Effect of Magnetization on the Permanent Twist of Nickel Wire.

by

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Pl. XXXVIII.

Professor Wiedemann, in a course of experiments on the mutual relation between torsion and magnetization, found that there was a reciprocal relation between the two. He found that whereas torsion changed the magnetization of iron, magnetization, on the other hand, changed the torsion. To establish the relation between the two, he made a series of experiments, which seemed to indicate many other intimate relations between the two. Experiments relating to the change of twist by longitudinal magnetization have been, so far as I am aware, tried only with iron and steel wires. The curious effect of torsion on the magnetization of nickel has induced me to try experiments in the same line, and find if there also exist similar reciprocal relations between magnetization and torsion in nickel wires. Want of apparatus did not allow me to try experiments on the effect of magnetization on nickel wires under different conditions of twist. The present paper is confined only to the discussion of the effect of magnetization on the permanent twist of nickel wires.

The apparatus used for twisting the wire and measuring the effect due to magnetization was essentially different from that of Professor Wiedemann. I employed an arrangement made on the same plan as that used by Professor F. Kohlrausch* in his experiments on the torsional elastic after-effect of wires. Fig. 1 shows the front view

* Pogg. Ann. 128.

of the apparatus. On a firm stand furnished with three levelling screws (*lll*), two stout pillars (*pp*) were erected. A cross bar of wood (*bb*) was fixed to these pillars. At the middle point of the cross piece, a torsion circle (*t*) was attached, with an arrangement for fixing the wire. Below this stood a magnetizing coil (*c*) on an auxiliary stand. To keep the wire twisted, two stout rods (*rr*) were raised vertically from a thick brass plate of circular shape, which was screwed to the stand (*s*). These rods were fastened to alidades, which were movable

Fig. 1.

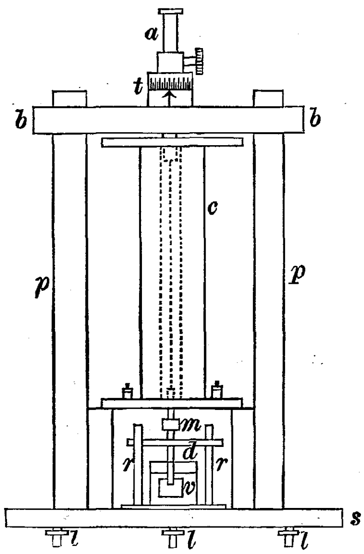

Fig. 2.

about an axis at the centre of the plate. Thus the rods could be fixed in any desired position, and made to catch the cross attached to the lower end of the wire. The cross was made of two rods at right angles to each other. The vertical rod had an arrangement for holding a small plane mirror (*m*). The horizontal rod was capable of sliding in the vertical, and could be clamped firmly to it by means of a screw. A vane (*v*) was attached to the lower end of the vertical rod. It dipped into a vessel filled with water, which served to stop the torsional oscillation of the wire, when the twist was released. The torsion circle had a stout rod (*a*) for vertical axis. This was capable of up and down motion by means of ratch work, and could be clamped by a screw. The lower end of the axis was cut, and made to bite the upper extremity of the wire. The wire is shown in Fig. 2. Two small pieces of thick brass plate were attached to the extremities of the wire. The upper end was placed between the terminal cleft of the axis, and clamped by a screwing nut, while the lower end was similarly caught at the upper end of the cross, and fixed by a screw which went through a hole in the plate, as shown in the figure.

In front of the mirror was placed a circular scale divided into half millimetres. The radius was 85.8 cm., so that one scale division corresponded, when seen by reflection, to one minute of arc. The scale was illuminated by gas jets, and the reflected image was observed by means of a telescope.

The magnetizing coil was 30 cms. long, and gave a field of 36.7 C. G. S. units by passage of a current of one ampere. In addition to the magnetizing coil, a small coil was inserted within the solenoid. Through this coil, a steady current was maintained to compensate the vertical component of the terrestrial magnetic force. The magnetizing current was generally obtained from Bunsen cells, and made to vary continuously by placing a liquid slide in the circuit. It was measured by a Thomson graded galvanometer. The different parts of the apparatus being as described above, the experiment was conducted in the following manner.

