THESIS

(a) The Influence of Temperature on the Magnetic Properties of a Graded Series of Carbon Steels, and the Presence of a Transformation Point in the neighbourhood of 200° C.

(b) The Effect of Thermal Treatment and the Effect of Longitudinal Strain in inducing a Sensitive State in certain Magnetic Materials.

(c) The Magnetic Properties of a Graded Series of Chrome Steels at Ordinary and Low Temperatures.

(d) The Permanent Magnetism of Chrome Steels.

The following thesis is an account of researches which have been carried out during the past four years in the Physical Institute of Glasgow University. These researches all deal with the general subject of the magnetisation of iron and various steels, but the following special branches of the subject have been particularly investigated:-

(a) The influence of temperature on the magnetic properties of a graded series of carbon steels.

(b) The effect of thermal treatment and the effect of longitudinal strain in inducing a sensitive state in certain magnetic materials.

(c) The magnetic properties of a graded series of chrome steels at ordinary and low temperatures, and

(d) The permanent magnetism of chrome steels.

Under these four headings therefore, I shall describe the work.

(a) On the Influence of Temperature upon the Magnetic Properties of a Graded Series of Carbon Steels, and the Presence of a Transformation Point in the Neighbourhood of 200° C.

The magnetic properties of iron, steel, nickel and cobalt, at moderate and high temperatures have been investigated by numerous experimenters, perhaps the most notable work being that carried out by J. Hopkinson[*], ~~M.~~ P. Curie[†], and D.K. Morris[‡]. Hopkinson employed the ring method of Rowland, insulating the windings from each other by means of asbestos, and deducing the temperature from the electric resistance of a platinum wire wound upon the specimen. He obtained magnetisation curves, at temperatures lying between ordinary room temperature and the critical temperature of the material, for soft iron, mild steel, hard steel, nickel and cobalt. In the case of soft iron he found that, for low valves of the magnetising force, the effect of increasing the temperature was to bring about an increase in the permeability, and as the temperature approached the critical temperature of the material this increase became very large. For a value of the magnetising force of 0.3 c.g.s. units the permeability was about 400 at room temperature; as the temperature was raised the permeability steadily increased, and at 600°C had attained a value of 900. From this point on, the increase in permeability with temperature became more rapid; at 700°C. the

[*] Phil.Trans.Roy.Soc.,1889,A,p.443. [†] Journ.de Phys.Vol.V. p.289, 1895.

[‡] Phil.Mag.Vol.XLIV.p.213,1897.

permeability was about 1900, at 750°C, it had the value 4000, and at 775° it reached the maximum value of 11,000. Further heating brought about a very rapid loss of magnetic quality, and at the temperature of 790°C the iron had become practically non-magnetic. At this temperature its permeability was about unity.

For large fields the permeability remained practically constant until a temperature of 600°C was reached; there was then a steady falling off in magnetic quality as the temperature rose to 790°C., when the iron became practically non-magnetic.

Specimens of mild and hard steel exhibited much the same general behaviour, increase of temperature increasing the permeability for low fields and diminishing it for high fields.

In 1895 an important paper on the magnetic properties of iron, nickel and cobalt at different temperatures was published by M. Curie* who employed fields up to 1350 c.g.s. units and temperatures extending from room temperature to 1400°C. He found the critical temperature of iron to be 760°C which is somewhat lower than Hopkinson's value, and he showed also that as the temperature is further increased the permeability remains practically zero up to 1300°C. when there is an abrupt increase in magnetic quality, indicating the existence of a further transformation point.

* Journ. de Phys. Vol.V. p.289, 1895.

In Hopkinson's work, and in that of many of his successors the procedure adopted was as follows:- The ring specimen was first heated up above the critical temperature, and allowed to cool to the temperature at which it was desired to carry out a test; the cooling was then arrested, and the test carried out by the method of reversals. The specimen was next submitted to the action of an alternating magnetic field of gradually diminishing strength, and thus, the initial value of this field being great and the final value zero, the specimen was left devoid of residual magnetism and magnetic history. The specimen was now allowed to cool by a suitable amount, when the cooling was again arrested and a further test carried out; and so on. In this way a series of magnetisation curves corresponding to various temperatures was obtained, and from these permeability - temperature curves corresponding to different field strengths were deduced.

It is to be carefully noticed in connection with what follows that in the [illegible] of Hopkinson the specimen was submitted to the action of the alternating magnetic field (in what follows I shall refer to this process, by means of which the specimen is rendered neutral, as a "process of reversals") <u>after</u> and <u>not</u> <u>before</u> each test <u>with its preliminary thermal change</u>. Thus a change in temperature intervened between each test and the previous application of the process of reversals.

Now it is not generally known that purely thermal treatment, no matter what temperature is reached in the process, develops in the specimen a peculiar state which renders additional precautions mecessary. The bearing of this fact upon magnetic testing has been investigated by Dr. J.G. Gray* and Mr. A.D. Ross who have shown that, in order that a magnetisation curve yielded by a specimen at a particular temperature (following upon a temperature change) should be characteristic of the material at the new temperature , it is necessary that the specimen should, before being tested, be submitted to a process of reversals <u>at the new temperature</u>.

The importance of attending to this point will be evident from the following results, which were obtained on testing a specimen of hard steel by the magnetometer method. The specimen was first tested at room temperature after having been rendered neutral, when the following readings were obtained:-

Magnetising current in amperes	0.2	0.4	0.6	0.8	1.0	1.5
Magnetometer deflection	32	73	117	167	221	365

The specimen was now submitted to a process of reversals at 15°C.; the temperature was then raised to 105°C., and a further test carried out with the following results:-

Magnetising current in amperes	0.2	0.4	0.6	0.8	1.0	1.5
Magnetometer deflection	40	88	139	195	253	410

Finally the specimen was submitted to a process of reversals at 105°C., and retested at that temperature, and the results

* "On Magnetic Testing," Phil. Mag., Jan.1911.

now obtained were as follows:-

Magnetising current in amperes	0.2	0.4	0.6	0.8	1.0	1.5
Magnetometer deflection	36	79	127	183	240	397

It will be seen that a magnetisation curve yielded by the specimen at 105°C. following upon the application of the process of reversals at 105°C. lies everywhere below the curve yielded by the specimen at 105°C. following upon the application of the process of reversals at 15°C. The former curve is the true magnetisation curve of the material corresponding to 105°C. If the latter curve is taken, the errors introduced into the results are very considerable.

If the temperature of a test-specimen is changed and a test carried out without first applying the process of reversals at the new temperature, the magnetisation curve obtained depends not only on the new temperature, but also on the thermal change effected. The magnetisation curve yielded by a test following upon a process of reversals carried out at the new temperature depends only on the temperature of the specimen.

In 1897 D.K. Morris* repeated Hopkinson's work for Swedish soft iron. His experiments differed from those of Hopkinson mainly in the fact that previous to the carrying-out of a test at a particular temperature, the specimen was submitted to a process of reversals at that temperature. The magnetisation curves employed by Morris in constructing his permeability-temperature curves are therefore the true magnetisation curves for the

* Phil. Mag. Vol. XLIV. p.213, 1897.

material at the various temperatures, but he does not point out in his paper that it is <u>essential</u> that the process of reversals should be carried out at the particular temperature at which it is desired to test the specimen. Morris's work agreed with that of Hopkinson in showing that, for small or moderate magnetising forces, heating the specimen resulted in a general improvement of the magnetic quality. His experiments also showed however that for small field strengths the permeability-temperature curve passed through several maximum and minimum points before the critical temperature was reached, and he verified the existence, first pointed out by M. Curie, of a transformation point at a temperature considerably above the critical temperature. The fact that turning points occur in the permeability-temperature curves indicates that as the temperature is increased the crystalline structure undergoes modifications; and Morris' work showed that for iron, in addition to the main critical point, there are at least three further such points lying between room temperature and the critical temperature.

In view of the above facts then, it seemed of importance to repeat Hopkinson's work on steels (1) in order to obtain the true magnetisation curves for the material at the various temperatures, and (2) to find whether there is any indication in steels of the presence of such transformation points as Morris found in iron.

Accordingly a series of specimens containing varying amounts of carbon was obtained from Messrs Armstrong, Whitworth & Co.Ltd., together with specimens of very pure soft iron for comparison.

These steels form a suitably graded series extending from mild steel, through medium carbon steel, to high carbon steel and cast-iron. The following table gives their compositions:-

Table I.

Composition of Steels tested

Description of Material	Percentage Composition,				
	C.	Mn.	Si.	P.	S.
Cast Iron	3.15	0.15	0.13	-	-
High Carbon Steel	1.64	0.13	0.85	0.02	0.02
Medium Carbon Steel	0.80	0.20	0.075	0.012	0.02
Low Carbon Steel	0.30	0.60	Trace	0.025	0.03
Soft Iron	0.06	0.10	-	-	-

The Specimens were supplied in the form of cylinders 20 cms. in length and 0.9 cms. in diameter. Previous to being tested each specimen was carefully annealed from 900°C. in a Fletcher gas furnace, precautions being taken to prevent oxidation. For the magnetic tests a Gray-Ross magnetometer* provided with the newest type of electric furnace† was employed. The furnace was contained within the magnetising coil of the magnetometer, and by its means the specimen could be brought to any desired temperature while under the influence of the magnetising helix. The furnace was air-tight, and consequently there was no possibility of the carbon being burnt out of the specimen.

* Proc.Roy.Soc.Edin. Vol. XXIX. p. 182, 1909.

† Proc.Roy.Phil.Soc.Glasg., Vol. XII, 1910.

The measurement of the temperature of the test-piece in the furnace was at first carried out by means of a platinum platinum-iridium pyrometer, which was placed in the furnace along with the specimen, and was connected up in series with a galvanometer and resistance box. This pyrometer was standardised by comparison with a standard Cambridge pyrometer marked to read temperatures in degrees Centigrade, but a later comparison was found to give rather different results - the same galvanometer deflection corresponding to temperatures differing in some cases by nearly 20°C. The galvanometer method was therefore abandoned, and the standard Cambridge pyrometer itself was used to determine the temperatures. To limit as far as possible any error in reading the temperatures, the readings of this pyrometer were checked by inserting it successively in steam, in melting lead, and in melting aluminium, and comparing its readings with these known fixed temperature points. The pyrometer readings were found to be a little lower than the true values, and corrections were accordingly made.

After the specimen had been annealed as described above, the procedure was as follows. The magnetometer having been adjusted, the test-bar was placed, along with the pyrometer, in position within the electric furnace in the solenoid. By means of the furnace the specimen was brought to the desired temperature, and was then submitted to the process of reversals and tested, the temperature being maintained constant throughout the operations. The temperature was then changed to a new value and the procedure repeated. In this way a series of magnetisation curves was obtained, characteristic of the specimen at various temperatures intermediate between room temperature and the critical temperature of the material under examination. From these curves susceptibility-temperature curves were then constructed corresponding to various definite values of the magnetising force. In deducing the effective field strengths from the applied field strengths the demagnetising factors investigated by Du Bois were employed.

Discussion of results obtained.

Cast Iron - Table 2 below gives the results obtained on testing a specimen of cast iron at various temperatures between room temperature and the critical temperature, and the corresponding curves are shown in fig.i.

Table 2. Fig.i.

Cast Iron. Data for I-H Curves.

Temp. of test.	15°C.	154°C.	332°C.	460°C	616°C	683°C	729°C	766°C.
H.	I.	I.	I.	I.	I.	I.	I.	I.
2.5	13.2	18.4	15.2	19.2	38	52	52	6.4
5	32.6	48.2	38.2	50.2	84.5	99.5	76.4	13.4
7.5	60	100	69	89	120.2	121.6	87.8	19
10	94	162.2	101.4	121.8	142.6	134.6	95.8	24.8
12.5	135	228.2	130	145	157.6	145.6	102.8	30.5
15	180.5	307	152.2	162.8	168.4	154.6	108.4	35.2

As the temperature increases up to about 150°C there is a very marked improvement in magnetic quality for all fields within the range examined, but by the time the temperature has reached 330°C a remarkable falling off in quality has taken place. With further increase of temperature however an improvement again takes place, and continues for very low fields until a temperature of 730°C is reached - a maximum for higher fields being reached at correspondingly lower temperatures. Any increase in temperature above that point results in a rapid falling off in quality for all fields, and by the time a temperature of 790°C is reached the intensity of magnetisation is practically zero.

From the curves of fig.i only a rough approximation to the susceptibility temperature curves could be obtained owing to the intervals allowed to elapse between the temperatures at which tests were made, and accordingly, to determine the form of the latter curves in the neighbourhood of the drop, a further series of tests ~~were~~ was made at intervals of about 50°C., until a temperature of ~~8~~3 50°C. was reached, by which time the behaviour of the specimen was again normal. From the curves obtained from this series of tests and the curves of fig.i., the susceptibility ($K = \frac{I}{H}$) at various temperatures was calculated for different values of H. The results obtained are shown in Table 3 and also graphically in fig.ii.

Table 3. Fig.ii./

Table 3. Fig.ii.

Cast Iron. Date for K -t Curves						
Field	2	5	8	10	12	14
Temp.	K	K	K	K	K	K
15°C	5.2	6.5	8.4	9.4	10.5	11.6
154°C	7.1	9.6	14.1	16.2	17.8	19.8
206°C	6.7	9.1	16.5	17.2	17.2	16.9
257°C	5.4	6.9	8.6	10.3	11.5	11.7
283°C	5.6	7.0	8.7	9.6	10.0	10.3
640°C	15.5	18.1	16.1	14.3	12.8	11
730°C	21.6	15.3	11.2	9.6	8.5	7.6
766°C	2.6	2.5	2.4	2.4	2.3	2.2

As the temperature increases from 15°C to 180°C., the susceptibility of the material for field strengths extending from 2 to 14 c.g.s. units steadily increases. At the latter temperature the slope of the curve diminishes rapidly; a maximum value is reached in the neighbourhood of 190°C., and the effect of further heating is to bring about an abrupt diminution in magnetic quality. The susceptibility arrives at a minimum value between 240°C and 270°C, the exact temperature differing with different field strengths, and after that point the curve again slopes steadily upwards until the temperature reaches 600°C., when a gradual decay of susceptibility for higher fields sets in. For lower fields however the susceptibility continues to increase, till the temperature is over 700°C. when a sudden fall takes place, and when the temperature reaches 790°C.,the susceptibility is practically zero for all fields.

It will thus be seen that for cast iron there is a transformation point in the neighbourhood of 200°C.

Further an inspection of fig.ii shows that,while the maximum on the susceptibility curve in the neighbourhood of the critical temperature is more marked for low fields than for high ones (as is usually the case), the maximum in the neighbourhood of 200°C is more marked for high fields than for low ones.

<u>High Carbon Steel</u>. - The results yielded by the specimen of high carbon steel are shown in Table 4 and Fig.iii. The behaviour under test of this specimen appeared at first sight to present some marked contrasts to that of cast iron. The I-H curves (Fig.iii) obtained at temperature intervals of about 150°C are almost normal in appearance,

Table 4. Fig.iii.

High Carbon Steel. Data for I-H curves.

Temp.of test.	15°C.	195°C	360°C	514°C	601°C	663°C	712°C	745°C
H	I	I	I	I	I	I	I	I
5	73.8	113	137.8	200	226	251	272	40.4
10	199	361	385	448	466.4	456.8	420	71.2
15	336.8	538.2	532.6	549.8	532.8	514	451	99.6
20	456.8	616.6	591.6	595	569.8	537.2	469	126.5
25	528.2	658.2	632	627	599	556	486	152
30	568	686.2	657.2	647.2	617.4	572.6	496.8	173.8

that is to say, while the saturation value of the intensity at first increases (for fields not greater than 40 c.g.s. units) as the temperature rises to about 200°C., succeeding rises in temperature result in lower saturation values, while at the same time the magnetic quality for low fields is improved. The only irregularity is in the curve for 360° which, while both starting and ending, as it normally would, between that for 195°C. and that for 514°C., lies, at the crossing of these curves, below them both instead of, as might be expected, above them. In the neighbourhood of the crossing then, i.e., for fields of 15 to 20 c.g.s. units, there is a drop in susceptibility about a temperature of 360°. An examination of the figures in Table 4 shows this irregularity very clearly, the intensity of magnetisation for fields 15 and 20 c.g.s. units being less at a temperature of 360°C than at either 195°C or 514°C. The presence of this slight irregularity, together with the behaviour of the cast iron specimen, and of some other specimens subsequently examined, suggested the advisability of a repetition of the tests for low temperatures at smaller intervals, and it was found that, as in the case of cast iron, a falling-off in magnetic quality, and therefore a drop in susceptibility, occurs between 200°C. and 300°C.

