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Magnetization and Magnetostriction of Nickel Steels, containing different Percentages of Nickel.

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With Plates I—III.

The results of our experiments[1] on the magnetostriction of nickel steels have been discussed by Guillaume[2] and Osmond.[3] The samples, which we had then tested, were only four in number, so that no definite conclusion as regards the effect on magnetostriction by varying the percentage content of nickel could be drawn. Having now examined eight new specimens,[4] we are able to infer how the magnetization and the magnetostriction go on varying as the proportion of nickel to iron is increased. The importance of investigat-

1) Nagaoka and Honda, Comptes Rendus, 3 Mars, 1902; Journal de physique, ctobre 1902.

2) Guillaume, Comptes Rendus, 3 Mars, 1902.

3) Osmond, Comptes Rendus, 17 Mars, 1902.

4) Our thanks are due to Mr. Ch. Ed. Guillaume, at whose kind request, the Company of Commentry-Fourchambault and Decazeville has liberally supplied us with specimens.

ing the magnetostriction of these valuable alloys appears from the following words of Mons. L. Dumas in his report on researches concerning nickel steels.

"M. Guillaume, d'autre part, a fait remarquer que notre hypothèse ne fournit aucune base pour l'interprétation des phénomènes de magnetostriction, signalés par Mess. Nagaoka et Honda comme constatés sur des aciers au nickel qui ont été mis à leur disposition par Imphy. Tel est l'état actuel de cette intèressante question." We hope that the present experiment will give some clue to a theory, which will explain not only the thermal, electrical, and magnetic behaviour of the metal, but also various metallurgical and mechanical properties.

Method of experiment.—The nickel steel rods were all turned into ovoids ($2a=20$ cm., $2b=1$ cm.), and placed axially in a coil (30 cm. long, 0.6 Ohm resistance, $4\pi n=379.7$). The magnetization was determined by means of a magnetometer, the effect of the coil being compensated by means of another coil of the same strength placed symmetrically on the other side of the magnetometer. The change of length was measured by means of an apparatus described in the Philosophical Magazine, February, 1894, and in this journal Vol. 16. Art. 8. The ovoids were sealed in dilatometer, and the change of volume measured by the displacement of the capillary meniscus. In all these experiments, the utmost care was taken to eliminate the effect of heating by waterjacketing the coil, and by observing the displacement, a few seconds after making the magnetizing current. The ovoids were demagnetized by the method of reversals of gradually decreasing currents before each observation.

Magnetization of nickel steels.—From experiments made with eight different specimens of nickel steels, varying from 26.2 to 44 percent of nickel, Dumont[1] found a gradual increase of susceptibility

1) Dumont, Comptes Rendus, p. 741, tom. 76, 1898.

as the amount of nickel became greater. The range of percentage difference in nickel was greater in the present experiment, so that some singular features in the course of the magnetization curves were revealed.[1]

The following table gives the observed magnetizations in different fields :—

70.32%		50.72%		46%	
$\mathfrak{H}$	$\mathfrak{I}$	$\mathfrak{H}$	$\mathfrak{I}$	$\mathfrak{H}$	$\mathfrak{I}$
0.24	9	0.42	9	0.29	7
1.52	120	1.86	58	2.30	79
3.90	500	2.92	207	3.02	175
5.60	576	4.13	489	4.08	279
11.30	720	8.81	726	4.92	362
32.6	902	12.78	868	5.88	473
63.5	967	24.50	1013	7.22	592
91.6	986	36.6	1074	8.22	684
168.4	1000	51.6	1135	11.10	793
232.4	1000	73.3	1178	17.15	909
299.4	1002	146.7	1222	33.8	1054
381	1003	252.4	1240	91.1	1171
451	1004	329	1241	266.7	1214
576	1006	520	1246	372	1219
672	1008	606	1249	533	1222

1) The percentages of nickel were given by Imphy.

