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Effect of Temperature on the Magnetization of Steels, Nickel and Cobalt, measured magnetometrically.

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(*With two plates*).

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§ 1. The importance of studying the effect of temperature on the magnetization of ferromagnetic bodies has long been recognised by physicists on account of its significant bearing on the molecular theory of magnetism. As early as 1825, Kupffer investigated the effect of heating upon the temporary magnetism of iron; later we find the names of Faraday, Wiedemann, Gaugain, Rowland, Baur, Trowbridge, Tomlinson, and Ledeboer[1] in the list of those who have investigated the effect of heating on magnetization.

The numerous experiments on the magnetization of ferromagnetic substances at different temperatures were for the most

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[1] Wiedemann's Elektricität, III. 1896; Ewing. Magnetic Induction; du Bois, Art. Propriétés magnetiques de la matière pondérable, *Rapports présentés au Congrès international de Physique*, Paris, 1900.

part qualitative until the decided advance in quantitative determination made by the researches of HOPKINSON[1] and CURIE.[2] Although the former used the ballistic method and his magnetizing field was not strong, yet he did not fail to bring to light the principal features of the change in magnetization near the critical temperature. CURIE utilized the mechanical force brought into play, when a ferromagnetic body is placed in a heterogeneous field. The magnetization could hardly have been uniform throughout, but the method was well adopted for heating the substance beyond the melting point and for examining its magnetic quality in fields scarcely attainable by means of a magnetizing coil. It would be superfluous to enter into a discussion of the advantages and disadvantages of the methods and arrangements of HOPKINSON and CURIE, suffice it to remark, that the magnetometric method is after all the best suited for the investigation of the change of magnetization near the critical temperature. We are however beset with difficulties in arranging the magnetizing coil and the heating apparatus within a small compass, so as to insure at the same time, the uniformity of the field and of the temperatures.

The present paper[3] gives a description of experiments made more than two years ago, for the purpose of studying the temperature effect on the magnetization of iron, various kinds of steels, nickel, and cobalt ovoids. The measurement of the intensity of magnetization was made by means of a magnetometer, and the heating was effected by gasflames, instead of following the usual method of raising the temperature by an electric current.

§ 2. *Method of Experiment.*—The method adopted in the

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[1] HOPKINSON, *Phil. Trans.* for 1889. p. 443.

[2] CURIE, *Ann.* de *Chim.* et de *Phys.* **5**, 289, 1895.

[3] An abstract of the paper is given in Reports of the Tōkyō Mathematico-physical Society for September, 1902.

present experiment permits examining the magnetizations at different temperatures up to about 1200°C., either by keeping the external magnetizing field constant, or in varying fields, by means of a simple magnetometer.

A magnetizing coil (length 40 cm., wound in 10 layers; $4\pi n = 394.4$ resistance $= 1.51$ ohm.) was waterjacketed and the inner face of the core protected by thick asbestos paper. A burner (Fig. 1) consisting of three branching copper tubes, coated with asbestos, was placed in the coil and fed with gas and air blast. Fine jets of flame (90 in all) issued horizontally, and played on the outer cover of the ferromagnetic ovoid. All the ovoids were 1 cm. thick and 20 cm. long, with the demagnetizing factor $N = 0.0836$. They were placed between the projecting knobs in the burner as shown in the figure. A platinum-rhodium and platinum junction was brought in contact with the ovoid at its thickest part, while the rest was insulated with asbestos paper.

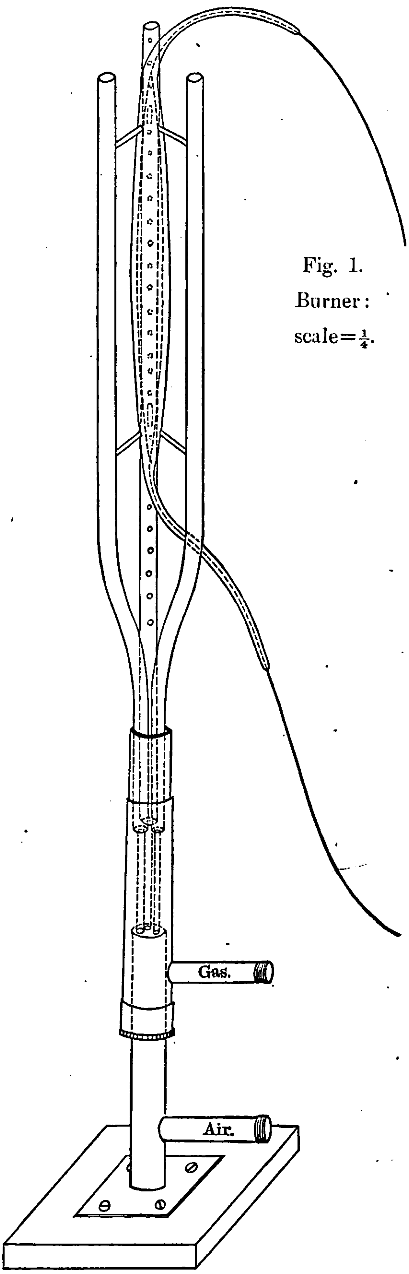

Fig. 1.
Burner:
scale $= \frac{1}{4}$.

The ovoid, together with the element leaving its extremities outside the coil, was thickly coated with asbestos paper, so that the temperature variation of the ovoid was very small even at 1000°C. The ovoid was placed vertically in the middle of the coil, as shown by the dotted lines in Fig. 1 and Fig. 2. The vertical component of the terrestrial magnetic field was compensated by a coil wound outside the magnetizing coil.

A magnetometer with a small bell-shaped magnet suspended by a fine quartz fibre was placed in such a position that the effect of a small vertical displacement of the ovoid was quite negligible. This was effected by placing the magnetometer in such a position that the line joining the centre of the ovoid with the magnetometer magnet was inclined at an angle, whose tangent $=\frac{1}{2}$ with the horizontal line, in the vertical plane containing the axis of the coil and the magnetometer. On the other side of the magnetometer symmetrical with the magnetizing coil, was placed another coil of the same strength, to compensate the effect of the coil on the magnetometer. In order to ensure the smallest possible displacement of the coils so as to get accurate compensation, they were placed on a wooden bench with V-shaped grooves lined with brass plates, on which the levelling screws of the coils rested. These coils were fed by accumulators. The current was measured by a Siemens and Halske amperemeter.

