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Experiments on the Magnetostriction of Steel, Nickel, Cobalt, and Nickel Steels.

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§ 1 Introduction.

In the course of our researches on magnetostriction¹⁾ of different ferromagnetic bodies, questions of various character presented themselves, both with regard to the method of measurement and the nature of the sample. The minuteness of the effect called forth precautions against diverse sources of error, such as the non-homogeneity of the magnetic field, and the mechanical force arising therefrom, the non-uniformity of temperature, a slight disturbance of which was in most cases sufficient to mask the strain, which we were seeking after. All those different sources of error, however intricate they may at first appear, can, by properly arranging the measuring apparatus, be eliminated. The method of observing the change of length and of volume, which we have already described in our former papers, and the agreement of the results obtained in different experiments with the same sample will be a sufficient warrant for the soundness of the apparatus and the method of measurement.

Apart from such instrumentalities, the diversity in the character of magnetostriction with different samples is hardly to be avoided. Experiments by Rhoads²⁾ with rolled or stretched sheets of iron sufficiently prove how the treatment of ferromagnetic bodies has great influence on the change of length accompanying the magnetization. In our former experiment on the magnetostriction of iron, steel, and nickel, the soft iron was what may be practically considered homogeneous, but the nickel ovoid was turned into shape from a thick plate. It thus seemed advisable to repeat the experiments with more homo-

1) Nagaoka and Honda, Journ. Sc. Coll. **9**, 253, 1893; **13**, 57, 1900; **13**, 263, 1900.

2) Rhoads, Phys. Rev. **7**, 65, 1898; Phil. Mag. Nov., 1901.

geneous metals. In addition to this, our investigation did not include the magnetostriction in cobalt, the only specimen hitherto examined being an ovoid,¹⁾ which was broken in two pieces, and firmly fixed together by wrapping thick paper over the broken edge. Unlike other experimenters, we tested cobalt in the present investigation in the cast and annealed states, and found an extraordinary difference in the change of length.

The curious property of *irreversible* nickel steel as regards magnetization was known for a long time by the beautiful experiment of Hopkinson. The question of magnetostriction in *reversible* nickel steels was a tempting subject for investigation, especially in connection with the remarkably small thermal expansion possessed by the metal, and its practical utility in the construction of scales and other instruments, which must not be affected by variations of temperature. Moreover it was very interesting to examine the nature of the magnetostrictions in nickel steel, as it is composed of two substances, whose length changes by magnetization are of opposite characters in weak fields, but similar in strong. A simple conjecture might suggest that the changes produced by magnetization are according to the relative proportion of the magnetostriction of the constituents, but the phenomenon is of a much complex character.

Associated with the changes of length and of volume, comes the Wiedemann effect, which is measured by the amount of torsion, caused by interaction of circular and longitudinal magnetizations. The measurement of the effect in cobalt must at present be postponed, as the metal can not be brought to a geometrical shape suitable for experiment, on account of its brittleness. Investigation of the effect in nickel steel of different percentages presents a phenomenon of the same

1) Nagaoka, Wied. Ann. **53**, 487, 1894; Rapports présentés au Congrès de Physique, Paris **2**, 536, 1900. For literature on magnetostriction, see Rapports.

aspect, as for the length change, and the sense of twist is the same as that of iron in weak fields.

A singular characteristic of magnetostriction is its reciprocity with the effect of stress on the magnetization of different ferromagnetic substances. In the present instance, we have turned our attention especially to cobalt and nickel steels. As will be expected from the nature of the length change, the former metal is characterized by the existence of a minimum point closely analogous to that bearing the name of Villari for iron, while with the latter, the effect of the longitudinal pull always results in an increase of magnetization. The parallel statements giving the correlation between the magnetization and the torsion, first introduced by G. Wiedemann, can thus be extended to other effects of stress and the strain resulting from the magnetization.

The present paper is limited to the mere description of the experimental investigation, the theoretical discussion being reserved for future consideration.

§ 2. Intensity of Magnetization.

In all of our measurements, we noticed the change of dimensions by magnetization and the strength of the field H ($H = H' - NI$, where H' is the external field, N the demagnetizing factor, and I the intensity of magnetization). It will therefore not be out of place to make a digression on the magnetization of the ferromagnetic substances here examined, in order to enable us to examine the various changes considered as functions of the intensity of magnetization.

The following table gives the dimensions as well as the demagnetizing factor N of the ovoids examined in the present experiments.

a : Semi-minor axis of the ovoid.

c : Semi-axis of rotation of the ovoid.

v : Volume of the ovoid.

ρ : Density „ „ „

No.	Metal.	a (cm.)	c (cm.)	v (c.cm.)	ρ	N
1	steel	0.493	10.00	10.40	7.85	0.0836
2	nickel	0.493	10.00	10.40	8.87	0.0836
3	cast cobalt	0.493	10.00	10.38	8.26	0.0836
4	annealed cobalt	0.495	10.02	10.52	8.20	0.0836
5	nickel steel (46% Ni)	0.494	10.01	10.45	8.15	0.0836
6	„ „ (36% Ni)	0.496	10.01	10.48	8.11	0.0836
7	„ „ (29% Ni)	0.492	10.01	10.43	8.12	0.0835
8	„ „ (25% Ni)	0.494	10.02	10.40	8.05	0.0836

The difference in the volume of the ovoids is to be attributed to the slight deviation from the exact geometrical shape.

As most specimens of cobalt contain more or less nickel, the cast and the annealed samples of the metal were subjected to chemical analysis, with the following results, for which our thanks are due to Mr. T. Suzuki, student in the chemical department of the University.

Cast cobalt.		Annealed cobalt.	
Co	93.36	Co	92.74
Ni	5.05	Ni	4.07
Fe	1.20	Fe	1.07
C	1.38	C	1.64
Si	0.39	Si	0.28
Cu	0.17	Cu	0.15
Mn	0.12	Mn	0.04

The specimen is not very pure, containing a small percentage of nickel as an impurity.