A carefully annealed nickel wire was fixed within the solenoid, its upper end being screwed to the axis of the torsion circle, and its lower end to the cross as before mentioned. While the wire was being set in position, the magnetizing force was zero within the solenoid, the vertical component of the terrestrial magnetic field being neutralised by a current in the small coil placed within the main coil. The reading of the torsion circle was then taken, and the two vertical rods (*rr*) were so placed, that they just touched the horizontal rod (*d*) of the cross on its opposite sides. The wire was now twisted by turning the torsion circle, and held in the twisted condition for some time. The reading of the scale was noted. The circle was then turned in the opposite direction so as to make the cross free of the vertical rods. When the residual twist was small, the torsion circle was brought back completely to its original position, and the small amount of residual twist was given by the difference in the initial and final scale readings. For large residual twists, however, turning the torsion circle back to its original position would have thrown the reflected beam off the scale. Accordingly the torsion circle was turned back through a convenient and known angle, so that the wire hung free, and the reflected beam remained on the scale.

In the preliminary course of experiments, after the wire was freed from torsional oscillations, the elastic after-effect was measured by simultaneously noting the successive scale readings and the corresponding times after the release. When the untwisting due to the after-effect had become very slow, the magnetizing force was applied, and the corresponding scale readings noted.

Before entering into the investigation of the effect of magnetization on the permanent twist, it was desirable to have some knowledge of the torsional after-effect of nickel. In every experiment, the wire was twisted and left for some time in this state. On releasing the torsion, torsional oscillations ensued. After its cessation, the wire continued gradually to untwist in virtue of the elastic after-effect. It was then necessary to know when the untwisting due to the after effect should cease, for otherwise the untwistings due to magnetization and to the elastic after-effect would be mixed together.

As a general rule, the after-effect for the same angle of twist is smaller as the wire becomes thicker. For this reason, Professor Wiedemann used tolerably thick iron wires. Although much certainty is gained as to the effect due to magnetization only by using thick wires, yet there is the great disadvantage that the amount of untwisting is very small. With nickel wires, the elastic after-effect is very small, and we can use thin wires without incurring the risk of mixing the effect due to magnetization and that due to elastic after-effect.

A nickel wire 0.51 mm. thick and 27 cms. long was kept twisted through 60° for an hour, the longitudinal pull acting on the wire being the weight of the cross before mentioned. When released from torsion, the wire had a permanent twist of 2° 38′. On the cessation of the torsional oscillations, the following deflections with simultaneous readings of the chronometer were taken.

Time		Torsion	
3^h $19^m.0$	p. m. (11th April 1889)	2° 38′.0	
20.5	,,	37′.6	(Temperature)
22.0	,,	37′.4	9°.5
24.0	,,	37′.2	
36.0	,,	37′.0	
7^h 42.0	a. m. (12th)	36′.2	(9°.2)

The readings show that the after-effect in nickel is very small. The wire above tested would have been untwisted through a few minutes more, if we had waited for some weeks or months. Loading the wire, however, increases the after-effect, but when compared with the after-effect in iron under similar circumstances, it is very small. It is unnecessary to give the result of numerous similar experiments. Suffice to say, they all lead to the same conclusion. The precautions which must be taken in discriminating the untwistings due to magnetization and to after-effect in nickel is greatly lessened as compared with the precautions necessary in the case of iron. If sufficient care be taken to wait till the after-effect becomes very small, we may use thin nickel wires in the investigation of the effect of magnetization on torsion. Generally I waited an hour after the cessation of torsional oscillation, but if the wire was loaded, it was left for a night.

The thicknesses of the wires used in the present investigation varied from 0.34 to 0.72 mm. Most of the experiments were tried with the thinnest, for with it the effects were greatest. The wire was always carefully annealed by means of a Bunsen flame. It so happened, that when the twist was very large, the wire once used assumed a spiral aspect as was observed by Himstedt.* Such wires were rejected, and other wires cut from the same specimen were used instead.

The experiment was first tried with the wires above mentioned, when the permanent twist was very small, and the wire was subjected to weak longitudinal stress. The following gives the readings of untwisting due to magnetization when the load was the weight of the cross only.

* Wied. Ann. 17. pg. 712.