36%		29.42%		29%	
$\mathfrak{H}$	$\mathfrak{J}$	$\mathfrak{H}$	$\mathfrak{J}$	$\mathfrak{H}$	$\mathfrak{J}$
1.27	32	0.68	12	1.00	11
2.45	73	1.58	41	2.95	131
3.07	123	2.46	66	7.60	207
4.00	176	4.41	92	19.60	272
5.86	345	9.90	118	—	—
9.50	524	22.40	138	—	—
11.55	624	35.3	147	—	—
16.05	714	43.7	150	67.1	307
30.4	853	83.6	160	—	—
65.1	953	135.7	164	143.7	315
110.5	989	210·5	174	244	321
203.5	1007	324	181	399	328
350	1012	440	189	515	333
473	1013	504	193	532	333
662	1014	657	201	738	341

28.72%		28.32%		26.64%	
$\mathfrak{H}$	$\mathfrak{I}$	$\mathfrak{H}$	$\mathfrak{I}$	$\mathfrak{H}$	$\mathfrak{I}$
0.29	6	0.52	6	—	—
1.61	70	2.42	23	—	—
4.20	156	6.40	37	23.5	2.0
13.70	242	14.58	48	—	—
29.2	278	24.24	53	—	—
46.2	292	43.1	58	70.5	5.2
87.0	305	97.2	69	119.3	8.0
159.4	313	206.0	84	219.1	11.8
233.4	318	327	98	356	15.2
407	325	596	119	493	17.5
474	326	672	126	626	19.5
675	331	752	128	750	21.2

24.40%		24.04%	
$\mathfrak{H}$	$\mathfrak{I}$	$\mathfrak{H}$	$\mathfrak{I}$
—	—	7.56	3
29.5	1.9	14.20	7
—	—	33.8	14
71.0	3.4	52.8	22
126.2	5.4	141.3	42
230.4	7.8	226.6	53
412	9.3	407	68
541	10.6	536	76
653	10.8	626	80
769	11.5	763	85

The greatest field (external field − demagnetizing factor × intensity of magnetization)[1] is about 700 Gauss. For this strength, nearly all the alloys here studied become saturated, so that further increase of the field would have been superfluous. As found by Hopkinson, the magnetization of 25 per cent Ni. is almost nil, while it increases as the content of nickel is increased or decreased. For want of material, the magnetization for percentages of nickel lower than 24.04 was not studied. For 29 per cent Ni., the magnetization attains a maximum value, thence to decrease with the increase of nickel. This decrease is, however, of very small amount, so that after reaching a minimum, the magnetization shows rapid increase and tends towards a maximum as the percentage of nickel becomes nearly equal to that of iron. Thus the magnetization curve for 46 per cent Ni. lies a little below that for 50.72 per cent Ni. The percentage content of nickel, which shows maximum susceptibility, becomes smaller as the field is increased, ultimately tending towards 50 per cent as will be seen in Fig. 2. From this maximum, the susceptibility gradually diminishes, so that the magnetization curves for 36 per cent and 70.32 per cent are nearly coincident, as shown in Fig. 1. In the descending branches of the curves of susceptibility, there is apparently no such singularity as in the ascending portion. An inspection of Fig. 2. will show how the magnetization varies as the percentage of nickel is gradually increased. It is evident that the intensity of magnetization does not follow the law of simple proportion to the specific magnetizations of the respective metals.

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1) It is to be noticed that in all of our former experiments, we had taken the demagnetizing factor (=0.836) into account.

Change of length by magnetization.—The following table gives the observed changes of length :—

70.32%		50.72%		46%	
$\mathfrak{H}$	$\frac{\delta l}{l} \times 10^6$	$\mathfrak{H}$	$\frac{\delta l}{l} \times 10^6$	$\mathfrak{H}$	$\frac{\delta l}{l} \times 10^6$
5.3	0.8	4.1	0.6	4.6	0.2
9.5	1.9	24.2	5.4	6.7	0.9
17.8	3.3	43.5	7.7	10.6	2.6
86.2	6.9	113.6	12.5	32.2	9.7
269.6	7.5	250.6	15.4	71.1	15.9
401	7.6	327	16.3	121.2	18.7
681	7.6	436	16.9	314	22.3
990	7.3	838	18.2	573	23.3
1155	7.2	1090	18.1	860	23.9
1537	7.1	1466	17.9	1508	24.8

36%		29.42%		29%	
$\mathfrak{H}$	$\frac{\delta l}{l} \times 10^6$	$\mathfrak{H}$	$\frac{\delta l}{l} \times 10^6$	$\mathfrak{H}$	$\frac{\delta l}{l} \times 10^6$
7.5	0.4	18.6	0.0	15.0	0.1
17.6	2.0	42.0	0.3	27.8	0.9
37.1	5.1	99.0	0.7	45.3	1.1
151.5	12.3	200.0	1.5	81.8	1.7
234.0	13.7	338	2.2	135.7	2.3
341	14.8	530	3.4	292.2	3.6
587	16.2	724	4.8	510	5.5
1050	18.3	1032	6.9	864	8.6
1342	19.8	1292	8.4	1238	12.2
1905	22.1	1556	10.2	1622	15.2