As the values of the susceptibility given in Table 5 and the

Table 5. Fig.IV./

Table 5. Fig.IV.

High Carbon Steel. Data for K-t curves

Field	1	5	10	15	20	30
Temp.	K	K	K	K	K	K
15°C	6	14.7	19.9	22.5	22.8	18.9
212°C	12.6	23.3	37.7	36.3	31.3	23.1
240°C	12.5	23.7	38.2	34.8	29.3	21.4
272°C	11	22.3	34.7	34.4	28.8	21.6
600°C	26.9	45	46.6	35.6	28.6	20.7
712°C	62	54.4	42	30.1	23.5	16.6
745°C	10	8.1	7.1	6.6	6.2	5.8

corresponding curves (Fig.IV) show, the maximum occurs for all fields in the neighbourhood of 210°-230°C., and the minimum between 250°C. and 270°C., the drop being covered by a smaller range of temperature than in the previous case, and also being much less marked. Beyond 300°C. the curves are perfectly normal, and illustrate well the great improvement in magnetic quality which takes place for low fields before the final drop. For a value of the magnetising force of 5 c.g.s. units for instance, the magnetic quality at first steadily increases with the temperature to a maximum of about 23 c.g.s. units in the neighbourhood of 230°C.; from 230°C. to 270°C it diminishes and, from this point on, it steadily increases reaching a second maximum of 55 c.g.s. units at about 730°C.; further increase of temperature brings about a rapid diminution in susceptibility, and the material becomes non-magnetic at about 770°C. For H = 30 c.g.s. units again, the curve slopes upward until the temperature becomes 220°C. after which there is an abrupt falling-off in magnetic quality succeeded by an abrupt increase, and a second maximum is arrived at when the temperature reaches 300°C. From 300°C. to 500°C the susceptibility remains practically constant; from 500°C to 700°C there is a gradual falling-off in magnetic quality, and finally the susceptibility becomes zero at 770°C.

It will be seen that the susceptibility-temperature curves for this high carbon steel present precisely the same general features as those which characterise the specimen of cast iron.

Medium Carbon Steel. Medium carbon steel, with which also two sets of tests were made, shows similar properties. Some of the results for this specimen are shown in Table 6 and the corresponding curves in Fig.V. As the temperature rises to 150°C an improvement in magnetic quality takes place; and this is followed by a falling off, and then a further improvement as the rise in temperature is continued. The improvement in quality for low fields continues till a temperature of 700°C is

Table 6. Fig. V. /

Table 6. Fig. V.

Medium Carbon Steel. Data for I-H curves.								
Temp.of test	14°C	152°C.	300°C	485°C.	597°C.	682°C.	708°C.	741°C.
H	I	I	I	I	I	I	I	I
2.5	20	27	23	31.3	49	61	44.5	12.5
5	51.5	71.5	65	83	122.5	162	74.5	23.5
7.5	101	141	126	166	211	242.5	105.5	32.5
10	171	220.5	190	238	283.5	293	134	41
12.5	257	306	259	301	335.5	324.5	161	49.5
15	348	380	322	346	361	342	186	59

reached, while for higher fields the maximum is attained earlier. As the temperature is further increased the fall becomes very rapid, and the specimen becomes practically non-magnetic at a temperature of about 760°C.

The values of the susceptibility obtained from the curves of Fig.V and others are shown in Table 7, and the susceptibility-temperature curves for the particular fields chosen are given in Fig.VI. These curves show, for all the fields considered, a drop in susceptibility of about the same magnitude as that shown for high carbon steel. The maximum in this case occurs about 180°C. and the mimimum about 220°C., the bend in the curve thus occurring at a lower temperature than in the cases of the specimens of cast iron and high carbon steel. For H = 2 c.g.s. units the susceptibility first increases till a value of 10.8 c.g.s. units is reached, then decreases to

7.9 c.g.s. units and after that increases again to a second

Table 7. Fig.VI.

Medium Carbon Steel. Data for K-t curves.				
Field	2	6	10	14
Temp.	K	K	K	K
15°C	7.4	11.6	17.1	22.5
172°C	10.8	16.5	22.4	25.7
212°C	8.8	14.2	17.6	20.5
300°C	8.7	14.8	19	21.2
680°C	23.1	33.4	29.3	24
704°C	34.6	17.2	15.2	13.6
740°C	5	4.6	4.4	4.2

maximum of about 35 c.g.s. units. When H =14 c.g.s. units, the susceptibility attains a maximum value of 25.7 c.g.s. units, after which it falls off to 20.2 c.g.s. units, and then increases again, this time however only to rise to 25.6 c.g.s. units. Thus we see again that while the maximum in the neighbourhood of the critical temperature is better defined for low fields than for high ones, exactly the reverse is the case for the maximum earlier in the temperature range.

Low Carbon Steel. A similar examination of a specimen of low carbon steel gave results, some of which are shown in Table 8. The values of the susceptibility for various fields and temperatures, derived from these and other readings, are given in Table 9.

Table 8.

Low Carbon Steel. Data for I-H curves.								
Temp.of test.	15°C.	167°C.	327°C.	471°C.	602°C.	702°C.	738°C.	780°C.
H	I	I	I	I	I	I	I	I
2	57	71	77.6	86.2	100	132	137	8.4
4	161.2	180.5	193	208.5	228.5	260	185.8	15.8
7	326	368	380	392	408.6	446	238.4	26

Table 9. Fig. VII.

Low Carbon Steel. Data for K-t curves.			
Field	2	4	7
Temp.	K	K	K
15°C	28.5	40.4	46.6
100°C	35.3	45.2	52.5
140°C	34.4	44.4	52.4
602°C	49.4	57.1	58.3
702°C	65.8	64.7	63.7
738°C	68.6	46.6	34.5
773°C	7.5	7.0	6.6

An examination of these tables, and also of the susceptibility-temperature curves in Fig.VII, shows that, while a drop in susceptibility again appears, it is much less marked than before, and also occurs at a lower temperature, and within a smaller range, - the maximum in this case occurring at a temperature of about 110°C. and the minimum in the neighbourhood of 140°C. For temperatures higher than this the behaviour of the specimen is normal, the improvement in magnetic quality continuing for moderate fields until a temperature of 740°C is reached, when there is a decided drop in intensity for fields above 2 c.g.s. units, though a continued improvement for lower fields. At a temperature of 770°C the fall is marked for all fields, and at 780°C the critical temperature is practically reached.

<u>Soft Iron.</u> - The next specimen examined, a bar of soft iron, appears, as the figures in Table 10, and the other tests carried out show, to be normal in its behaviour, each I-H curve as the temperature

Table 10.

Soft Iron. Data for I-H curves.							
Temp.of test.	18°C.	170°C.	349°C.	505°C.	639°C.	690°C.	761°C.
H	I	I	I	I	I	I	I
4	175	205	219	225	242	277	266
8	416	456	467	473	494	526	323
12	661	697	705	710	702	694	341
16	815	829	814	797	779	763	358
20	891	880	858	840	830	809	373

is raised starting above and ending below the previous one, the maximum intensity being reached for low fields at a temperature of about 740°C and for higher fields at lower temperatures. At 760°C the magnetic quality has fallen off considerably for all fields and at 785°C the specimen is practically non-magnetic. The values of the susceptibility given in Table 11 show no indication of a set-back

Table 11. Fig.VIII.

Soft Iron. Data for K-t curves.						
Field	4	7	10	12	15	20
Temp.	K	K	K	K	K	K
18°C.	43.8	50	54.4	55.1	52.2	44.6
170°C.	51.5	55.1	58.6	58.1	53.6	44
349°C.	55	57.4	59.7	58.8	52.9	42.8
505°C.	56.3	58.3	60.8	59.2	52.0	42
639°C.	60.3	61.4	62	58.5	50.8	41.5
690°C.	69.3	66.1	63.9	57.8	49.8	40.4
761°C.	66.3	45.1	33.4	28.3	23.6	18.7
785°C.	2.4	2.4	2.4	2.4	2.4	2.4

in the susceptibility before the final drop near the critical temperature, and readings taken at much closer intervals only serve to show that the behaviour of this specimen differs in this respect from the rest of the series examined. The susceptibility-temperature curves are shown in Fig. VIII, and it is to be noted at this point that no attempt has been made to obtain results for very low fields, below say 1 or 2 c.g.s. units. What is the case for the fields examined is therefore not necessarily true for very low fields, and the contradiction between the results for soft iron given above and those previously mentioned as obtained by Morris is only an apparent one, the permeability-temperature curves found by him to have several turning points between room temperature and the critical temperature being the curves belonging to values of the magnetising force less than 2 c.g.s. units.

In the following table, Table 12, the most important of the preceding results are collected together for the sake of comparison. In the table, T_1 is the temperature at which the first maximum appears in the susceptibility-temperature curve, and T_2 is the temperature at which the first minimum appears.

Table 12.

Variety of Steel.	Percentage of Carbon.	T_1	T_2
Cast Iron	3.15	180°C-200°C.	240°C-270°C.
High Carbon	1.64	210°C-230°C.	250°C-270°C.
Medium Carbon	0.8	180°C	220°C.
Low Carbon	0.3	110°C	140°C.
Soft Iron	0.06	-	-

Comparing first the temperatures of minimum susceptibility, we see that, while that for cast iron and that for high carbon steel are almost the same, that for medium carbon steel is lower than either, and that for low carbon steel is lower still. Also, the range of temperature within which the bend takes place, which varies from about 65°C in the case of cast iron to 30°C in the case of low carbon steel, tends to become smaller as the percentage of carbon diminishes. Again, comparing the magnitude of the drop in the various cases in the neighbourhood of 200°C., we see from the figures showing the susceptibility-temperature curves that that for high carbon steel is much less marked than that for cast iron. The drop for medium carbon steel is practically the same as that for high carbon steel, but that for low carbon steel is less marked still. For soft iron there is no bend in the curve at all for fields above 2 c.g.s.units.

In general then, it would appear that, as the percentage of carbon in a carbon-steel diminishes, the drop in susceptibility in the neighbourhood of 200°C becomes less marked, occurs within a smaller range, and is over at a lower temperature, and when the percentage of carbon is as low as 0.06% the drop is no longer perceptible. In order to determine whether this transformation point is a peculiarity of carbon steels or not, two other specimens were submitted to tests in exactly the same way as those already discussed, namely, an aluminium steel containing 2.3% of aluminium, and a tungsten steel containing 4% of tungsten.

Aluminium Steel. - In the behaviour of the specimen of aluminium steel, which was examined only for fairly low fields up to about 8 c.g.s. units, (see Table 13), there is the same peculiarity as that exhibited by those first described. An improvement in magnetic quality as the temperature is raised to 150°C is followed by a drop at a temperature

Table 13.

Aluminium Steel Data for I-H curves.								
Temp.of test.	17°C.	155°C.	331°C.	464°C.	586°C.	636°C.	683°C.	719°C.
H	I	I	I	I	I	I	I	I
2	66	66	60.5	77	104.5	113.5	59	11
4	157	160	151.5	180	218.5	239	101	22
7	297	319	312	346	409	433.5	158.5	38.5

of 330°C, after which an improvement again sets in, which continues for moderate fields until a temperature of about 670°C. is reached. As the temperature is raised above that point the intensity of magnetisation begins to fall off, and becomes zero at about 770°C. The susceptibility, as the results contained in Table 14 and the corresponding susceptibility-temperature curves in Fig.IX show, reaches a maximum value in the neighbourhood of 160°C, and falls to a minimum at about 270°C, the bend in the curve thus covering a fairly long range, though the total drop in susceptibility is small.

Table 14. Fig. IX.

Aluminium Steel. Data for K-t curves.			
Field	2	4	7
Temp.	K	K	K
15°C.	33	39.4	42.4
155°C.	33	39.4	45.6
275°C.	28.9	36.4	43.3
331°C.	30.3	38	44.4
636°C.	56.9	59.6	62
683°C.	29.8	25.3	22.6
720°C.	5.6	5.5	5.4

Tungsten Steel- The results obtained on testing the specimen of tungsten steel are shown in Tables 15 and 16 below, and in the susceptibility-temperature curves of Fig.X.

Table 15./

Table 15.

Tungsten Steel. Data for I-H curves.								
Temp.of test.	14°C.	165°C.	332°C.	471°C.	616°C.	672°C.	704°C.	737°C.
H.	I	I	I	I	I	I	I	I
2	9	14	22	33	50.5	70	70	9
5	47	69.5	100	127.5	184.5	219	130	23
8	118	171	216	254.5	320	344	166	37

Table 16. Fig.X.

Tungsten Steel. Data for K-t curves.			
Field	2	5	8
Temp.	K	K	K
15°C	4.6	9.4	14.7
165°C	6.9	13.8	21.4
332°C	11	19.9	27
672°C	35	43.8	43
704°C	34.8	26	20.8
737°C	4.5	4.5	4.5

These results show no indication of a set-back in magnetic quality early in the range, the susceptibility increasing to a maximum as the temperature is raised, and then falling off rapidly near the critical temperature. The intensity of magnetisation continues to improve for moderate fields till a temperature of nearly 700°C is reached when it begins to fall off. At a temperature of 740°C the

intensity is small, and the specimen becomes practically non-magnetic at a temperature of 785°C.
No further steels were examined in this connection as the results obtained from these two, the aluminium and the tungsten, were sufficient to show (1) that a transformation point below the critical temperature of the material is not a peculiarity of carbon steels, the presence of one being indicated in the aluminium steel also, and (2) that, as the behaviour of the tungsten steel shows, such a transformation point does not appear to be present in all steels.

In concluding my account of this part of my work I would remark that I have not detected any indication of the presence of a transformation point for steel in the neighbourhood of 200°C. in the curves obtained by previous workers in magnetism. It may appear at first sight rather remarkable that these bends in the curves apparently so definite have not been previously noted, but, when the fairly narrow limits within which the bend takes place are considered, it is perhaps not surprising that it should have been overlooked by workers whose attention was after all concentrated rather on the effects of the higher temperatures nearer the critical temperature. In the work of Hopkinson* already referred to, for instance, no tests were made between room temperature and 300°C, and in the case of hard steel the lowest temperature above room temperature at which a test was made was 511°C. When this work was begun by the present writer too, and curves were taken at temperature intervals of about 150°C, it was only in the case of two of the steels that there was

*Phil. Trans. Roy.Soc., 1889, A p.443.

any definite indication of the existence of a bend, and it was only when the work was repeated at temperature intervals of about 50°C. that it was found to be present in nearly every case.

It also appeared to be possible that another reason for the detection of the bends in this case might be found in the conditions under which the work was done,- namely, the careful removing, before each test was made, of the peculiar condition of sensitiveness to magnetisation, which has been already discussed, and which is brought about by change of temperature, and accordingly it was decided to make an extensive investigation into the amount of sensitive state induced by different thermal treatment, especially that produced by rises of temperature in the neighbourhood of the bend. If the sensitive state in the neighbourhood of the minimum point was found to be very much more marked than at other parts of the curve, it could be assumed that in previous work the presence of the sensitive state had been sufficient to mask the bend in the curve. Before going on to describe that work however, it may be as well to state here, what I shall show more fully later, that such was not the case - the presence of sensitive state tending to make the first maximum more pronounced rather than the minimum less so. The first suggested explanation must then be taken as the true one, and it seems to be sufficient to cover the facts.

