PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Magnetic Qualities of Nickel

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XI. *Magnetic Qualities of Nickel.*

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[Plates 15, 16.]

Although determinations of the magnetic permeability of nickel have been made by Rowland and others,* there appears to be no published investigation of the effect of cyclic magnetising processes. The study of such processes is interesting not only in its direct bearing on the relation of magnetisation to magnetising force, but indirectly as yielding data from which one may calculate the dissipation of energy that occurs in reversal or other variation of magnetism, in consequence of hysteresis in the relation of magnetisation to magnetising force. Cyclic processes have been very fully examined for various kinds of iron and steel,† and one object of the following experiments was to obtain information of the same kind with regard to nickel. Another object was to examine the effects of longitudinal stress on the magnetisation of this metal in the same manner as they had been examined in iron by one of the writers.‡ Sir William Thomson's early results in this subject had shown that, when subjected to longitudinal pull, nickel undergoes much change of magnetism, of a kind opposite to that which ordinarily occurs in iron,§ and it seemed that a fuller investigation of the effects of stress might be useful.

The experiments, with the exception of one group described at the end of this paper, were made with specimens of nickel wire supplied by Messrs. Johnson and Matthey. The wire was 0·068 cm. in diameter, and was supplied in what appeared to be a hard-drawn state, in which its magnetic susceptibility was decidedly less than when the wire was annealed. Its magnetic quality was examined both when in this hard-drawn state and after annealing. The direct magnetometric method was employed, in the same manner as in the experiments on iron referred to above.‖ A

* Rowland, 'Phil. Mag.,' Aug., 1873, and Nov., 1874; H. Meyer, 'Wiedemann, Annalen,' vol. 18, p. 251.

† Ewing, 'Phil. Trans.,' 1885, p. 523; Hopkinson, *ibid.*, p. 455.

‡ Ewing, *loc. cit.*, §§ 69–113.

§ Sir W. Thomson, 'Phil. Trans.,' May, 1878; or 'Reprint of Papers,' vol. 2, p. 382.

‖ Ewing, *loc. cit.*, § 18.

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straight piece of the wire, from 300 to 400 diameters long, was hung in a vertical position with its upper end due east (magnetically) of a small mirror magnetometer. Over the wire a tube was slipped on which the magnetising solenoid was wound, and on the same tube there was another solenoid in which a constant current was kept up, of just sufficient strength to neutralise the vertical component of the earth's magnetic force. The field within the tube was therefore wholly due to the current in the magnetising solenoid, and was exactly reversed when that current was reversed. The strength of the magnetising current was adjusted by a slide resistance consisting of a column of solution of sulphate of zinc, with two fixed blocks and one sliding block of amalgamated zinc for terminals; and a revolving commutator between the slide and the solenoid allowed the current to be rapidly reversed. The slide was used to vary the current slowly in studying the relation of magnetism to magnetising force, and, in conjunction with the rapid commutator, it served also to demagnetise the wire under examination by the method of reversals (that is, by numerous successive reversals of a magnetising force which decreased slowly from a strong value to zero). The magnetising current was taken from a secondary battery of ample capacity, and was measured by a mirror galvanometer, calibrated to read the current in absolute measure, which was included in the circuit of the magnetising solenoid. The current which served to neutralise the vertical component of the earth's field was adjusted by substituting for the nickel wire a wire of soft iron, and subjecting that to demagnetisation by reversals; it was only when the earth's field was very exactly balanced that this process gave complete demagnetisation. In all the results given below the magnetising force $\mathfrak{H}$ and the intensity of magnetism $\mathfrak{I}$ are expressed in absolute c.g.s. units.

Cyclic Magnetisation of Nickel.

Fig. 1, Plate 15, exhibits the cyclic magnetisation of a piece of nickel wire, 0·068 cm. in diameter and 25·4 cm., or 374 diameters long, in the hard-drawn state, as supplied by Messrs. JOHNSON and MATTHEY. Previous to this test the wire had been strongly magnetised and demagnetised by reversals, and at the beginning there was a little residue which this process had failed to wipe out. Nickel, like hard steel, is much less easily demagnetised to a perfectly neutral state than soft iron. The following are the observed values of $\mathfrak{H}$ and $\mathfrak{I}$ during the first part of the experiment, and the values of κ, the susceptibility, which is $\mathfrak{I}/\mathfrak{H}$.

HARD-DRAWN Nickel Wire.

$\mathfrak{H}$	$\mathfrak{I}$	κ
0	12	
3·0	19	
8·7	37	
14·9	104	7·0
19·1	187	9·8
23·0	255	11·1
37·5	341	9·1
54·0	378	7·0
75·4	404	5·4
104·4	420	4·0

After this the magnetising force was gradually removed and reversed, then re-applied, then removed to zero, and then re-applied in the same direction as at first. The curves in the figure show these subsequent actions sufficiently well to make it unnecessary to quote the observed values of $\mathfrak{I}$ and $\mathfrak{H}$. After magnetising with a force of 104 and getting an induced magnetism of 420, there was a residual magnetism of 299, or 71 per cent. of the induced magnetism. It took a reversed force of 18·5 to remove this. This is the quantity which HOPKINSON has called the "coercive force."* The greatest susceptibility (κ) was reached when $\mathfrak{H}$ was 24 and $\mathfrak{I}$ was 270; its value is 11·2, which gives 142 for the maximum permeability μ. The energy dissipated through hysteresis in the large cycle, by double reversal of a magnetising force of say 100 c.g.s. units ($-\int \mathfrak{I}\, d\,\mathfrak{H}$), was 25,400 ergs. In simple removal and re-application of the force without change of sign there was but little hysteresis, and the dissipation of energy in that process was relatively insignificant. The greatest value of the magnetic induction $\mathfrak{B}$ $(= 4\pi\mathfrak{I} + \mathfrak{H})$ reached in this experiment was 5380.

The full lines in fig. 2 show in the same way the cyclic magnetisation of the same piece of nickel wire after it had been annealed by heating to bright redness in the flame of a Bunsen burner and cooling slowly in air. The greatest magnetisation now reached under a force, $\mathfrak{H}$, of 100 is barely so high as before, but the susceptibility at earlier stages is much greater, and the coercive force and the dissipation of energy are much less. The following values refer to the first part of the process; here, as in the former case, there was some initial magnetism which the process of demagnetising by reversals (applied before these observations were taken) did not remove :—

* HOPKINSON, *loc. cit.*, p. 460.

ANNEALED Nickel Wire.

$\mathfrak{H}$.	$\mathfrak{I}$.	κ.
0	22	
4·0	36	
6·5	83	12·8
8·0	177	22·1
9·5	223	23·5
10·9	251	23·0
12·3	273	22·2
24·6	325	13·2
52·6	371	7·1
79·7	392	4·9
100·4	401	4·0

In this case the greatest susceptibility was 23·5, when $\mathfrak{H}$ was 9·5. This gives 302 as the maximum value of μ.* These numbers are just about one-tenth of what they would be for an iron wire annealed in the same way. The residual magnetism is 284, or 71 per cent. of the induced, and the coercive force is 7·5, or a good deal less than half of what it was before the wire was annealed. The energy of the cycle of double reversal of magnetism ($\int \mathfrak{I}\, d\, \mathfrak{H}$) is 11,200 ergs.

The broken lines in fig. 2 show a magnetising cycle performed on another piece, cut from the same coil of nickel wire, which, after being softened in a Bunsen flame, was mechanically hardened by being stretched enough to give it some permanent extension (namely, from a length of 26·6 cm. to 27 cm.). Here the maximum susceptibility is only 8·3, the coercive force is 18, and the highest value of $\mathfrak{I}$, reached by applying a force of 117, is only 340. The cycles for annealed and hardened nickel differ in much the same way as the corresponding cycles for annealed and hardened iron.

