JOURNAL OF THE COLLEGE OF SCIENCE, IMPERIAL UNIVERSITY,
TOKYO, JAPAN.
VOL. XVI, ARTICLE 9.

Change in Length of Ferromagnetic Wires under Constant Tension by Magnetization.

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With Plates I—II.

1. In his earliest experiment on the change in length by magnetization of iron and steel rods, Joule¹⁾ noticed that the effect of tension is to diminish the magnetic elongation, and that if the tension exceeds a certain limit, the magnetization causes contraction instead of elongation. Repeating the same experiment, S. Bidwell²⁾ made special investigations on this point. His results can be stated in the following words : Tension diminishes the magnetic elongation of iron, and causes the magnetic contraction to take place with a smaller magnetizing force ; it increases the contraction in strong fields. These changes become greater as the tension is increased. For nickel, the magnetic contraction is diminished by tension in weak fields ; but it is increased in strong fields. These changes also

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1) Joule, Phil. Mag. **30**, 76, 225, 1847.

2) Bidwell, Pro. Roy. Soc. **40**, 109, 257, 1886 ; Pro. Roy. Soc. **47**, 469, 1890 ; Ewing's Magnetic Induction p. 240.

increase with tension. Cobalt is practically unaffected by tension. B. Brackett,⁽¹⁾ G. Klingenberg⁽²⁾ and K. Tangl⁽³⁾ also investigated the same subject and obtained results similar to those of Bidwell.

In Bidwell's experiment, which is generally regarded as the most reliable, the wire to be tested carried the magnetizing coil with it, so that even the smallest tension was greater than 3 kilograms per square millimeter. Hence the effect of small loading, which is remarkable in nickel, was not well studied. The reason which led him to adopt such an arrangement, was, according to his statement, to avoid the disturbance due to the electromagnetic action between the wire and the magnetizing coil. Moreover the sensibility of his apparatus could no longer be considered to be sufficiently delicate. It was, therefore, desirable to repeat his experiment with an arrangement giving higher accuracy.

A few month ago, Professor Nagaoka and one of us measured the magnetic elongation of the nickel steel, kindly placed at our disposal by Dr. Ch. Ed. Guillaume. It showed a remarkable anomaly with regard to the magnetic elongation. Much interested by the result, we proceeded to examine the effect of loading on the magnetic elongation of the alloy as well as other ferromagnetic metals.

2. The apparatus used in the present experiment is, in principle, the same as that used by Professor Nagaoka. The chief difference consists in using a rotating cylinder⁽⁴⁾ to cause a reflecting mirror to turn through a minute angle, instead of the three pivots system.

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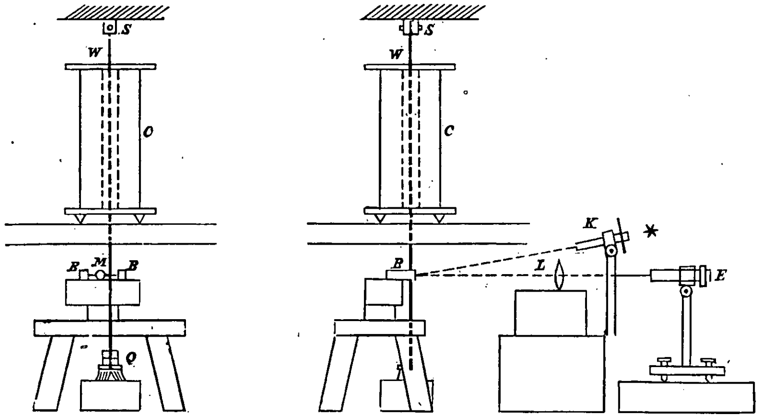
1) Brackett, Phy. Rev. [5] **5**, 257, 1897.

2) Klingenberg, Inaug.-Diss., Berlin, 1897; Beibl. **21**, 897, 1897; Inaug.-Diss., Rostock, p. 34; Beibl., **23**, 270, 1899.