28.72%		28.32%		26.64%	
$\mathfrak{H}$	$\frac{\delta l}{l} \times 10^6$	$\mathfrak{H}$	$\frac{\delta l}{l} \times 10^6$	$\mathfrak{H}$	$\frac{\delta l}{l} \times 10^6$
28.9	0.3	36.0	0.0	—	—
85.3	0.9	39.0	0.0	—	—
144.6	1.5	179.0	0.1	—	—
264.7	2.1	403	0.4	—	—
461	3.5	513	0.7	236	0.0
710	5.2	710	1.2	671	0.1
896	6.7	1025	2.0	882	0.2
1155	9.3	1340	2.9	—	—
1532	12.6	1861	4.5	1850	0.4

24.40%		24.04%	
$\mathfrak{H}$	$\frac{\delta l}{l} \times 10^6$	$\mathfrak{H}$	$\frac{\delta l}{l} \times 10^6$
—	—	89	0.0
186	0.00	181	0.1
—	—	288	0.4
407	0.02	414	0.7
683	0.04	688	1.3
988	0.07	1045	1.8
1419	0.07	1508	2.4
1867	0.09	1877	2 8

All the nickel steels hitherto examined show increase of length. The behaviours of the alloys containing 24.04 to 46 per cent are similar as regards the change of length, and do not indicate the existence of maximum elongation up to 2000 Gauss. It is, however, to be remarked that the rate of increase diminishes as the percentage increases. Ultimately, with further additions of nickel, the maximum elongation makes its appearance, and is already present for 50.72 per cent in field of 1000 Gauss; with 70.32 per cent Ni., this occurs in $\mathfrak{H}=170$. It thus appears that the increase of nickel beyond 50 per cent displaces the maximum point in the direction of the lower field. In fact, the character of the change resembles that in iron. With further additions of nickel, the metal will show contraction, which goes on increasing with the field. This remarkable change in the character of elongation will probably occur, when the metal approaches pure nickel. Further it is to be noticed that the elongation in all these specimens exceeds that of the constituent ferromagnetics.

An examination of Fig. 4 discloses how the transition between the elongation in iron and the contraction in nickel takes place. The curves of elongation plotted against the percentage content of nickel are similar to those of magnetization, showing two maxima and two minima between 24 per cent and 50 per cent of nickel. The alloy indicating the maximum elongation is little greater than 40 per cent, which nearly coincides with that showing greatest susceptibility.

Change of volume by magnetization.—The observed changes of volume are given in the following tables :—

70.32%		50.72%		46%	
$\mathfrak{H}$	$\frac{\delta v}{v} \times 10^6$	$\mathfrak{H}$	$\frac{\delta v}{v} \times 10^6$	$\mathfrak{H}$	$\frac{\delta v}{v} \times 10^6$
2	−0.00	5	0.05	68.1	0.03
57	−0.06	47	0.09	284.5	0.42
86	−0.04	75	0.11	386	0.60
158	−0·01	272	0.34	592	1.13
339	+0.08	443	0.54	679	1.28
635	+0.23	688	0.90	893	1.59
808	+0.29	985	1.35	994	2.19
1212	+0.46	1197	1.79	1327	3.00
—	—	1322	1.84	1452	3.55
1614	+0.63	1607	2.46	1618	4.38

36%		29.42%		29%	
$\mathfrak{H}$	$\frac{\delta v}{v} \times 10^6$	$\mathfrak{H}$	$\frac{\delta v}{v} \times 10^6$	$\mathfrak{H}$	$\frac{\delta v}{v} \times 10^6$
7.6	0.03	19	0·38	6.5	0.06
11.8	0.05	35	1.25	25.7	0.71
30.8	0.24	88	2.93	62.4	1.49
93.5	0.87	153	4.91	113.6	2.91
209.1	2.35	333	10.5	227.5	6.52
309	4.28	517	16.3	425	12.5
682	9.10	765	23.2	659	20.3
1042	14.3	979	29.3	989	29.7
1333	18.4	1370	39.9	1260	38.7
1669	23.0	1685	47.4	1687	51.1