$r=0.17$ Perm. Twist $=1^{\circ}.6$		$r=0.24$ Perm. Twist $=7^{\circ}.2$		$r=0.35$ Perm. Twist $=3^{\circ}.3$	
$\mathfrak{H}$	τ	$\mathfrak{H}$	τ	$\mathfrak{H}$	τ
7.1	9′.3	6.0	4′.7	4.4	2′.9
9.8	17′.1	10.3	12′.3	6.3	5′.8
13.2	25′.6	13.2	16′.4	8.2	9′.1
15.9	30′.0	16.7	20′.6	10.3	12′.4
20.7	37′.3	24.1	25′.9	13.4	15′.9
25.2	43′.0	35.4	29′.8	16.0	18′.1
31.3	48′.0	42.2	31′.3	18.5	19′.5
40.7	52′.6	54.1	32′.9	25.8	23′.0
52.0	55′.5	67.2	34′.0	38.4	26′.7
65.0	57′.6	157.8	34′.6	53.2	28′.1
82.9	59′.1	...	...	66.7	28′.8
112.7	60′.1	...	...	103.0	29′.7
184.3	60′.7	...	...	184.3	29′.9

The above table shows how the untwisting proceeds as the strength of the field is increased. With the increase of the magnetizing force, untwisting becomes greater and greater, until at a certain point, the ratio of the untwisting to the corresponding magnetizing force reaches a maximum; in other words, the curve of untwisting has a wendepunkt. After this, the untwisting takes place very slowly, so that ultimately the curve (Fig. I, Pl. XXXVIII) becomes almost straight. Up to $\mathfrak{H}=180$, the curve does not reach a maximum.

In comparing the curves obtained with different wires, we easily see that the untwisting is greater for the thinner wire. For it will be noticed in the experiments first given that the permanent twist is greater for the thicker wire. Nevertheless, even with such handicapping, it is the thinner wire which has the greater untwisting as shown at a glance on the curves.

If after the magnetizing field has attained a certain value, it be gradually decreased, the wire again twists back. The twisting produced by the removal of the magnetizing force is, however, far smaller than the untwisting produced by the increase of the magnetizing force. Consequently, the return curve goes above the other, as is shown by the dotted line in curve (1) Fig. I. This fact can be briefly expressed by saying that there is magnetic after-effect in the twisting which becomes conspicuous by the removal of the magnetizing force. So long as the amount of permanent twist remains very small, the curve showing the torsional effect of a continuously changing magnetic force resembles the ordinary curve of magnetic hysteresis.

The above remark does not hold when the permanent twist exceeds a certain limit. The decrease of twist with increase of magnetization soon reaches a maximum. After this, the wire begins to twist in spite of the increase of magnetizing force. The amount of twisting of course varies with the permanent set of the wire as well as with the amount of pulling stress. The following table gives the amount of change of twist with the wire of 0.17 mm. radius.

Perm. Twist 6°.7		Perm. Twist 10°.6		Perm. Twist 861°	
$\mathfrak{H}$	τ	$\mathfrak{H}$	τ	$\mathfrak{H}$	τ
4.7	11′.5	2.7	7′.0	6.7	26′.5
7.0	18′.2	5.9	15′.8	10.0	38′.6
10.0	24′.7	8.8	19′.6	12.3	45′.5
13.3	26′.8	12.8	23′.0	15.1	52′.0
17.0	26′.9	17.1	25′.8	17.7	54′.9
18.2	26′.9	20.5	26′.8	23.1	61′.0
27.9	26′.2	32.0	28′.1	31.6	64′.2
42.2	25′.1	47.0	26′.9	50.1	60′.9
62.3	24′.7	72.6	22′.0	62.8	56′.1
125	24′.2	12.4	11′.5	88	46′.2
...	...	...	...	157	19′.0

These readings are plotted in curves (1) (2) (3) Fig. 2. respectively. Curve (4) is plotted from an experiment made with a wire of the same thickness, with a permanent twist of 1621°. These curves show that the untwisting on the first application of the magnetizing force is very large. When the twist is small the untwisting immediately becomes very small, and the wire begins to twist. But the further increase of the magnetizing force is of very little effect. The curve, shortly after the maxinum is attained, becomes nearly parallel to the line of no twisting.