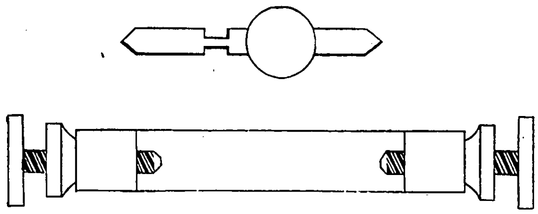
3) K. Tangl, Drud. Ann. **6**, 34, 1901.

4) H. Hertz, Instrumentenkundte, **3**, 17, 1883; Gesammelte Werke, 1, p. 227.

The accompanying figure shows the front and side views of the apparatus. *C* is the magnetizing coil, and *W* the wire to be tested, whose upper end is clamped to the support *S*, while its lower end carries a weight *Q*. *M* is a reflecting mirror fixed to the rotating cylinder, the ends of which terminate in cones and fit lightly in the agate cups on the heads of screws in brass sockets *BB*. *K* is a collimator, *L* a lens,and *E* a micrometer with ocular scale. The slit of the collimator is illuminated by a gas flame ; the light leaves the collimator adjusted for a parallel beam and is reflected by the mirror *M* and converges in the micrometer field through the lens *L*. In the middle of the slit, a very fine glass fibre is stretched parallel to the edge, the image of which is clearly seen in the micrometer. A wire of about 1.5 mm. in diameter touches the rotating cylinder under a suitable pressure ; if the wire elongates or contracts, the mirror rotates through a small angle and the corresponding displacement of the image of the fibre is observed in the micrometer field.



The magnetizing coil was 30 cm. long and gave a field of 37.97 C.G.S. units at the centre by passing a current of one ampere. The current was measured by a Thomson graded galvanometer which was from time to time compared with a deciampere balance. The wire to be tested was soldered into well annealed copper wires of about the same diameter, as shown in the annexed cut. It was hung vertically in the axial line of the magnetizing coil so as to lie nearly in the uniform field. The pan attached to the lower end of the wire carried on its under face a few pieces of cotton which softly touched a piece of wood for the purpose of damping without producing sensible pressure. The lens had a focal length of 66.95 cm., and the number of divisions of the micrometer ocular was 100 to 1 cm. The form of the rotating cylinder is drawn in actual size in the annexed figure. It was made of steel; the thickness of the cylinder, on which the thin vertical wire came in contact, was 2.85 and 1.51 mm. for nickel and other metals respectively. The front view of the brass socket for holding the steel cylinder is shown in the same figure. The stand on which it was fixed, could be made to move up and down as well as forward and backward by means of screw adjustment. By this arrangement, the cylinder could be made to touch the vertically suspended wire with suitable pressure, and a small rotation of the mirror be given at our disposal. The arrangement is omitted in the first figure.



The sensibility of the apparatus can easily be changed by simply altering the thickness of the rotating cylinder. In the present experiment, it was such that one division of the micrometer ocular corresponded to an elongation or contraction of 5.13×10^{-7} in one case and 2.72×10^{-7} in the other. As $\frac{2}{10}$th of the micrometer scale can be easily observed, a dilatation of 0.6×10^{-7} per cm. was accurately measured in the latter case.

3. Observations were conducted according to the following method. The wire to be tested was hung vertically and stretched by a weight of 5 kilograms for 3 or 4 hours to make it straight. To begin with, all the weights were once taken away, and again loaded with a weight of 0.5 or 1 kilogram. After one or two hours, the observations were completed in the following order. The wire was first demagnetized, and then magnetized by passing successively increasing currents and the corresponding deflections taken, the demagnetization being repeated before each magnetization. A set of observations being thus taken, successively increasing loadings were applied and the corresponding sets of observations noted. The observations were, for the most part, taken at night to avoid small disturbing vibrations of the wire due to the shaking of the laboratory building.

Since the resistance of the magnetizing coil was only 0.6Ω, the thermal expansion of the suspended wire due to the heating of the coil was negligibly small for the current used in the present experiment; but for safety, the deflection was taken as soon as possible. Substituting for the steel cylinder a brass one of the same thickness, exactly the same results were obtained, showing that the influence of the magnetic action between the coil and the steel cylinder is insensibly small.