The temperature of the ovoid was measured by a thermoelectric junction with a D'Arsonval galvanometer in series, and the constant of the pyrometer was tested by means of a mercury thermometer to about 300° and by the melting point of sodium chloride at 780°.

The annexed figures show the arrangement in plan and in elevation.

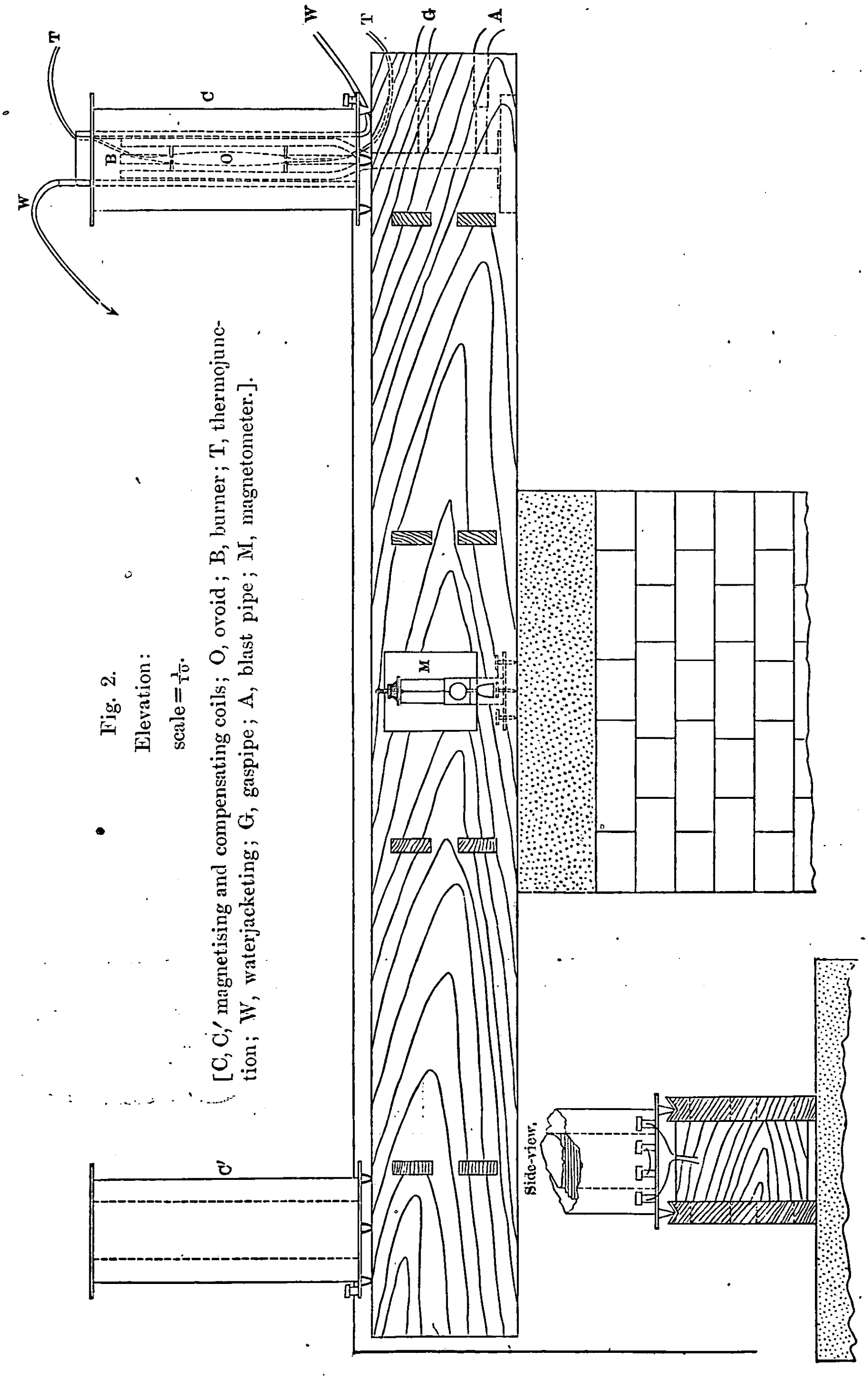

Fig. 2.

Elevation:

scale = $\frac{1}{10}$.

[C, C′ magnetising and compensating coils; O, ovoid; B, burner; T, thermojunction; W, waterjacketing; G, gaspipe; A, blast pipe; M, magnetometer.]