Effects of Stress on the Magnetic Susceptibility and Retentiveness of Nickel.

The effects of stress, consisting of longitudinal pull, were examined (1) by magnetising wire from which a constant load of greater or less amount was hung, and (2) by loading and unloading wire which was exposed to a constant magnetising force of greater or less intensity. The same pieces of wire that served for the experiments in cyclic magnetisation were tested for effects of stress, both before and after annealing, and after being hardened by stretching.

While still in the hard-drawn original condition the wire of fig. 1 was tested for induced and residual magnetism under varying magnetising forces: first, when not exposed to stress, then when under a longitudinal pull of 2 kilogrammes, and lastly when under a pull of 12 kilogrammes. The observations were made by applying magnetising force, noting the induced value of $\mathfrak{I}$, reducing the magnetising force to

* ROWLAND (*loc. cit.*) gives 302 as the maximum of μ in a specimen of cast nickel.

zero, and noting the residual value of $\mathfrak{I}$ (which will be distinguished as $\mathfrak{I}_r$), then applying a stronger magnetising force, and so on. By this means curves were drawn showing the relation of the induced magnetism $\mathfrak{I}$ to the force $\mathfrak{H}$, and also the residual magnetism $\mathfrak{I}_r$ to the force $\mathfrak{H}$, in each of the three conditions of stress. Before passing from one to another load, the wire was demagnetised by reversals, and this process was repeated after the new load had been put on. This precaution was taken because it had been found in experiments on iron that the exact form which the curve of $\mathfrak{I}$ and $\mathfrak{H}$ took under any assigned load depended on whether the process of demagnetising had or had not been performed after the load was applied.*

The results of these experiments with nickel wire in the hard-drawn state are given below, and are shown in fig. 3. In the Table a column is added to show the ratio of residual to induced magnetism.

HARD-DRAWN Nickel Wire.

No load.			Ratio.	2 kilos.			Ratio.	12 kilos.			Ratio.
$\mathfrak{H}$	$\mathfrak{I}$	$\mathfrak{I}_r$	$\mathfrak{I}_r/\mathfrak{I}$	$\mathfrak{H}$	$\mathfrak{I}$	$\mathfrak{I}_r$	$\mathfrak{I}_r/\mathfrak{I}$	$\mathfrak{H}$	$\mathfrak{I}$	$\mathfrak{I}_r$	$\mathfrak{I}_r/\mathfrak{I}$
5·7	15	0	0	5·5	14	0	0	7·9	8	0	0
11·1	41	14	0·34	10·6	34	8	0·23	12	13	0	0
12·7	57	27	0·47	13·2	51	18	0·36	29	30	2	0·07
18·4	169	120	0·71	25·2	169	106	0·63	56	66	8	0·12
25·6	276	216	0·78	40·4	273	186	0·68	92	109	16	0·15
59·8	386	280	0·73	71·8	353	214	0·60	115	135	21	0·18
84	410	286	0·70								
102	411	286	0·70								

As the section of the wire was 0·363 sq. mm., each kilogramme of load corresponds to a stress of 2·75 kilogrammes per sq. mm.

These results agree with Sir WILLIAM THOMSON's experiments, which were made by loading and unloading a nickel rod exposed to constant magnetising forces, in showing that longitudinal pull reduces the magnetic susceptibility of nickel. The reduction is, in fact, enormous even under so moderate a load as 12 kilos. (or 33 kilos. per sq. mm.), a load well within the elastic limit of the wire.† Great as the effects of stress are on the induced values of $\mathfrak{I}$, they are still greater on the residual values, so much so that a load of 12 kilos. may be said almost to do away with the retentiveness of the wire with respect to such magnetising forces as the experiments deal with. In magnetisation by very low forces nickel, like iron, retains sensibly none of the induced magnetism when the force is withdrawn, and one effect of longitudinal pull is to extend the range of magnetising force for which this is true.

* EWING, *loc. cit.*, §§ 96–105.

† A specimen of this wire, which was loaded until it broke, showed little elongation until a load of 18 kilos. was reached. It broke with 23 kilos., after extending 9 per cent.

After the same piece of wire was annealed, a precisely similar set of experiments was made, with results which are given below, and shown in fig. 4.

ANNEALED Nickel Wire.

No load.			Ratio.	2 kilos.			Ratio.	12 kilos.			Ratio.
$\mathfrak{H}$	$\mathfrak{I}$	$\mathfrak{I}_r$	$\mathfrak{I}_r/\mathfrak{I}$	$\mathfrak{H}$	$\mathfrak{I}$	$\mathfrak{I}_r$	$\mathfrak{I}_r/\mathfrak{I}$	$\mathfrak{H}$	$\mathfrak{I}$	$\mathfrak{I}_r$	$\mathfrak{I}_r/\mathfrak{I}$
5·3	29	9	0·31	3·8	17	5	0·30	9·2	3	0	0
8·2	84	52	0·62	11·0	83	48	0·58	15·1	9	0	0
11·1	162	118	0·73	16·9	140	86	0·61	32·5	26	4	0·15
12·6	193	147	0·76	25·4	194	112	0·58	72	73	14	0·19
22·5	285	213	0·75	58·7	298	140	0·47	78	88	16	0·18
32·8	327	234	0·72	113·5	372	148	0·40	112	112	16	0·14
100	401	285	0·71								

To exhibit more fully the effect which the presence of tensile stress has in reducing the magnetic susceptibility of nickel, the same piece of wire (namely, that of the full-line cycle in fig. 2) was again tested under various loads ranging from 0 to 12 kilos. The results are shown in fig. 5, Plate 16, and from the curves drawn there the following values of the maximum susceptibility κ have been measured :—

Load in kilos.		Maximum susceptibility κ.
Total.	Per sq. mm.	
0	0	15
2	5·5	9·1
4	11	4·5
6	16·5	2·6
8	22	1·9
10	27·5	1·5
12	33	0·95

The value of $\mathfrak{H}$ which corresponds to the maximum of susceptibility becomes higher as the load is increased; with 12 kilos., in fact, the maximum appears not to be reached even when $\mathfrak{H}$ is 115. By comparison with the full-line cycle of fig. 2, the no-load test in this group shows that the wire had lost some of the susceptibility given by annealing, probably because the load of 12 kilos. which had been applied after the cycle of fig. 2 had been completed, and before these observations were made, had produced a slight permanent hardening effect.

To examine the effects of applying and removing stress in a constant magnetic field another piece of the same nickel wire was softened by heating, and was then loaded up to 12 kilogrammes and unloaded, repeatedly, while a strong field was maintained in action. Fig. 6 shows the resulting changes of $\mathfrak{I}$, first when the magnetic field was 6·9, then 21·8, then 53·5, and lastly 116. The dotted lines in the same figure show the changes caused by loading and unloading on the residual magnetism that was left after the strongest field (116 c.g.s.) had ceased to act.

The curves show that stress of pull, acting either on residual or on induced magnetism in nickel, produces a large and continuous diminution of the magnetism, and that cyclic variations of stress are attended by exceedingly little hysteresis in the relation of magnetism to stress. The "off" curves lie distinctly below the "on" curves, but only a little way below them. The hysteresis here is far less than in the case of iron.

The same piece of wire was next hardened somewhat by stretching it till the original length of 26·6 cms. was changed to a length of 27 cms., and the process of loading and unloading was repeated, this time up to 18 kilos. The results are shown for two magnetic fields in fig. 7. In the stronger field the "on" and "off" curves so nearly coincide that a single line only has been drawn. The piece of wire dealt with in this experiment was the same, and in the same state, as the piece with which the cycle shown by broken lines in fig. 2 was performed.