When the pressure in the contact surface between the cylinder and the wire was moderate, repeated applications and removals of the magnetizing field showed no trace of slipping in the cylinder.

The wires tested had the following dimensions :—

Specimen.	Soft iron.	Wolfram steel.	Wolfram steel.	Nickel.
Length.	20.74 cm.	20.97 cm.	20.74 cm.	20.70 cm.
Diameter.	0.139	0.060	0.135	0.136

Specimen.	45% nickel steel.	45% nickel steel.	35% nickel steel.
Length.	20.73 cm.	20.93 cm.	20.75 cm.
Diameter.	0.144	0.050	0.150

4. *Soft Iron.* Fig. 1 represents the curves of the change of length in soft iron plotted against the magnetizing field; T is the tension per square millimeter. The curve T=0 is the result obtained by means of Professor Nagaoka's apparatus; our arrangement can not be used for the measurement of the change of length corresponding to no tension. The comparison of this curve with the others shows the trustworthiness of the present arrangement for measuring the minute change in length.

The specimen was very well annealed, and so the initial elongation was greatly reduced. The effect of tension is to reduce the elongation in weak fields and to increase the contraction in strong fields. This diminution of elongation becomes greater as the tension increases, till the initial elongation vanishes in a tension of about 4 kilograms per square millimeter. When the tension exceeds this value, the course of the curve is changed. In higher fields greater than 40 C.G.S. units, all the curves are nearly parallel to each other. It is also observed that the effect of tension is comparatively larger when the load is small than when it is heavy.

By making use of Fig. 1, the curves showing the relation between the change of length and the tension under a constant field are drawn in Fig. 2. We learn from these curves that the effect of tension on the magnetic change of length is not linearly related to tension.

Generally speaking, these results coincide with those of Bidwell. In our case, the reduction of the initial elongation by tension is far greater than that in Bidwell's wire. The smallest tension, by which the elongation vanishes, is about 4 times greater for the latter case than in the former. The discrepancy perhaps arises from the fact that our specimen is comparatively soft as regards the magnetic quality; this inference was actually verified in the case of wolfram steel.

Some observed changes in length under different tensions are exhibited in the following tables:—

$T=167$ gr.		$T=827$ gr.		$T=2145$ gr.		$T=4125$ gr.	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
6.3	0.82	7.0	0.55	6.5	0.08	6.8	—0.08
15.9	1.89	16.3	1.13	16.3	0.22	15.7	—0.25
23.2	2.11	23.1	1.29	23.3	0.27	23.2	—0.49
40.6	1.89	34.1	1.32	38.3	0.14	36.4	—0.61
57.4	1.65	49.6	1.10	57.6	—0.22	53.7	—1.04
82.1	1.34	74.0	0.77	79.8	—0.58	74.4	—1.35
124.3	0.77	97.9	0.27	110.1	—1.13	97.5	—1.85
212.9	—0.77	156.1	—0.82	180.4	—2.61	155.2	—2.99
345.1	—2.94	277.1	—2.99	308.5	—4.71	275.4	—5.16
491.4	—4.58	430.4	—4.97	496.7	—7.14	427.0	—7.27
728.7	—5.71	728.5	—6.89	737.2	—8.43	732.0	—9.30

Here T is the tension per square millimeter, H the external field, and $\frac{\delta l}{l}$ the elongation of the wire.

5. *Wolfram Steel.* Fig. 3 represents the results for wolfram steel hardened by stretching; the anomaly of the change of length for the steel was already pointed out by Professor Nagaoka and one of us. The anomaly gradually disappears as the tension is increased; and by a tension of 25.63 kilograms per square millimeter, the steel behaves like a well annealed soft iron. The amount of the diminution of the magnetic elongation per gram is considerably smaller than that of other ferromagnetics.