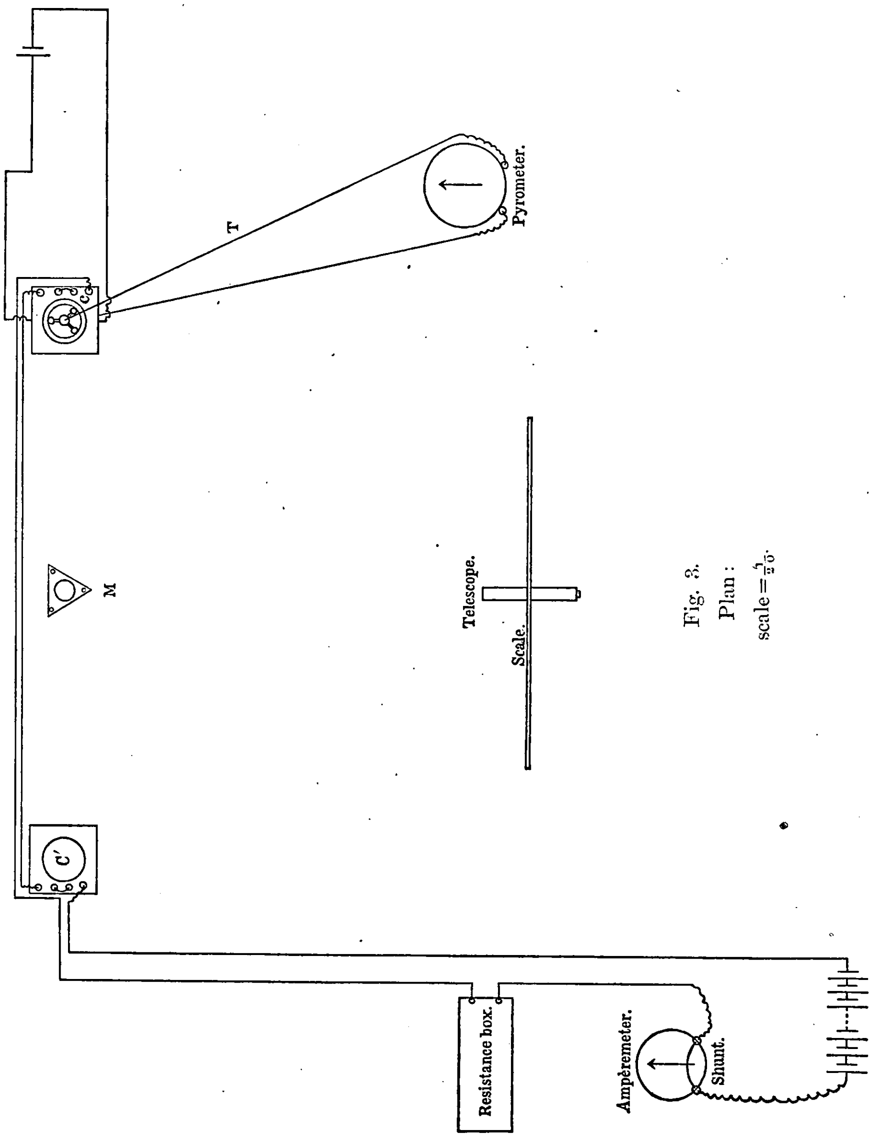

Fig. 3.
Plan:
scale $= \frac{1}{20}$.

In order to avoid external disturbances, the observations were made during the night. The scale readings could be easily read to $\frac{1}{10}$ of a mm., which corresponded to ca. 4.6 C.G.S. in the intensity of magnetization, but it was impossible to read the D'Arsonval galvanometer more accurately than to within a few degrees of the centigrade scale, when temperature was above 700,° although the fluctuations were generally slow.

It may here be mentioned that a magnetometric study on the effect of temperature on the magnetization of basalt has been made recently by ALLAN,1) although the heating was done with electricity.

§ 3. As the results obtained with iron ovoids do not differ particularly from those already obtained by HOPKINSON2), CURIE3) LYDALL and POCKLNGTON,4) MORRIS,5) and WILLS,6) we shall describe only our experiments with steels, nickel and cobalt.

Steels. Ordinary steel behaves qualitatively like iron, with the only difference that the transformation takes place at a higher temperature. Up to about 500°, the diminution of magnetization due to temperature rise is generally insignificant, but with increased temperatures the rate of diminution gradually increases till it approaches the critical temperature, which lies very close to 820°.

In cast steel, the same course as for ordinary steel is repeated at a somewhat higher temperature. The critical temperature of the specimen which we experimented with, was about 920°, being about 100° higher than that for ordinary steel.

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1) ALLAN, *Phil. Mag.* Jan. 1904, p. 45.

2) HOPKINSON, *loc. cit.*

3) CURIE, *loc. cit.*

4) LYDALL and POCKLINGTON, *Proc.* R. S., **52**, 213. 1892.

5) MORRIS, *Phil. Mag.* Sept. 1897, p. 229-230.

6) WILLS, *Phil. Mag.* July 1900. p. 1-43.

Tungsten steel behaves like ordinary steel, the only difference being that the critical temperature is about 900°.

Nickel. The susceptibility of nickel decreases with rise of temperature; which is more marked as we approach the transition stage; the magnetization soon reaches saturation, so that its increase after $\mathfrak{H}=100$ is extremely small. The specimen was nearly pure, and indicated evanescence of magnetization at about 500°. It must, however, be borne in mind that these temperatures in all the ferromagnetics depend on the field strength as well as on the history of the previous heating or cooling, as will be shown later in the experiments in fields of constant strength.

Cobalt. Of all the ferromagnetic substances which we examined, cobalt alone was characterized by several remakable changes by magnetization due to the raising of its temperature, although most of the effects were equally participated in by other ferromagnetics.

The magnetization at ordinary temperatures is generally weak in low fields, but gradually increases at a steady rate, so that even in a field of 500 units, the magnetization can not be said to be in a saturated condition. With increase of temperature, the ‚ wendepunkt ‘ gradually recedes towards low fields, and the magnetization on the whole increases in all fields. At about 500°, the increase reaches its maximum, and is about twice as great as at ordinary temperatures. Thus the effect of temperature is singularly large in cobalt. With further increase of temperature, the magnetization in low fields increases while that in high fields decreases, and the nature of the change wrought by raising the temperature of the metal resembles that in iron and nickel. The curves of magnetization at high temperatures gradually become less steep in high fields, while those at low temperatures show the opposite tendency. Retaining these features up to about 900°, the rate of the fall of magnetization with a still further increase of temperature becomes very great, and the curve of magnetization at 1140° lies flat along the axis of null magnetization.

One of us had already shown that cast cobalt undergoes remarkable changes by annealing both as regards magnetization and magnetostriction. The specimen here experimented upon was an annealed ovoid; it showed that successive heatings produce small changes, so that after cooling the metal the curve of magnetization is slightly displaced as shown in the figure.

The following table contains the results of observations.