(b) The Effect of Thermal Treatment and the Effect of Longitudinal strain in inducing a Sensitive State in certain Magnetic Materials.

In discussing the method of procedure employed in obtaining I-H curves at various temperatures for a series of carbon steels, I have mentioned the peculiar state of sensitiveness to magnetism which is brought about in a specimen when it is heated. So far, this peculiar condition has been regarded simply as a source of error, and the only concern with it has been to see to its complete removal. Circumstances already mentioned however, pointed to the desirability of a careful investigation of the phenomenon, and such an investigation I accordingly decided to undertake.

The presence of this effect was first detected and partially investigated by Ewing*, who found that a specimen of steel freshly annealed gave, on being submitted to a magnetic test, an I-H curve which, for low and moderate fields, lay entirely above the normal curve of the specimen, and further that a hysteresis curve taken with the specimen in the freshly annealed condition did not form a closed loop, and was moreover not symmetrical.
In Ewing's experiments, and in those of Searle and Bedford**, who have also investigated the effect to some extent, the specimens in the form of long wires were annealed by passage through a bunsen

* Phil. Trans. Roy.Soc., 1885, p.570.

** Phil. Trans. Roy.Soc., 1902, p.70.

flame, and thus only a rough estimate can be formed of the temperature to which the specimen was raised. This temperature has since been shown by Gray and Ross *, who have done a great deal of work in this connection, to be a very important factor in the case. These experimenters have also shown that even a small change of temperature is sufficient to induce this "sensitive state", as they have called it, and that the effect is produced by <u>change</u> of temperature only, not by prolonged exposure to any temperature, high or low. It has also been shown by Gray and Ross that, when once the sensitive state has been induced in a specimen, it cannot be completely got rid of, except by submitting it to a demagnetising process, though, as the full curve of Fig.XI., reproduced from one of their papers*, shows, even one reversal of the field may very considerably diminish it. This curve O A B C D E is the hysteresis curve obtained on testing a specimen of hard steel which has been annealed from 900°C, the field employed being gradually increased from 0 to 9 c.g.s. units, then gradually diminished from 9 c.g.s. units to - 9 c.g.s. units, and finally increased again to 9 c.g.s. units. The point E, it will be seen, is considerably below the point A, and the vertical distance of A above O is much greater than that of C below O. The dotted curve O A'B'C'D'E' is the curve obtained when the process was repeated after the specimen had been thoroughly demagnetised. It is important to notice that we have now a symmetrical closed curve, E' coinciding with A'. O A' and not O A is the true magnetisation curve of the specimen in the annealed condition.

* Proc. Roy.Soc. Edin., XXVIII. pp. 239 and 615 (1908.)

Though much has been done by previous experimenters then, there still remains a wide field for further investigation, and, at the suggestion of Dr. J.G. Gray, I began in January 1911 a detailed examination of a number of steels, with a view to finding how they compared with one another when subjected to similar thermal treatment, and how differing thermal treatment affected the same specimen.

After considerable progress had been made in this research, it was suggested by Dr. Gray, with a view to obtaining further information about the nature of the "sensitive state", that the effect of strain in inducing it should also be investigated.

That the "sensitive state" could be induced by application or removal of longitudinal stress had already been pointed out by Ewing*, but no attempt had been made to compare the magnitude of the sensitive state induced under different circumstances and in different materials.

This research was accordingly undertaken in conjunction with that previously begun, the general aim of the work being to ascertain to what extent the two treatments, the thermal treatment and the strain treatment, produced similar effects.

A description of the work therefore falls into two parts:-

I. An account of the effect of thermal treatment in inducing sensitive state in five different specimens, and a comparison of the results obtained for the different specimens.

* Trans. Roy. Soc. CLXXVI. p. 580 et seq.

II. An account of the effect of longitudinal strain in inducing sensitive state in five different specimens, and a comparison of these results among themselves, and with the results given in Part I.

I. Effect of Thermal Treatment in inducing Sensitive State.

The specimens used in this investigation were with one exception in the form of cylinders 20 cms. in length, and about 0.9 cm. in diameter, the exception being a piece of steel wire of

Table 17.

Description of Material	Percentage Composition.					
	C.	Mn.	Si.	P.	S.	Tungsten.
Medium Carbon Steel	0.80	0.20	0.075	0.012	0.02	-
Hard Steel	1.321	0.339	0.143	2.745	0.023	-
Steel Wire	0.755	0.660	0.066	0.027	0.017	-
Cast Iron	3.15	0.15	0.13	-	-	-
Tungsten Steel	0.51	0.13	0.19	-	-	4.01

the same length, but only 0.2 cm. in diameter.

Table 17 above gives the composition of the specimens. Previous to being tested, each specimen was carefully annealed from 900°C in a Fletcher gas furnace, care being taken to exclude air from contact with the specimen during the process. For the magnetic tests a Gray - Ross magnetometer* provided with an electric furnace† was employed, and in the case of each specimen the procedure was as follows. -

* Proc. Roy.Soc.Edin., vol.XXIX p.182,1909.

† Proc. Roy.Phil.Soc.Glasg. vol.XII, 1910.

The specimen was first carefully demagnetised by the process of reversals - that is to say, it was submitted to the action of an alternating magnetic field of gradually diminishing strength; the initial value of this field being great and the final value zero, the specimen was left devoid of magnetism and magnetic history.

The specimen was then, while in its position in the solenoid, raised by means of the electric furnace to a temperature of about 50°C., put through a magnetic test, demagnetised by reversals to remove the sensitive state, and tested again. The difference between the first and second readings is a measure for any field strength of the sensitive state induced by the previous thermal treatment. The specimen was then demagnetised once more, and the temperature raised another 50°C., and the process repeated, and this continued till a temperature of about 600°C. was reached. This enables the amount of sensitive state induced by a rise of about 50°C. at different parts of the temperature scale to be determined.

The same process was then repeated at intervals of 100°C. instead of 50°C., and tests were also made to determine the effect of a rise of temperature from room temperature to about 100°, 200°, 300°, 400°, 500°, and 600°C., the effect of fall of temperature from these temperatures to room temperature, and also the effect of rise and fall of temperature without intermediate demagnetisation.

The values of the sensitive state are expressed in the usual manner as the percentage by which the magnetic intensity for the specimen in the sensitive condition exceeds the normal value, and the figures for each specimen are taken for the particular field for which, for that specimen, the effect is about a maximum.

The effects produced by successive rises of 50°C. and 100°C. are shown graphically by ordinates erected at the temperature points at which readings are taken. This method was adopted as showing more clearly than a continuous curve could do exactly what measurements were obtained, and also because the successive rises were not in every case exactly the same, and therefore the process could hardly be described as a continuous one.

The other effects however - of rise of temperature, of fall of temperature, and of rise and fall of temperature - are all shown graphically in curve form with the temperatures as abscissae and the percentage sensitive state as ordinates.

Discussion of Results.

Medium Carbon Steel -- A complete set of readings for the determination of the sensitive state induced by various thermal processes, together with the values of the sensitive state deduced from them, is contained in Tables 18 to 22, and the various results are collected and shown in graphical form in Figs. XII, XIII and XIV. As the sensitive state is required to be expressed only in the form of a percentage, and values of the intensity are therefore not required, the readings are not reduced to absolute measure, the actual magnetometer deflection corresponding to various currents being given. Slight differences in readings in certain of the normal curves, which should be the same, are due to the fact that the specimen was frequently removed from the solenoid in order that the magnetometer zero might be tested, and was not always returned to precisely the same position. As however the specimen was never removed during the course of a double test, i.e., the taking of a sensitive and corresponding normal curve at any temperature, these differences do not affect the values of the percentage sensitive state, or the correctness of the general results.

Table 18 /

Table 18.

Medium Carbon Steel.										
Temp. of demag^n.	15°	52°	52°	110°	110°	158°	158°	204°	204°	258°
Temp. of test.	52°	52°	110°	110°	158°	158°	204°	204°	258°	258°
Intermediate thermal process	15°–52°	none	52°–110°	none	110°–158°	none	158°–204°	none	204°–258°	none
C	ℑ	ℑ	ℑ	ℑ	ℑ	ℑ	ℑ	ℑ	ℑ	ℑ
.2	61	56	61	54	67	47	47	38	Curves coincide.	
.4	134	126	143	128	157	121	117	88		
.6	222	211	242	224	256	206	194	155		
.8	321	308	347	327	364	308	280	235		
1.0	423	411	454	433	469	416	370	326		
1.2	530	517	562	542	579	525	468	425		
Percentage Sensitive State for field (H=8 C=.33)	9		14		38		30.5		0	

Temp. of demag.	258°	318°	318°	382°	382°	440°	440°	505°	505°	560°
Temp. of Test.	318°	318°	382°	382°	440°	440°	505°	505°	560°	560°
Intermediate thermal process	258°–318°	none	318°–382°	none	382°–440°	none	440°–505°	none	505°–560°	none
C	ℑ	ℑ	ℑ	ℑ	ℑ	ℑ	ℑ	ℑ	ℑ	ℑ
.2	Curves coincide.		Curves coincide.		27	22	64	59	63	60
.4					115	109	143	137	147	143
.6					214	209	238	230	244	242
.8					312	307	341	334	352	350
1.0					417	411	448	441	462	461
1.2					521	515	555	549	571	571
Percentage Sensitive State for field (H=8 C=.33)	0		0		7		4.5		3.5	

Table 19.

Medium Carbon Steel.												
Temp. of Demag.	15°	114°	114°	212°	212°	311°	311°	394°	394°	518°	518°	625°
Temp. of test.	114°	114°	212°	212°	311°	311°	394°	394°	518°	518°	625°	625°
Intermed. thermal process	15°-114	none	114°-212	none	212°-311	none	311-394°	none	394°-516	none	516°-625	none
C												
.2	63	50	44	34	46	45	Curves coincide		63	58	72	68
.4	151	126	115	82	101	99			146	134	167	160
.6	247	220	195	148	177	173			242	229	268	261
.8	350	322	286	230	266	262			345	336	381	374
1.0	461	429	377	320	367	362			453	446	499	494
1.2	570	539	472	416	469	464			560	552	608	603
Percent. Sensitive State(H=8 C=.33)	20		41		2.5		0		8.5		6.5	

Table 20

Medium Carbon Steel.												
Temp. of demag.	15°	110°	15°	211°	15°	311°	15°	418°	15°	505°	15°	612°
Temp. of test.	110°	110°	211°	211°	311°	311°	418°	418°	505°	505°	612°	612°
Intermed. thermal process	15°-110	none	15°-211	none	15°-311	none	15°-418	none	15°-505	none	15°-612	none
C												
.2	63	50	50	37	53	44	59	52	78	72	96	89
.4	152	126	126	90	134	104	147	123	173	156	199	182
.6	245	218	208	156	224	182	243	208	272	250	304	283
.8	352	321	297	239	322	276	247	310	380	354	418	397
1.0	459	429	391	330	421	375	455	416	489	462	530	513
1.2	566	539	490	430	523	479	560	524	601	576	647	626
Percentage Sensitive state(H=8 C=.33)	20		38.5		24		20		12		9.5	

Table 21.

Medium Carbon Steel.												
Temp. of demag.	114°	15°	211°	15°	311°	15°	418°	15°	505°	15°	612°	15°
Temp. of test.	15°	15°	15°	15°	15°	15°	15°	15°	15°	15°	15°	15°
Inter. thermal process.	114°-15°	none	211°-15°	none	311°-15°	none	418°-15°	none	505°-15°	none	612°-15°	none
C	∂	∂	∂	∂	∂	∂	∂	∂	∂	∂	∂	∂
.2	58	47	56	48	58	47	62	49	70	56	70	56
.4	141	118	147	119	144	118	145	122	161	133	158	132
.6	230	204	242	205	238	204	238	208	252	216	250	214
.8	329	302	344	305	338	300	341	304	351	313	351	313
1.0	430	403	448	408	442	402	443	406	451	414	452	414
1.2	537	512	553	512	549	508	549	510	557	516	558	519
Percentage Sensitive State (H=8 C=.33)	21		25		24		21.5		23		20	

Table 22.

Medium Carbon Steel.												
Temp. of demag.	15°	15°	15°	15°	15°	15°	15°	15°	15°	15°	15°	15°
Temp. of test	15°	15°	15°	15°	15°	15°	15°	15°	15°	15°	15°	15°
Inter. thermal process.	15°-108°-15°	none	15°-215°-15°	none	15°-310°-15°	none	15°-410°-15°	none	15°-502°-15°	none	15°-605°-15°	none
C	∂	∂	∂	∂	∂	∂	∂	∂	∂	∂	∂	∂
.2	49	43	60	49	57	47	66	48	61	53	59	49
.4	126	118	146	124	140	118	141	121	142	128	138	119
.6	214	204	239	211	230	205	230	207	233	215	229	202
.8	311	302	345	312	332	304	332	306	330	308	327	300
1.0	410	403	445	411	434	407	434	407	430	406	430	401
1.2	514	510	545	517	538	511	538	509	533	508	530	504
Percentage Sensitive State (H=8 C=.33)	8		18.5		20		20		11		18	

In the tables the changes of temperature from t_1 to t_2, from 15°C to t, from t to 15°C, and from 15°C to t and back to 15°C are indicated thus, - t_1-t_2, 15°C-t, t-15°C and 15°C-t-15°C.

The first figure of this series, Fig. XII, shows the effect of successive rises of temperature of about 50°C, (see Table 18) and illustrates very clearly how greatly the effect of a certain rise of temperature depends on its position in the temperature scale, for while a rise from 100°C to 150°C induces a sensitive state of nearly 40%, a rise from 200°C to 250°C has an entirely negligible effect. The most susceptible part of the temperature scale is from 0°C to 200°C, especially about 150°C; after that further rises of 50°C induce no sensitive state till a temperature of 400°C is reached, after which successive rises of 50°C induce a sensitive state of about 5%.

The next figure, Fig. XIII, showing the effect of successive rises of 100°C, gives exactly the same division of the scale into susceptible and non-susceptible parts - the greatest effect being produced in the interval 100°-200°C, which gives a sensitive state of over 40%. Fig. XIV shows curves (a), (b), and (c), - (a) showing sensitive state due to rise of temperature, (b) sensitive state due to fall of temperature and (c) sensitive state due to rise and fall of temperature.

(a) shows a marked maximum about the region of 200°C, and lies above both (b) and (c) until a temperature of 300°C is reached, when it crosses (b) and finally lies below (c) also: (b) remains pretty steadily between 20% and 25% for all temperatures, and (c), which is below (b) for all temperatures, rises rapidly at first, then slowly, till a temperature of 400°C is reached, when it falls somewhat, then rises once more.

<u>Hard Steel</u>. -- In describing the results obtained on testing this and other specimens, I shall not give a complete set of readings for the determination of the sensitive state, but shall simply show the values of the percentage sensitive state deduced from them, and the corresponding curves which show the results at a glance.

The results obtained on testing the specimen of hard steel appear in Tables 23 to 27 and in Figs. XV, XVI and XVII.

Table 23. Fig. XV.

Hard Steel.					
Percentage Sensitive State due to successive rises of temperature of about 50°C.					
Temp. change.	Sensitive State.	Temp. change.	Sensitive State.	Temp. change.	Sensitive State.
15°-55°C	4%	200°-254°C	4.5%	405°-448°C	7.9%
55°-107°C	8.8%	254°-304°C	2.7%	448°-503°C	3.3%
107°-156°C	23%	304°-364°C	2.5%	503°-553°C	0
156°-200°C	13%	364°-405°C	0	553°-603°C	0

Table 24. Fig. XVI.