Once more a set of curves of $\mathfrak{I}$ and $\mathfrak{H}$ were taken with this piece (hardened by stretching), under loads ranging from 0 to 18 kilos. These are given in fig. 8. They show the same characteristics as those of earlier figures, with a still more striking absence of susceptibility under the greater loads used here. With 18 kilos., for instance, equivalent to about 50 kilos. per sq. mm., a force of 100 c.g.s. produced an intensity of magnetisation amounting to barely 50. In the earlier curves of this series the dotted lines show the magnetic changes that occurred as the magnetising force was gradually withdrawn.

Finally, the initial parts of the curves in this group were examined by repeating the earliest portion of each magnetisation with the wire placed much nearer to the magnetometer. This was to determine whether there is in nickel any crossing of the curves similar to the crossing that occurs in iron, in consequence of the "Villari reversal" of the effects of stress.* Nothing of the kind was discovered in this metal.† The results of this experiment are given in fig. 9, and from them one may find the *initial* magnetic susceptibility, or ratio of $\mathfrak{I}$ to $\mathfrak{H}$, at the very commencement of the magnetising process. The first part of each curve is sensibly a straight line, until $\mathfrak{H}$ reaches a value of about 5 c.g.s. units. In other words, for forces less than this the susceptibility is as nearly as possible constant. When there was no load the initial

* *Cf.* THOMSON, *loc. cit.;* EWING, *loc. cit.*

† October 4, 1888.—It is, of course, possible that a crossing may take place at higher values of the magnetic force than were reached in these experiments, but the analogy to iron points rather to a crossing in the early portion of the curves, such as was looked for and not found in these experiments. With regard to this point, see an experiment by THOMSON, 'Phil. Trans,' 1879, p. 83.

susceptibility was 1·7. With each addition of load this was reduced, until it fell with 18 kilos. to 0·7. These numbers should be compared with those given for iron by Lord RAYLEIGH,* who has shown that under very feeble magnetising forces the susceptibility of that metal has a finite and sensibly constant value. For one specimen of unannealed Swedish iron he gives 6·4, and for another specimen 6·8 as the initial value of κ, which is constant only up to a magnetising force of about 0·04 c.g.s. units. Thus in nickel the initial susceptibility is much less than in iron (just as the maximum susceptibility, at a later stage in the magnetising process, is much less), but the range of magnetic force within which a sensibly constant value applies is immensely greater.

Magnetisation of Impure Nickel.

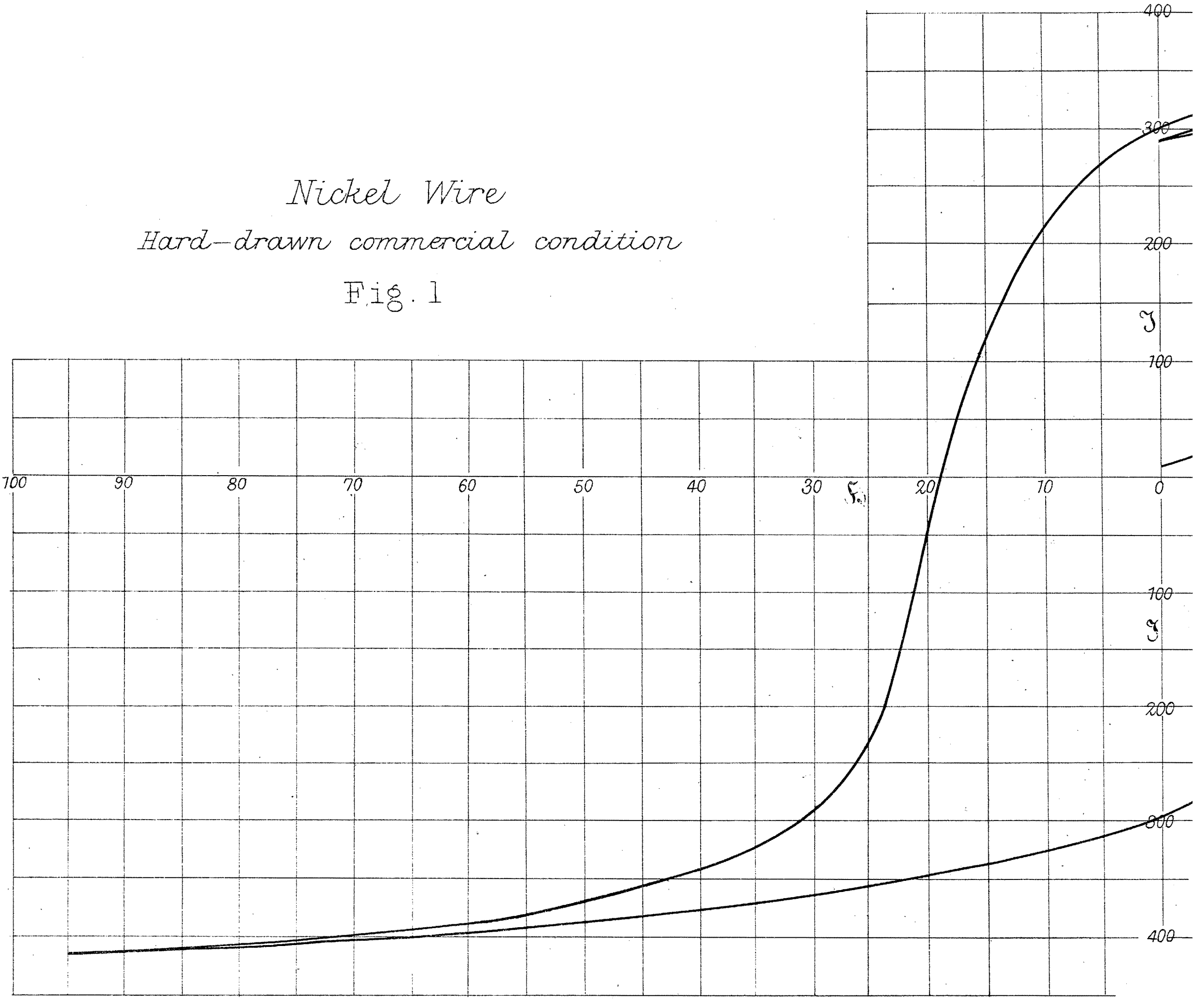
A few supplementary experiments were made with a specimen of cheap commercial nickel wire, 0·154 cm. in diameter, which was found to contain about 4 per cent. of iron. A piece 41 cms. long was annealed and was subjected to cyclical magnetisation, with results which are shown in fig. 10. The chief difference between this curve and that of fig. 2 is the higher limit to which $\mathfrak{I}$ tends in the present case, which is no doubt to be ascribed to the presence of iron in this impure specimen. A set of readings of residual magnetism were afterwards taken, and these, along with the ratio of residual to induced magnetism, are also shown by curves in fig. 10. The maximum ratio of residual to induced was 0·74. The dissipation of energy by hysteresis in the cycle of fig. 10 was 12,600 ergs. The effects of stress on the magnetic qualities of this wire were also examined, and were found to agree in all general features with the effects observed in purer samples of nickel, which have been described above.

* 'Phil. Mag.,' March, 1887.