Ordinary steel.	
$\mathfrak{H}$	$\mathfrak{I}$
Temperature =18.°	
0.9	24.1
2.6	93.5
3.5	125.4
4.0	170.2
4.8	219.7
5.8	284.0
6.0	335.7
6.5	385.5
8.4	465.3
9.1	565.7
17.2	801.6
35.9	1102.
81.0	1229.
146.7	1321.
209.4	1364.
255.8	1406.
300.5	1424.
319.7	1432.
Temperature =738±7.°	
0.3	37.5
1.5	108.7
2.0	158.2
4.0	208.2
5.2	297.8
13.4	386.5
25.5	475.0
49.8	568.0
101.1	609.4
173.2	641.6
194.2	649.8
250.4	662.7
309.6	682.9
Temperature =817°±3.°	
97.2	0.9
175.6	3.6
235.4	5.6
336.0	8.8

Cast steel.	
$\mathfrak{H}$	$\mathfrak{I}$
Temperature =17°5.	
1.3	40.9
2.8	125.8
3.2	152.8
4.0	174.8
4.3	223.9
5.3	284.9
6.4	354.1
7.3	418.6
8.0	473.0
9.4	537.2
16.1	619.6
25.9	892.6
36.8	1034.
55.1	1132.
70.2	1190.
93.0	1123.
123.1	1270.
137.0	1287.
163.3	1316.
182.5	1335.
205.9	1354.
232.1	1376.
261.7	1396.
Temperature =831°±5.°	
3.7	3.2
12.1	68.8
18.9	115.2
22.1	141.8
25.6	176.7
34.4	215.2
49.6	274.8
81.5	343.5
129.7	402.0
182.7	434.6
252.9	455.2
324.3	475.3
Temperature =903°±3.°	
2.5	9.6
40.3	15.6
120.0	37.6
195.8	44.1
281.4	45.9
360.6	43.6*

Tungsten steel.	
$\mathfrak{H}$	$\mathfrak{I}$
Temperature =19°5.	
1.7	5.6
7.9	53.9
8.6	91.1
12.8	140.3
14.0	185.8
15.6	249.8
16.9	473.2
22.3	698.6
29.9	940.9
49.9	1107.
70.2	1169.
114.6	1242.
173.9	1298.
212.4	1324.
253.4	1346.
298.1	1365.
Temperature =564°±4.°	
2.1	23.7
6.9	88.3
8.3	116.6
10.6	181.6
12.7	234.1
16.8	335.6
21.8	420.4
48.6	581.1
109.4	688.4
174.8	740.9
217.7	766.2
252.5	786.0
337.5	816.8
Temperature =845°±2.°	
10.4	37.2
34.0	38.1
52.4	45.5
125.4	57.6
234.5	64.1
320.0	65.0

Cobalt.	
$\mathfrak{H}$	$\mathfrak{I}$
Temperature =17.°	
5.7	6.3
11.9	14.9
16.8	23.0
20.4	29.8
28.4	46.1
34.8	65.5
47.9	95.8
70.9	141.8
93.1	185.2
129.2	243.8
170.6	292.6
218.6	339.0
264.8	380.9
320.8	416.0
428.7	477.3
497.5	512.3
Temperature =533°±3.°	
7.5	95.8
8.7	119.7
10.4	150.0
12.5	207.7
15.8	269.6
22.6	357.0
35.5	426.0
73.3	601.7
136.2	733.4
207.6	816.2
285.3	869.2
393.2	918.1
462.4	938.5
Temperature =1138°±2.°	
79.1	9.0
201.0	10.8
338.8	11.3
454.6	9.9*

Nickel.	
$\mathfrak{H}$	$\mathfrak{I}$
Temperature =18.°	
0.9	14.2
3.7	102.5
5.1	150.6
6.3	192.6
8.0	243.1
10.3	295.5
11.3	329.4
14.5	349.2
18.9	373.7
23.2	391.2
40.6	415.2
82.5	444.8
127.2	458.5
186.1	466.0
250.8	469.8
310.1	472.6
368.5	473.1
451.2	473.5
513.6	473.5
Temperature =400°±2.°	
3.6	4.3
15.9	25.0
20.1	30.7
29.3	44.4
35.5	54.3
50.5	82.2
159.8	100.6
239.3	100.6
383.3	101.5
501.4	103.4

N. B. Small numbers with the prefixed double sign denote the greatest deviation of temperature during the experiment.

* When the temperature is very high, a change of one or two degrees may have great influence upon the intensity of magnetization and give rise to an irregularity of this kind.

§ 4. The advantage of the magnetometric over the ballistic method becomes very marked in the observation of the change of magnetization when the field is kept constant and the temperature of the ovoid varied. Several inconveniences of the ballistic method can be avoided by making continuous observations of the magnetometric deflection. The change of magnetization takes place rather slowly, and we can follow it by the magnetometric method, while the ballistic method does not allow us to trace the change in its successive phases.

Ordinary Steel. The curve (Fig. 9, Pl. II.) shows the slight, increase of magnetization with temperature rise. The fall of magnetization takes place very rapidly after passing 700°, until it finally vanishes at about 830°. A remarkable feature is revealed on cooling. The return curve does not retrace the heating curve, but the metal must be cooled about 40° below the critical temperature, before the magnetization, which had disappeared in the heating, again makes its appearance. The increase of magnetization in cooling takes place slowly after reappearance, but eventually the increase becomes very rapid, and attains such values that the curve crosses the heating curve, and lies above it when the temperature is below 650.°

Further cooling results in a slight increase of magnetization. The curve representing the variation of magnetization with temperature is generally very smooth.

Tungsten steel. The change in tungsten steel is of a complex character. Before reaching the temperature of the sudden drop in magnetization on heating and after passing that of the sudden rise on cooling, we notice at least five corrugations in the curves of magnetization in a constant field. In an experiment in $\mathfrak{H}'=39.8$, the corrugations lie at about 300°, 430°, 510°, 580° and 730°. The curve drops abruptly between the temperatures 830° and 880°, showing evanessence of magnetization at about 910.° The retardation in the reappearance of magnetization on cooling is very remarkable. When once the magnetization disappears it can not be recovered until the temperature is lowered by about 240°, so that it reappears at about 570°, indicating a sudden increase between 630° and 620.° The increase, however, goes on slowly when the metal is cooled below 600°, and the curve displays singular trends, at temperatures nearly coinciding with those above mentioned. The magnetization below 380° becomes greater than that on the heating course, so that on reaching ordinary temperature, the difference between the final and initial intensities of magnetization amounts to one-third of the total intensity. In experiments in stronger fields ($\mathfrak{H}'=118$) the same characteristics are shared by the heating and cooling curves as shown in Fig. 10, Pl. II. The corrugations are made more conspicuous and lie at somewhat higher temperatures.