This appearance is confined to those cases where the permanent twist is small. With a residual torsion of 10°.6 in the same wire, the curve acquires quite a different appearance. The rate of increase of untwisting with the increase of magnetizing force becomes less, so that the untwisting gradually approaches the maximum. Thereafter the twisting takes place gradually and steadily. On removing the magnetizing force, there is at first untwisting which reaches a maximum in a magnetizing field less than that corresponding to the maximum untwisting on the first application of the magnetizing force. The wire then again begins to twist, but on the complete removal of the magnetizing force, the wire remains untwisted relatively to its first position. The most striking difference between the curves in Fig. 1 and those of Fig. 2 is that the latter has a maximum point and the former has none. This maximum which seems to be closely connected with the amount of residual torsion occurs in weak magnetizing fields when the twist is small, but as the twist is increased, it occurs in stronger fields.

When the permanent twist is very large, the features of the curve do not change essentially. Curves (3) (4) Fig. 2. show the state of things for the twists of 861° and 1621° respectively. From these it will be seen that the untwisting does not increase proportionally with the permanent twist. On the contrary, the untwisting for the twist of 861° is greater than that for the twist of 1621°. The course of the curve, after passing the maximum becomes steeper with the larger permanent twist as the comparison of (1) (2) with (3) (4) will show. Thus, when the twist is large, and the magnetizing force sufficiently great, the curve may be expected to cut the line of no twisting.

Another difference in the curves of torsion obtained for different permanent twists consists in the course of the curve on the removal of the magnetizing force. In curve (2), we find that the "off" returns below the "on" curve, while in curve (3), it returns above it. In the former there is hysteresis or lagging, in the latter priming or negative hysteresis. This distinctive feature in the curves obtained for different twists also varies with the thickness of the wire.

It is unnecessary to give numerical details for the various experiments made with different wires and with different twists. The characteristics above described are illustrated in the curves of Fig. 3, which gives the results for nickel wires of diameters 0.5, 0.4, 0.7 mm. For these also the untwisting reaches a maximum for a comparatively low field, and a *twisting* begins to set in, and continues to the highest field used.

The following experiment shows that this twisting may proceed so far as to result in a final condition of *twistedness relatively to the original condition of the wire.* The wire, 0.34 mm. thick and 30 cms. long was twisted through eight complete revolutions of the torsion circle, and then released. It thus acquired a permanent twist of 2548°. The magnetizing current was derived from a shunt dynamo. The current strength was adjusted by the liquid slide before described.

Field.	Untwisting.
14.3	+20′.0
36.6	49′.0
68.0	53′.0
89.4	51′.0
152.0	34′.0
200	24′.0
245	12′.3
303	+ 6′.0
361	− 4′.0
432	−10′.0

The application of the magnetizing force showed at first an untwisting, which reached a maximum in a field strength of about 65 C. G. S. units. The wire then began to twist. In a field of about 335 units, it came back to the condition in which it was after release before the magnetizing force was applied. Thereafter the wire continued steadily to twist with the increase of magnetizing force, so that when $\mathfrak{H}=432$, the wire became twisted 10′ from its initial position of equilibrium. Thus a nickel wire with large permanent twist can be twisted by applying sufficiently great magnetizing force. As the course of the curve after passing the maximum is less steep in thick than in thin wires, still stronger magnetizing fields will be necessary to twist the former.

The next set of experiments has to do with nickel wires under longitudinal stress. The only change in the process of experimenting consisted in loading the wire. The vane was detached from the lower end of the cross and a short hook placed in its stead. A pan of weights hung from this hook, and was completely immersed in the water.

Different experiments were tried with wires of various thicknesses, and with different amounts of twist. Some of the results are shown plotted in Figs. (5) and (6). In all of these the untwisting by magnetization becomes greater by loading. When the permanent twist is small, the curve representing change of torsion reaches a maximum quite abruptly. The course of the curve immediately after passing the maximum is quite steep for some time, but after the magnetizing force attains a certain value, the return twist becomes very small. Moreover, there is hysteresis on the gradual removal of the magnetizing force. An inspection of the figures will be of more service than mere verbal description.