28.72%		28.32%		26.64%	
$\mathfrak{H}$	$\frac{\delta v}{v}\times 10^6$	$\mathfrak{H}$	$\frac{\delta v}{v}\times 10^6$	$\mathfrak{H}$	$\frac{\delta v}{v}\times 10^6$
25	0.55	24	0.27	—	—
76	2.29	38	0.34	—	—
142	4.25	89	0.90	—	—
257	7.73	176	1.67	179	0.07
449	14.2	384	3.95	392	0.27
666	20.3	530	5.86	—	—
857	25.6	632	7.20	635	0.60
1076	31.6	920	11.1	929	0.96
1355	39.8	1315	16.8	1318	1.76
1662	47.6	1636	21.4	1640	2.65

24.40%		24.04%	
$\mathfrak{H}$	$\frac{\delta v}{v}\times 10^6$	$\mathfrak{H}$	$\frac{\delta v}{v}\times 10^6$
176	0.00	175	0.04
387	0.02	391	0.14
641	0.07	640	0.17
925	0.17	942	0.30
1325	0.23	1351	0.55
1651	0.27	1671	0.69

As has been already noticed in the previous contribution, the increase of volume in nickel steels by magnetization is nearly proportional to the strength of the field. The change is enormously large compared with that in the constituent metals iron and nickel. The maximum effect is observed in 29 per cent Ni., being about

50×10^{-6} in a field of 1600 Gauss. We noticed a slight decrease of volume for 70.32 per cent Ni. specimen in weak fields.

Plotting the volume change in constant fields (Fig. 6) against the percentage content of nickel, we notice a sudden ascent for 25 per cent to 29 per cent, and then a sudden descent to about 40 per cent. The decrease in the volume change becomes gradually less as the alloy approaches pure nickel.

On several occasions, we have remarked that the volume change by magnetization is of a differential nature, since

Volume change in ovoid = elongation parallel to magnetization
+2. elongation perpendicular to magnetization.

Generally, the elongation in the direction of magnetization is of opposite sign to that in the direction perpendicular to it. In iron and nickel, the sum of these elongations representing the volume change nearly vanishes, while in nickel steels, this is by no means the case. The sum of these respective elongations is maximum in 29 per cent Ni., in which the position of maximum effect is very prominent. The phenomenon is the more remarkable as this point nearly coincides with the corresponding points for magnetization and elongation by magnetization. The border line which marks the transition of nickel steel from *acier dur* to *acier doux* is also little short of the same percentage, which will probably explain the existence of the maximum change of volume, considered as a differential effect.

Connexion with other physical properties of nickel steel.—When we examine various other physical properties of this valuable alloy, we cannot but be struck with the singular coincidence of the changes attending the magnetization in the neighbourhood of 29 per cent Ni. with those attending the elastic and thermal behaviour as the metal is transformed from *acier dur* to *acier doux*. For the said percentage content of nickel, the resistance to rupture is least, but the elongation on the application of breaking stress is maximum ; it is for about the same percentage that the irreversible metal can be made reversible, while the temperature of transformation by cooling becomes very low ; and for the same percentage, the rate of decrease of the thermal coefficient of expansion due to the addition of nickel is the greatest.

These coincidences do not appear to be merely accidental and further researches as to electric and thermal conductivities will probably reveal similar singularities in the same region. A really satisfactory theory of the constitution of the alloy must explain, not only the metallurgical aspect of the metal, but also its various physical characteristics, and unite them in a common bond. For this purpose, different investigations by changing the conditions under which the metal is tested, will give valuable clues to the exposition of a theory

Fig. 1.

Magnetization of Nickel Steels.