Nickel Wire

Hard-drawn commercial condition

Fig. 1

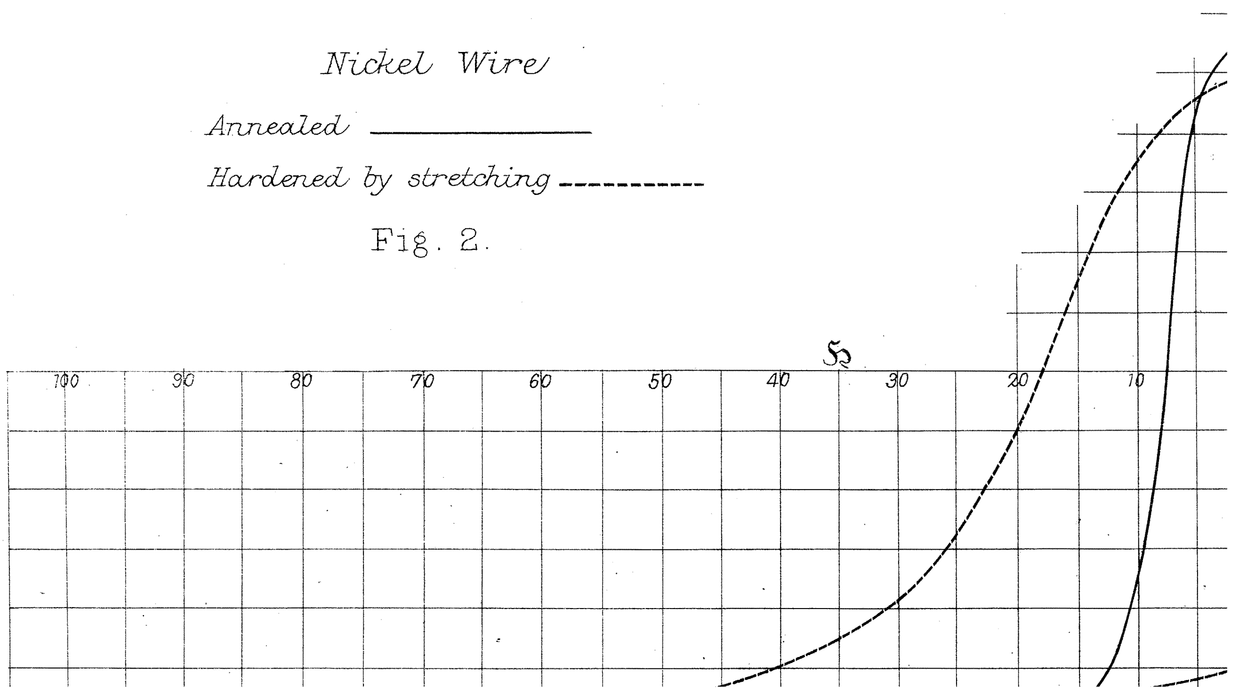


Nickel Wire

Annealed ——————

Hardened by stretching - - - - - - - -

Fig. 2.



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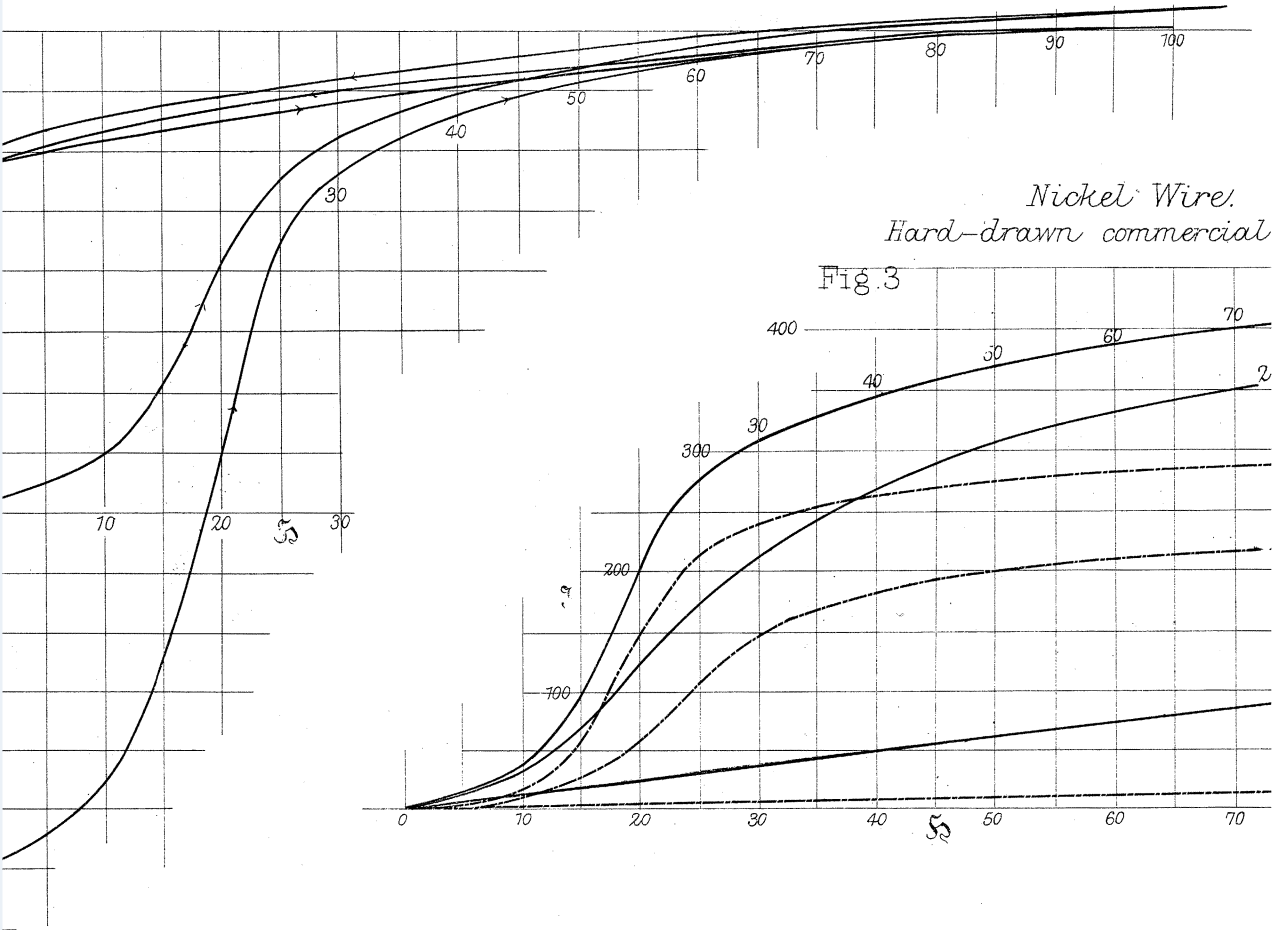
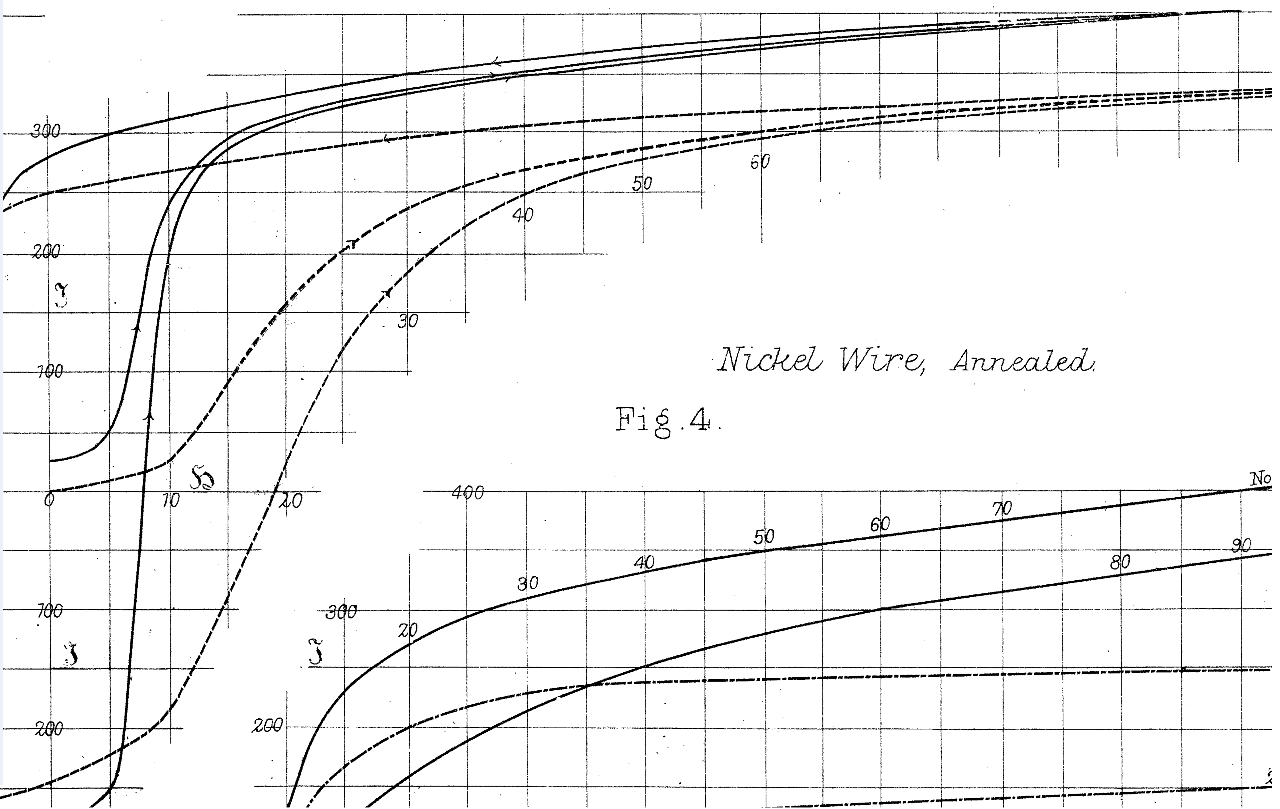