Hard Steel.	
Percentage Sensitive State due to successive rises of temperature of about 100°C	
Temp. change	Sensitive State.
15°-105°C	10.7%
105°-220°C	10.8%
220°-322°C	2.4%
322°-412°C	2.4%
412°-504°C	1%
504 -601 C	0

Table 25. Fig. XVII (a)

Hard Steel.	
Percentage Sensitive State due to rise of temperature from 15°C	
Temp. change	Sensitive State.
15°-105°C	10.7%
15°-220°C	15%
15°-300°C	16.3%
15°-398°C	21%
15°-506°C	8.6%
15°-600°C	3.9%

Table 26. Fig. XVII (b).

Hard Steel.	
Percentage Sensitive State due to fall of temperature to 15°C.	
Temp. change.	Sensitive State.
220°-15°C	17.1%
300°-15°C	19.2%
398°-15°C	20%
506°-15°C	21.9%
600°-15°C	20.3%

Table 27. Fig. XVII (c).

Hard Steel.	
Percentage Sensitive State due to rise and fall of temperature	
Temp. change.	Sensitive State.
15°-100°-15°C	5.6%
15°-200°-15°C	17.1%
15°-300°-15°C	11.8%
15°-400°-15°C	13.2%
15°-500°-15°C	11.6%
15°-600°-15°C	20%

As the results shown in Table 23 and in Fig. XV show, the effect on hard steel of a rise of 50°C is, as in the case of the previous specimen, greater for the rise from 100°C to 150°C than at any other part of the scale, though the effect in this case is only about half as great; but in this specimen, on the other hand, a rise of 50°C. at any part of the temperature scale, except above 500°C. produces some effect. The effects of rises of 100°C (see Table 24 and Fig. XVI) are somewhat similar to, but less marked than, those due to rises of 50°C.

Tables 25, 26 and 27 give the results from which the (a), (b) and (c) curves shown in Fig. XVII are obtained. These curves for this specimen are somewhat similar in general form to those of the last, but the maximum in the (a) curve does not appear till about 400°C and is much less marked, the maximum value reached being only 21 per cent. in this case as compared with 38 per cent. in the other. Indeed the sensitive state induced in this specimen by all varieties of thermal treatment employed is much less marked than in the case of medium carbon steel. In this case, except just in the neighbourhood of 400°C where it reaches its maximum value, the (a) curve lies entirely below the (b) curve, which remains fairly steadily between 16 per cent. and 22 per cent. Except just about 200°C, the (c) curve lies below both (a) and (b) till a temperature of between 400°C and 500°C is reached, when it crosses (a), and, by the time the temperature has reached 600°C, it has risen to meet (b) also.

Steel Wire. -- The results obtained on testing this specimen appear in Tables 28 to 32 and in Figs. XVIII, XIX, and XX. The effect of increasing the temperature by 50°C. or 100°C. is still less marked in this case than before, but the greatest effects still show at 100°-150°C and 100°-200°C.

Table 28. Fig. XVIII.

Steel Wire.			
Percentage Sensitive State due to successive rises of temperature of about 50°C.			
Temp. change.	Sensitive State.	Temp. change.	Sensitive State.
15°-57°C	2.6%	320°-358°C	1.1%
57°C-106°C	3.9%	358°-425°C	0
106°-156°C	11.7%	425°-458°C	0
156°-222°C	6.1%	458°-507°C	0
222°-265°C	.0	507°-561°C	0
265°-320°C	.0	561°-620°C	0

Table 29. Fig.XIX.

Steel Wire.	
Percentage Sensitive State due to successive rises of temperature of about 100°C.	
Temp. change.	Sensitive State.
15°-112°C	4.2%
112°-234°C	8.3%
234°-320°C	0
320°-430°C	1.9%
430°-510°C	1.3%
510°-620°C	0

Table 30. Fig. XX (a)

Steel Wire.	
Percentage Sensitive State due to rise of temperature from 15°C.	
Temp. change.	Sensitive State.
15°C-106°C	4%
15°-207°C	10.3%
15°-338°C	8.3%
15°-400°C	4.1%
15°-502°C	4.3%
15°-609°C	1.2%

Table 31. Fig. XX. (b).

Steel Wire.	
Percentage Sensitive State due to fall of temperature to 15°C	
Temp. change.	Sensitive State.
106°-15°C	7.1%
207°-15°C	12.8%
338°-15°C	14.7%
400°-15°C	12.4%
502°-15°C	14.0%
609°-15°C	10.9%

Table 32. Fig. XX (c).

Steel Wire.	
Percentage Sensitive State due to rise and fall of temperature.	
Temp. change.	Sensitive state
15°-105°-15°C	0
15°-202°-15°C	5.4%
15°-307°-15°C	4.5%
15°-400°-15°C	3.4%
15°-502°-15°C	7.1%
15°-612°-15°C	8.0%

The (a), (b) and (c) curves which are shown in Fig. XX are again somewhat similar to those already examined, the (b) curve in particular having almost exactly the same form, and lying for almost the whole course of the range between 10 and 15 per cent. The maximum in the (a) curve is much less definite than in the previous cases - so little is it marked indeed that the (a) curve never rises above the (b) curve. The (c) curve lies below both (a) and (b) till a temperature of about 400°C is reached, when it crosses the (a) curve, but remains below the (b) curve throughout the range.

<u>CAST IRON</u>. -- The effect of increasing the temperature by 50°C or 100°C. (See Tables 33 and 34 and Figs. XXI and XXII) is in the case of cast iron greater than for steel wire, but not so great as for hard steel. This specimen, however, shows one point of difference from those previously examined, - the most effective part of the temperature scale in producing sensitive state being for it 150°-200°C, instead of, as in

all the other cases 100°-150°C. As might be expected 100°-200° C is still the most sensitive interval for rises of 100°C.

Table 33. Fig. XXI.

Cast Iron.			
Percentage Sensitive State due to successive rises of temperature of about 50°C.			
Temp. change.	Sensitive State.	Temp. change.	Sensitive State.
15°-56°C.	3.5%	312°-378°C.	2.5%
56°-107°C	6 %	378°-416°C	1.5%
107°-155°C	6.5%	416°-460°C	0
155°-208°C	17.5%	460°-510°C	3%
208°-258°C	2 %	510°-558°C	0
258°-312°C	4 %	558°-610°C	0

Table 34. Fig. XXII.

Cast Iron.	
Percentage Sensitive State due to successive rises of temperature of about 100°C.	
Temp. change.	Sensitive State.
15°-116°C	9.5%
116°-217°C	11.0%
217°-310°C	2.0%
310°-412°C	4.5%
412°-512°C	0
512°-604°C	0

Table 35. Fig. XXIII (a)

Cast Iron.	
Percentage Sensitive State due to rise of temperature from 15°C.	
Temp. change.	Sensitive State.
15°-116°C	8.5%
15°-206°C	13.5%
15°-300°C	9.5%
15°-400°C	6.0%
15°-500°C	3.5%
15°-603°C	2.5%

Table 36. Fig. XXIII (b).

Cast Iron.	
Percentage Sensitive State due to fall of temperature to 15°C.	
Temp. change.	Sensitive State.
116°-15°C	10%
206°-15°C	12%
300°-15°C	17.5%
400°-15°C	21%
500°-15°C	15.5%
603°-15°C	20 5%

Table 37. Fig. XXIII (c)

Cast Iron.	
Percentage Sensitive State due to rise and fall of temperature	
Temp. change.	Sensitive State
15°-116°-15°C	2%
15°-206°-15°C	5%
15°-300°-15°C	10.5%
15°-404°-15°C	9.5%
15°-500°-15°C	8.5%
15°-601°-15°C	13.5%

While the (a) curve for this specimen (Table 35, Fig. XXIII) strongly resembles in form the corresponding curve for medium carbon steel, rising to a maximum value (of only 13 per cent however,) in the neighbourhood of 200°C, and then falling off steadily, the (b) curve (Table 36, Fig. XXIII) differs considerably, as, instead of maintaining a fairly steady value, it rises from 10 per cent at 100°C to a maximum of over 20 per cent at 400°C, then falls off, and later rises once more. The (c) curve, the figures for which are given in Table 37, lies entirely below the (b) curve, and is similar to it in form.

<u>Tungsten Steel.</u> -- This specimen, with which we leave the carbon series, displays some very decided differences in behaviour from those previously examined. Tables 38 to 42 and Figs. XXIV, XXV, and XXVI, give the results obtained when it was tested for sensitive state. It is to be noticed, first of all, that this specimen shows

much less sensitive state than any of the others, and that the most susceptible part of the scale is now about 300°C - from 300°C to 350°C for rises of 50°C, and from 200°C to 300°C for rises of 100°C.

Table 38. Fig. XXIV.

Tungsten Steel. Percentage Sensitive State due to successive rises of temperature of about 50°C.			
Temp. change.	Sensitive State.	Temp. change.	Sensitive State
15°-56°C	0	304°-360°C.	1.5%
56°-112°C	0	360°-414°C	0.6%
112°-160°C	0	414°-464°C	0
160°-212°C	0	464°-522°C	0
212°-266°C	0	522°-568°C	0
266°-304°C	0.9%	568°-624°C	0

Table 39, Fig. XXV.

Tungsten Steel. Percentage Sensitive State due to successive rises of temperature of about 100°C.	
Temp. change.	Sensitive State.
15°-105°C	0
105°-216°C	1.2%
216°-321°C	1.7%
321°-404°C	1.1%
404°-505°C	0.8%
505°-615°C	0.8%

Table 40, Fig. XXVI (a)

Tungsten Steel. Percentage Sensitive State due to rise of temperature from 15°C.	
Temp. change.	Sensitive State
15°-105°C	0
15°-203°C	0.6%
15°-303°C	1.2%
15°-420°C	1.7%
15°-504°C	1.1%
15°-598°C	1.3%

Table 41. Fig. XXVI (b)

Tungsten Steel.	
Percentage Sensitive State due to fall of temperature to 15°C	
Temp. change.	Sensitive State.
106°–15°C	0
203°–15°C	1.6%
303°–15°C	2.3%
420°–15°C	7.0%
504°–15°C	7.5%
598°–15°C	8.2%

Table 42. Fig. XXVI (c).

Tungsten Steel.	
Percentage Sensitive State due to rise and fall of temperature.	
Temp. change.	Sensitive State.
15°–108°–15°C	0
15°–204°–15°C	0
15°–301°–15°C	0
15°–416°–15°C	3.0%
15°–504°–15°C	2.6%
15°–602°–15°C	3.3%

Also, for low temperatures the specimen is very insensitive, rises of 50°C having no effect in producing sensitive state below the 300° to 350°C rise while in rises of 100°C., 0° to 100°C. has no effect; the maximum sensitive state produced in any of these intervals is less than 2 per cent.

Of the (a), (b) and (c) curves, the (b) curve shows much the more important effect, rising from zero for a fall of temperature from 100°C to room temperature, to 8 per cent for a fall from 600°C to room temperature; while the (a) curve, beginning to rise at the same point, never rises above 2 per cent. The (c) curve, again, only begins to rise after a rise and fall of temperature of more than 300°C, and it only rises to between 3 and 4 per cent.

Coming now to compare the results given by these five specimens, we note first of all the very great difference between the four belonging to the carbon group and the tungsten specimen. Not only is the sensitive state induced in the latter much less marked, and the most sensitive part of the temperature scale much higher up, but rises of temperature at the beginning of the scale have no effect at all.

Between the different members of the carbon group very strong resemblances appear. The part of the temperature scale, which is most pronounced in producing sensitive state, is in each case very nearly the same, being only a very little later in the case of cast iron. It would appear, then, that the addition of a marked quantity of carbon tends to raise the temperature of maximum susceptibility, though the addition of smaller quantities has no appreciable effect. It may also be noted here, in connection with the work previously described on the presence of a transformation point in the neighbourhood of 200°C, that the maximum sensitive state in the specimens of medium carbon steel and cast iron occurs in each case about the temperature of the maximum on the susceptibility - temperature curves and not in the neighbourhood of the minimum, and therefore omitting to remove the sensitive state should not mask the presence of the bend, and therefore of the transformation point, but should rather make it more apparent.

Returning now to the comparison of the different members of the carbon group, we see that, considered generally, the specimen of the four showing the least sensitive state is the specimen of steel wire, while that showing most is the specimen of medium carbon steel. As the percentages of carbon in the two are very nearly the same, .755 per cent and .80 per cent, it is probable that the smaller sensitive state is connected with the greater percentage of manganese in the steel wire specimen. The specimen of hard steel shows the next greatest effect, and cast iron comes third in the list.

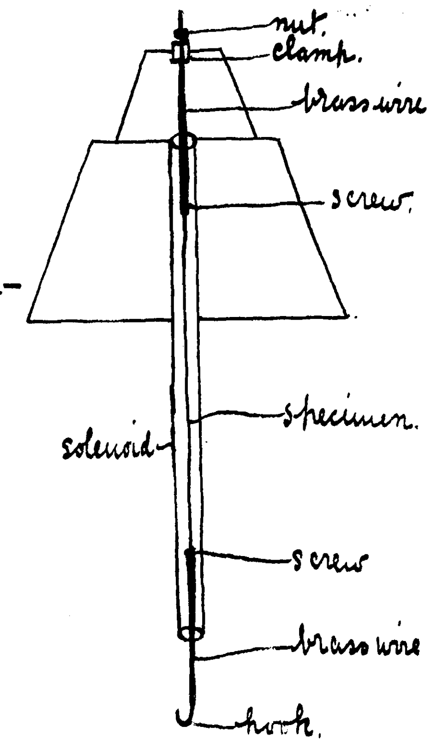
Taking maximum values of sensitive state reached in the temperature range chosen, we find, for fall of temperature, for steel wire 15 per cent., for medium carbon steel 25 per cent., for hard steel 24 per cent., and for cast iron 21 per cent.; while for rise of temperature, for the same four specimens, we have 10, 38, 22 and 13 per cent. These maximum effects appear of course at very different temperatures.

Again, looking at the (a), (b), and (c) curves generally, we find that as a rule the (b) curve lies above both the (a) and (c) curves, and for lower temperatures the (a) curve lies above the (c) curve, while for higher temperatures the reverse is the case. That is to say, if we consider any given temperature, we can generally induce a greater sensitive state by rendering the specimen neutral at that temperature, and then allowing it to cool, than by either heating it up to that temperature, and then testing, or by heating and then cooling before testing. Of these two methods, the former is likely to be the more efficacious if the temperature considered lies below 400°C., the latter if it lies above.

II. Effect of Longitudinal Strain in inducing Sensitive State.

A Gray - Ross magnetometer was employed in this investigation also, but, as it was desired to apply longitudinal stress to the specimen, while it was in such a position that it could be tested magnetically, a solenoid in a vertical instead of in a horizontal position was used, and the one-pole method was adopted. A long narrow solenoid, about 70 cms. in length, was attached vertically, by means of a framework, to the magnetometer board, so that one end was about 10 cms. above the level of the magnetometer needle. An oblong hole in the magnetometer board, and in the table below it, allowed the solenoid to pass through, and also allowed of its being moved nearer to or further from the needle as required. The solenoid carried, in addition to the ordinary coil used for magnetising the specimen, a second coil through which a small current could be passed to balance, within the solenoid, the effect of the earth's vertical field.

In order to fix the specimen in the solenoid in such a way that it might be readily removed and adjusted, and at the same time be firmly enough fixed not to alter its position when subjected to stress, the following methods were adopted. Each specimen, cut to a length of about 50 cms., was made at each end to screw into shorter lengths of thicker brass wire. Of these brass wires, one could be clamped firmly into position just above the upper end of the solenoid, the clamp being fixed vertically above the centre of the solenoid in a smaller frame attached to the top of the solenoid frame. To the other was attached a strong brass hook from which could be hung the weights applied, and the specimen, when in position in the solenoid hung from the upper brass wire with its ends about equally distant from the ends of the solenoid. A small brass nut screwed on to the end of the brass wire and resting on the clamp prevented any possibility of the wire slipping even when a large weight was attached to it. Also, the upper brass wire could be moved through a small distance up and down at the clamp, till that position was obtained which brought the pole of the specimen most nearly opposite to the magnetometer needle. This was done by passing a certain current through the solenoid, and then moving the specimen up and down till the maximum magnetometer deflection for that current was obtained.