The magnetization was magnetometrically determined with the following results :—

Steel. (cast)		Nickel.		Cobalt. (cast)	
H	I	H	I	H	I
0.8	44	1.0	14	2.7	30
1.3	135	2.7	76	5.6	83
1.6	319	5.5	139	14.7	274
3.1	633	7.8	198	19.4	340
7.4	878	11.7	252	30.0	467
23.0	1122	18.2	314	44.7	572
140.0	1433	33.3	377	89.8	778
302.0	1555	59.9	426	256.3	984
511	1627	115.9	459	473.6	1080
598	1644	482	484	643	1119
672	1648	796	486	720	1136

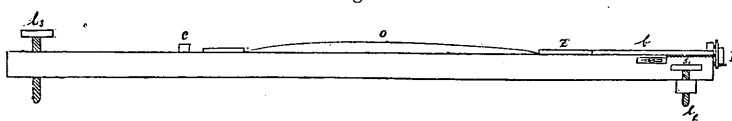
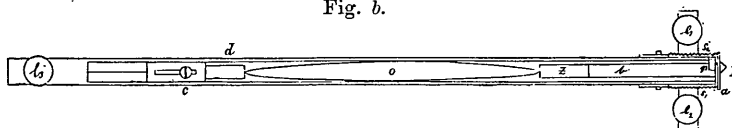
Cobalt. (annealed)		Nickel steel(46%)		Nickel steel(36%)		Nickel steel(29%)	
H	I	H	I	H	I	H	I
3.6	4	0.9	36	1.7	38	1.2	24
13.4	22	2.7	102	4.8	134	2.6	81
22.4	38	4.2	241	9.4	352	6.4	139
42.6	90	6.2	465	14.6	524	13.3	188
77.5	188	16.9	926	30.4	720	24.7	224
194.9	367	35.5	1108	85.5	900	46.2	243
281.0	439	119.7	1274	150.1	934	68.8	249
364.3	527	231.3	1303	261.5	953	140.2	256
460.8	568	380.0	1323	367.4	962	324.7	264
617	633	557	1333	510	971	575	273
788	699	778	1345	818	992	893	280

The curves of magnetization are represented in Fig. 1, Pl. I. The most magnetic of the ferromagnetic metals here examined is cast steel, whose magnetization comes very near to that of soft iron. Of the two kinds of cobalt, the cast specimen is nearly midway between steel and nickel; but with annealed specimen, the susceptibility is small in weak fields, and less than in nickel, but the differential susceptibility $\left(\frac{dI}{dH}\right)$ is greater in the strong, so that the intensity of magnetization becomes ultimately greater than in nickel.

Of the three kinds of reversible nickel steels, the 46% Ni specimen approaches steel, the 36% Ni lies near cast cobalt, and the 29% Ni is less magnetic than pure nickel. The magnetization reaches asymptotic value in fields less than those for steel or cobalt. The 25% specimen is only feebly magnetic, so that its magnetization is scarcely to be detected by the magnetometer. There we notice the singular fact, that the intensity of magnetization in nickel steel is not proportional to that of the constituent metals.

§ 3. Description of the Apparatus for Measuring Changes in Length.

The vertical and horizontal projections of the apparatus are represented in Figs. *a* and *b*. The essential part consists of a stout

Fig. *a*.Fig. *b*.

brass bar 53 cm. long, 1 cm. broad, and 1.1 cm. high. It is provided with three levelling screws l_1, l_2, l_3 . A carefully polished V-groove is

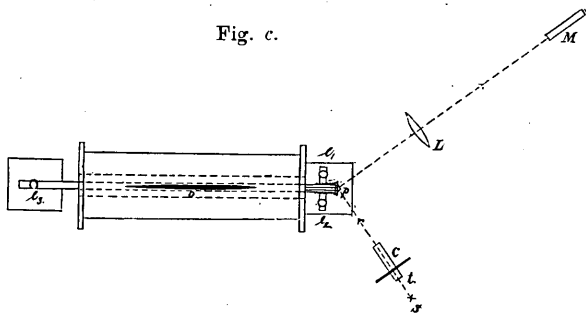
cut along the bar ; the groove is slightly widened at the middle of the bar, so as to allow the ovoid o to be so placed that the line of its axis passes through the centre of the optical lever (a). A small rectangular brass pillar p is erected at one corner of the bar. A small vertical V-groove is cut in it, and on this two points of the optical lever rest. The lever is a small rectangular piece of brass with three steel points, of which two rest on the pillar p , and the remaining one is in the same line as the axis of the ovoid, and rests on small plane glass plate, which is fixed to the end of the movable brass rod b . The lever arm is equal to 1.168 mm. Preliminary testing showed that the relative positions of these three steel points were not directly affected by the magnetizing force. The lever is pulled on both sides by small spiral springs of hard brass wire. These springs can be adjusted by slide arrangements, so that the lever turns its two points about on p , without being pushed out by the displacement of the ovoid. The reflecting face of the prism P attached to the lever was silvered. The greatest difficulty in the measurement of change of length by magnetization arises from the temperature changes produced by the magnetizing current. The temperature effect can, however, be greatly compensated for by applying the principle of the gridiron pendulum. This end was achieved by using zinc rods of suitable length, so that, in any combination, the total expansion due to small changes of temperature in particular lengths of zinc and the ovoid was equal to that in a particular length of brass. Zinc rods 5 mm. thick were carefully turned on a lathe and cut into proper lengths.

A brass rod (b) 5 mm. thick is placed in contact with the zinc rod (z). At the end of the brass rod, a plane glass plate is attached, so that the steel point of the lever comes in contact with it. At the other extremity of the row of rods and the ovoid is a stop. It consists of a triangular prism of brass to which a brass rod (d) 5 mm. thick is

attached. The prism fits in the V-groove, and is fixed tightly by means of a clamping screw c . To adjust the length bc , it is provided with a slit g . The screw c can be fixed at any part of the slit, and the position of the movable system can be so adjusted that the plane of the lever is perpendicular to the axis of the system. The slight push exerted by the springs s_1 , s_2 on the movable system prevents the play of different parts among one another, and was sufficient to overcome friction during the displacement of the system.

The ovoid was placed inside a solenoid 30 cm. long, which lay in a horizontal position magnetic east and west. The resistance of the solenoid was 0.63Ω , and gave a field of 37.97 C.G.S. units for a current of one ampere. The internal diameter of the solenoid was 3.2 cm. and no part of the measuring apparatus came in contact with it. Care was taken to place the apparatus along the axis of the solenoid, and so to place the ovoid that its centre coincided with that of the solenoid.

The optical arrangement for measuring the change of angle of the optical lever is shown in Fig. *c*. A fine glass thread t is placed

Fig. *c*.

vertically in the focus of a collimator c , and illuminated by a gas lamp. The ray after passing the lens, is reflected by a right angled prism p attached to the lever. The ray then traverses an achromatic lens L (focal length = 66.95 cm.). The image of the glass thread is

then observed by means of a microscope provided with micrometer ocular. By using filar micrometer, the accuracy of the measurement may be increased several times, but it was found quite superfluous. One division of the micrometer, the tenth of which can be easily estimated, was equivalent to an elongation of 4.35×10^{-7} .

Fig. *c* shows the horizontal plan of the arrangement while the perspective view is given in Fig. *d*.