Nickel Wire. Hard-drawn commercial

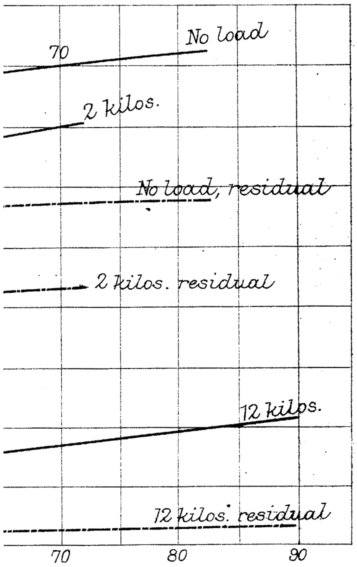
Fig. 3

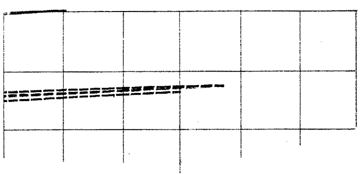


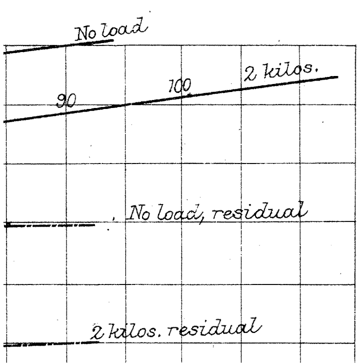
Nickel Wire, Annealed.

Fig. 4.

ire.
ercial condition.







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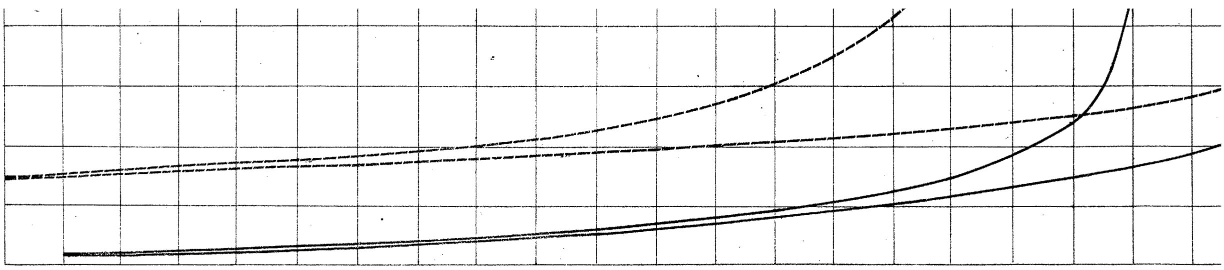

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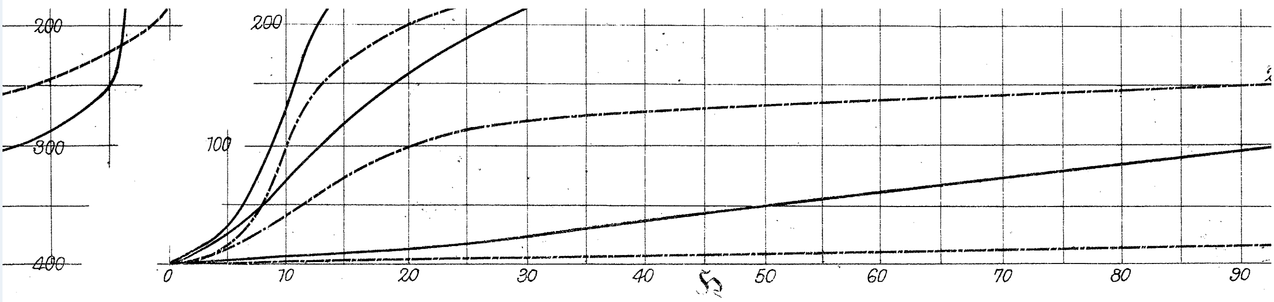

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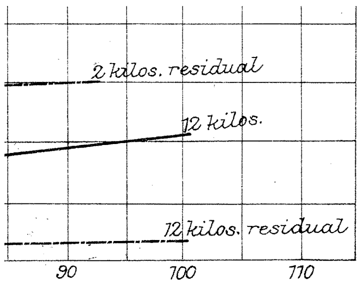

West, Newman & Co. lith.

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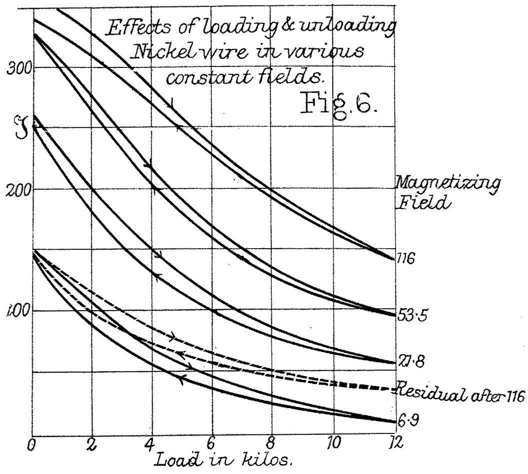
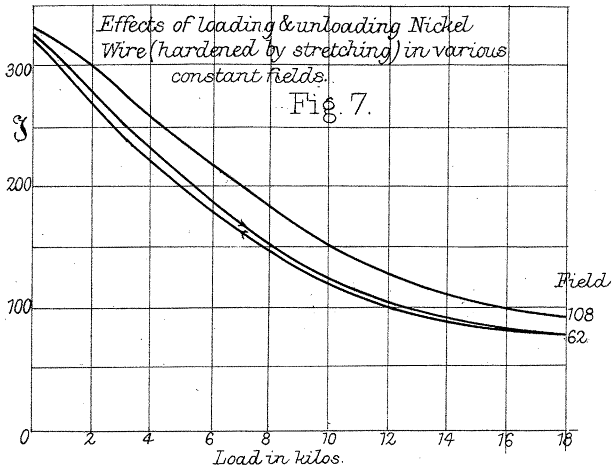

Effects of loading & unloading Nickel wire in various constant fields.
Fig. 6.
$\mathfrak{I}$
300
200
100
Magnetizing Field
116
53·5
21·8
Residual after 116
6·9
0
2
4
6
8
10
12
Load in kilos.