Fig. 4 shows the relation between the change of length and the tension under a constant field. In this case, the proportionality between the tension and its effect on the magnetic change of length is almost satisfied.

Another wire of wolfram steel was well annealed and tested, giving the results shown in Fig. 5. Here we notice that the annealing quite effaces the anomaly, increasing at the same time, the effect of tension on the change of length.

The following table contains some of the results of observations on the hard-drawn wolfram steel:—

$T=4430$ gr.		$T=7965$ gr.		$T=15030$ gr.		$T=25630$ gr.	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
36.8	0.63	34.0	0.33	34.9	0.41	34.8	0.16
46.7	1.11	45.7	0.98	43.7	0.71	50.3	0.60
68.4	2.07	67.0	1.71	62.1	1.33	75.1	0.79
89.9	2.45	88.0	2.26	82.6	1.52	99.7	0.82
138.5	2.64	137.2	2.39	125.2	1.60	158.2	0.35
256.2	2.17	252.7	1.88	209.0	1.14	278.8	—0.54
385.2	1.70	382.5	1.30	346.8	0.41	432.2	—1.36
557.8	1.36	549.0	0.87	493.2	—0.16	603.0	—1.82
740.8	1.06	733.8	0.49	733.9	—0.46	742.5	—2.23

6. *Nickel.* As will be seen from Fig. 6, the effect of tension in weak fields is to diminish the contraction due to magnetization, and the amount of diminution increases, as the tension is increased. In strong fields, the contrary is the case. Fig. 7 shows the relation between the change of length and the tension under a constant field. Each of the curves has a minimum point except in weak fields. As the field is increased, the minimum occurs by greater tension.

Some of the results of measurement are given in the following table :—

$T=863$ gr.		$T=2239$ gr.		$T=4304$ gr.		$T=5680$ gr.	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
6.1	— 1.1	6.5	— 0.6	7.0	— 0.4	7.5	— 0.1
17.0	— 8.2	14.7	— 3.3	14.9	— 1.0	16.1	— 0.6
23.1	—12.1	23.5	— 7.5	23.5	— 2.8	23.4	— 1.4
30.4	—15.8	32.2	—12.0	34.3	— 5.6	32.7	— 2.6
38.6	—19.3	40.6	—16.1	49.5	—10.5	43.6	— 4.3
56.9	—24.4	56.0	—22.7	61.2	—14.8	61.4	— 8.4
81.4	—28.5	81.4	—29.1	78.9	—21.3	88.5	—16.9
122.9	—32.6	123.4	—35.0	110.1	—29.4	136.7	—28.9
208.3	—36.3	207.8	—40.1	179.3	—37.2	245.8	—38.9
306.8	—37.7	——	——	277.1	—41.8	345.1	—42.0
489.6	—38.8	——	——	382.5	—43.5	431.3	—42.8

In Bidwell's experiment, the effect of loading less than 3.5 kilograms per square millimeter was not studied ; but his general results agree with those of the present experiment.

7. *Nickel Steel.* The magnetic change of length under constant tension of the annealed nickel steel (45% Ni) whose thickness is 1.44 mm. is shown in Fig. 8. The anomaly of the magnetic elongation in nickel steel had been already observed by Professor Nagaoka and one of us. The existence of a maximum elongation, which is the characteristic for iron, is not observed, but the wire singularly elongates to an asymptotic value, as the field is increased. Apart from other ferromagnetics, the effect of tension on the magnetic elongation is considerably large; the tension diminishes the elongation, and by a tension of 1.4 kilograms per square millimeter, the elongation is already diminished to half its value corresponding to no tension.

To study specially the effect of heavy loadings, a wire 0.50 mm. thick was made of the same alloy. After a moderate annealing, it was subjected to an experiment to see whether it would become shorter than the initial length when magnetized under a heavy loading. This actually occurred as shown in Fig. 9. With a tension of 26.9 kilograms per square millimeter, the length of the wire was decidedly shortened when magnetized. Since the degree of annealing was different in the thick from the thin wire, the magnetic change of length for these two wires in the same field and tension did not exactly coincide.