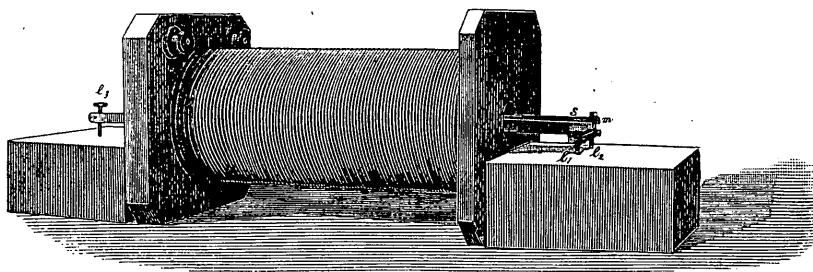


Fig. *d*.

§ 4. Change of Length in Different Ferromagnetic Bodies.

We consider the different sorts of iron, which were examined in our former experiments as homogeneous, as the general character of the change is both qualitatively and quantitatively nearly alike, and they are always subject to very careful annealing. Any new experiment would therefore have been superfluous.

(*a*) Cast Steel (Fig. 2, Pl. I.).

Dr. H. du Bois was kind enough to give us a piece of cast steel, which was regarded as the most homogeneous specimen at present obtainable. The rod was turned into an ovoid and its change of length measured in the usual manner with the following result.

H	$\frac{\delta l}{l}$
1.9	0.39×10^{-6}
3.2	0.61
14.8	1.79
26.3	2.53
122.6	1.53
247.2	-0.44
451.0	-3.96
676.5	-6.10
919	-6.80
1389	-7.75
1739	-8.28

In low fields, the length increases and at last reaches a maximum, whence it gradually diminishes, till it indicates no elongation. The decrease goes on steadily, but the rate of change becomes gradually less, and at last assumes an asymptotic value. As will be seen from the graphical representation (Fig. 2), the general feature of the curve representing the length change resembles that for iron, with slight difference in quantitative details.

(b) Nickel (Fig. 2, Pl. I.).

The nickel ovoid, which we have formerly used for the measurement of length and volume changes, was prepared from a thick plate of the same metal. Although the ovoid was annealed in charcoal fire for several days, lack of homogeneity was undeniable. To guard against such mischances, we have tested a new specimen, supplied by Johnson and Matthey, turned in the form of ovoid from a cylindrical rod.

The nature of the change does not materially vary from the

former specimen. In weak fields, the contraction takes place at first slowly, but gradually at an increased rate. Between fields 5 and 100, the rate of the diminution is very rapid, but the change becomes at last asymptotic, when it amounts to about 38×10^{-6} . It appears from the curve that the diminution of length will be but slight even if the field be increased to several thousand units. The following table gives the observed changes of length.

H	$\frac{\delta l}{l}$
3.9	$- 1.1 \times 10^{-6}$
9.8	$- 5.2$
22.8	$- 13.1$
42.6	$- 20.8$
72.1	$- 26.2$
127.8	$- 30.9$
238.6	$- 33.8$
473.0	$- 35.3$
794.0	$- 35.7$
1171	$- 36.1$
1508	$- 36.5$
1881	$- 36.9$

(c) Cobalt (Fig. 2, Pl. I.).

One of us has already examined the change of length in cobalt ovoid, which unfortunately was broken in two pieces. The result was, notwithstanding, in conformity with that already discovered by Bidwell.

Rods of cobalt, obtained from Johnson and Matthey, were turned

into ovoids of the same dimensions as for the two former metals. One of the ovoids was examined in the state, in which it issued from the lathe, while the other was annealed in charcoal fire for about 4 hours, after being carefully wrapped in asbestos paper. As the change of length by magnetization and the intensity of magnetization were characterized by a remarkable difference in character, it would be well to describe the phenomena separately for cobalt ovoids, which underwent different treatments.

Cast Cobalt. The behaviour of cast cobalt, as regards the length change, is similar to that in nickel in weak fields. Instead of reaching an asymptotic value as in nickel, the contraction of cobalt reaches a maximum at about $H=160$, from which the metal gradually recovers with increasing fields, till it attains its initial length in $H=750$. The metal however goes on elongating, but at a less rapid rate, till $H=2000$, which is the strongest field employed in the present experiment.

H	$\frac{\delta l}{l}$	H	$\frac{\delta l}{l}$
12.0	-0.78×10^{-6}	643.3	-0.87
19.4	-1.53	735	-0.13
29.1	-2.62	1114	+2.83
49.6	-5.14	1464	+4.11
76.3	-7.11	1807	+5.14
166.3	-8.11		
332.5	-6.28		
501.4	-3.36		

The table gives the observed changes; representing the change by means of a curve (Fig. 2), we notice a singular

trend, somewhat resembling the inverted form of the curve showing the same change for iron and steel. If the existence of the maximum elongation in iron warrants the existence of the Villari point, a point of opposite character must exist in cobalt if the metal be subject to loading.

Annealed Cobalt. The cast cobalt has silvery hue, similar to nickel, only lacking the yellowish lustre of the latter. By annealing cobalt, the surface colour turns ashy gray, and the permeability of the metal diminishes in a remarkable degree, as will be seen from the curves of magnetization (Fig. 1). The change of length by magnetization takes place at first slowly, but goes on steadily increasing till it amounts to nearly 25×10^{-6} in $H=2000$. The observed values are as follows :—

H	$\frac{\delta l}{l}$
12.6	-0.04×10^{-6}
39.8	-0.09
59.6	-0.13
92.0	-0.48
204.3	-2.14
458.0	-5.67
772	-11.33
1150	-17.44
1465	-20.71
1905	-25.06

The curve representing the change is therefore very simple, approximating to a straight line. As will be found later on, we found the reciprocity between the strain and the effect of stress again

established, since the longitudinal pull only produces diminution of magnetization.

(d) Reversible nickel steels (Fig. 3, Pl. I.).

The beautiful experiment of Hopkinson revealed a singular property of irreversible nickel steel as regards magnetization. The discovery of reversible nickel steel called forth new demands for the metal on account of its practical utility. Among the various physical properties of nickel steel, the small thermal expansion claims a prominent position in the different applications of the metal, such as for the construction of scales, or the compensation of chronometers and others of similar nature. Unfortunately no investigation has as yet been made appertaining to the deformation of the metal by magnetization.

Through the kindness of Messrs. Guillaume and Dumas, who supplied us the different samples of nickel steels, manufactured by Commentry-Fourchambault and Decazeville, we were enabled to examine the magnetostriction of the reversible nickel steel in its various aspects.

The samples to be tested were either turned into ovoids of the same dimensions as for the other metals, or used in the form of wires. These two different sets of metals do not show serious discrepancies in the observed results, which are given below for specimens containing different percentages of nickel, either in the form of ovoids or wires. It is to be remarked that the annealing of nickel steel wires was conducted in a glass tube, through which hydrogen gas was kept in constant circulation, and heated to 500° C. for more than three hours.