Effects of loading & unloading Nickel Wire (hardened by stretching) in various constant fields.
Fig. 7.
$\mathfrak{I}$
300
200
100
0
Field
108
62
2
4
6
8
10
12
14
16
18
Load in kilos.

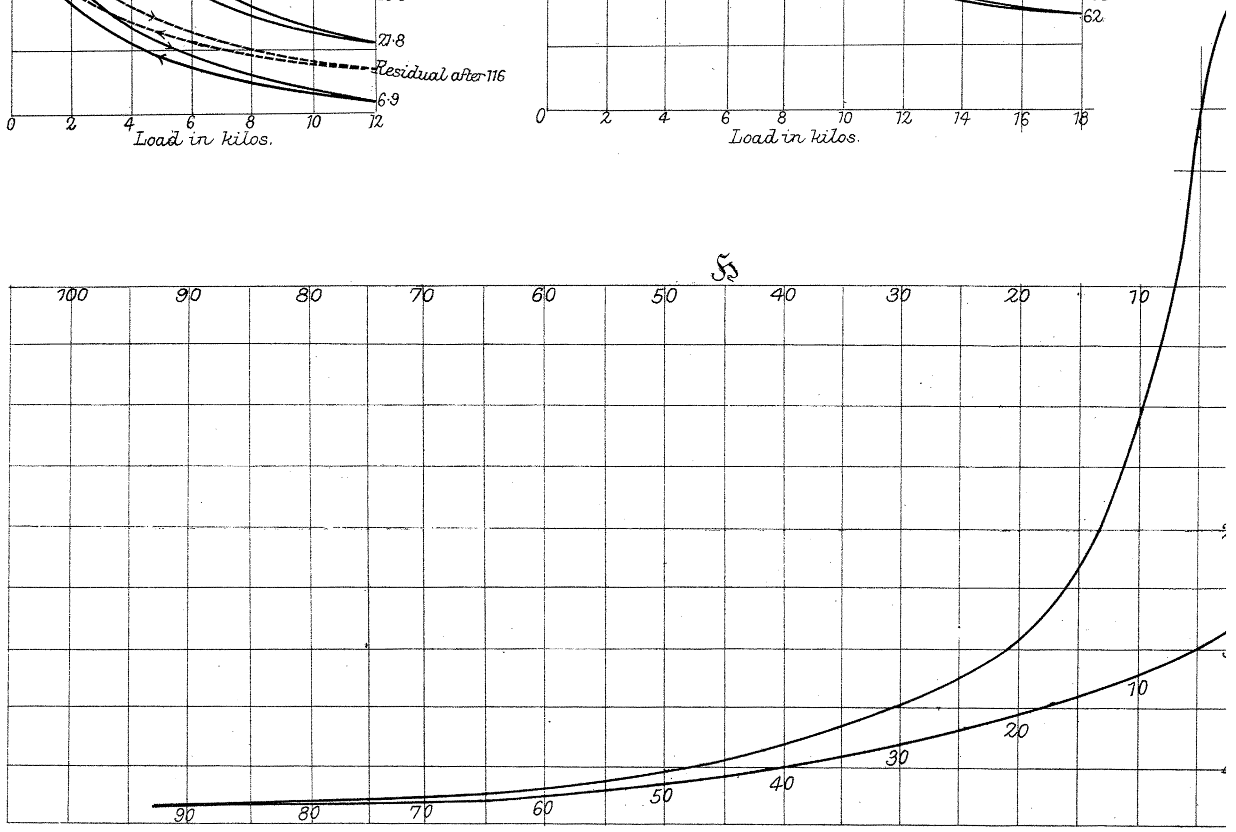
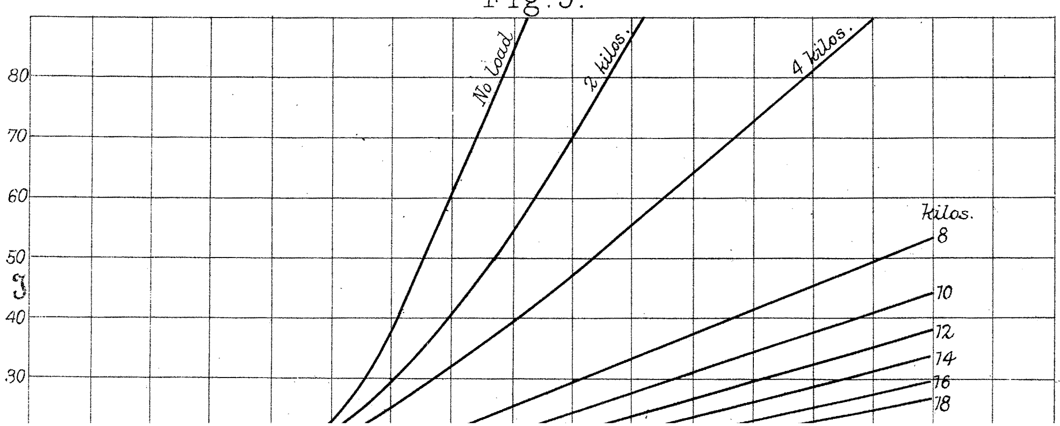

$\mathfrak{H}$
100
90
80
70
60
50
40
30
20
10

Fig. 9.


No Load
2 kilos.
4 kilos.
kilos.
8
10
12
14
16
18
$\mathfrak{I}$
80
70
60
50
40
30