The curves showing the relation between the change of length and the tension under a constant field is shown in Fig. 10. Here we observe that the rate of the diminution of the magnetic elongation becomes less, as the tension is increased.

Some of the results of observations are given in the following table :—

$T=463$ gr.		$T=1389$ gr.		$T=2613$ gr.		$T=5070$ gr.	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
6.3	2.87	5.4	2.34	6.8	1.33	6.7	0.51
15.2	6.77	15.2	5.18	15.7	3.33	16.3	1.03
23.5	9.34	34.3	8.31	23.5	4.36	33.9	1.59
46.7	13.08	43.4	9.24	46.2	5.64	49.2	1.92
68.2	14.68	61.6	10.26	67.7	6.21	67.4	2.05
89.4	15.50	81.9	10.82	88.9	6.67	88.5	2.16
138.5	16.47	125.0	11.34	137.6	6.93	136.8	2.36
256.2	17.44	213.3	12.10	252.7	7.44	251.0	2.41
385.1	17.80	350.4	12.67	381.6	7.75	381.6	2.57
636.1	18.00	658.9	13.44	625.6	8.01	627.4	2.87

With the other annealed nickel steel (35% Ni), whose thickness is 1.50 mm., the nature of the magnetic elongation and the effect of tension are generally the same as those of the former alloy, as shown in Fig. 11. The course of the curve for heavy loading is, however, quite different from that for light loading. For a tension of 4.76 kilograms per square millimeter, the wire first contracts and then elongates when the field is gradually increased, so that the form of the curve is similar to that of the magnetic change of length in cobalt. Fig. 12 shows that the rate of diminution of the magnetic elongation by tension decreases as the tension is increased.

The curves corresponding to T=0 in Figs. 8 and 11 are the results obtained by Professor Nagaoka and one of us, and are reproduced here for the sake of comparison.

The following table contains some of the results of our measurements :—

$T=435$ gr.		$T=1299$ gr.		$T=2452$ gr.		$T=4752$ gr.	
H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$	H	$\frac{\delta l}{l}\times 10^6$
5.9	1.92	7.2	1.49	6.8	0.52	6.8	+0.03
16.9	4.67	15.7	2.60	14.9	0.89	17.1	—0.06
20.3	5.60	23.2	3.29	23.5	1.12	23.3	—0.23
34.3	6.77	34.1	3.66	34.3	1.17	36.2	—0.28
66.6	7.99	68.1	4.32	73.9	1.43	73.6	—0.49
82.6	8.23	89.4	4.58	97.7	1.62	109.6	—0.52
136.8	8.59	138.1	4.89	155.9	1.75	179.3	—0.57
247.6	9.58	252.7	5.44	277.1	2.15	306.8	—0.14
375.0	9.88	378.2	5.81	427.0	2.78	503.8	+0.54
693.8	10.43	618.8	6.87	774.0	4.04	720.0	+1.14

It was our first intention to perform the same experiment on a cobalt wire in order to examine Bidwell's results; but having no such material at our disposal, we leave the subject for future considerations.

In conclusion, we wish to express our best thanks to Professor H. Nagaoka, and also to Professor A. Tanakadate for valuable advice and guidance.

