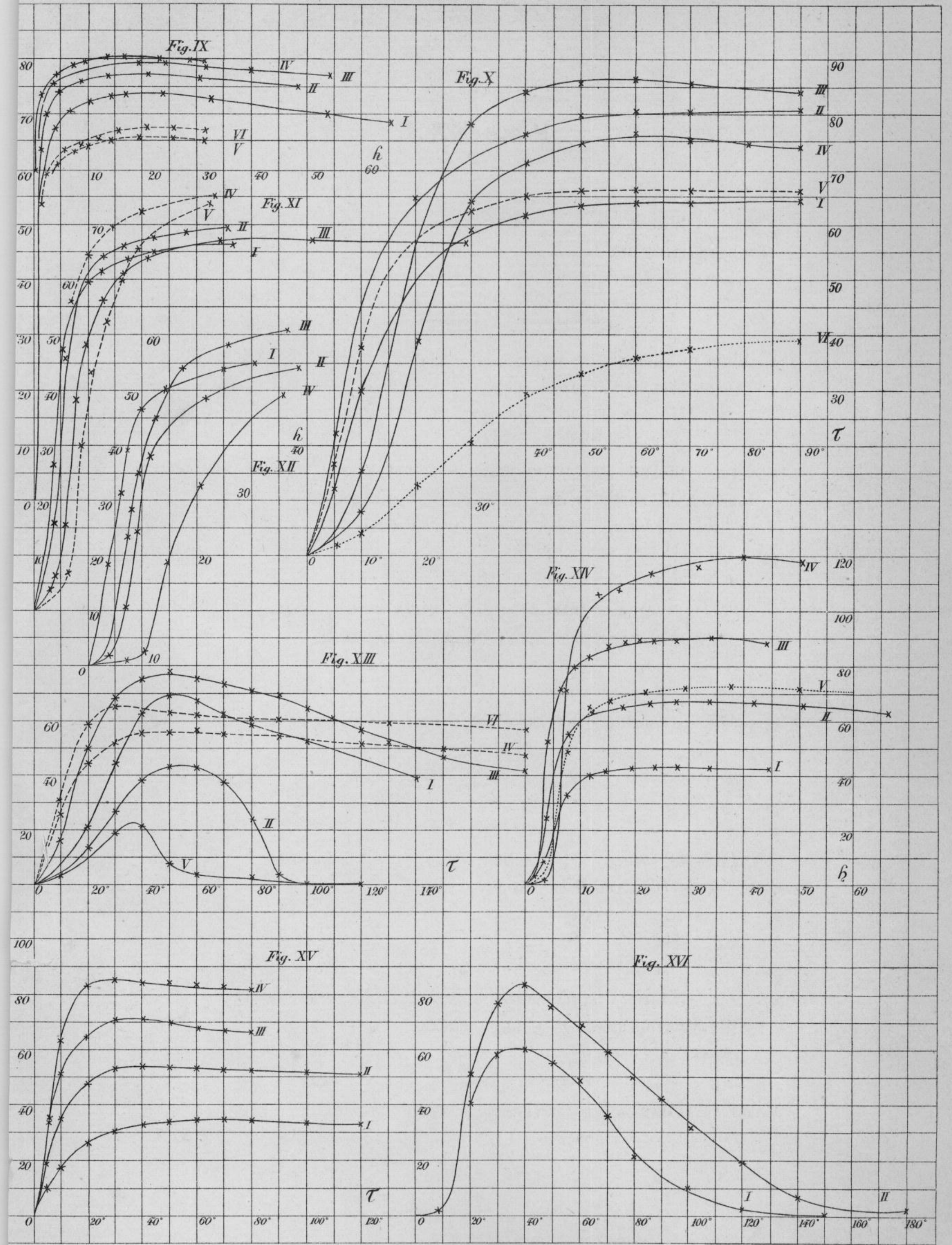
Fig. IX
Fig. X
Fig. XI
Fig. XII
Fig. XIII
Fig. XIV
Fig. XV
Fig. XVI
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