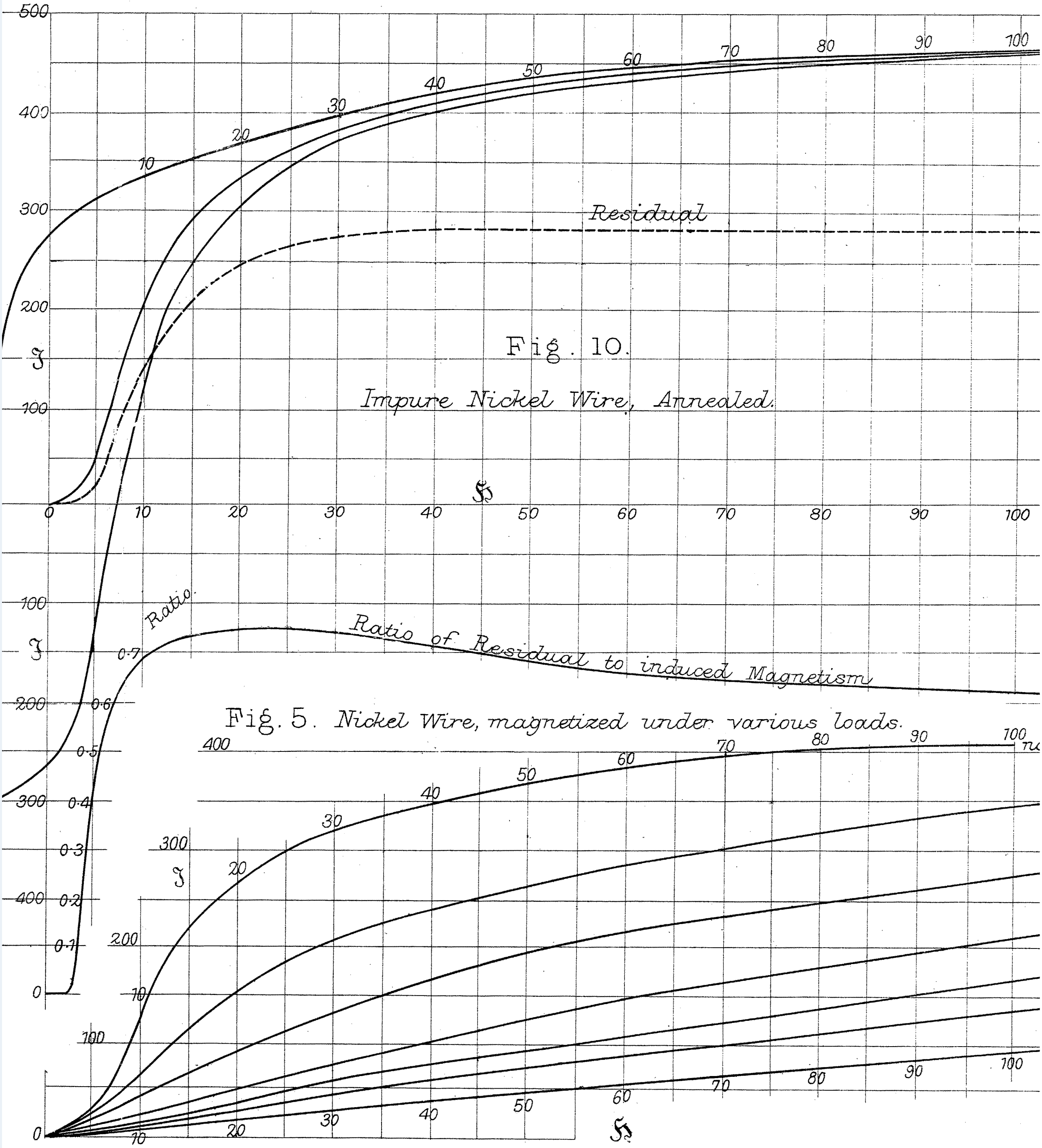


Fig. 10. Impure Nickel Wire, Annealed.

Fig. 5. Nickel Wire, magnetized under various loads.

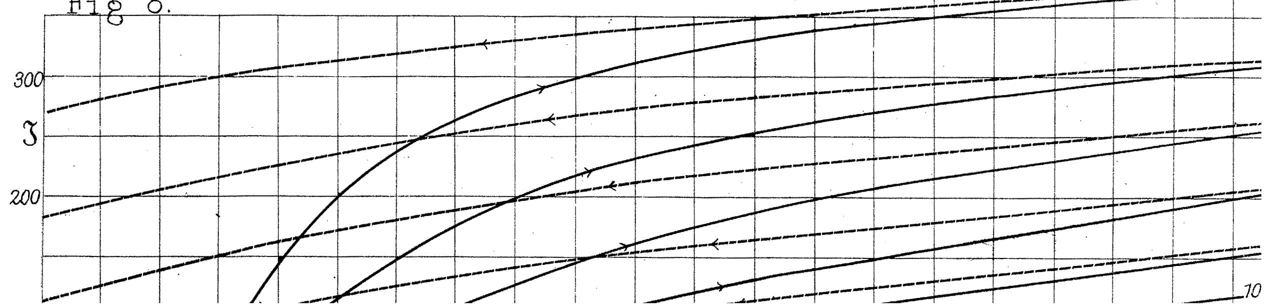


Fig 8. Nickel Wire, hardened by stretching, magnetized under various loads.

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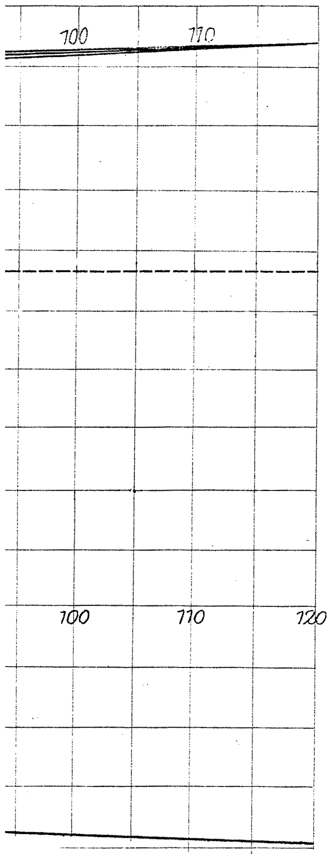

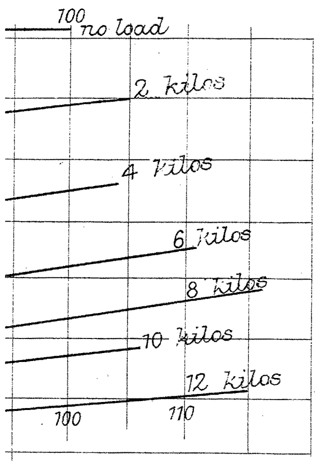

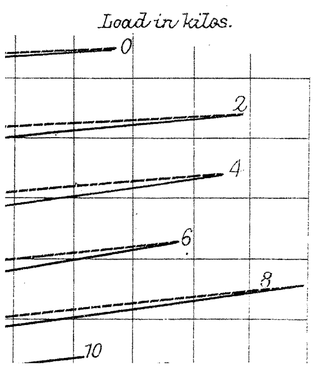

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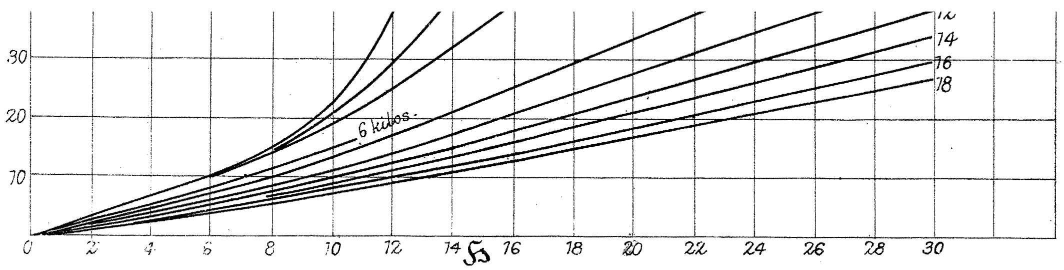