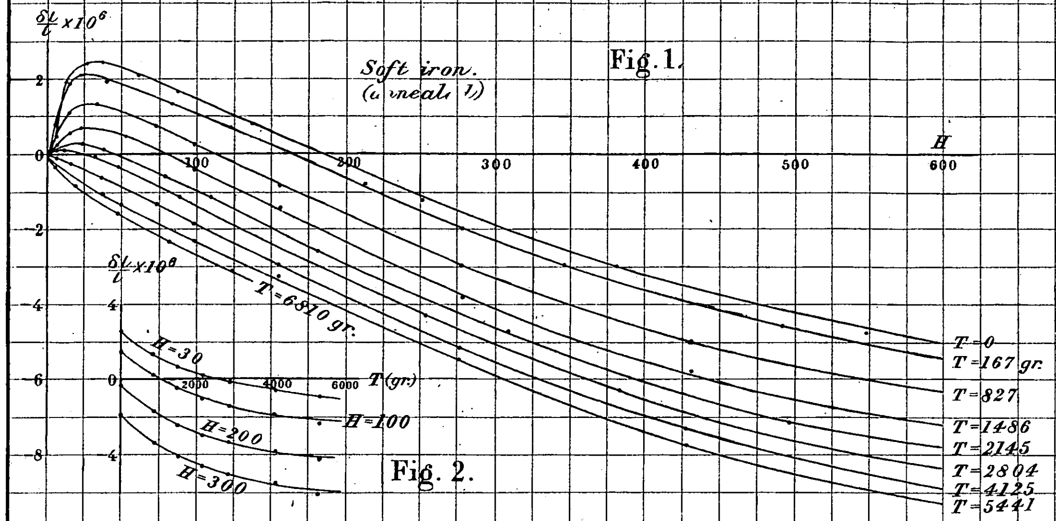


Fig. 1.

Fig. 2.

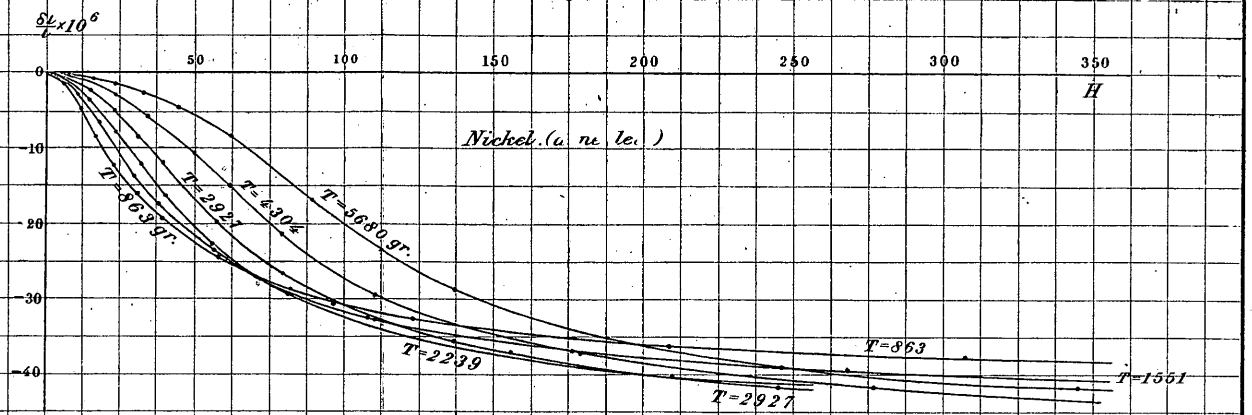


Fig. 6.

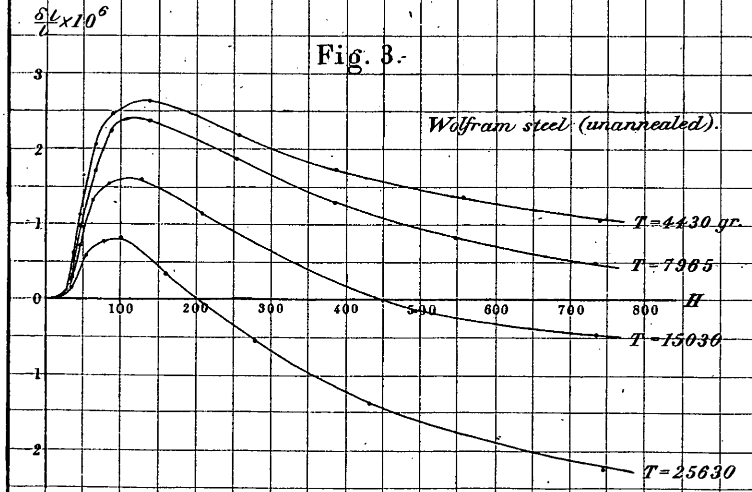


Fig. 3.