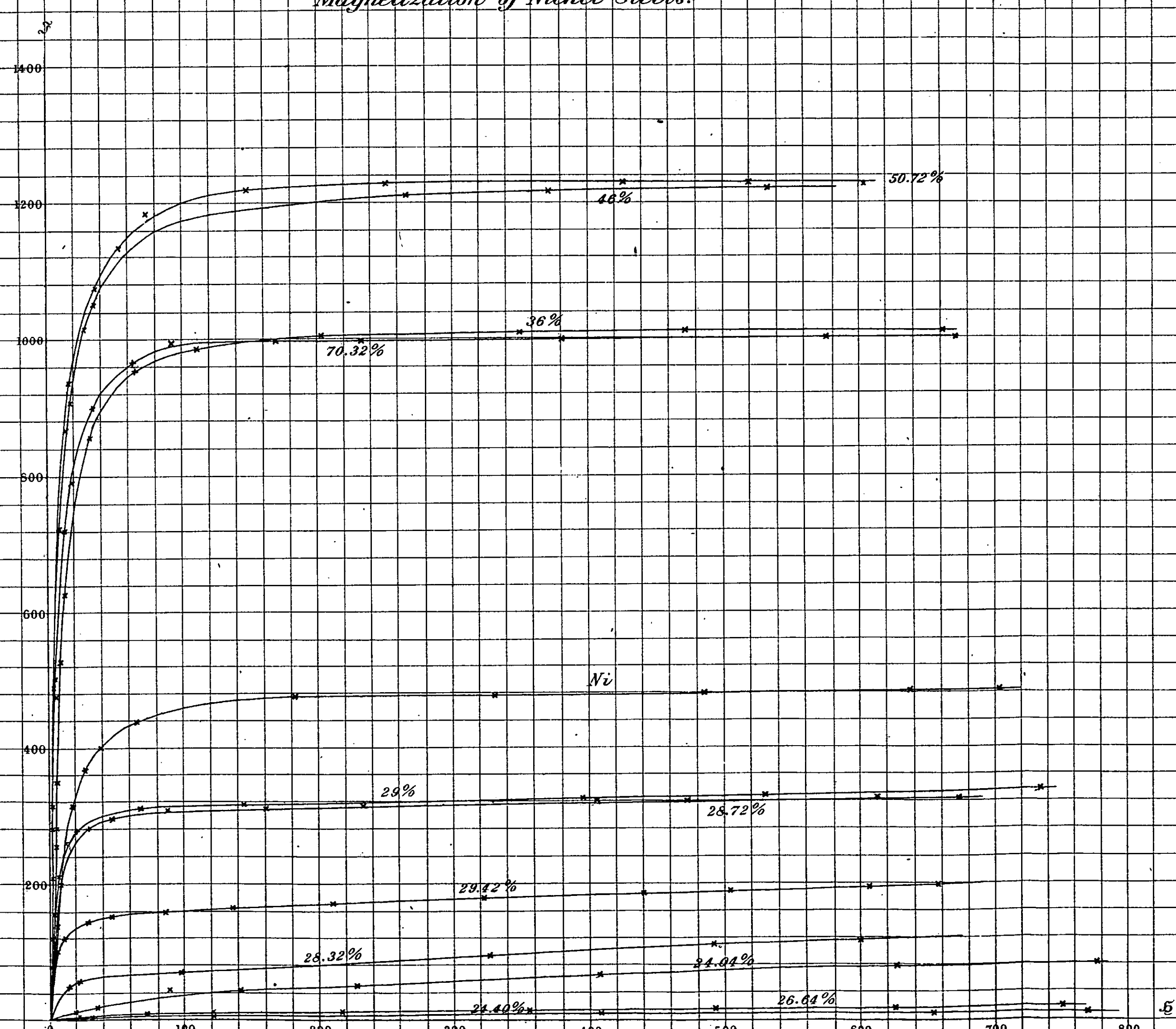


Fig. 2.