In order to determine the current required to balance the earth's vertical field in the solenoid, the specimen was placed in position, and was as far as possible demagnetised by reversals. The earth's field however prevented its being completely demagnetised, and the magnetometer needle remained deflected to one side. The balancing coil was then connected up with a dry cell through a resistance box, and the specimen was again demagnetised. If the magnetometer needle now took up its zero position, the current produced a field in the solenoid which exactly balanced the earth's field, and the required condition was obtained. If however the needle was still deflected either to the same or the opposite side, the current was first reversed if necessary, and then increased or decreased until demagnetisation by reversals left the specimen devoid of magnetism.

To apply longitudinal stress to the specimen, a scale-pan was in the first instance hung on the hook attached to the lower brass wire and different weights were placed in it. It was however found that it was very difficult to place many weights in the scale-pan without jarring the specimen, and as it has been shown both by Ewing, and more fully by Gray and Ross, that vibration greatly diminishes the sensitive state some other method had to be tried. Accordingly a large can was obtained capable of holding about a cubic foot of water, and fitted with a guage, and also a tap near the bottom. This can was hung on the hook attached to the brass wire, and a gentle stream of water was allowed to flow into it, until the desired weight, which was read off on the guage was obtained. In this way any desired stress could be applied with an almost entire absence of vibration. To diminish the weight by any fixed amount, it was only necessary to turn on the tap near the bottom of the can, and allow the required amount of water to flow out.

The five specimens tested were all steel wires, 50 cms. in length, and about $\frac{1}{10}$ inch in diameter. This thickness of wire, which is moderately large, was chosen so that the effect of small stresses per unit of area might be the better examined. A weight of 1 kilogramme applied to such a wire gives a stress of 19.74 kilos per square cm. Of the five specimens used, four, supplied by Messrs W.N. Brunton & Son, form a graded carbon series having respectively 0.15 per cent, 0.55 per cent, 0.8 per cent, and 1.2 per cent carbon in their composition. The fifth is interesting as being a specimen of the same wire as was used in Part I., and the results obtained by the two methods are therefore for it directly comparable.

Each specimen was, before being tested, carefully annealed from 900°C in a Fletcher gas furnace, and then stretched several times by the application and removal of the maximum weight to be employed. Unless this was done, it was found that the specimen was not in a stable condition, and that repetition of the same processes did not produce the same results.

The specimen was then placed in position in the solenoid, carefully demagnetised, subjected to a certain strain, by the application of a weight <u>w</u>, say, tested, demagnetised, and tested again, and from the two curves obtained the percentage sensitive state due to an increase of stress from o to <u>w</u> was determined. The specimen was then demagnetised again, the strain was removed, and the sensitive state due to decrease of stress from <u>w</u> to o was obtained, and this was repeated for various values of <u>w</u> from o up to 20 kilogrammes. The effect of the cycle o - w - o was also determined, and also the effect of increasing or decreasing the stress by successive differences of 2.5 and 5 kilos.

In the course of the carrying out of the tests, the specimen was very frequently removed, in order that the zero might be tested, a proceeding which was found to be very necessary, as the small changes in the position of the zero which took place in the course of a test were sometimes found to be large enough to make the readings for sensitive state quite unreliable, and a large number of readings had frequently to be taken before agreement could be obtained.

Before going on to the discussion of the results obtained for the different specimens, it may be worth while pointing out how very close is the analogy between the effect of strain, and the effect of thermal treatment.

Fig. XXVII shows a hysteresis curve for specimen I (0.15 per cent.C.) taken after the specimen had been demagnetised with a load of 10 Kilos on, and the load had been removed, that is to say, when the specimen was ~~is~~ in the sensitive condition due to alteration of stress from 10 kilos to 0. As will be seen, the hysteresis curve is not closed, as it would have been had the specimen been demagnetised after the removal of the load instead of before it, and the value of the intensity of magnetisation corresponding to the maximum field employed is distinctly less after even one reversal of the field. Indeed, the first reversal removes about 50 per cent of the total improvement produced by the alteration of stress. If we compare with this curve that already shown in Fig.XI, a reproduction from a paper by Gray and Ross on the effect of thermal treatment in inducing sensitive state, we see the remarkable similarity of effect produced by the two methods of treatment.

Discussion of Results.

Specimen I. (0.15 per cent C.) - The most interesting results obtained for this specimen are shown in Tables 43,44 and 45, and the corresponding curves appear in Fig.XXVIII. The values of the percentage sensitive state only are shown, and not, as in Tables 18 to 22, a complete set of figures for the curves from which these values were obtained, though of course to each sensitive state value given belongs a pair of curves from which it was derived. The three curves shown are lettered as in the previous part of the paper, the (a) curve showing the effect of increasing the stress from zero to w, the (b) curve showing the effect of decreasing the stress from w to zero, and the (c) curve showing the effect in producing sensitive state of the cycle o - w - o.

As the stress is increased from 0 to 10 kilos. both (a) and (b) curves rise rapidly to a maximum. Further increase in the value of w is followed by a slight drop in the value of the sensitive state, but a second, though lower, maximum occurs about 15 kilos,

Table 43.Fig.XXVIII (a)

Specimen I.(0.15%C).	
Percentage Sensitive State due to application of stress.	
Stress change.	Sensitive State
0-2.057 Kilos.	1.7 %
0-5.307 "	4.9 %
0-7.5 "	6.3 %
0-10 "	7.5 %
0-12.5 "	5.7 %
0-15 "	6.8 %
0-17.5 "	4.4 %
0-20 "	5.7 %

Table 44.Fig.XXVIII (b).

Specimen I.(0.15%C.	
Percentage Sensitive State due to removal of stress.	
Stress change.	Sensitive state.
2.057-0 kilos.	3.6 %
5.307-0 "	10.3 %
7.5 -0 "	13.4 %
10 -0 "	15.1 %
12.5 -0 "	13.5 %
15 -0 "	13.3 %
17.5 -0 "	13.0 %
20 -0 "	14.5 %

Table 45. Fig. XXVIII (c).

Specimen I (0.15%C.)			
Percentage Sensitive State due to Application and removal of stress.			
Stress change.	Sensitive State.	Stress change.	Sensitive State.
0-2.057-0 kilos.	0	0-12.5-0 kilos.	3.4%
0-5.307-0 "	0	0-15-0 "	4.9%
0-7.5-0 "	4.2%	0-17.5-0 "	7.1%
0-10-0 "	4.2%	0-20-0 "	7.9%

and at the end of the range the curves are rising once more. The maxima and minima of the two curves occur at almost the same points, and the (b) curve lies entirely above the (a) curve, the percentage sensitive state due to decrease of stress being indeed about twice as great as that due to the corresponding increase. The (c) curve shows only one maximum and one minimum in the range, and lies below both (a) and (b), till a stress of 15 kilos is passed, where it crosses (a), but remains below (b) till the end of the range.

Specimen II (0.55 per cent.C. -- The principal results obtained on testing this specimen for sensitive state are shown in Tables 46, 47 and 48, and in the curves of Fig. XXIX. Strain treatment applied to this specimen gives on the whole much higher percentage values of sensitive state than in the case of the previous specimen, but the first maximum appears in the (b) curve only at 12.5 kilos, and in the (a) curve not till 15 kilos. Both curves show also a minimum value within the limits of the range, and are rising at the end of it; but this time too, the turning-point appears later in the (a) curve than in the (b) curve. In the case of this specimen too, like that first examined, the (b) curve lies entirely above the (a) curve, and both of these are above the (c) curve, which does not at any point of the range rise above a value of four per cent.

Table 46. Fig.XXIX (a).

Specimen II (0.55% C)	
Percentage Sensitive State due to application of stress.	
Stress change.	Sensitive State.
0-2.057 Kilos.	1.0%
0-5.307 "	1.3%
0-7.5 "	2.5%
0-10 "	6.4%
0-12.5 "	10.5%
0-15 "	13.7%
0-17.5 "	11.9%
0-20 "	14.0%

Table 47. Fig. XXIX (b).

Specimen II (0.55% C).	
Percentage Sensitive State due to removal of stress.	
Stress change.	Sensitive State
2.057-0 Kilos.	9.7%
5.307-0 "	9.9%
7.5 -0 "	10.1%
10 -0 "	17.1%
12.5 -0 "	25.0%
15 -0 "	18.7%
17.5 -0 "	20.5%
20 -0 "	30.1%

Table 48. Fig. XXIX (C).

Specimen II (0.55%C)			
Percentage Sensitive State due to application and removal of stress.			
Stress change.	Sensitive State.	Stress change.	Sensitive State.
0-2.057-0 Kilos.	0	0-12.5-0 Kilos.	2.6%
0-5.307-0 "	0.7%	0-15-0 "	0
0-7.5-0 "	0	0-17.5-0 "	2.5%
0-10-0 "	3.9%	0-20-0 "	1 %

<u>Specimen III (0.8 per cent. C.)</u> The sensitive state values for this specimen, the most interesting of which are given in Tables 49, 50 and 51, and in graphical form in Fig. XXX. are, particularly in

Table 49. Fig. XXX (a).

Specimen III (0.8%C)	
Percentage Sensitive State due to application of stress.	
Stress change.	Sensitive State.
0-2.057 Kilos.	5.9%
0-5.307 "	7.1%
0-7.5 "	5.8%
0-10 "	5.8%
0-12.5 "	5.7%
0-15 "	7.1%
0-17.5 "	7.3%
0-20 "	10.1%

Table 50. Fig. XXX (b).

Specimen III (0.8%C)	
Percentage Sensitive State due to removal of stress.	
Stress change.	Sensitive State
2.057-0 Kilos.	8.3%
5.307-0 "	9.4%
7.5 -0 "	9.0%
10 -0 "	8.2%
12.5 -0 "	8.2%
15 -0 "	10.8%
17.5 -0 "	13.9%
20 -0 "	17.0%

Table 51. Fig. XXX (C).

Specimen III (0.8%C)			
Percentage Sensitive State due to application and removal of stress.			
Stress change.	Sensitive State.	Stress change.	Sensitive State.
0-2.057-0 Kilos.	0	0-12.5-0 Kilos.	0.6%
0-5.307-0 "	0	0-15-0 "	0
0-7.5-0 "	1.2%	0-17.5-0 "	0
0-10-0 "	1.7%	0-20-0 "	4.8%

the case of the (b) curve, lower than those reached in either of the previous specimens, so far as the range examined goes, and, though there is a slight indication of a maximum near the beginning of the range in both the (a) and (b) curves, the values of the sensitive state remain in each fairly constant till a stress of 12.5 kilos is reached, after which both curves rise fairly steadily. Neither has reached a maximum, however, within the limits of the range. The (c) curve shows only very small values, and lies below both the others throughout the whole range.

Specimen IV. (1.2 per cent. C.) -- The (a) and (b) curves for this specimen (see Tables 52 and 53 and Fig. XXXI) show smaller values of the sensitive state than do any of the others. Both remain

Table 52. Fig. XXXI (a).

Specimen IV (1.2%C).	
Stress change.	Sensitive State.
0-2.057 Kilos.	1.4%
0-5.307 "	1.4%
0-7.5 "	1.4%
0-10 "	1.4%
0-12.5 "	2.1%
0-15 "	2.8%
0-17.5 "	4.2%
0-20 "	4.9%

Table 53. Fig. XXXI (b).

Specimen IV. (1.2%C)	
Stress change.	Sensitive State
2.057-0 kilos.	2.8%
5.307-0 "	2.8%
7.5 -0 "	2.8%
10 -0 "	2.8%
12.5 -0 "	3.5%
15 -0 "	4.2%
17.5 -0 "	4.9%
20 -0 "	5.6%

steady for low values of the stress, and only rise very slowly as the stress is increased, the (b) curve lying entirely above the (a) curve throughout the whole range. The sensitive state induced by the stress cycle 0-W-0 is negligible for all values of W from 0 to 20 kilos.

Table 54. Fig. XXXII (a).

Specimen V. (0.755%C).	
Percentage Sensitive State due to application of stress.	
Stress change.	Sensitive State.
0-2.057 Kilos.	0
0-5.307 "	1.9%
0-7.5 "	2.9%
0-10 "	7.9%
0-12.5 "	3 %
0-15 "	5 %
0-17.5 "	11.9%
0-20 "	12.2%

Table 55. Fig. XXXII (b).

Specimen V. (0.755%C.)	
Percentage Sensitive State due to removal of stress.	
Stress change.	Sensitive State
2.057-0 Kilos.	0
5.307-0 "	3.4%
7.5 -0 "	3.6%
10 -0 "	8.2%
12.5 -0 "	18.6%
15 -0 "	13.0%
17.5 -0 "	15.8%
20 -0 "	19.6%

Table 56. Fig. XXXII (C).

Specimen V. (0.755%C)			
Percentage Sensitive State due to application and removal of stress.			
Stress change.	Sensitive State.	Stress change.	Sensitive State.
0-2.057-0 Kilos.	0	0-12.5-0 Kilos.	1.5%
0-5.307-0 "	0	0-15-0 "	0
0-7.5-0 "	1.6%	0-20-0 "	1.6%
0-10-0 "	0		

<u>Specimen V. (0.755 per cent. C.)</u> -- This specimen, the results for which appear in Tables 54, 55 and 56, and the curves of Fig. XXXII shows on the whole more sensitive state than Specimen III., and less than Specimen II., a result quite to be expected if the sensitive state induced depends on the carbon content of the material. The form of the (b) curve is very similar to that of the (b) curve of Specimen II., but the (a) curve has its turning-points at lower instead of at higher stress values as was the case with that specimen. The (c) curve lies throughout the range below the 2 per cent. line.

The figures showing the effect of increasing or decreasing the stress by successive differences of 2.5 or 5 kilos, have not been shown, as they are hardly of sufficient interest to merit separate discussion. As a rule effects of decrease rather than increase of stress were examined, as the (a) and (b) curves showed decrease to be the more effective in inducing sensitive state. Decrease by small amounts had very little effect so long as the applied stress remained above 12.5 kilos. The decrease from that to 10 kilos was however generally productive of some appreciable amount of sensitive state, and also any further decreases below that point. Perhaps the most interesting fact in this connection is that in every case examined the greatest effect was produced by the last decrement of all, the final removal of the applied stress - the final removal of even a small stress being much more effective in inducing sensitive state than the removal of a larger stress when some weight was still left on.

Comparing now among themselves the results obtained for these five specimens, we notice, first of all, that in each the (b) curve, representing the percentage sensitive state induced by removal of stress, invariably lies above the (a) curve, which exhibits the percentage sensitive state induced by the application of stress, and as a general rule the (c) curve, which shows the effect of the cyclic process of application followed by removal of stress, lies below both. Also, the (a) and (b) curves pretty nearly follow the same course, rising and falling together, except in the case of Specimen II (0.55 per cent. C), where the rise and fall in the (a) curve come later than in the (b) curve, and Specimen V (0.755 per cent. C.), where the reverse is the case.

Again, a comparison of the general values of the sensitive state reached within the chosen range by each of the specimens shows that higher values are reached by Specimen II. than by any of the others, and that these high values correspond to greater stress-values than do the high values of specimen.I. Specimen V shows lower values than Specimen II, (though it also shows one maximum in each of its curves within the stress range,) Specimen III much lower values and Specimen IV lower values still, but all these specimens show~~ing~~ increasing values towards the end of the range, and therefore probably show a maximum effect for stresses beyond the limits of the chosen range.

All these facts, then, seem to point to the probability that, with an increasing percentage of carbon in the steel, up to a certain point at any rate, a higher possible sensitive state may be induced,but that to induce it greater stresses are required as the percentage of carbon rises. That a harder steel should require the application of a greater stress to produce a maximum effect is only what might have been expected, but further investigation is required in which, by the use of thinner wires or greater applied stresses, increased strains may be produced, in order to determine definitely to what extent increasing percentage of carbon goes along with increasing values of the sensitive state induced.