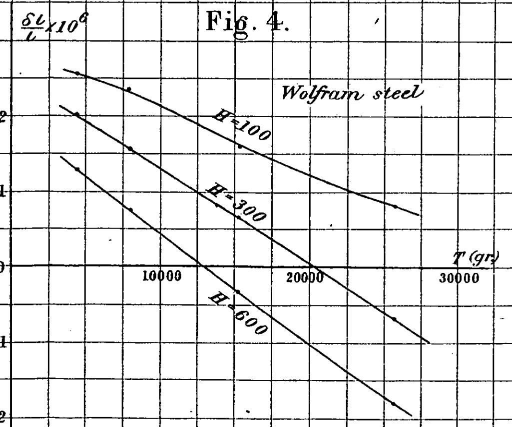


Fig. 4.

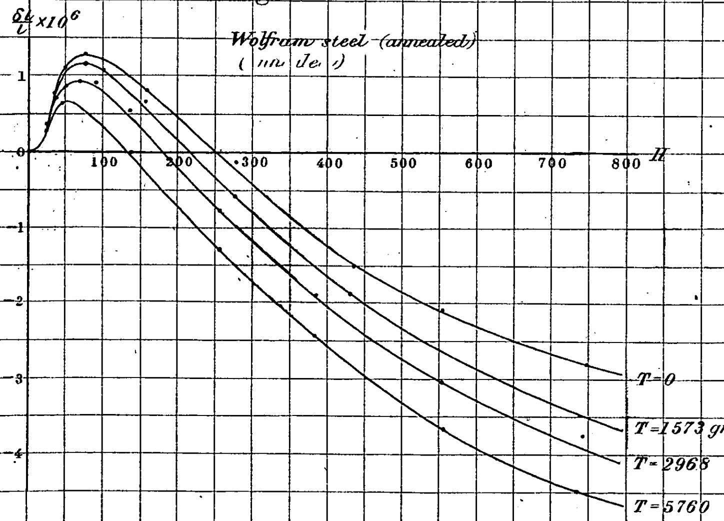


Fig. 5.