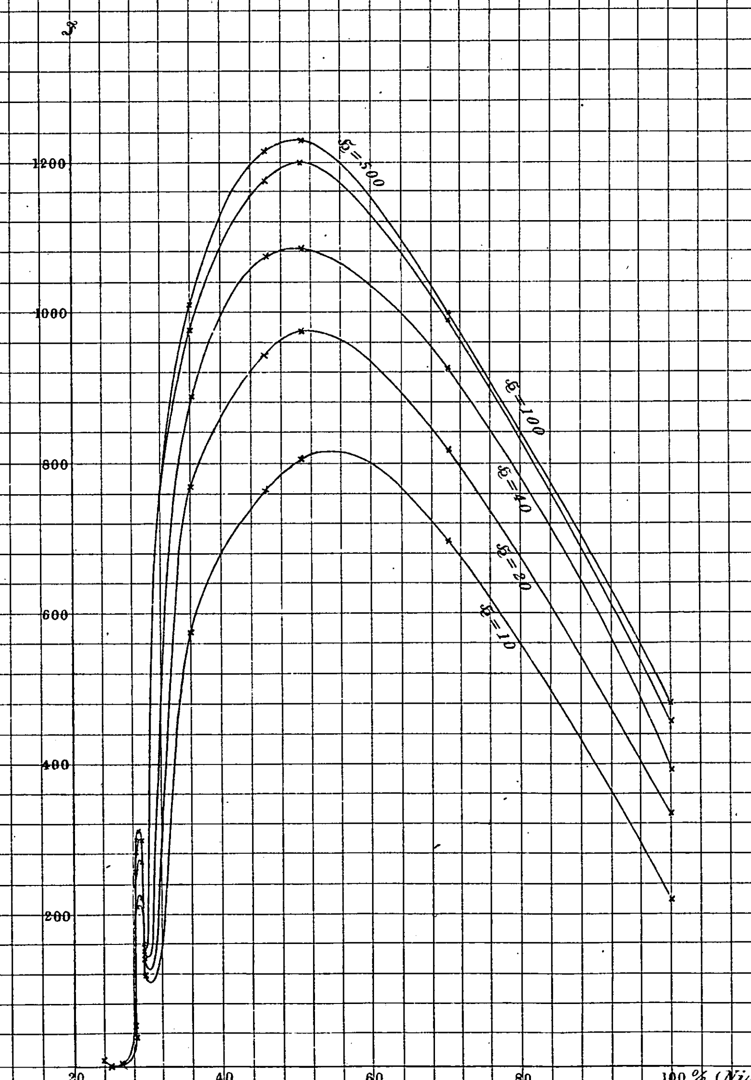


Fig. 3.