The observed changes of length are given in the following tables :—

Nickel steel ovoids.

46%		36%		29%	
H	$\frac{\delta l}{l}$	H	$\frac{\delta l}{l}$	H	$\frac{\delta l}{l}$
4.0	0.08×10^{-6}	7.5	0.44×10^{-6}	1.2	0.04×10^{-6}
4.6	0.22	17.6	2.00	15.0	0.13
6.7	0.87	37.1	5.05	27.8	0.87
10.6	2.61	66.5	8.62	45.3	1.13
32.2	9.67	151.5	12.32	81.8	1.70
71.4	15.89	234.0	13.72	135.7	2.26
121.2	18.72	341.2	14.80	292.2	3.57
314.2	22.29	400.8	15.15	509.7	5.49
573.1	23.30	587.1	16.24	864	8.62
860	23.91	1050	18.29	1238	12.19
1508	24.78	1342	19.81	1622	15.20
1908	24.99	1905	22.12	2040	18.55

Nickel steel wires.

45% (annealed)		45% (unannealed)		35% (annealed)		35% (unannealed)	
H	$\frac{\delta l}{l}$	H	$\frac{\delta l}{l}$	H	$\frac{\delta l}{l}$	H	$\frac{\delta l}{l}$
2.6	0.93×10^{-6}	11.8	0.34×10^{-6}	3.3	0.29×10^{-6}	5.1	0.12×10^{-6}
6.2	3.49	22.9	1.22	12.2	4.20	14.7	0.34
11.7	7.36	30.7	1.68	21.8	6.93	29.8	0.84
21.2	11.78	61.4	4.25	30.9	8.70	50.5	1.80
30.5	14.51	98.7	6.77	66.5	11.35	108.6	4.20
61.2	18.76	145.5	9.34	109.7	12.19	205.7	7.31
182.9	22.04	337.8	14.76	238.5	13.26	471.1	11.77
404.5	23.05	508.7	16.40	510.0	14.70	647.7	13.78
711	23.56	817	17.58	827	16.30	701	14.37
933	23.64	1246	18.09	1407	18.49	1033	16.55
1499	24.28	1485	18.51	1541	19.83	1509	18.99
1901	24.49	1831	18.84	1928	21.76	1846	21.09

The curves of the length change are plotted in Fig. 3.

All the nickel steels indicate increase of length in fields up to about $H=2000$. The character of the change for 46% Ni resembles that for nickel with opposite sign, inasmuch as the curve of elongation has great similarity to that of magnetization. The elongation in very weak fields takes place slowly, but in fields of about 30 units, the rate of change is most rapid and soon reaches an inflexion point, after which the increase in length takes place only very slowly and in an asymptotic manner.

With the 36% Ni, we observe similar features in the curve of elongation. The inflexion point lies in higher field, but the elongation is less than in 46% alloy. After this stage is passed, the ovoid goes on increasing in length at an almost constant rate, which is greater than for 46% Ni. Although the field, at which the curves for 46% and 36% Ni intersect has not yet been reached, we can easily infer that if the field be sufficiently increased, the elongation in 36% Ni, which is the least expansible by rise of temperature, will exceed that for 46% Ni. The contrast between 46% and 36% Ni is similar to that between 36% and 29%, so that what has already been remarked with respect to the two former alloys, equally applies to the relation between the two latter metals. It is also remarkable to observe that the 29% Ni, which will apparently indicate the largest increase in length, if the field be made sufficiently strong, is the least susceptible of the three nickel steels. With the 25% Ni, we could not detect any change, which is within the scope of measurement now attainable with the present arrangement.

The nickel steel wires, in the annealed state, present changes in length as similar to those of the ovoids. In the hard drawn state, the change is decidedly less than in the annealed.

The curves of the length change in iron or nickel, placed side by side with those in nickel steel, present a singular contrast. As is well known, nickel contracts, instead of expanding as in iron, the amount of contraction being several times that of iron. The feature here presented by nickel steel is similar to nickel as regards the amount and the character of the change, but as to the sense of elongation, it is similar to iron in weak fields increasing instead of diminishing as in nickel. It thus appears that the length change by magnetization is not of a simple nature, and not to be easily determined from the percentages of the constituent metals.

(e) Nickel steel wires in low fields (Fig. 4, Pl. I.).

Urged by the question of the practical utility of the metal, we made special investigations into the change of length in low fields, such as may habitually occur in the neighbourhood of electric installation or in terrestrial magnetic field. The question will be of utmost utility in deciding the effect of the terrestrial field ; as one instance, we may mention that in using Jäderin's wires of nickel steel in geodetic measurements. One may wonder from what has already been described, if the effect of the magnetic field will not be of the same magnitude as that of thermal expansion, which, as is well known, is of very minute amount. Our results for low fields are as follows :—

45% Ni (annealed)		45% Ni (unannealed)		35% Ni (annealed)		35% Ni (unannealed)	
H	$\frac{\delta l}{l}$	H	$\frac{\delta l}{l}$	H	$\frac{\delta l}{l}$	H	$\frac{\delta l}{l}$
3.5	1.18×10^{-6}	8.0	0.01×10^{-6}	3.5	0.50×10^{-6}	9.0	0.04×10^{-6}
7.6	4.22	11.0	0.17	5.2	1.56	11.7	0.21
11.7	6.64	15.7	0.62	8.9	3.12	14.5	0.32
14.7	8.40	19.7	1.07	15.8	5.23	18.2	0.63
21.0	10.60	21.7	1.09	21.2	6.60	22.0	0.77

From the above table, we gather the fact that the magnetostriction plays no important part in the use of nickel steel scales ; only in measurements of extreme accuracy, it will be necessary to add a very small factor of correction to the measured values, according as the scale is placed in the magnetic meridian or perpendicular thereto. As will be seen from the curves of elongation (Fig. 4), the difference in a metre will generally be less than $\frac{1}{10} \mu$ for measurements made in the said directions.