Nickel. The critical temperature of this metal lies far below that of iron and cobalt, and the heating and cooling curves assume smooth courses. The specimen tested was of nearly pure nickel; the critical temperature for $\mathfrak{H}'=39$ being about 500°; it rose to 580° for $\mathfrak{H}'=177$, showing that the said temperature increases with the field strength. On cooling, we notice that the magnetization begins to recover at temperatures about 100° lower than that at which it vanishes on heating, just as in iron and steel. The difference in the magnetization after cooling down to ordinary temperature is tolerably large in moderate fields, but becomes smaller as the field strength is increased. An inspection of the curve in Fig. 11, Pl. II. will make these points clear.

Cobalt. The general character of the curve of magnetization plotted against temperature is the same as for other ferromagnetic bodies, but as already noticed, the variation in the magnetization of the metal surpasses all other substances thus far examined. This remarkable difference can be easily traced in the curves, of which three are given in Fig. 12, Pl. II. e.g. $\mathfrak{H}'=39.3$, 97.1, and 186.7.

In the first place, the increase in the magnetization at 500° is nearly double the intensity at ordinary temperatures. The maximum intensity at about 500° is highly characteristic of this metal, for the decrease in the intensity takes place quite steeply as the temperature is further increased. The place of sudden decrease is carried to higher temperatures as the magnetizing forces become stronger. The cooling curve cuts the heating curve and reaches the maximum at about 360°, which is about 140° lower than that for heating. The change of magnetization either on cooling or on heating wears a rather irregular aspect, of which it is not easy to give a simple description, but the inspection of the curves will reveal the complicated nature of the change.

§ 5. *Recalescence of Tungsten steel.* The curious behaviour of tungsten steel on cooling after heating seemed at first sight to have an intimate connection with recalescense; it can be easily observed in the case of a rod of this metal. Upon heating it with the burner described above to about 800°, and then exposing it to the air, and observing the dazzling metal in the dark, we first notice a shade of dusky hue at both extremities; this gradually spreads upwards and downwards, just as dilute ink soaks into a red blotting paper. The dark portions gradually spread toward the middle of the rod, but with the lapse of time, the ends begin again to brighten. The colour now somewhat resembles that of the setting sun just emerging from a thick cloud; that part of the rod, which a few minutes before was scarcely visible, becomes tinged with red, and the clouds recede towards the middle, where they meet and disappear. The somber red thus prevails throughout the reheated rod, till it fades to a faint glimmer and disappears in complete darkness.

To ascertain the temperature at which this singular phenomenon takes place, a small hole was bored axially through a tungsten steel cylinder, into which the thermojunction could be introduced. Heating the cylinder to 900° and then leaving exposed to the air (at 21°), the temperature of the metal during the cooling process was observed with the time; Fig. 13, Pl. II. At 660,° there was an increase of temperature for a few minutes, and then a gradual decrease. This point is marked by a conspicuous prominence in the curve of cooling. At somewhat lower temperatures, we notice slight corrugations in the temperature curve, which may have some connection with similar features presented by magnetization. The approximate coincidence of the temperature of recalescence with that of steep ascent in magnetization leads us to the conclusion that they are both due to the establishment of a certain molecular arrangement at that temperature. Whether the temperature at which recalescence sets in depends on the magnetizing force, which evidently affects the cooling curve of magnetization, is a question still to be solved.

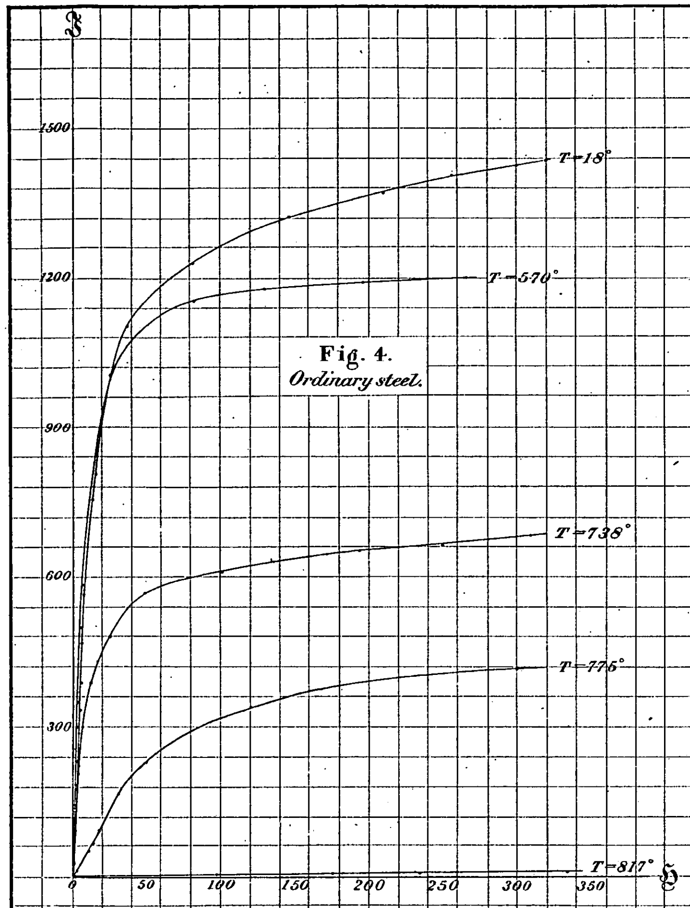

Fig. 4.
Ordinary steel.