It was my original intention to carry out this investigation to a definite conclusion by obtaining various series of thinner and thinner wires, the application of greater external stresses being out of the question with the apparatus at my disposal.

I found, however, that in the case of the specimens examined, the magnetometer readings given by the two least magnetic, namely III and IV., even when the solenoid was as near the magnetometer needle as it could conveniently be, were sufficiently small to make the possible observational error of considerable importance. Indeed an error of one scale division (= $^1/20$ cm.) in reading the magnetometer made a difference of about one per cent. in the percentage sensitive state values. These readings were repeated sufficiently often to make the probable observational error very small, but it was obviously quite impossible to attempt to carry out the same series of experiments for thinner wires of the same composition. As therefore the Specimens III and IV would certainly have had to be omitted from the series of thinner wires, and as moreover it was not even certain that the other three specimens were all sufficiently magnetic to give satisfactory results, when examined in the form of thinner wires, it was decided not to carry the investigation any further, especially as sufficient data had been obtained to admit of a comparison being made between the effect of thermal treatment and the effect of longitudinal strain in inducing sensitive state.

When we come to compare these effects, we notice first of all the rather striking similarity between them, that in both cases the (b) curve is generally above the other two,- that is to say, removal of stress and cooling correspond in producing a greater effect than the other processes; application of stress and heating also correspond in producing a greater effect than the cyclic operations of application and removal of stress, and heating and cooling for all stresses, (except in the case of specimen I), and for low and moderate temperatures.

Though so far the effects of the two methods of treatment are very similar, it is to be noted on the other hand, that the thermal curves show far more irregularities than do the strain curves, and also that the (a) curve has in the first case a distinct tendency to rise to a maximum above the (b) curve - a tendency of which there is no trace in the curves of the second set. The effects produced by strain, too, are in general, so far as the range examined goes, much less marked than those produced by thermal treatment, though in the case of Specimen V. - the steel wire specimen of the first treatment, - both the values reached and the general form of the curves, especially the (b) curves, obtained by the two methods are very similar. It is therefore probable that the application of greater stresses would in other cases have given sensitive state values quite comparable with those due to thermal treatment. The field for which the effect is maximum is however much lower in the case of strain treatment.

The phenomena in the two cases then, while showing decided similarities are far from being identical, and at the present stage of the research it seems to be impossible to come to any conclusion as to whether there is a connection between them or not.

In explanation of the general effect of thermal treatment and of longitudinal strain in inducing sensitive state I have no theory to offer. The effect produced by the strain cycle O-W-O certainly admits of explanation, as Ewing* has pointed out, on the ground of the presence of hysteresis. He has shown that if a specimen, under the influence of a moderate magnetic field of constant value, has gradually increasing stresses applied to it, the intensity of magnetisation of the specimen increases, and that, when the load is gradually removed, the intensity does not return to its original value, but remains above it. This hysteresis effect shows that the specimen, when under the influence of a magnetic field of a constant value, has its magnetisability increased by the application and removal of stress, and it is quite possible to conceive of the magnetisability of the specimen as existing apart from the actual presence of a magnetic field, and being increased, even when the field-strength is zero, by the application and removal of stress. Such an improvement

* Trans. Roy. Soc. CLXXVI p. 612 §§96-101

in magnetisability would naturally be removed when the specimen was demagnetised by reversals.

This explanation then adequately covers the case of the cyclic process of application and removal of stress, but the presence of hysteresis as described does not supply any satisfactory explanation of the sensitive state induced, either by application of stress, or by removal of stress, and as there is no trace of a similar hysteresis effect* in the case of a specimen heated and cooled under the influence of a constant magnetic field, a similar explanation cannot be found, even for the cyclic process, in the case of thermal treatment.

All that can be said at present then is, that while the sensitive state due to the cyclic process O-W-O does admit of explanation on the ground of hysteresis, the same does not apply to the sensitive state otherwise induced, and the similarity existing between the effects of thermal and of strain treatment certainly suggests that the phenomena in the two cases should be capable of similar explanation.

Further investigation is probably required however before any such explanation can even be suggested, and certainly, before it could be accepted as adequate, a considerably increased knowledge of the facts of the case would be necessary.

* Trans. Roy. Soc. CLXXVI §121.

(C). The Magnetic Properties of a Graded Series of Chrome Steels at Ordinary and Low Temperatures.

I have already pointed out in an earlier part of this paper, that the effect of raising the temperature of a piece of iron or steel is generally to increase its susceptibility for low fields, and to diminish it for high ones. It is to be expected then that if the temperature of a test-piece be lowered, the effect should be exactly reversed, and the susceptibility should be diminished for low, and augmented for high fields. That such is actually the case has been shown for various magnetic materials by Honda and Shimizu*, and more recently by Gray and Ross†, who have all used the temperature of liquid air, - 190°C., as the low temperature at which they have made their investigations. They have shown also that, while alike in this one respect, different materials differ very considerably both in the amount of change in susceptibility brought about by the change of temperature, and in the value of the field strength for which the effect reverses its sign.

Now in any such examination particular interest always attaches to the observation of the effect of similar treatment on the different members of a graded series, either of steels or alloys, the changes in effect being directly due to the changes in the content of the specimens under examination.

I accordingly decided to examine magnetically a specially prepared series of cobalt-manganese alloys containing respectively

* Phil.Mag., X., p.548, 1905.

† Trans.Faraday Soc., Vol.VIII., Part I., 1912.

5, 10, 15, 20, 25 and 30 per cent. manganese, the rest of the content of the specimen being pure cobalt. The proper proportions of the two elements forming the various specimens were therefore weighed out, and sent to be fused and cast, and a specimen of pure cobalt was obtained for comparison. At this point however an unexpected difficulty was met with, which ultimately led to the abandonment, for the time being at any rate, of the investigation of this series. It was found that all the ordinary methods, which are usually successful in fusing metals, were in the case of the first specimen of the series ineffectual. It was probable that those specimens with higher percentages of manganese would fuse more easily, but as it was desired to have the complete series prepared by the same method, they were not attempted, and as any other methods which might have been tried were unlikely to give homogeneous alloys, the examination of this particular series had to be abandoned. I therefore decided to investigate instead the magnetic properties at ordinary and low temperatures of a graded series of chrome steels. Such a series was accordingly obtained from Messrs Armstrong, Whitworth & Co. Ltd., - a series consisting of six specimens containing respectively 1, 4.05, 8, 12, 16 and 20 per cent chromium.

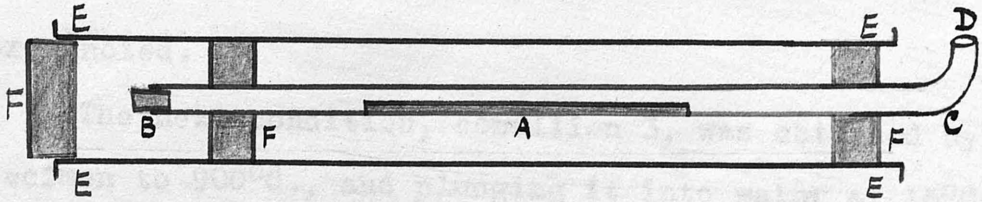
The specimens were supplied in the form of cylindrical rods 20 cms. long and 0.9 cms. in diameter, and the conditions in which they were tested were as follows:-

1. As supplied (viz., forged and rolled).
2. Annealed from 900°C.
3. Quenched from 900°C in water at 15°C.

In the first condition the specimen is in a state of internal strain brought about by the treatment to which it has been subjected in the course of preparation, and is in general far from homogeneous. Each specimen in this condition was tested magnetically in a Gray-Ross magnetometer, and then changed, end for end, and tested again. The two sets of readings in each case were found to differ appreciably, thus showing the want of homogeneity of the specimen. The results of the tests carried out with the specimen in this condition are therefore of comparatively little importance, and are not included in the tables of results.

The effect of annealing the specimen from 900°C. is to remove the internal strains, and bring it into a standard homogeneous condition. In annealing the specimens a Fletcher gas furnace, which could be heated to 900°C., was used, and each specimen, before being placed in the furnace, was carefully wrapped in copper foil, to exclude air and prevent oxidation.

Each specimen after being annealed was tested magnetically in the usual way, and was then as before changed end for end, and the test repeated. In the case of each specimen the two tests gave identical results, showing that the material was now homogeneous. The specimen was next immersed in liquid air, and tested at the temperature - 190°C., care of course being taken after every change of temperature to apply the process of demagnetisation by reversals, to wipe out the sensitive state induced in the specimen by the change of temperature. To bring the specimen to the temperature of liquid air the arrangement shown in the diagram below was employed. The



specimen A was enclosed in a glass tube B C D, of which the end B was closed with a cork and the end D was open and bent up. Cork bungs F, F were fitted on the tube so as to bring the axis of the specimen into coincidence with that of the solenoid EE inside which the tube is slipped. A third bung F, or a pad of cotton-wool, was used to prevent access of warm air into the interior of the solenoid, and a covering of cotton-wool wound closely round the tube prevented conduction of heat to the specimen. The liquid air was poured in at the bent end of the tube D, and the specimen kept completely immersed in it, for long enough to ensure its temperature being reduced to -190°C before a magnetic test was made.

In order to make quite certain that the specimen was in exactly the same position when tested at room temperature, and at the temperature of liquid air, it was inserted in the tube before the test at room temperature, and not moved between that test and the test at - 190°C. The specimen was then allowed to heat up to 15°C again, and tested once more to find whether the lowering of the temperature had had any permanent effect upon its susceptibility or not. In addition to the tests already mentioned, each specimen was also tested both at 15°C and at - 190°C for magnetic hysteresis, and the effect of the lowered temperature upon the residual magnetism and the coercive force noted.

The next condition, condition 3, was obtained by heating the specimen to 900°C., and plunging it into water at 15°C. With the specimen in that condition exactly the same series of tests was gone through, as in the case of the specimen in the annealed condition. Each complete test was in every case carried out twice, and excellent agreement obtained between the two sets of results.

It may be mentioned at this point that there are in the Physical Institute of Glasgow University exceptional facilities for low temperature work, as an air-liquifying machine on the premises enables liquid air to be obtained on the spot, and obviates the trouble and expense involved in procuring it from a distance.

Discussion of Results.

1 per cent. Cr. - The first specimen tested was a steel containing 1 per cent. chromium. The chief results obtained are shown in Table 57 and the corresponding curves in Fig. XXXIII. The first set of results corresponding to the curve marked I gives the

Table 57. Fig. XXXIII/

Table 57. Fig. XXXIII.

1% Cr.				
Thermal Treatment.	Annealed at 900°C.		Quenched at 900°C.	
Temperature of test.	15°C.	-190°C.	15°C	-190°C
H	I	I	I	I
5	190	130	16	10
10	460	480	60	40
20	680	708	210	143
40	844	878	588	504
60	940	978	796	762
100	1040	1082	960	944
150	1117	1159	1076	1060

readings for the I-H curve taken with the specimen at room temperature in the annealed condition. The corresponding curve marked I′ belongs to the second set of results, and is the curve characteristic of the annealed specimen at the temperature of liquid air. It is to be noticed that this latter curve starts below the former as was to be expected, but crosses it very early in the range, the value of the magnetising force at the crossing point being only about 8 c.g.s. units. Thereafter the curve at -190°C. lies entirely above the curve taken at room temperature, and the improvement in magnetic quality becomes more marked as the field is increased in value. The results of the next test, made after the specimen had again reached room temperature are not included in the table nor in the diagram. The curve belonging to this test, however, almost coincides with the previous curve taken at room temperature lying only very slightly below it at the beginning of the range, and slightly above it later on, the crossing of the curves in this case also being in the neighbourhood of H = 8. That is to say, the effect on the specimen of immersion in liquid air is to give it a permanent set magnetically in the direction of its condition at -190°C. The change in susceptibility is however very small.

The other two curves, the dotted curves marked II and II′ belong to tests 3 and 4 in Table 57, and show the results obtained on testing the specimen in the quenched condition. II is the curve taken at ordinary temperature, II′ is the curve belonging to -190°C. In this case the liquid air curve lies every where below the curve taken at room temperature, and the form of the curves shows that crossing will only occur for a very high value of the magnetising force. The third test, made when the specimen had again reached room temperature, gives a curve which exactly coincides with curve II., showing that in the quenched condition the lowering of the temperature of the specimen to -190°C does not permanently affect its magnetic quality. The general effect of quenching on the specimen is to diminish its susceptibility particularly for low and moderate fields. Some of the hysteresis curves obtained for this specimen are shown in Fig. XXXIX. The curves marked I and I′ are as before the curves obtained on testing the specimen in the annealed condition at 15°C and -190°C respectively. It will be noted that for low fields the curves are coincident, though for high fields I′ lies above I. The residual magnetism at both temperatures is about 400 c.g.s. units, and the coercive force about 5 c.g.s. units.

The dotted curve marked II is the hysteresis curve of the quenched specimen at 15°C. To prevent confusion of the diagram the curve taken at -190°C is not shown, but it very nearly coincides with II. The values of the residual magnetism at 15°C and -190°C are respectively 600 and 605 c.g.s. units, and the values of the coercive force 28 and 33 c.g.s. units.

4.05 per cent Cr. - The results obtained on testing this specimen are contained in Table 58. These readings and the corresponding curves of Fig. XXXIV show that this specimen is magnetically very similar to the previous one except in one or two points. As before the curve taken at -190°C., when the specimen is in the annealed condition, starts below and finishes above the curve taken at 15°C., but in this case the crossing occurs for a much higher field value, namely, 70 c.g.s. units. The curve taken at room temperature, after the test at -190°C, is again slightly below I at the beginning of the

Table 58. Fig. XXXIV.

4.08% Cr.				
Thermal Treatment.	Annealed at 900°C.		Quenched at 900°C.	
Temperature of test.	15°C.	-190°C	15°C	-190°C
H	I	I	I	I
10	160	125	38	24
20	680	608	95	68
40	892	878	317	270
60	980	970	630	590
100	1078	1088	840	820
150	1142	1158	945	935

range, and slightly above it at the end, but the improvement only sets in when the field is greater than 110 c.g.s units. The effect of quenching in reducing the susceptibility of this specimen is more marked than in the case of the previous specimen, but the effects of lowering the temperature after quenching are exactly similar in the two cases, - the curve taken at -190°C lying everywhere below that taken at room temperature, and the two curves taken at room temperature, the one before and the other after immersion in liquid air, exactly coinciding.

<u>8 per cent. Cr. -</u> The results obtained on submitting this specimen to the various tests (see Table 59 and Fig. XXXV) were again somewhat similar, but the saturation value of the intensity was found to be lower than previously, and the effect of quenching even more

Table 59. Fig. XXXV.

8% Cr.				
Thermal Treatment.	Annealed at 900°C.		Quenched at 900°C.	
Temperature of test.	15°C	-190°C	15°C	-190°C
H	I	I	I	I
10	88	78	18	17
20	400	340	48	42
40	790	778	130	120
60	888	878	304	286
100	984	980	600	580
150	1060	1070	744	724

marked than before. The crossing of the curves at the two temperatures in the annealed state occurs at a field value of 102 c.g.s. units, and the magnetic quality at 15°C after immersion in liquid air is lower than before immersion for fields less than 170 c.g.s units. An examination of this specimen when quenched produced exactly the same results as in the previous cases - that is to say, the magnetic quality when the temperature is lowered to -190°C is less than at room temperature for the whole range examined, and returns to its original value when the temperature is allowed to rise again.

<u>12% Cr., 16% Cr., 20% Cr.</u> - The next three specimens showed on examination no marked peculiarities, so I shall not discuss them separately. The results obtained on testing them are exhibited in Tables 60, 61 and 62, and the corresponding curves are shown in Figs. XXXVI., XXXVII and XXXVIII. In the annealed condition the saturation value of the intensity is lower in each specimen than it was in the

Table 60. Fig. XXXVI.