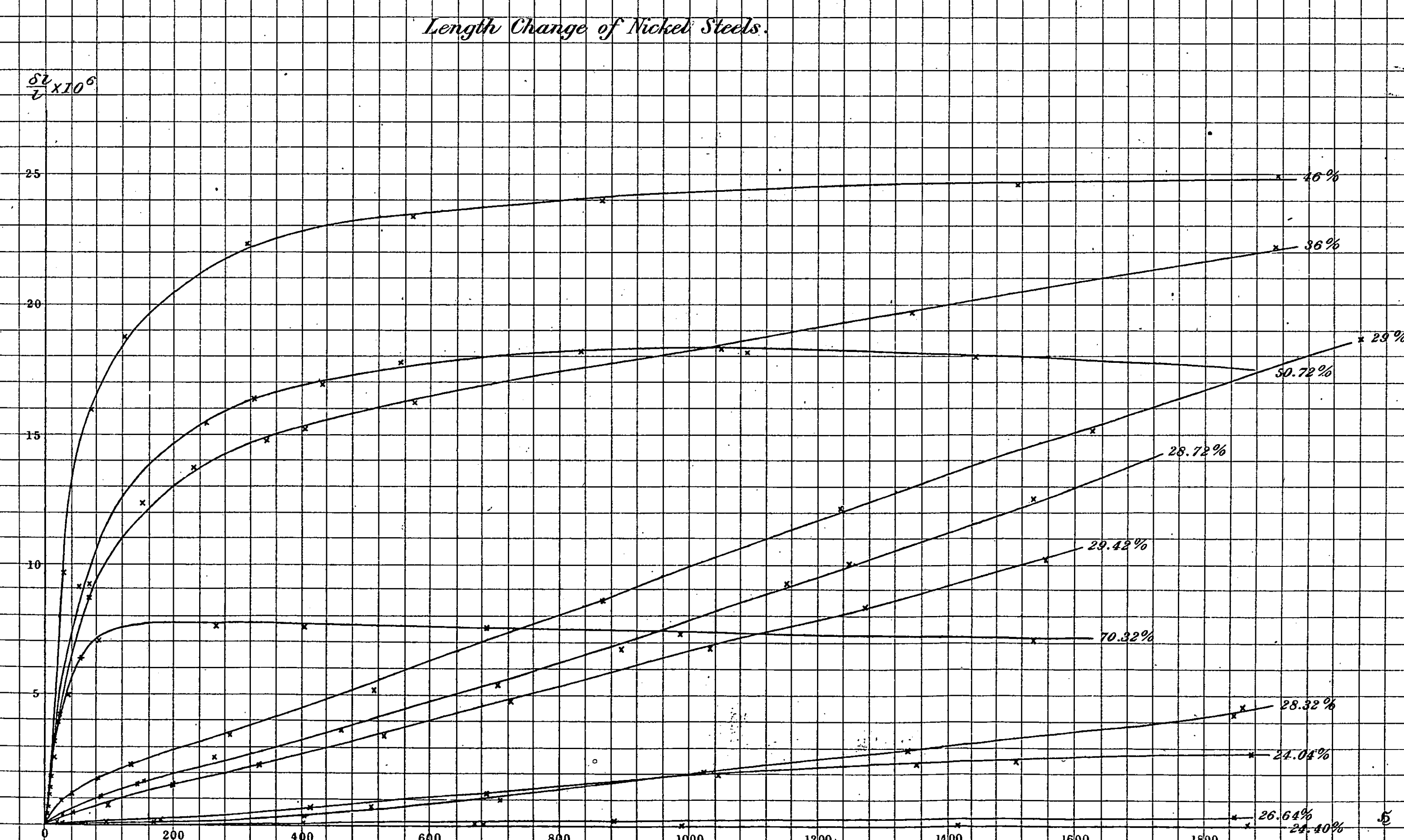
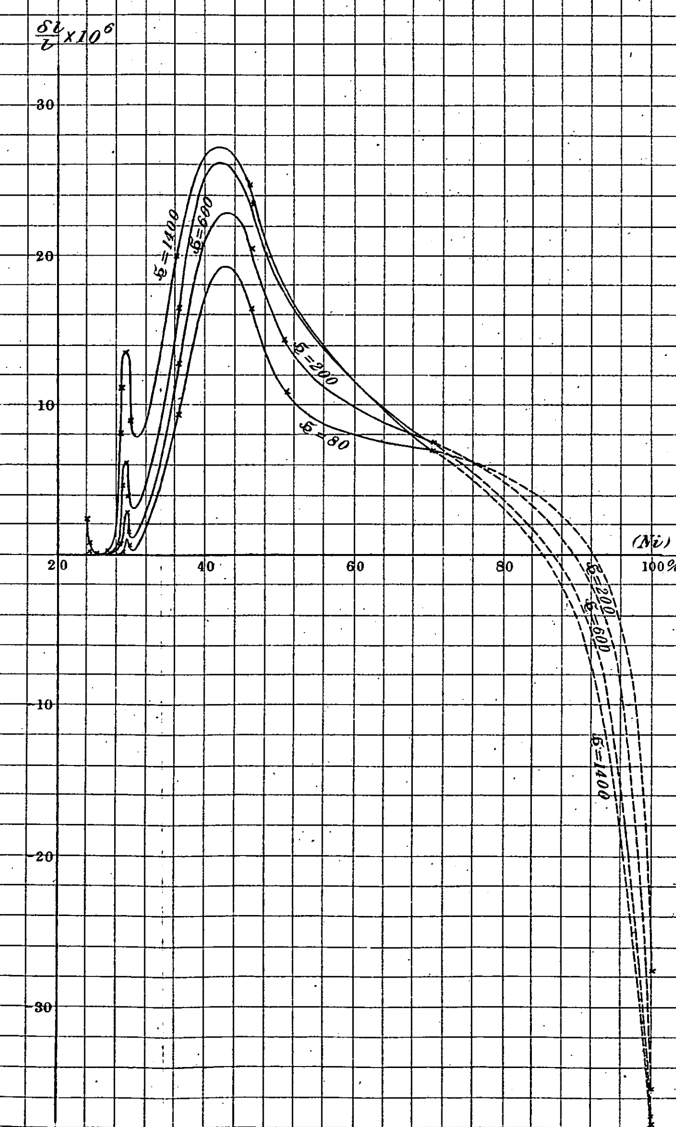
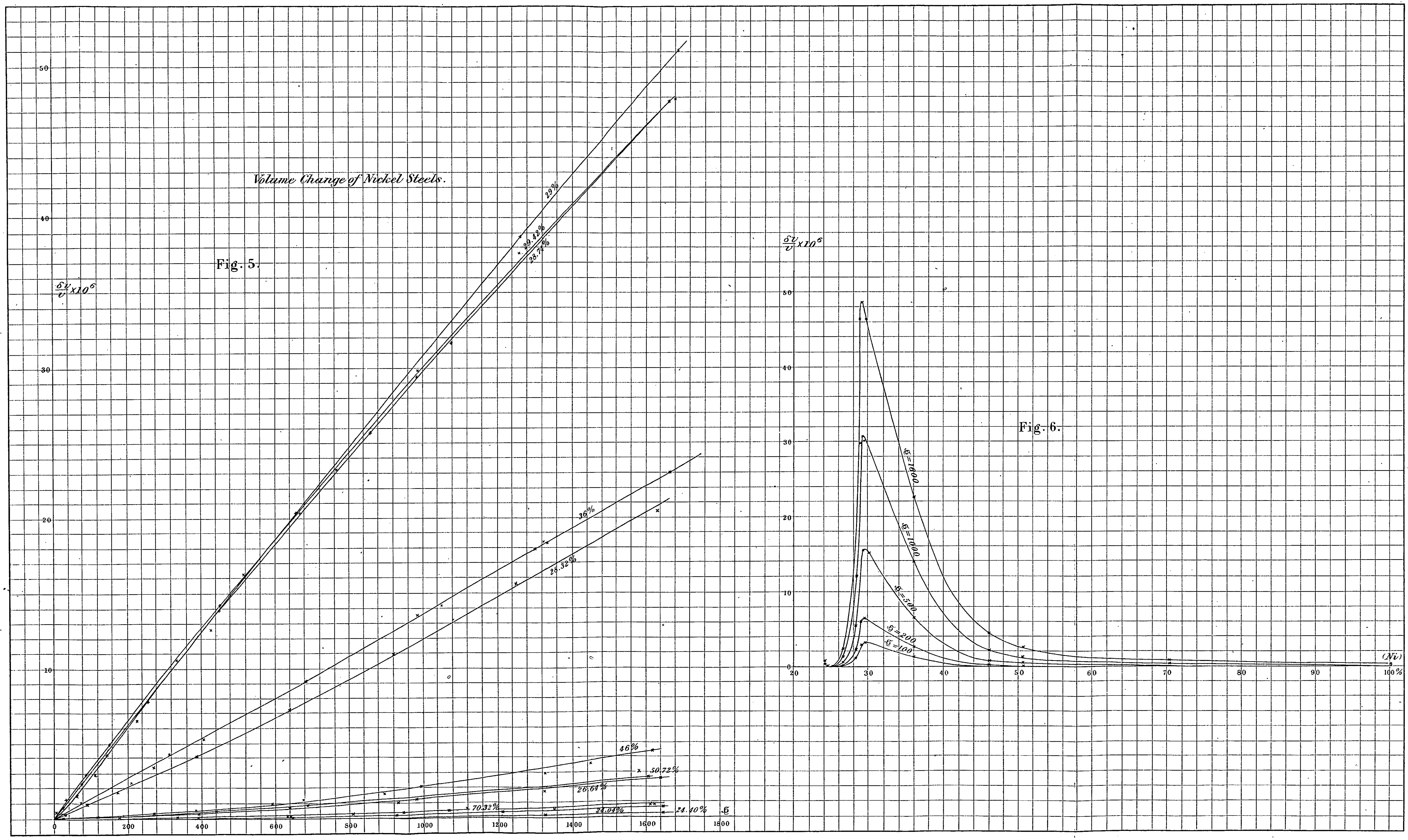

Length Change of Nickel Steels.
δl/l x10^6
25
20
15
10
5
0
200
400
600
800
1000
1200
1400
1600
1800
46%
36%
29%
30.72%
28.72%
29.42%
70.32%
28.32%
24.04%
26.64%
24.40%
𝔖

Fig. 4.


δl/l x10^6
30
20
10
10
20
30
20
40
60
80
100%
(Ni)
𝔖=1400
𝔖=600
𝔖=200
𝔖=80


Volume Change of Nickel Steels.
Fig. 5.
δv/v x10^6
29%
29.42%
28.74%
36%
25.32%
46%
50.72%
26.64%
70.32%
24.04%
24.40%
0
200
400
600
800
1000
1200
1400
1600
1800
10
20
30
40
50
Fig. 6.
δv/v x10^6
ℌ=1600
ℌ=1000
ℌ=500
ℌ=200
ℌ=100
(Ni)
20
30
40
50
60
70
80
90
100%