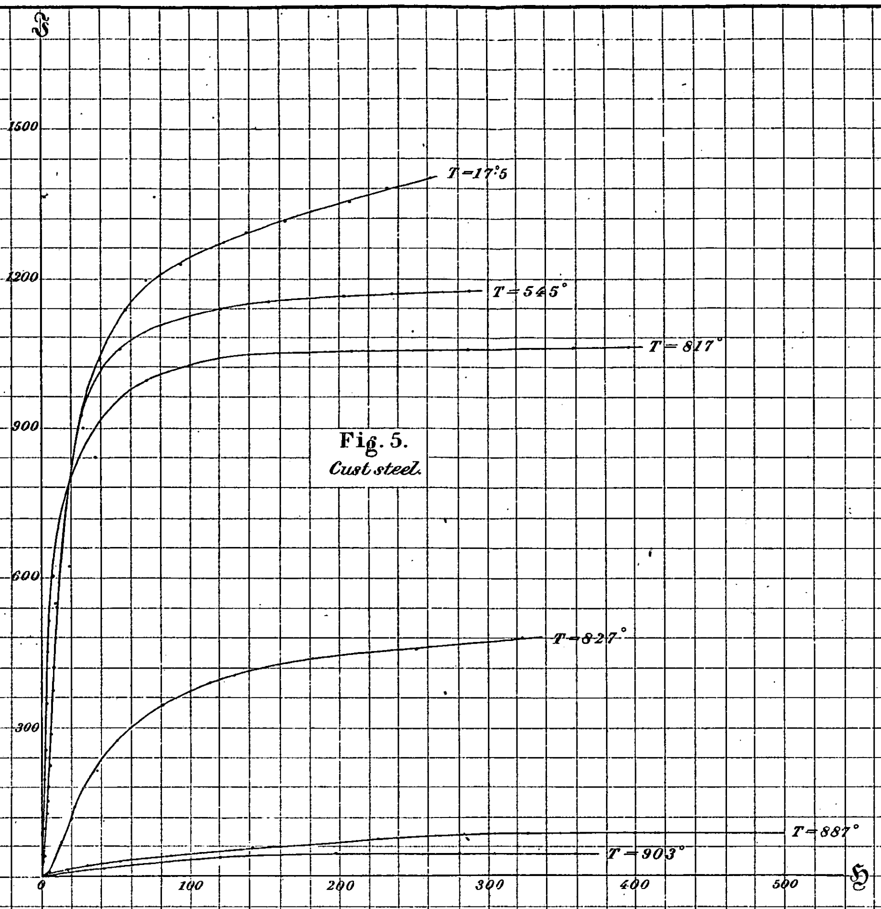

Fig. 5.
Cast steel.

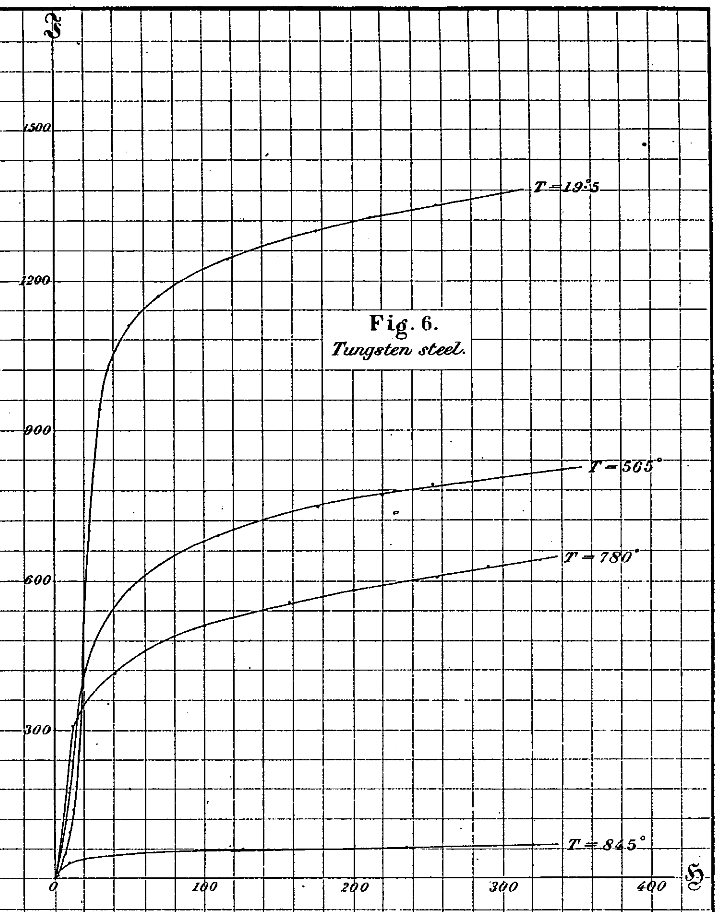

Fig. 6.
Tungsten steel.

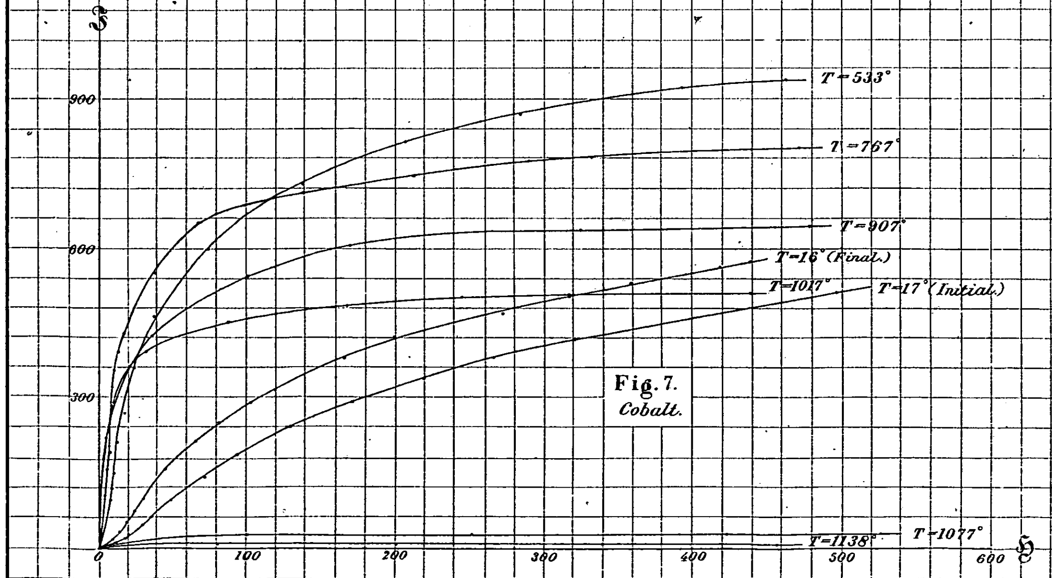

Fig. 7.
Cobalt.