With large twists, the features of the curve of torsion do not greatly differ from those obtained with the unloaded wire. The chief change wrought by the loading is that after the maximum untwisting has been passed, the curve goes down more steeply than in the case when there is no load. This evidently suggests the possibility that the curve for the loaded wire will cut the line of no untwisting in magnetizing fields smaller than those needed to effect the same for unloaded wires. And this I found to be the case, as shown by the readings on the following page, which were made on a wire of 0.17 mm. diameter under a load of 342 grm. weight.

The former readings are shown plotted in curve (2) Fig. 4, and the first part of the latter in (4) Fig. 6, and the readings in strong fields in curve (3) Fig. 4. The comparison of these two curves with (1) shows that with the loaded wire the initial position is reached at smaller magnetizing fields than with the unloaded wire. Moreover, there is hysteresis when the permanent twist is moderate, but priming when the twist becomes large.

Finally the effect of transverse magnetization on the permanent twist was investigated. The wire being treated as before described,

Perm. Twist 95°.		Perm. Twist 583°.	
Field	Untwisting	Field	Untwisting
5.8	16′.1	6.1	8′.0
10.8	26′.2	7.5	15′.0
14.6	32′.7	10.9	23′.5
19.4	36′.8	14.1	33′.0
24.6	41′.0	17.4	39′.4
28.6	42′.6	24.5	53′.6
33.5	42′.8	39.4	73′.0
38.8	41′.6	50.3	76′.2
44.1	40′.0	54.4	77′.2
52.2	36′.4	66.7	76′.0
61.5	32′.0	85.6	69′.5
72.6	27′.0	98.6	62′.0
98.1	16′.9	164.2	25′.0
125.7	9′.5	191.9	17′.0
182.1	−1′.3	271	− 4′.0
...	...	328	−12′.2

was placed between two flat coils, through which magnetizing currents of various strength were passed. The wire, however, did not show the least sign of being affected by transverse magnetization, although the apparatus was capable of measuring 0.′1 of deflection.

The next point of inquiry was a comparison of these effects with those produced by twisting magnetized nickel wires. The apparatus used for examining the latter was similar to that used by Professor Wiedemann, in his investigation on the effect of twist on magnetization, and described in his 'Elektricität' Bd. 3. A nickel wire 1 mm. thick and 30 cm. long had two pieces of stout brass wire soldered at the ends. The wire was placed magnetic east and west, and carefully annealed in this position. It was then slid into a magnetizing coil, and its extremities firmly clamped to the twisting apparatus. The magnetizing current was gradually increased by means of the liquid slide, and then slowly removed. Thereupon the deflection of the magnetometer mirror with corresponding angle of twist was read. The following table gives the changes produced on the permanent magnetism in arbitrary scale unit, the amount of permanent magnetism being proportional to the number of scale divisions when the twist is zero.

Twist	(I)	(II)	(III)	(IV)	(V)
0	589	455	183	83	41
5°	549	410	161	74	27
10°	550	385	159	78	20
15°	554	378	173	88	19
20°	558	384	194	102	24
25°	560	393	212	119	33
30°	559	402	224	131	40
35°	554	405	233	141	47
40°	551	405	238	149	52
45°	...	404	238	153	...
50°	540	403	239	155	62
60°	529	397	237	158	68
70°	...	...	235	160	71
80°	...	...	...	160	...
90°	...	...	...	161	74
120°	...	...	...	160	75
180°	...	...	...	...	76
270°	...	...	...	...	74

The examination of the above table shows that the first effect of twist is always to decrease the magnetism of the wire. This decrease soon ceases, and an increase sets in as the twist becomes larger. When the permanent magnetism is large, the increase is small, and the original value of the magnetic moment is not recovered. On the other hand, for small values of permanent magnetism, the increase is considerable; and as the twisting continues the wire acquires a greater magnetic moment than it had originally. When the wire is further twisted, the magnetic moment reaches a maximum, and begins to decrease. The maximum comes earlier for greater values of permanent magnetism. The maximum increase in weakly magnetized wire occurs at tolerably large twists, as an examination of the above table will show. In addition to this, the range of change in permanent magnetism by twisting does not increase, but rather seems to diminish with the amount of permanent magnetism, for moderate angles of twist.

The experiments hitherto described show close relations between the effects produced by twisting the permanently magnetized wire, and those produced by magnetizing the permanently twisted wire. The relation between the two can be most clearly represented by collecting the results in the following parallel statements.