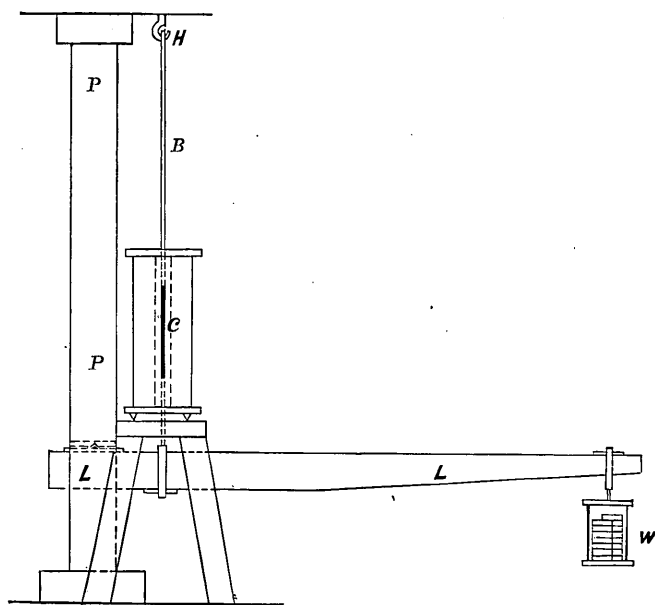
One distinct feature of the curves of elongation is the effect of annealing. In both 45% and 35% Ni, the wire elongates several times more in the annealed than in the hard drawn state, so that in cases when the change caused by magnetization is to be feared, we shall be able to eliminate the errors due to magnetostriction in a considerable degree by using the unannealed metal.

§ 5. Effect of Longitudinal Stress on Magnetization and the Reciprocal Relations.

A remarkable feature of magnetostriction is the reciprocal relation between the strain caused by magnetization and the effect of stress on magnetization. We have already examined the different changes from this stand-point for iron and nickel, and found that the relations between strain and stress are generally reciprocal in these two metals. In the present experiment, we made special examination into the effect of longitudinal pull on the magnetization of cobalt and nickel steels in the same light.

The annexed diagram shows the scheme of arrangement for examining the effect of pull on magnetization. A wooden lever LL , furnished with a knife edge, rested horizontally against a vertical pillar PP . The lever arm held a brass rod B , hang by a hook H from the ceiling ; a cobalt cylinder C (length 27.3 cm., diameter 1.36 cm.)

was brazed to the rod and placed axially in the interior of the magnetizing coil, which was placed vertically on a separate tripod stand.



The other end of the lever was loaded by the weight W . The change due to longitudinal stress was measured by means of a magnetometer.

In weak fields, the magnetization of cast cobalt decreases by loading. As the field strength is increased, the amount of the decrease reaches a maximum and then gradually lessens. Ultimately the field where the longitudinal pull does not affect the magnetization is reached. When this stage is passed, the magnetization increases by loading, so that the effect is reversed. The existence of a critical point in cobalt analogous to that of Villari in iron is thus established (Fig. 5, Pl. I.).

With annealed cobalt, the effect is simpler. As will be seen from the curves in Fig. 5, the longitudinal pull always causes a diminution of magnetization, which increases with the field. Thus the

behaviour of cast and annealed cobalt stands in reciprocal relation with that of the change of length produced by magnetization, as will be clear in the following parallel statements.

Cast cobalt.

Magnetization produces diminution of length in low fields, which after reaching a maximum gradually lessens, and finally produces increase in strong fields.

Mechanical elongation produces diminution of magnetization in low fields, which after reaching a maximum gradually lessens, and finally produces increase in strong fields.

Annealed cobalt.

Magnetization produces diminution of length, which gradually increases with the strength of the field.

Mechanical elongation produces diminution of magnetization, which gradually increases with the strength of the field.

The effect of mechanically elongating nickel steel always results in the increase of magnetization, as will be seen in Fig. 6, Pl. II. The change caused by stretching depends on the strength of the field, and is generally greater in the weak than in the strong. The correlation between the elongation due to magnetization and the effect of stretching on magnetization may be expressed in following words:

Magnetization produces increase of length in nickel steel.

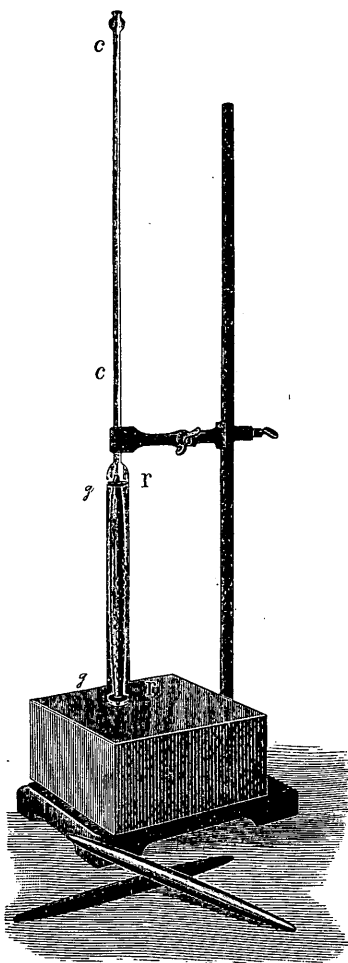
Mechanical elongation produces increase of magnetization.

§ 6. Change of Volume by Magnetization.

In spite of the well known experiments of Joule showing that iron does not change in bulk by magnetization, experiments by Knott, and ours sufficiently prove that this is by no means the case. It was suggested by Rhoads, that the change of volume may in a great part be due to the heterogeneity of the material under examination, while in some the arrangement of the experiment was not

free from errors, which, though very small, were sufficient to disguise the minute effect. One serious drawback in these experiments is the use of an unproportionally large mass of iron, which if the ratio of dimensions be sufficiently great, would not have been altogether objectionable, but as it generally happened to be, did not give the expected result. Non uniformity of the field is another source of error, which unfortunately has been too often neglected; the result

obtained in fields, which are not uniform, will indeed be very difficult of interpretation. If the material under test be not placed axially in the direction of magnetization, and the mechanical force urging the magnetic substance in one or other direction, comes into existence, the change of shape of volumenometer will in some cases be of such an amount, that it not only diminishes the measured change, but screens the desired effect. These various sources of error may, by proper construction of the volumenometer, be easily eliminated.



The accompanying cut, taken from a photograph, shows the arrangement of the volumenometer, which we have used in our observations. Into a glass tube *gg*, to which is hermetically sealed a capillary tube *cc* of about 0.4 mm. internal diameter, fit two brass rings *rr*. These rings are partly open, and by the elastic force, fit the tube quite tightly. The extremities of the ovoid

project out of the openings, and its axis is kept in coincidence with that of the tube. The axis of the magnetizing coil, which is all the while water jacketed, also coincides with that of the volumenometer during the experiments, so that the effect of the mechanical force and the non-uniformity of the field (the length of coil being 30, while that of the ovoid is 20 cm.) will not enter the measured results.

The motion of the capillary meniscus was noted by means of a microscope provided with a micrometer ocular. The magnifying power of the microscope was generally so chosen, that the range of motion during the experiment lay within the field of view. Although the magnetizing coil was water jacketed, the lack of temperature compensation, as in the experiments on the length change, made it desirable to notice the motion of the liquid shortly after making the current. In some of the metals, the change was generally almost instantaneous, but in a few specimens we noticed a distinct time-lag.