12% Cr.				
Thermal Treatment.	Annealed at 900°C.		Quenched at 900°C.	
Temperature of test.	15°C	-150°C	15°C	-150°C
H	I	I	I	I
10	80	70	20	13
20	440	380	45	36
40	765	750	112	100
60	850	840	235	210
100	936	932	485	470
150	1008	1018	653	638

Table 61. Fig. XXXVII.

16% Cr.				
Thermal Treatment.	Annealed at 900°C.		Quenched at 900°C	
Temperature of test.	15°C	-190°C	15°C	-190°C
H	I	I	I	I
10	70	55	17	12
20	320	235	41	35
40	635	608	84	76
60	710	695	162	145
100	780	784	360	340
150	850	865	508	492

Table 62. Fig. XXXVIII.

20% Cr.				
Thermal Treatment.	Annealed at 900°C.		Quenched at 900°C	
Temperature of Test.	15°C	-190°C	15°C	-190°C
H	I	I	I	I
10	122	106	12	12
20	413	380	25	20
40	636	625	50	42
60	700	698	110	98
100	774	782	276	258
150	820	832	404	390

previous one, and the susceptibility at -190°C is less at the beginning and greater at the end of the range than at 15°C, the crossing occurring for the 12% Cr., 16% Cr., and 20% Cr. specimens at points corresponding to field values of 125, 95 and 65 c.g.s.

respectively. The permanent lowering of the magnetic quality due to immersion in liquid air is seen in these specimens too, the new room temperature curve lying slightly below the former one for the whole range examined in the case of the specimens containing 12 and 16 per cent. chromium, and till the magnetising force reaches a value of 90 c.g.s. units in the case of the specimen containing 20 per cent.

In the quenched condition, the diminution in magnetic quality with the increase in chrome content is very marked, but otherwise the behaviour of these specimens is exactly the same as that of the three specimens first examined, the curve II′ lying invariably below the curve II, and the curve taken, when the temperature of the specimen had risen again to 15°C, exactly coinciding with II. In all the specimens, the form of the curves shows that crossing will only take place for very high values of the magnetising force.

Two of the hysteresis curves for the specimen containing 16 per cent. chromium are shown in Fig. XL. These are the curves taken at room temperature in the annealed and in the quenched conditions. The curves taken at -190°C are not shown as they follow almost exactly the lines of those taken at 15°C, and lie for the greater part of the range just outside them, the residual magnetism and the coercive force both being slightly greater at -190 C than at 15°C. The distinctive features of these curves are characteristic in a more or less marked degree of all the specimens of the series, the most notable being probably the extraordinary widening of the hysteresis loop, and the consequent increase in the coercive force brought about by quenching. The slight improvement in both the residual magnetism and the coercive force, when the temperature is lowered to -190°C., is also a characteristic common to all the specimens.

A comparison of these curves with the hysteresis loops for the specimen containing 1 per cent chromium (see Fig. XXXIX) shows that while in the case of the 1% Cr. specimen the residual magnetism is greater in the quenched than in the annealed condition, in the 16% Cr. specimen the reverse is the case. These results are not however so irregular as they appear, for as an examination of Table 63 below shows, the residual magnetism in the annealed condition increases with increasing percentage of chromium to a maximum

Table 63.

	Residual magnetism.		Coercive force.	
	Annealed.	Quenched.	Annealed.	Quenched.
1% Cr.	400	660	5	28
4.05% Cr.	500	600	21	39
8% Cr.	660	580	20	46
12% Cr.	510	435	19	54
16% Cr.	490	340	17	56
20% Cr.	440	320	15	44

value for the specimen containing 8 per cent., and thereafter steadily diminishes, while, in the quenched condition, the maximum residual magnetism is attained with the lowest percentage of chromium, and every additional amount of chromium produces a diminution in its value. A similar regular change takes place also in the values of coercive force, but the value in the quenched condition is invariably much greater than the value in the annealed state.

Coming now to a comparison of the effects produced by lowering the temperature of the different specimens we find that these effects are on the whole very similar. Considering the quenched specimens first, we see, indeed, that they behave, so far as the range examined goes, in exactly the same manner, the curve taken at the temperature of liquid air lying in each case below that taken at room temperature, and the curves taken at room temperature before and after immersion in liquid air exactly coinciding.

The specimens in the annealed state, however, show some slight differences in behaviour, for while the effect of lowering the temperature to -190°C. is in each case to diminish the susceptibility for low fields and to increase it for high fields, there are considerable variations in the value of the magnetising force for which crossing of the curves taken at the two temperatures occurs, the actual values of the field strength corresponding to the crossing point being 8, 70, 102, 125, 95 and 65 c.g.s. units for the specimens containing respectively 1 per cent, 4.08 per cent., 8 per cent., 12 per cent., 16 per cent., and 20 per cent. chromium. As the chrome content increases from 1 per cent. up to 12 per cent., that is to say, higher and higher values of the magnetising force are required to produce crossing of the curves. Further additions of chromium, beyond that point, however, tend to lower the position of the crossing point in the range.

In the case of the annealed specimens, again, the effect of lowering the temperature to $-190^{o}C$ is not merely a temporary effect, which passes away when the temperature is allowed to rise again, but immersion in liquid air produces in the specimen a permanent effect lowering its susceptibility for low fields and raising it for high, and the crossing points of the two curves taken at room temperature, one before and one after immersion in liquid air, vary in position exactly as do those of the curves I and I$'$, the crossing for the specimen containing 12 per cent. chromium occurring at a higher point in the range than any of the others.

Briefly then the results of this investigation may be summarised as follows:-

(1) The effect of lowering the temperature of a chrome steel is to diminish its susceptibility for low fields, and to increase it for high fields.

(2) The crossing of the curves at $15^{o}C$ and at $-190^{o}C$ in the annealed condition takes place for higher values of the magnetising force as the chrome content is increased up to 12 per cent., but further additions after that point lower the value of the field for which crossing occurs.

(3) Immersion in liquid air produces a permanent effect on the annealed specimen, which is not wiped out when the temperature is allowed to rise to room temperature again.

(4) For specimens in the quenched condition the crossing point of the curved at $15^{o}C$ and $-190^{o}C$ occurs at very high values of the magnetising force probably much greater than 160 c.g.s. units.

(5) Immersion in liquid air has no permanent effect on quenched specimens, and

(6) In both the annealed and quenched conditions the residual magnetism and the coercive force are greater at -190°C than at 15°C.

(d) Permanent Magnetism of Chrome Steels.

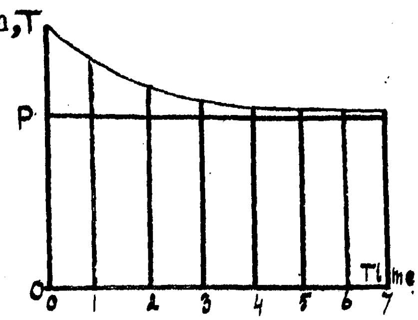
The magnetism of ~~permanents~~ permanent magnets is a subject of wide interest and of considerable importance, the value of many different machines depending first and foremost on the constancy of permanent magnetism.

It is a well-known fact that of the residual magnetism, which a specimen holds when the applied field is reduced to zero, only a part is held with such a degree of firmness that it can be considered permanent. In the case of some steels, the application of a very small negative magnetising force is sufficient to reduce the residual magnetism to zero, while in the case of others a very considerable negative field must be applied. This negative field is equal and opposite to what is known as the coercive force, which can therefore be considered as a measure of the firmness with which the residual magnetism is held. The hysteresis curve of a specimen then, in indicating the values both of the residual magnetism and the coercive force, gives us a considerable amount of information regarding its permanent magnetism.

Professor Sil~~vaus~~vanus P. Thompson, in a paper* read before the Institution of Electrical Engineers, has collected and described the results obtained by various workers in the subject. He shows first of all that, while in the preparation of a satisfactory magnet the material of which it is to be composed is naturally of primary importance, the shape and size must also be considered, and in addition the heat treatment to which it is subjected before magnetisation, a

*Journ. Inst. Elec. Engineers. Feb. 1913. p.80.

steel hardened by rapid quenching from a high temperature having in general a much greater coercive force than a specimen of the same steel cooled more slowly. Even when a suitable steel of suitable dimensions is chosen, however, and carefully hardened before magnetisation, it is found that it does not retain all of its residual magnetism permanently, but that mechanical shock, change of temperature, contact with other magnets, exposure to demagnetising forces, and even mere lapse of time all tend to diminish its value. It is found indeed that while a part of the residual magnetism seems to be really permanent, a part is only apparently so, and this part gradually disappears. The figure illustrates the law of decay of magnetism,



the heights of the ordinates representing the residual magnetism diminishing as time goes on. The height, OP, represents the really permanent part; the part, P T, representing that part which is removable. Now this decay of magnetism can be hastened in several ways, by the repeated application of mechanical shock for instance, or by alternate gentle heating and cooling, or by prolonged exposure to a gentle heat, and thus the magnet can be brought rapidly into a permanent state. This process by which the removal of the non-permanent part of the residual magnetism is hastened is termed "maturing" the magnet.

In the investigation of this subject a number of carbon and alloy steels have been examined by various experimenters. Many steels with high values of the residual magnetism have been found to have a very small coercive force, and therefore lose their magnetism readily, while others again have a large coercive force, but only a conparatively small amount of residual magnetism. Neither of these then makes the best kind of permanent magnet, and the ideal at present aimed at is the production of an alloy steel which shall have, after suitable treatment, a coercive force of 80 c.g.s. units and a residual magnetism of 800 c.g.s. units.

Though many steels have been examined then, there is still need for further investigation of the permanency of the magnetism of various series of alloy steels. I therefore decided to undertake the examination of some of these series, and commenced my work in this subject with the series of chrome steels with which I had just been dealing. The hysteresis curves in the annealed and quenched conditions showed the coercive force in the former case (see Table 64) to be so small as to make it not worth while investigating the permanent magnetism, and accordingly attention was concentrated on the quenched specimens

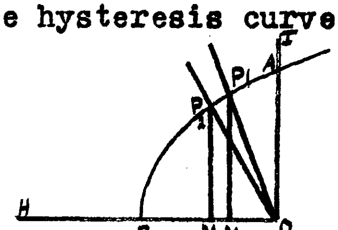
Table 64

Percentage of Chromium.	Annealed Specimen.		Quenched Specimen.	
	Residual Mag.	Coercive Force.	Residual Mag.	Coercive Force
1	400	5	660	28
4.05	500	21	600	39
8	660	20	580	46
12	510	19	435	54
16	490	17	340	56
20	440	15	320	44

which, though none of them fulfil the desired ideal, yet retain sufficient permanent magnetism to make useful magnets.

The method of procedure adopted in magnetising the specimens before testing the permanence of the magnetism was as follows:-
Each specimen, after being quenched from 900°C in water at room temperature, was placed inside the magnetising helix of a Gray - Ross magnetometer, and magnetised in a field of sufficient strength to saturate it. The field was then gradually diminished to zero, (a gradual diminution having been found to give more satisfactory results than a sudden removal of the magnetising force), and the residual magnetism noted. The field was then reversed, and gradually increased in value, until the residual magnetism was exactly zero, and the value of the applied field on which the coercive force depends was noted. The specimen was then demagnetised, and saturated once more, and the field again reduced to zero, when the specimen was ready to be tested for permanent magnetism. The value of the residual magnetism, obtained in this way, is much less than that obtained from the hysteresis curve, owing to the demagnetising influence of the ends of the magnet,- an influence for which corrections were made in obtaining the absolute values of I and H belonging to the hysteresis curve. This influence depends for its value largely on the dimension ratio of the specimen, a long narrow magnet being generally much less affected than a short thick bar.

Professor Ascoli of Rome has suggested a method by which the intrinsic residual magnetism can be obtained from the hysteresis curve, the dimension ratio of the magnet being known. If O A be the residual magnetism, and O B the coercive force, then lines O P etc. may be drawn from O such



that tan A O P represents the demagnetising coefficient of the specimen, which depends for its value on the dimension ratio; then the ordinate M P represents the intrinsic residual magnetism. As the bar diminishes in length the demagnetising coefficient increases, and therefore the value of M P becomes smaller. This diagram also shows that for a specimen of given dimensions, that is to say, for a given demagnetising coefficient, the ratio of the intrinsic to the corrected residual magnetism increases with the coercive force when the hysteresis curves are similar in form.

The specimens examined - a graded series of chrome steels containing respectively 1, 4.05, 8, 12, 16 and 20 per cent chromium - were as has been stated in the previous part of the paper all cylindrical rods about 20 cms. in length and 0.9 cms. in diameter. The variation of permanence of magnetism with dimension ratio does not therefore enter into the investigation, and the comparison instituted is simply between the behaviour, under similar conditions, of specimens similar in form, but varying in composition.

In testing the specimen for permanence of magnetism, the effect of repeated application of mechanical shock was first observed. Each specimen, after its intrinsic residual magnetism had been observed, was dropped, end-on, from a height of 1 metre on to a wooden slab. To prevent the specimen being differently affected in its two directions, it was dropped alternately on either end, and tested magnetometrically after 1,2,6,12,20,30 and 40 falls, or until its magnetism reached a constant value unaffected by further falls. The specimen was then placed inside a steam coil, which was fitted inside the magnetising solenoid, so that the specimen could be heated to 100°C. while in position for testing. It was then alternately heated to 100°C, and allowed to cool to room temperature again, magnetometer readings being taken at both temperatures. The specimen at first lost a greater amount of magnetism at each heating than it regained at the subsequent cooling, but the difference between the loss and the gain became smaller as the process was repeated, till a steady state was reached, in which the loss of magnetism on heating was exactly balanced by the gain due to cooling. The specimen was then laid away, and left for about a month, when its magnetism was tested once more, and the processes of application of shock, and heating and cooling repeated. After that, it was left for some three or four months more, and tested again, but not this time subjected to any further treatment. The results obtained for the different specimens are discussed separately below.

Specimen I. (1 per cent. Cr.) - The intrinsic residual magnetism of this specimen was only 295 c.g.s. units as compared with 660 c.g.s. units as the corrected value of the residual magnetism obtained from the hysteresis curve, and the coercive force was 28 c.g.s.units. The first fall reduced the magnetism to 287 c.g.s. units, and, though subsequent falls had less effect, it was only after the specimen had been dropped 20 times that further percussion ceased to affect it, the intensity of magnetism then equalling 275 c.g.s. units. When further percussion ceased to have any effect, the permanence of the magnetism under varying temperature conditions was tested.

The specimen whose remanent magnetism was now 275 c.g.s. units was heated to 100°C., when the value of the intensity was found to have fallen to 254 c.g.s. units. On cooling the magnetism increased again, though not to its former value, and, on the alternate heating and cooling being continued, it was found that, after seven heatings in all, the change in magnetism became cyclic, subsequent heatings and coolings simply causing a variation between the limits 238 and 247 c.g.s. units. One peculiar point is however to be noticed in the behaviour of this specimen. After having been heated and cooled three times, when the magnetism at 100°C equalled 243 c.g.s. units, and at room temperature 250 c.g.s. units,- that is, before the steady state had been reached,- the specimen was laid aside for about a month. On being examined after that lapse of time, it was found that its magnetism had in the interval spontaneously increased to 260 c.g.s. units. Other two heatings however quickly wiped out this improvement, and, when the temperature had been raised and lowered other twice, a constant state was reached. No indication of spontaneous improvement was noticed in any of the other specimens examined, but in all the other cases the alternate heating and cooling was continued until the steady state was reached, without any long interval of time elapsing between heatings.

After this, the specimen was once more laid aside for a month and then tested again. The magnetism was found to have deteriorated slightly, by about 2 c.g.s. units indeed, but ten falls had now no effect in reducing the magnetism, and neither had another rise and fall of temperature. After four months interval the specimen was once more tested, when its magnetism was found to have undergone no further alteration.