1 The permanent magnetism of nickel wire is at first diminished by twisting.

I. The permanent twist of nickel wire is at first diminished by magnetization.

2. With *large* permanent magnetism, the decrease increases with increased twist.

II. With *small* permanent twist, the untwisting increases with the strength of magnetization.

3. Unless the permanent magnetism is very *large*, the decrease produced by twisting reaches a maximum. Further twisting in-

III. Unless the permanent twist is very *small*, the untwisting produced by magnetization reaches a maximum. The twisting produced creases the magnetism, so that it becomes greater than its original value.

by further increase of magnetization is so large, that the wire acquires greater twist than it originally had.

It appears from the readings given above for the changes in permanent magnetism, that there is a tendency to a decrease *again* setting in at the higher twists. This suggests that there may be untwisting in very strong fields, after the wire has been for some time twisting under the influence of magnetization. The current at my disposal did not allow me to try experiments with fields much over 400. Up to that limit, the twisting continued. It still remains undecided if further increase of magnetizing force gives a maximum twisting, corresponding to the maximum value of permanent magnetism obtained by twisting.

When the subject is viewed from the theory of rotating molecular magnets, we fall into difficulties which cannot be easily explained. Professor Wiedemann in coordinating the mutual relations between twist and magnetization of iron and steel wires, assumes that the molecules are subject to disturbances in trying to point their poles in the direction of magnetization. Drawing an analogy from the effect of mechanical disturbance applied to the twisted wire, he concludes that the disturbance caused by magnetization must untwist the iron or steel wires. This easily explains the effect of magnetization on the permanently twisted iron wire. It seems quite probable that a similar explanation can be applied to the untwisting observed in nickel wires. The effect of magnetization, however, is not so simple in nickel as in iron. It seems very difficult to explain the maximum untwisting observed in nickel. Moreover the disturbance caused in molecular groupings is not limited to longitudinal magnetization only. Transverse magnetization must likewise produce similar changes among the molecules. Thus the permanent twist would be affected by transversal as well as by longitudinal magnetization. In my experiments, transversal magnetization by flat coil had no sensible effect.

The change of permanent magnetism by twisting is more complex in nickel than in iron. If we have to explain the maximum decrease in permanent magnetism on Wiedemann's theory, we must assume that the nickel molecules rotate only through a certain angle by twisting, but beyond that angle, they move back towards the original position. This we have no right to assume. It seems hopeless to find any explanation of the various relations between twist and magnetization in terms of a really satisfactory theory of rotating molecules.

PLATE XXXVIII.

Fig. 1.

(1) $r=0.17$, $T=1^{\circ}.7$, $w=25$.

(2) $r=0.24$, $T=7^{\circ}.2$, $w=25$.

(3) $r=0.36$, $T=3^{\circ}.3$, $w=25$.

Fig. 2.

(1) $r=0.17$, $T=6^{\circ}.7$, $w=25$.

(2) $r=0.17$, $T=10^{\circ}.6$, $w=25$.

(3) $r=0.17$, $T=861^{\circ}$, $w=25$.

(4) $r=0.17$, $T=1621^{\circ}$, $w=25$.

Fig. 3.

(1) $r=0.25$, $T=626^{\circ}$, $w=25$.

(2) $r=0.20$, $T=1269^{\circ}$, $w=25$.

(3) $r=0.35$, $T=1349^{\circ}$, $w=25$.

Fig. 4.

(1) $r=0.17$, $T=2548^{\circ}$, $w=25$.

(2) $r=0.17$, $T=95^{\circ}$, $w=342$.

(3) $r=0.17$, $T=583^{\circ}$, $w=342$.

Fig. 5.

(1) $r=0.36$, $T=4^{\circ}.3$, $w=218$.

(2) $r=0.20$, $T=22.^{\circ}$, $w=218$.

(3) $r=0.20$, $T=16^{\circ}.7$, $w=411$.

(4) $r=0.20$, $T=968^{\circ}$, $w=218$.

Fig. 6.

(1) $r=0.17$, $T=18^{\circ}.5$, $w=156$.

(2) $r=0.17$, $T=584^{\circ}$, $w=156$.

(3) $r=0.17$, $T=260^{\circ}$, $w=342$.