As announced by Quincke,¹⁾ change of volume in the liquid filling the volumenometer may be caused by the pressure in the magnetic field. To guard against this point, we have specially examined the volumenometer readings by simply filling it with water or ferric chloride, and did not find the effect within the range of field used in the present experiment, as might well be expected, as the pressure is proportional to the square of the field strength.

Cast Steel. The metal shows increase of volume in fields up to about 2000. The following gives the measured change.

1) Quincke, Sitzungsberichte d. Berliner Akademie d. Wissenschaften, 20, p. 391, 1900.

H	$\frac{\delta v}{v}$	H	$\frac{\delta v}{v}$
1.8	0.01×10^{-6}	346.3	0.18
2.6	0.02	774	0.32
9.1	0.06	1028	0.42
36.8	0.14	1344	0.57
142.4	0.16	1729	0.80

In weak fields, the change is very small, but the rate is tolerably large ; as the field increases, the curve (Fig. 7, Pl. II.) reaches an inflexion point. The change goes on somewhat slowly for fields amounting to a few hundred units ; it again reaches an inflexion point, whence to increase steadily and almost at a constant rate as the field is further increased.

Nickel. In our two former experiments, we noticed a discrepancy in the nature of the volume change in this metal. With a bar of square section, we noticed a diminution, while an ovoid showed an increase. How this may be easily accounted for, we have already discussed in our former paper, so that it will be now unnecessary to take up the subject anew.

With the present specimen, which may be regarded as the more homogeneous, we noticed a slight increase of volume, which is of about the same amount as that observed in the former experiments.

The character of the change is similar to that in steel, the curve (Fig. 7.) of the change presenting two inflexional points. These points do not appear in such a remarkable degree as in steel, but their whereabouts can be ascertained at a glance. The observed changes in volume are given below :—

H	$\frac{\delta v}{v}$
10.4	0.00×10^{-6}
16.5	0.01
27.5	0.02
53.7	0.03
124.9	0.04
384.6	0.07
638	0.10
1052	0.13
1539	0.16
1983	0.22

Cobalt. (Fig. 7.) Just as we have noticed a difference in the length change and the intensity of magnetization in the cast and annealed metals, we notice a difference in the volume change for these two bodies.

The behaviour of cobalt is unlike other ferromagnetic substances; instead of showing increase, the magnetization causes diminution of volume, which in the annealed state bears close resemblance to the character possessed by nickel, indicating glimpse of two inflexion points in the curve of volume change. With the cast specimen, this feature is still more different from the other ferromagnetic substances. The diminution of volume takes place quite rapidly in weak fields, so that the curve soon reaches an inflexion point. The rate of diminution after passing this point is very small, the curve passing on almost parallel to the axis of the field. This state prevails in a large range of fields, but the curve, in place of showing another inflexion point, reaches a point of maximum diminution

of volume. The course of the curve turns and proceeds in the same direction as far as the present experiment goes. This character is possessed by cast cobalt only among the numerous specimens of ferromagnetic substances hitherto experimented upon. Further we may notice that the amount of the change is, to a certain extent, greater in cobalt than in iron, steel, or nickel.

The results of measurements in cobalt are given below :—

Cast cobalt.		Annealed cobalt.	
H	$\frac{\partial v}{v}$	H	$\frac{\partial v}{v}$
12.4	-0.07×10^{-6}	28.7	-0.02×10^{-6}
19.1	-0.17	41.9	-0.04
24.1	-0.27	58.1	-0.06
72.2	-0.83	90.4	-0.08
162.3	-1.17	204.2	-0.27
378.5	-1.35	468.8	-0.60
665	-1.50	800	-1.09
1068	-1.55	1127	-1.58
1457	-1.47	1473	-1.84
1889	-1.38	1916	-2.10

Nickel steel. (Fig. 8.) The volume change in nickel steel is characterized by the simplicity and the large amplitude of the effect.

The following table gives the measurements made on three specimens of nickel steels containing different percentages of nickel.

46% Ni.		36% Ni.		29% Ni.	
H	$\frac{\delta v}{v}$	H	$\frac{\delta v}{v}$	H	$\frac{\delta v}{v}$
68.1	0.03×10^{-6}	7.6	0.03×10^{-6}	6.5	0.06×10^{-6}
284.5	0.42	11.8	0.05	25.7	0.71
386.1	0.60	30.8	0.24	62.4	1.49
592.0	1.13	93.5	0.87	113.6	2.91
679	1.28	209.1	2.35	227.5	6.52
893	1.59	309.0	4.28	425.2	12.49
994	2.19	682	9.10	659	20.30
1327	3.00	1042	14.25	989	29.7
1452	3.55	1333	18.44	1260	38.7
1618	4.38	1669	22.99	1687	51.1

The common feature of the change is the approximate proportionality of the effect to the magnetizing force.

The amplitude of the change is, however, not directly proportional to the intensity of magnetization, as the 46% Ni shows a smaller effect than the 29% Ni, which is the least magnetizable among the samples, with the exception of the 25% Ni, whose magnetization is scarcely to be detected by ordinary means. In fields of 1600 C.G.S. units, the change amounts to

$$\begin{aligned}
 \frac{\delta v}{v} &= 4.2 \times 10^{-6} \text{ for 46\% Ni} \\
 &= 22.0 \times 10^{-6} \text{ „ 36\% Ni} \\
 &= 48.7 \times 10^{-6} \text{ „ 29\% Ni} \\
 &= 0.2 \times 10^{-6} \text{ „ 25\% Ni} \\
 &= 1.2 \times 10^{-6} \text{ „ soft iron.}
 \end{aligned}$$

The difference between steels containing different percentages of

nickel is indeed remarkable, as the changes here noticed far exceed those hitherto observed in simple ferromagnetic substances. The change in 29% Ni is nearly 40 times greater than in soft iron; in fact, the motion of the capillary meniscus could be easily followed by the naked eye, as the displacement, which took place almost instantaneously with the making of the current, was nearly 5 mm. in the strongest field at our disposal. Even the 25% Ni sample showed a volume change, which, in spite of the minute magnetizability, could be distinctly measured by a microscope.

From the above result, it follows that there is a certain alloy, whose percentage content of nickel will lie somewhere between 25% and 36%, which will indicate the greatest change of volume; the change will indeed be the greatest, that we can observe in the ferromagnetic substances of common occurrence.

When we consider the magnitude of the volume change in nickel steels and compare it with that observed in iron or nickel, we are struck with the immensity of the effect, which is not shared in such an extraordinary degree by either of the constituents of the alloy. The same remark applies to the magnetizability of the samples. That the alloy of two strongly magnetizable substances should give rise to an almost neutral body is in no way an object of curiosity, when considered in the same light as the enormous effect of magnetization on the bulk of the alloy. In the present instance, we are at a loss to decide which of the two metals plays a predominating part in the magnetostriction of nickel steel; perhaps a complete study of the subject from the lowest percentage to the pure nickel, and the comparative investigation of the phenomena in the succeeding stages will reveal to us the groupings of the constituent metals while entering into an alloy, as well as the part played by them in the magnetization and in the various phenomena attending it.