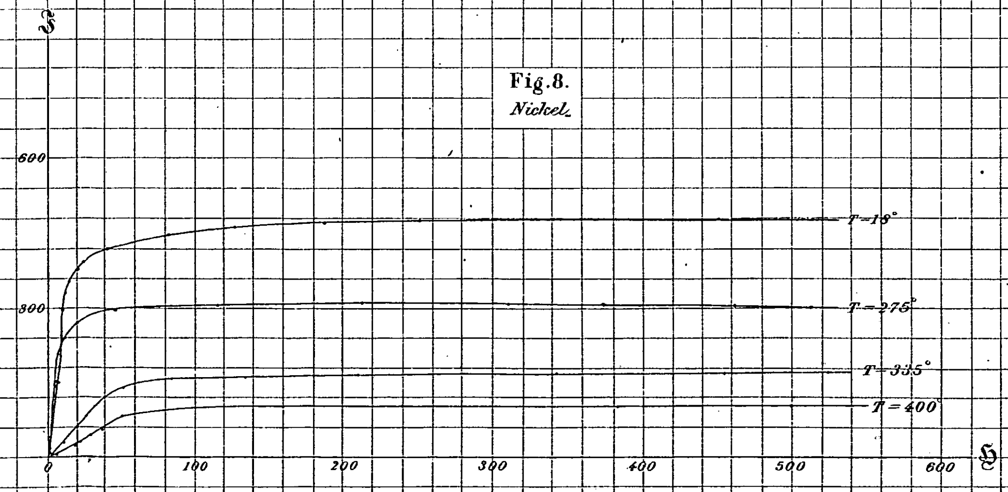

Fig. 8.
Nickel.

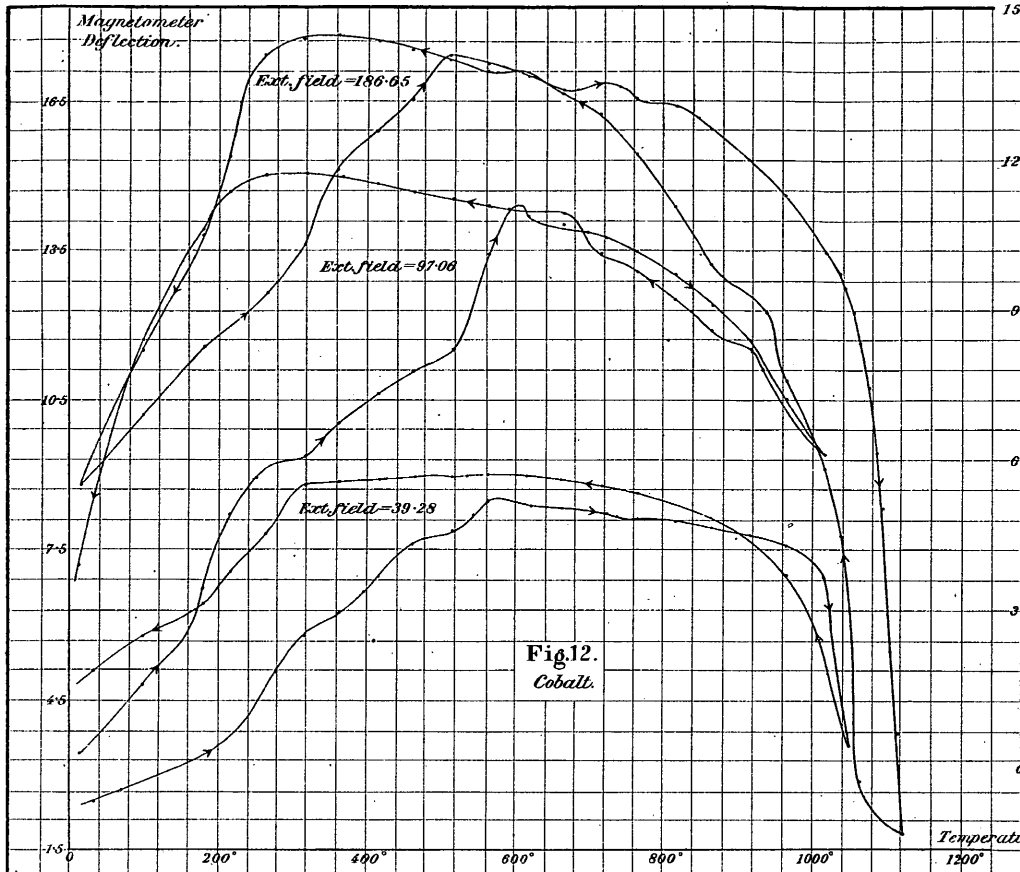

Fig. 12.
Cobalt.