(4) $r=0.17$, $T=583^{\circ}$, $w=342$.

r gives radius in mm.,

T ,, permanent twist in degrees,

w ,, longitudinal stress in grm. weight.

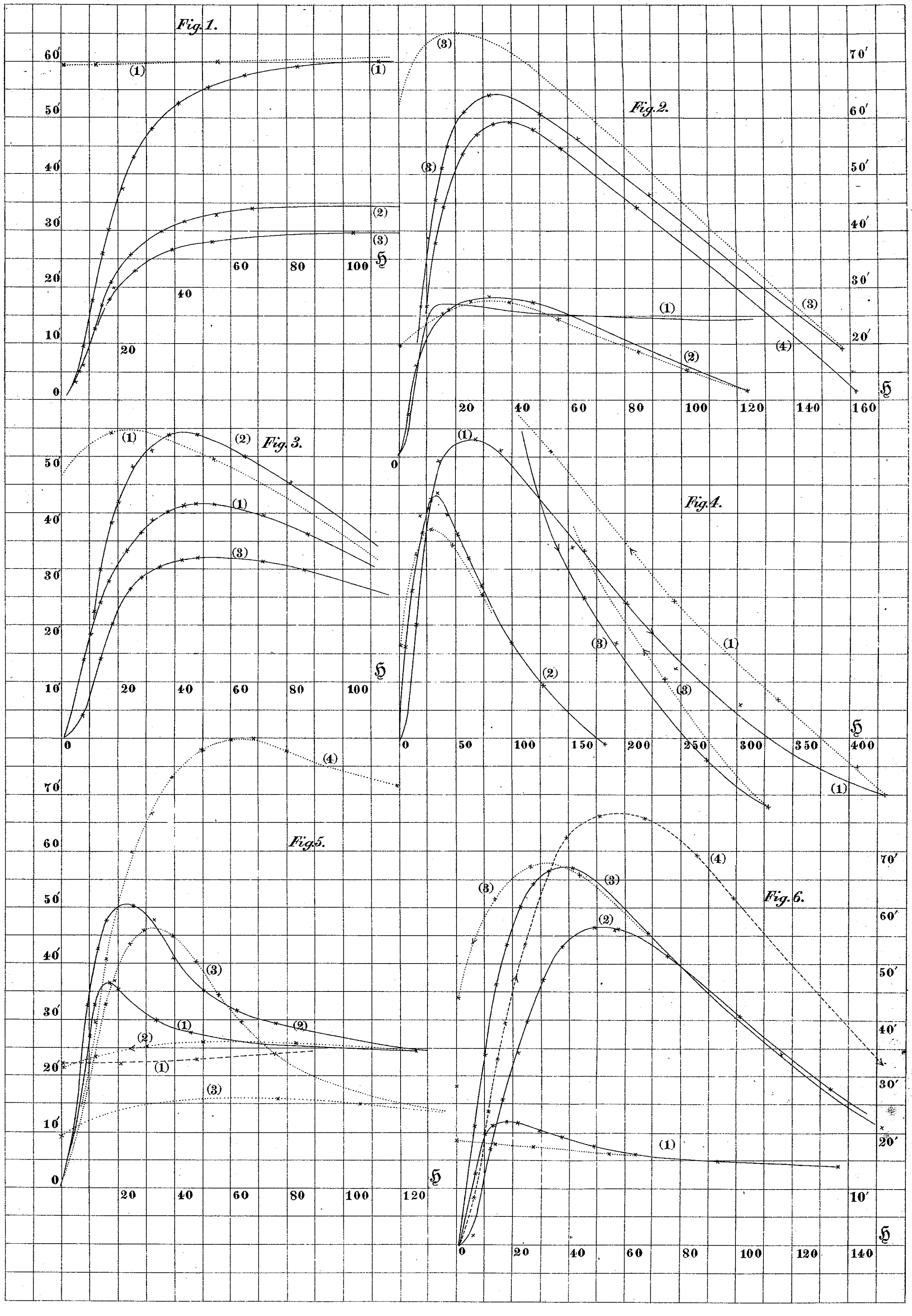
Fig. 1.
Fig. 2.
Fig. 3.
Fig. 4.
Fig. 5.
Fig. 6.