Fig. 7. *Nickel*

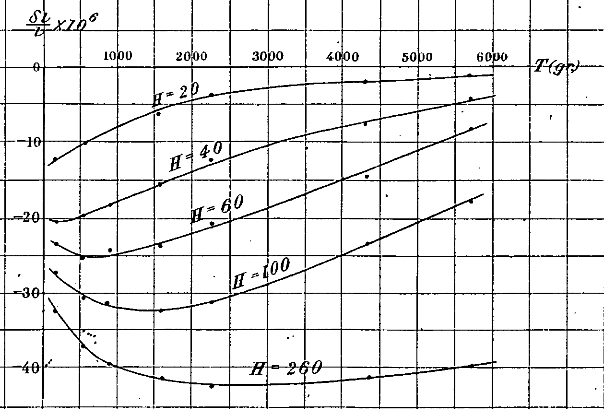


Fig. 8. *Nickel steel (45% Ni)*

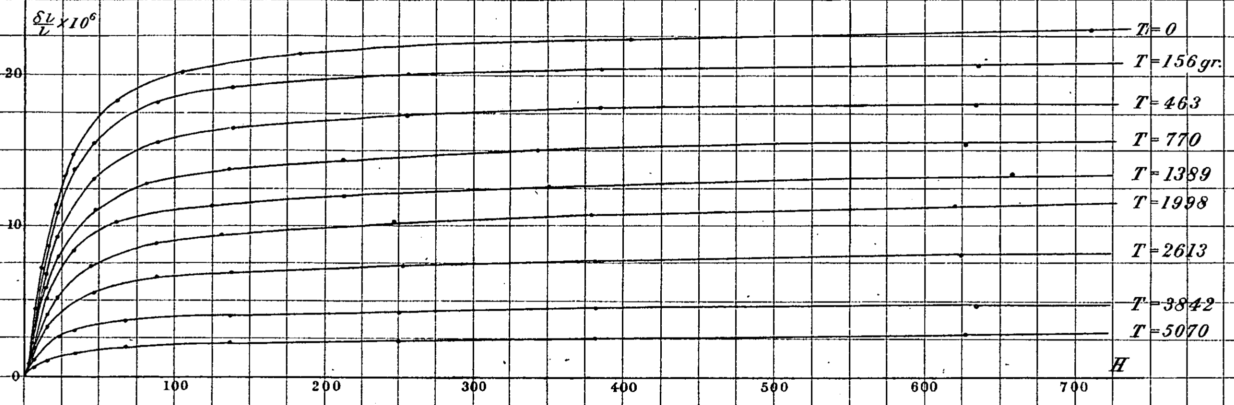


Fig. 9. *Nickel steel (45% Ni)*

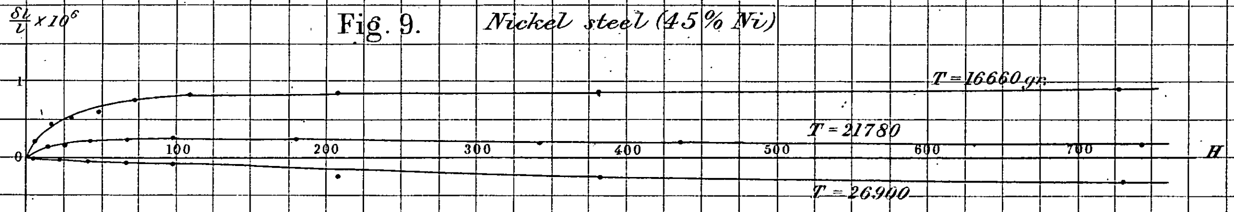


Fig. 10.

Nickel steel (45% Ni)

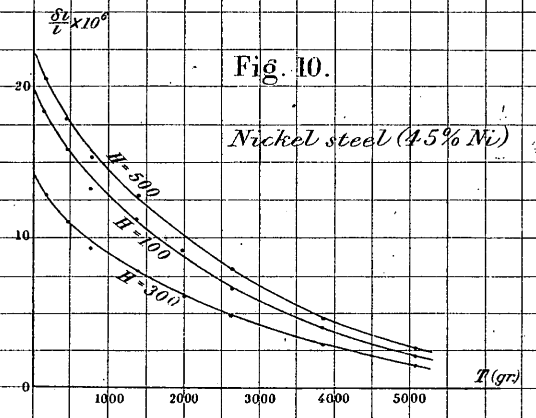


Fig. 11. *Nickel steel (35% Ni)*

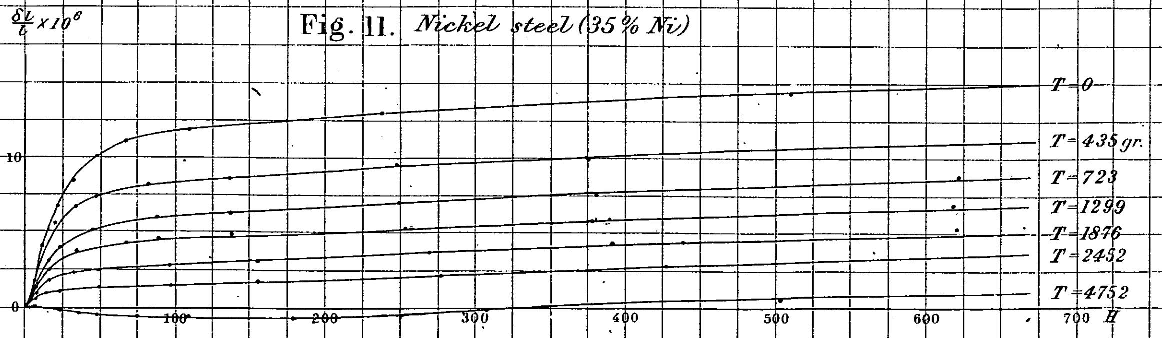


Fig. 12.

Nickel steel (35% Ni)