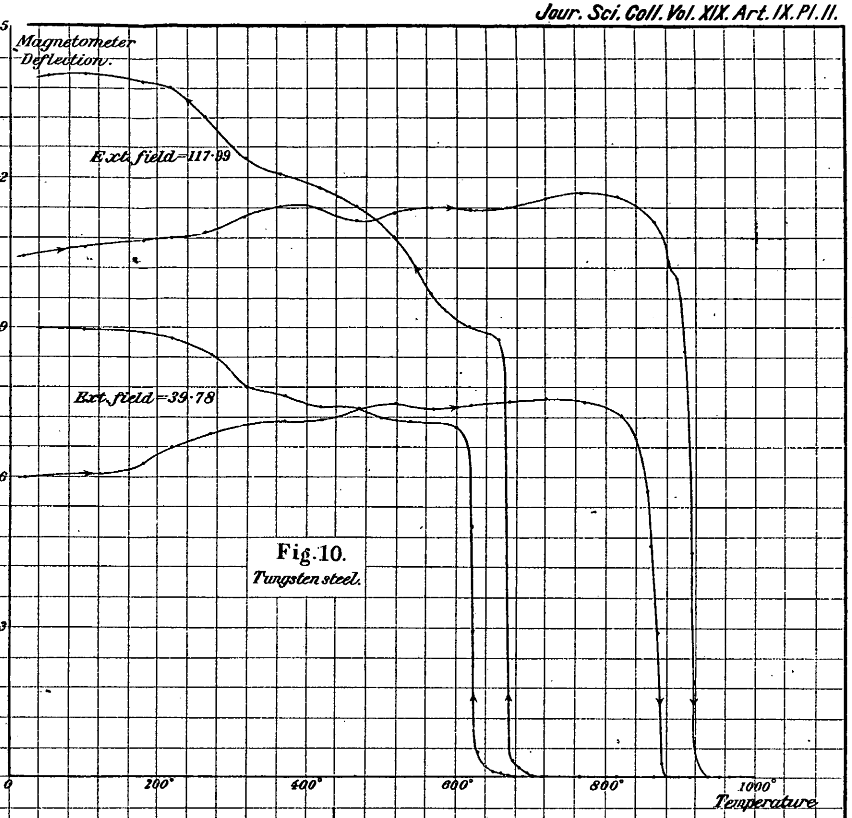

Fig. 10.
Tungsten steel.

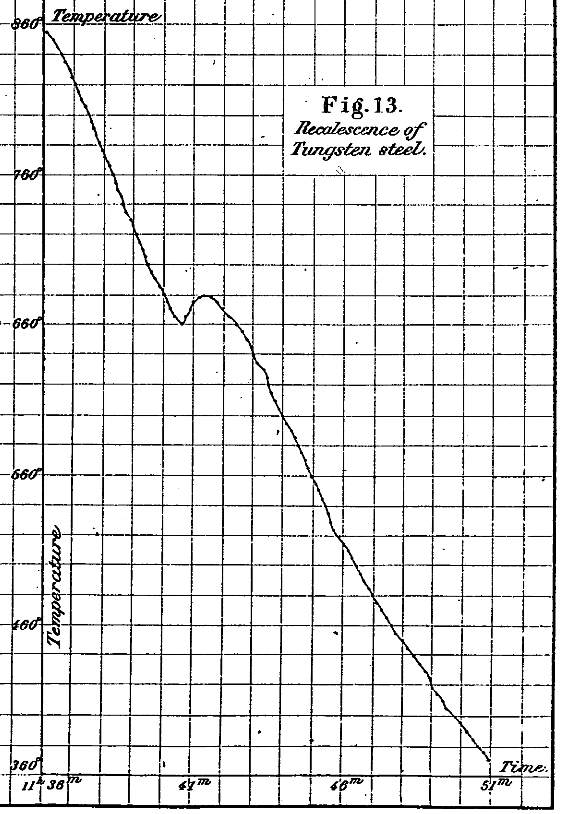

Fig. 13.
Recalescence of Tungsten steel.

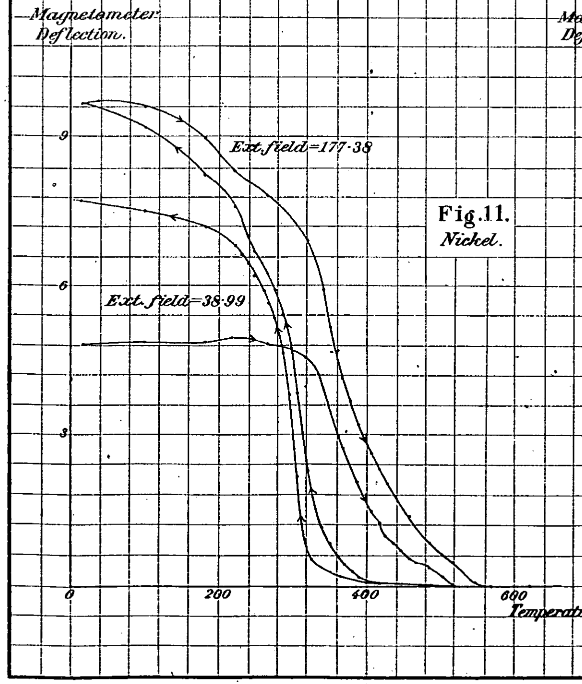

Fig. 11.
Nickel.

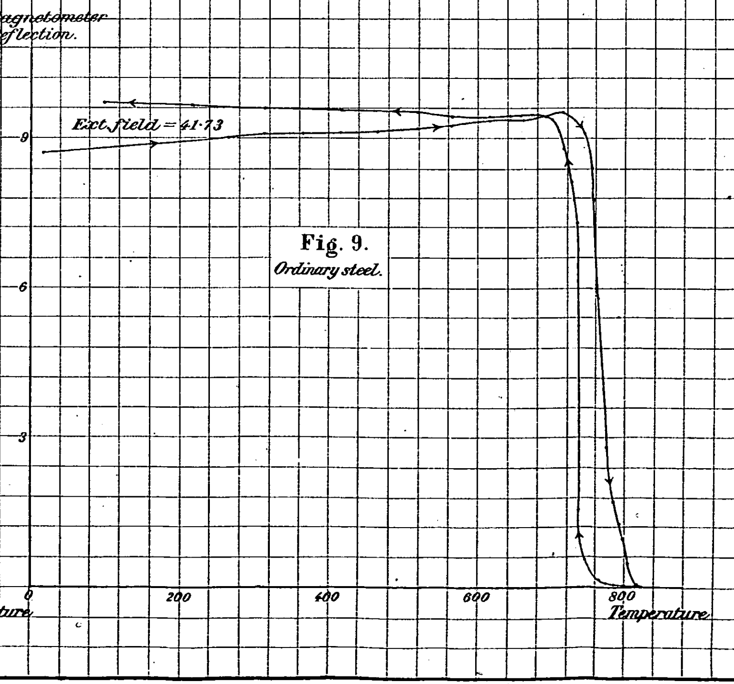

Fig. 9.
Ordinary steel.