It may at first sight appear that the smallness of the thermal expansion in nickel steel necessarily entails the minuteness of the change of length and of volume, but no connection seems to exist between the magnetostriction and the deformation due to temperature variation, as illustrated in the preceding experiments.

§ 7. Wiedemann Effect in Nickel Steel.

As closely allied to the change of volume and of length, the Wiedemann effect comes into our consideration as due to magnetostriction. Unfortunately we could not investigate the phenomenon in cobalt for want of material of geometrical shape, suitable for the investigation. The results for iron, steel, and nickel have been already described in our former paper, so that we shall consider only nickel steels, which have not yet been investigated.

The effect was measured in the usual way by suspending the wire vertically in a magnetizing coil, and by passing an electric current of known strength, the angle of torsion due to the combined action of circular and longitudinal magnetizations was measured by the rotation of a fine mirror attached to the end of the wire. The vertical component of the terrestrial magnetic force was compensated for by another coil inserted within the coil. The wire was of such length (21 cm.) that the magnetic field was practically uniform throughout. For the different sorts of wires tested, we are indebted to Mr. Ch. Ed. Guillaume.

The measured angles τ of torsion per cm. in seconds of arc are given for different samples of wires in the following table :

45% nickel steel. (annealed) $c=134.0 \left(\frac{\text{amp.}}{\text{cm}^2} \right)$		39.2% nickel steel. (unannealed) $c=371.5 \left(\frac{\text{amp.}}{\text{cm}^2} \right)$		23.6% nickel steel. (unannealed) $c=310.0 \left(\frac{\text{amp.}}{\text{cm}^2} \right)$	
H	τ	H	τ	H	τ
0.8	8.3"	7.3	7.6"	4.9	0.7"
2.8	15.7	23.5	20.4	17.0	2.8
4.0	23.1	50.6	21.8	37.6	6.6
8.1	32.3	81.8	17.9	85.0	6.9
26.7	25.9	117.0	14.7	135.6	4.6
44.5	18.0	322.0	6.4	367.0	1.1
104.0	6.0	452.6	4.1	589.3	0.0
283.2	-1.6	742	2.3	873	-1.4
937	-4.6	1104	1.6	1230	-2.1
1522	-4.9	1531	1.6	1350	-2.1

The direction in which a nickel steel wire twists is the same as in iron. If the north pole of the wire suspended vertically be at the free end, and the direction of the current traversing the wire be downwards, the torsion of nickel steel seen from above is in the direction of the hands of a watch.

The amount of torsion (Fig. 9.) increases with the magnetic field, but it soon reaches a maximum, to decrease afterwards quite slowly as the field becomes stronger, and the torsion of the wire is reversed in strong fields. With the samples tested, the torsion increases with the percentage of nickel. The 23.6% Ni and 39.2% Ni samples were examined in a hard drawn state; but the 45% Ni wire was examined after annealing it in hydrogen, as already described.

§ 8. Summary of the Results.

The results obtained in the present investigation can be summarised in the following statements.

Magnetization.

1. The magnetization of cast cobalt is different from that of the annealed metal, the latter being only about half as magnetizable as the former. The magnetization of cobalt in the annealed state is characterized by its high differential susceptibility in strong fields.

2. The magnetization of 46% nickel steel is between iron and cobalt, while that of the 36% Ni is nearly the same as in cobalt. The 29% Ni is nearly half as magnetizable as nickel, and the 25% Ni is only feebly magnetic. The course of the magnetization curve in nickel steel resembles that in nickel.

3. (a) In cast cobalt, mechanical elongation in the direction of magnetization produces diminution of magnetization in low fields, which gradually lessens as the field strength is increased. Ultimately there is increase of magnetization by elongation. Thus, there is a critical point in cobalt, which has a character opposite to that bearing the name of Villari in iron.

(b) In annealed cobalt, mechanical elongation in the direction of magnetization produces diminution of magnetization, which increases with the field.

4. Mechanical elongation in the direction of magnetization produces increase of magnetization in nickel steel.

Change of Length by Magnetization.

1. The quality of the change is not seriously affected by the small non-homogeneity of the sample.

2. In cobalt, the character of the change is different in the cast and in the annealed state.

(a) Cast cobalt contracts in low fields and attains the minimum length in $H=130$, whence it returns to its former length in $H=750$, and goes on elongating at a slow rate, as the field is increased (result already obtained by Bidwell). This stands in reciprocal relation with the effect of mechanically elongating cast cobalt on magnetization.

(b) Annealed cobalt contracts without showing a minimum length up to $H=1800$. The character of the change is similar to that of iron after passing the maximum elongation. This stands in reciprocal relation with the effect of mechanically elongating annealed cobalt on magnetization.

3. Nickel steel elongates by magnetization. The character of the change is similar to that of nickel, but the sense is different. The rate of change $\left(\frac{de}{dH}\right)$ in high fields is greater in 29% Ni than in 36% Ni, in which it is again greater than in 46% Ni. The amount of the change is in inverse order up to $H=2000$.

Nickel steel elongates to a greater degree in the annealed than in the hard drawn state.

4. The elongation of nickel steel in very low fields (comparable with the terrestrial magnetic field) is generally less than 10^{-7} .

Change of Volume by Magnetization.

1. Iron, steel, and nickel show increase of volume by magnetization, but cobalt (cast and annealed) shows contraction.

2. (a) Cast cobalt contracts at a rapid rate in low fields, but above $H=100$, the rate becomes less and the contraction reaches a maximum in $H=900$, whence to return gradually with further increase of the field.

(b) Annealed cobalt contracts in volume at a steady rate as the field is increased. The contraction becomes ultimately greater than in cast cobalt.

3. The increase of volume in 46% Ni, 36% Ni, and 29% Ni steels takes place almost proportional to the strength of the field. The amount of the increase becomes greater as the percentage of nickel becomes less. The volume change in 29% Ni is the greatest that has ever been observed, and is nearly 40 times that in iron in strong fields.

Wiedemann Effect.

The torsion produced by the combined action of circular and longitudinal magnetizations in nickel steels increases with the longitudinal field and reaches a maximum whence to decrease gradually as the field is further increased. In some specimens, the torsion ultimately takes place in the opposite direction. The direction in which nickel steel twists is the same as in iron.