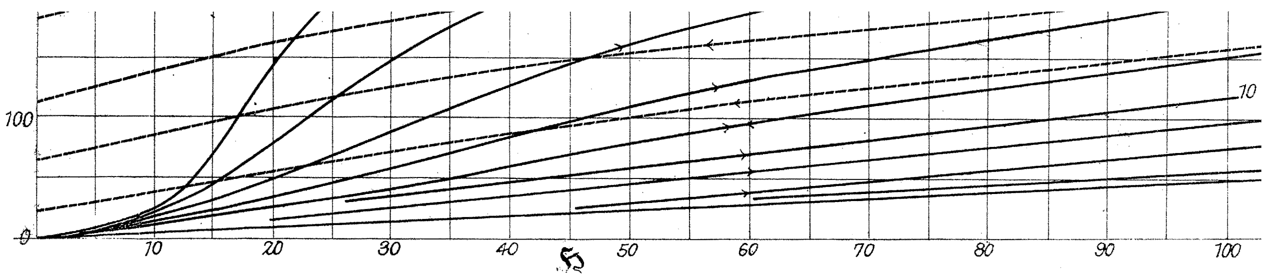

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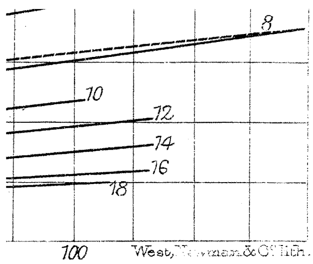
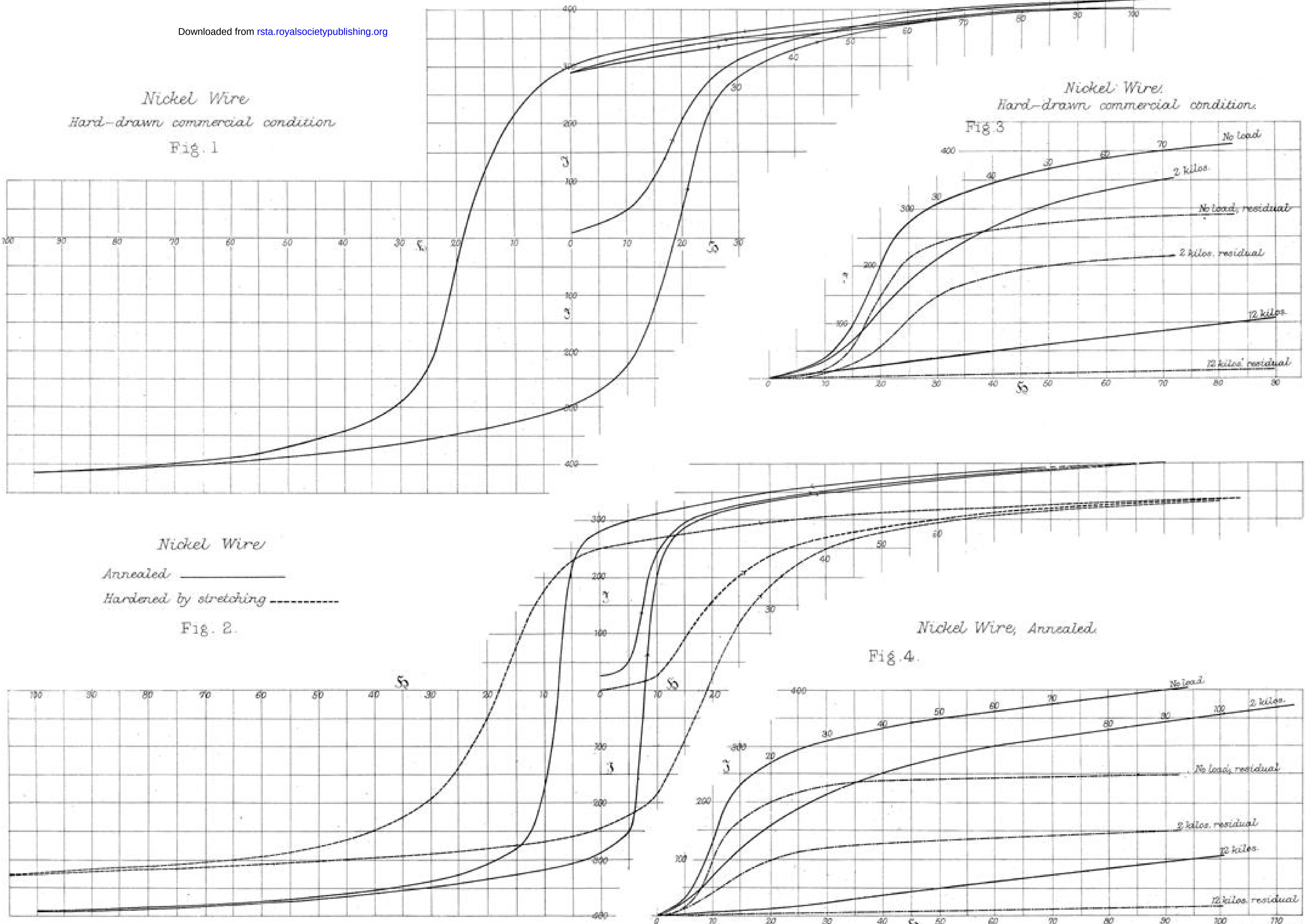


West, Newman & Co. lith.



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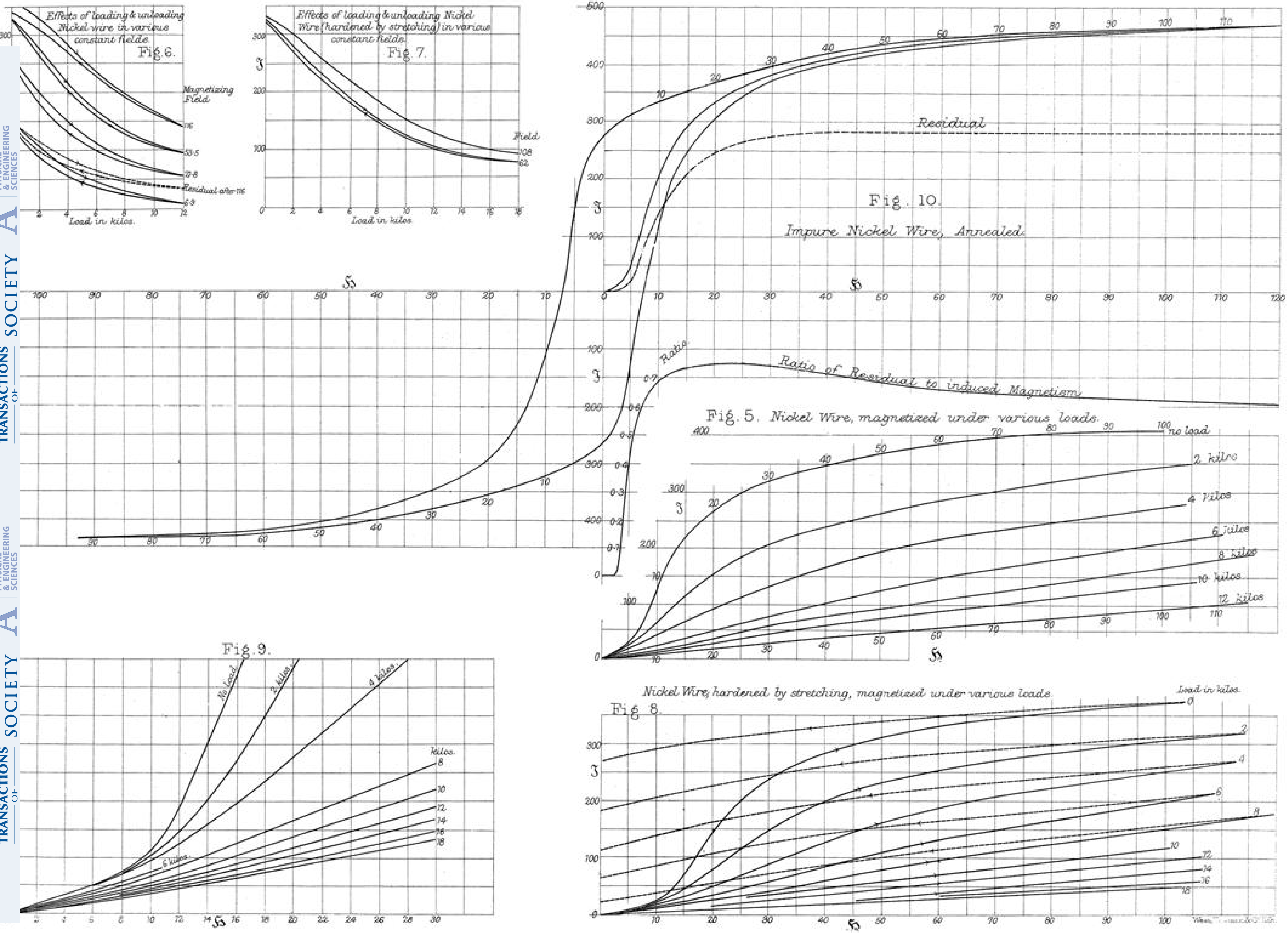
Effects of loading & unloading Nickel wire in various constant fields.
Fig. 6.
Magnetizing Field
116
53.5
27.8
Residual after 116
6.8
Load in kilos.
Effects of loading & unloading Nickel Wire (hardened by stretching) in various constant fields.
Fig. 7.
Field
108
62
Load in kilos
Residual
Fig. 10.
Impure Nickel Wire, Annealed.
Ratio
Ratio of Residual to induced Magnetism
Fig. 5. Nickel Wire, magnetized under various loads.
no load
2 kilos
4 kilos
6 kilos
8 kilos
10 kilos
12 kilos
Fig. 9.
No Load
2 kilos
4 kilos
6 kilos
kilos
8
10
12
14
16
18
Nickel Wire, hardened by stretching, magnetized under various loads.
Fig. 8.
Load in kilos.