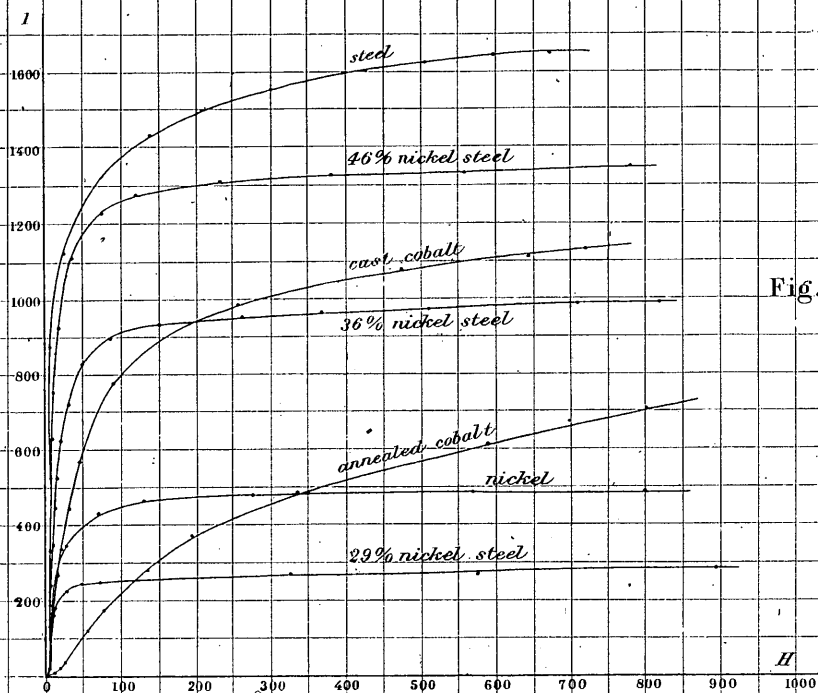


Fig. 1.

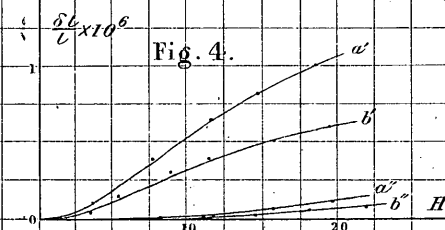
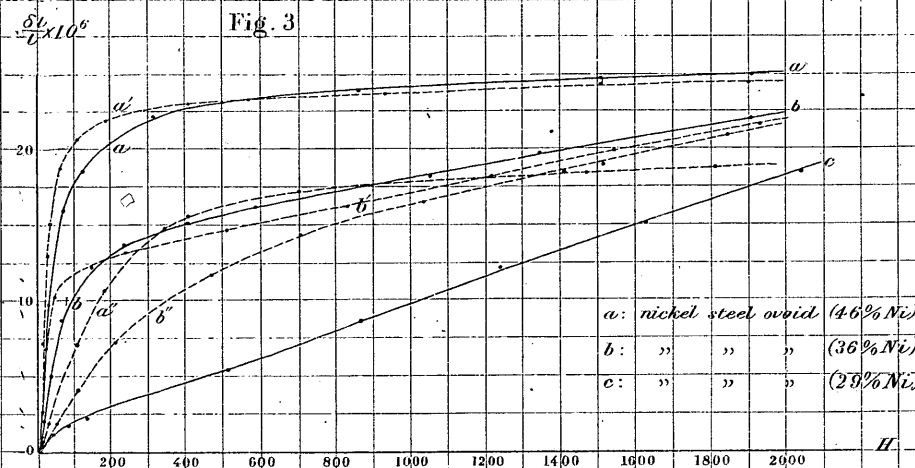


Fig. 4.

a: nickel steel wire (4.5% Ni).
(annealed).
a': " " " (unannealed).
b: nickel steel wire (3.5% Ni).
(annealed).
b': " " " (unannealed).

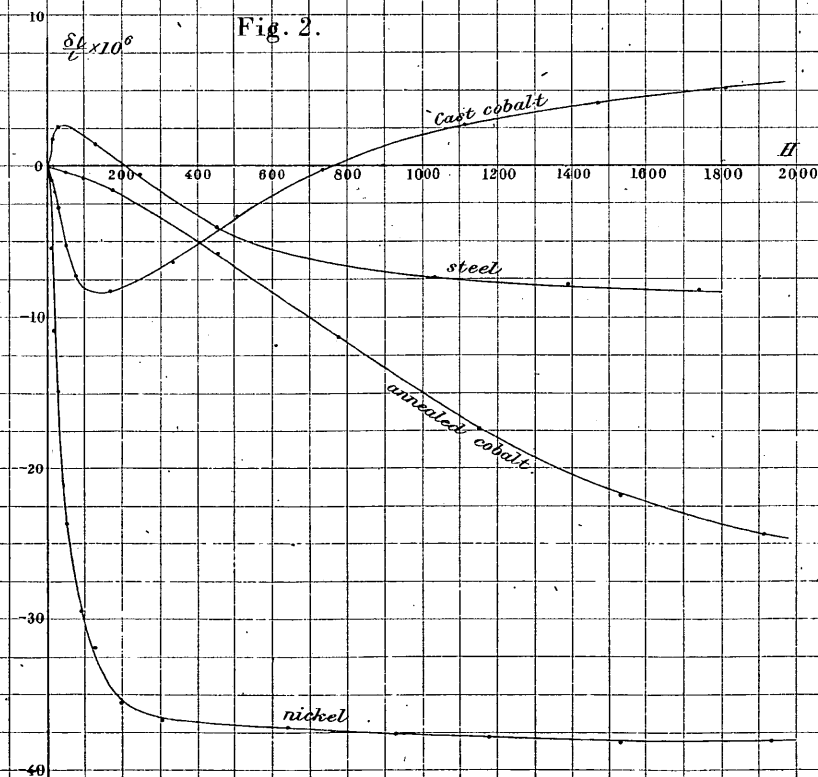


Fig. 2.

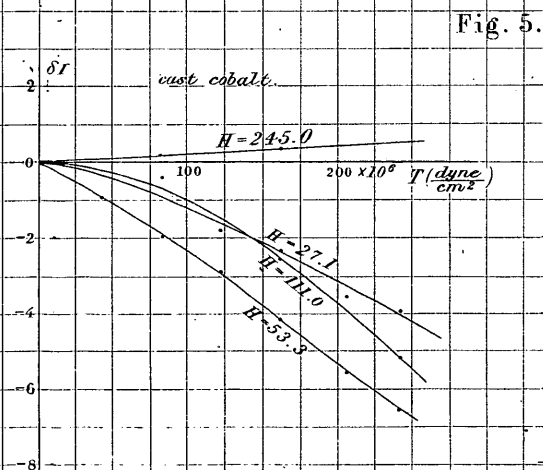


Fig. 5.