The effect of percussion on this specimen was, then, to reduce its residual magnetism by 6.8 per cent., while the effect of alternate heating and cooling was to reduce it further by about 9.5 per cent of its original value. Lapse of an interval of one month then brought about a reduction of less than 1 per cent., after which neither percussion, nor heating, nor lapse of some considerable time appeared to have any further effect.

Specimen II. (4.05 per cent Cr.) - The next specimen examined, which contained 4.05 per cent chromium, had a smaller corrected residual magnetism, namely 600 c.g.s. units, but its coercive force was 39 c.g.s. units, and its intrinsic residual magnetism 374 c.g.s. units. Once again the first fall had the greatest effect, reducing the magnetism by 10 units, just half of the total reduction due to percussion, and after thirty falls percussion ceased to affect the magnetism at all. The value of the intensity, which was then 354 units, was reduced on the first heating to 335, and rose again on cooling to 340. Only five successive heatings were required to bring about a constant state in this specimen, after which the magnetism at 100°C was 325 and at room temperature 334 c.g.s. units. Lapse of one month had no effect on the specimen, and neither further percussion, nor heating and cooling produced any apparent change. When examined again at the end of three and a half months, the same value of the magnetism was still maintained. In the case of this specimen the total loss of magnetism from all causes amounted to 10.6 per cent. of the original value, half of that being due to percussion, and half to thermal treatment.

Specimen III. (8 per cent Cr.) - In this specimen the value of the residual magnetism obtained from the hysteresis curve was again somewhat lower, but the coercive force and the intrinsic residual magnetism were increased, the actual values in the three cases being 580, 46 and 385 c.g.s. units. The first fall reduced the magnetism to 377 units, and after twenty falls in all it became constant at

371 units, a reduction of 3.6 per cent. The first rise and fall of temperature gave values of 361 and 368 c.g.s. units respectively, and a cyclic state was set up after only four heatings and coolings, the magnetism then varying for subsequent changes of temperature from 364 c.g.s. units at 15°C. to 355 c.g.s. units at 100°C. The total loss due to changes of temperature was in this case very small, being only 1.9 per cent. of the original value of the intrinsic residual magnetism. Further treatment after the lapse of one month had no adverse effect, and the same value was still maintained when the specimen was tested again some fifteen weeks later.

Specimen IV. (12 per cent Cr.) - Though this specimen had a greater coercive force than any of the others already examined, 54 c.g.s. units, its residual magnetism was so much lower than before that its intrinsic magnetism was also smaller than in the previous case, being only 332 c.g.s. units. As was to be expected from the large value of the coercive force, percussion had comparatively little adverse effect on the magnetism, one fall producing no measurable effect, and twelve falls reducing it to a constant value of 328 c.g.s. units. After three successive heatings and coolings further similar thermal treatment produced no further change, and the magnetism of thr specimen took up the values 322 and 313 c.g.s. units at 15°C. and 100°C. respectively. The same constant values were maintained when the specimen was tested and treated again after the lapse of one month, and tested once more at the end of other three and a half months. The total loss of magnetism sustained by this specimen was only 3 per cent., 1.2 per cent. being due to percussion, and 1.8 per cent to thermal treatment.

<u>Specimen V. (16 per cent Cr.)</u> - In the case of this specimen the two values of the residual magnetism, the corrected value and the intrinsic, were again smaller being only 340 and 286 c.g.s. units, but the coercive force, 56 c.g.s. units was once more slightly greater. Twelve falls were again sufficient to make the specimen impervious to shock, and the reduction in magnetism thus brought about was only 2 c.g.s. units, about 0.7 per cent. of the original value. As in the case of Specimen IV, three successive heatings and coolings were sufficient to set up a cyclic state, and further heatings and coolings after the third only caused the magnetism to vary between the constant limits 272 and 278 c.g.s. units, the loss of magnetism at room temperature due to thermal treatment being 2.1 per cent. When this specimen was tested again after a month had passed, its magnetism was found to have improved very slightly reaching a value of 279 c.g.s. units, and this improvement was maintained even when the specimen was subjected to shock and change of temperature. A later test, after the lapse of three and a half months, showed no further change in magnetism.

<u>Specimen VI. (20 per cent Cr.)</u> - This specimen was, from every point of view, inferior as a magnet to the last, the values of the corrected residual magnetism, the intrinsic residual magnetism and the coercive force being respectively 320, 252 and 44 c.g.s. units. Thirty falls had to be given to the specimen before percussion ceased to affect it, and the reduction in its magnetism due to this cause was 13 c.g.s. units or 5.2 per cent. Heating and cooling had not such an adverse effect, the reduction produced by thermal treatment being only 1.2 per cent. or 4 c.g.s. units. Four rises and

falls of temperature were required to set up the constant state. Further percussion and thermal treatment after the lapse of one month did not lower the magnetism, and at the end of three and a half months a further test yielded again the same result.

In Table 65 the chief results obtained for the six specimens are collected for the purposes of comparison.

Table 65.

Percentage of Chromium.	Residual Magnetism	Intrinsic Residual Magnetism.	Coercive Force.	Magnetism after Percussion.	Magnetism after Heating and Cooling.	Percentage Loss by Percussion.	Percentage Loss by Heating & Cooling.	Total Percentage Loss.
1	660	295	28	275	245	6.8	9.5	16.3
4.05	600	374	39	354	334	5.3	5.3	10.6
8	580	385	46	371	364	3.6	1.9	5.5
12	435	332	54	328	322	1.2	1.8	3.0
16	340	286	56	284	278	0.7	2.1	2.8
20	320	252	44	239	235	5.2	1.5	6.7

It will be noticed first that, while the corrected values of the residual magnetism diminish steadily with increasing percentage of chromium, the intrinsic residual magnetism at first increases, and then steadily falls off, the specimen containing 8 per cent having the largest value, namely 385 c.g.s. units. The values of the coercive force also increase to a maximum, and then fall off with increasing chrome content, but the maximum in this case is only reached with the fifth specimen of the series.

Specimen I, which has a coercive force of only 28 c.g.s. units, loses by percussion and thermal treatment 16.3 per cent. of its magnetism. Specimen II loses 10.6 per cent., and Specimen III, which has the greatest intrinsic residual magnetism both before and after treatment, loses 5.5 per cent. The next two specimens retain a very great proportion of their magnetism, losing only 3 and 2.8 per cent. respectively, but while Specimen IV is after treatment nearly as magnetic as Specimen II, Specimen V is considerably less so. The last specimen of all, Specimen VI, is less magnetic still, and loses nearly 7 per cent. of its magnetism in maturing.

Considering them from the point of view of satisfactory magnets then, Specimens I and VI would be at once discarded, as being both less strongly magnetic and less permanent than some of the others. From the point of view of retentivity, Specimens IV and V are almost equally good, but as the amount of magnetism held by IV is considerably greater than that held by V the former makes undoubtedly the superior magnet. Specimen III retains most magnetism of all, and, though it loses over 5 per cent. in maturing, is still even after that more magnetic than any of the others. Specimen II is originally much more magnetic than IV, and not much less so than III, but, losing over 10 per cent. of its magnetism on being submitted to percussion and thermal treatment, it is eventually only a little better than IV.

It would appear then that in making a chrome steel magnet of the dimension-ratio of the specimens examined, the choice would lie between that containing 8 and that containing 12 per cent. chromium. If retentivity were the first consideration, then the 12 per cent.

specimen would be superior, while if a considerably stronger magnet were desired, and the retentivity might be to some extent sacrificed, the specimen containing 8 per cent. would be the more satisfactory. It is perhaps of some interest to compare these results with those obtained by W. Brown*, who has also examined the effect of percussion on the permanent magnetism of chrome steels. The series examined by him also consisted of six specimens, none of which however contained as much as 10 per cent. chromium. Table 66 shows some of his results, and from it, it will be seen that the most satisfactory

Table 66.

Percentage of Chromium.	Magnetic moment per gm.	Percentage loss by percussion.
1.75	38.2	1.9
1.96	50.4	0.5
2.11	52.5	2.2
3.50	41.7	7.9
5.79	38.7	7.0
9.22	42.2	1.3

percentage of chromium for a permanent magnet seems to be about 2 per cent. The dimension ratio of the specimens used in this investigation was however 33, as compared with about 21 in the case of my work, and it is well known that the steel which makes the most satisfactory magnet of one dimension-ratio, is generally not the best, if a magnet of a different dimension-ratio be desired. Madame Curie has also examined some chrome steels in the form of square bars, 20 cms. long and 1 cm. broad, the dimension ratios of

* Proc. Roy. Dub. Soc. vol. 12 p. 349, 1910

which are nearly equal to those of the steels I used, and her work shows (see Table 67) an improvement in magnetic moment with increasing percentage of chromium beyond the percentage found to be best by Brown.

Table 67.

Percentage of Chromium.	Magnetic moment per gramme.
2.486	59
2.831	64
3.445	68

A general comparison between the behaviour of the steels of different dimension-ratios as shown in Tables 65,66 and 67 suggests therefore, that, while a fairly high percentage of chromium gives the most satisfactory magnet when the dimension ratio is about 20, smaller percentages of chromium are desirable if the dimension ratio is to be increased.

It was mentioned earlier that certain other processes, prolonged gentle heating for instance, had also the effect of hastening the settling down of the magnet into a permanent condition, but as the tests already carried out gave a fairly good idea of the permanence of the magnetism, it was decided not to carry the maturing process any further, but rather to examine the effects of the same processes upon several other series of alloy steels, particularly the more highly magnetic steels, such as tungsten. The examination of these other series is therefore the next stage in the work, the ultimate aim of which is to elicit if possible some information that may be of use in the attempt to obtain an alloy that, both in retentivity and in intensity of residual magnetism, shall attain the desired ideal, and have a coercive force of 80 and a residual magnetism of 800 c.g.s. units.

In concluding this account of the work upon which I have

been engaged during the past years, I desire to take the opportunity of acknowledging my indebtedness to Professor Gray under whose supervision and in whose laboratory the various researches have been carried out, and to Dr. J.G. Gray for the helpful interest he has taken in the work and for many valuable suggestions.

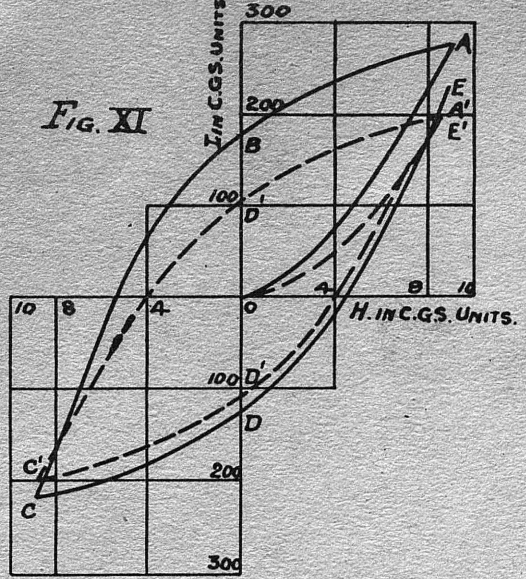


Fig. XI

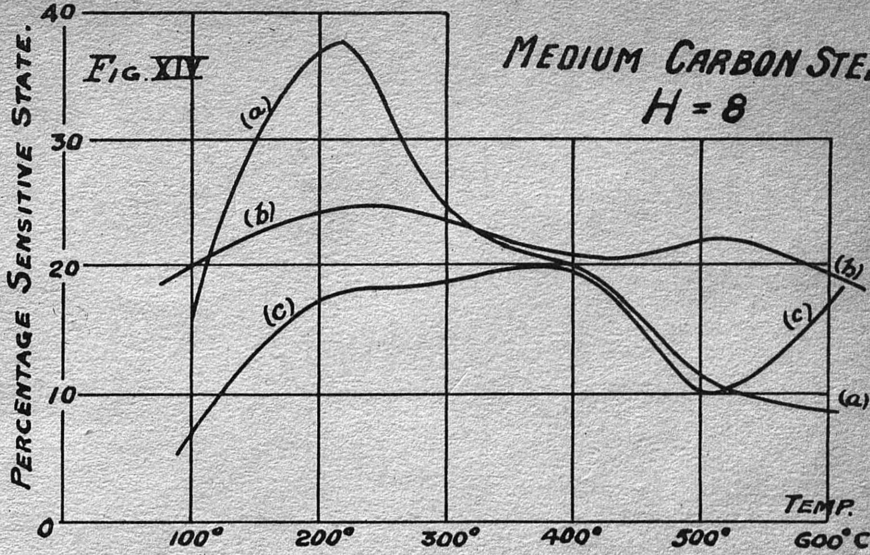


Fig. XIV

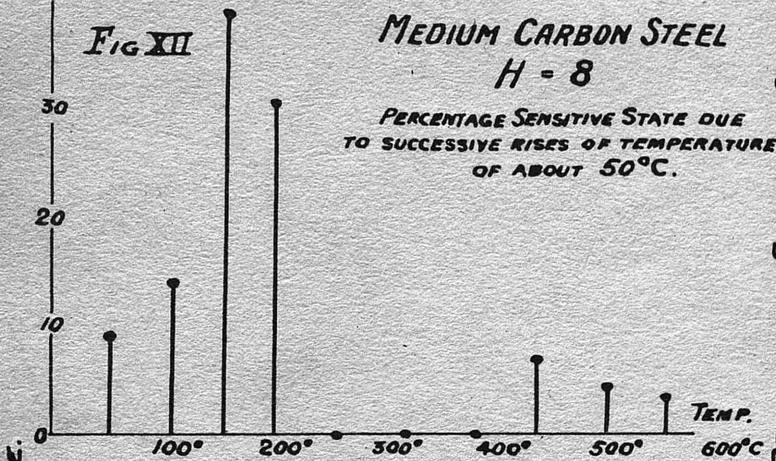


Fig. XII

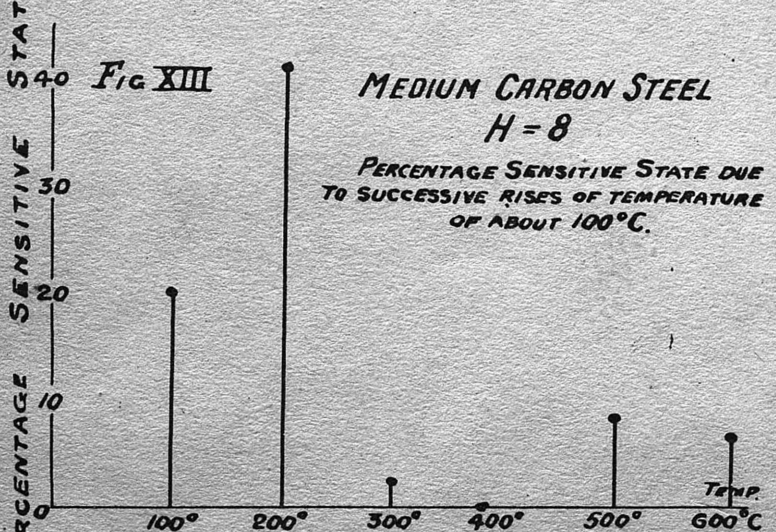


Fig. XIII

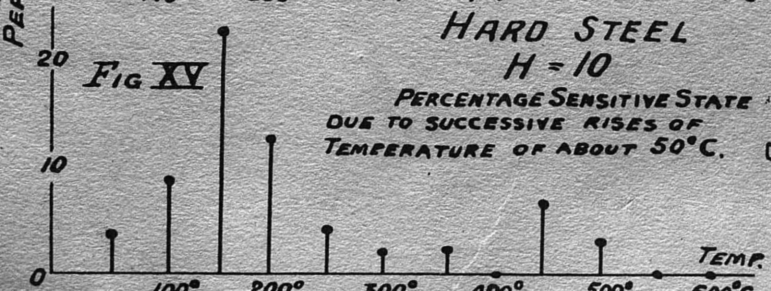


Fig. XV

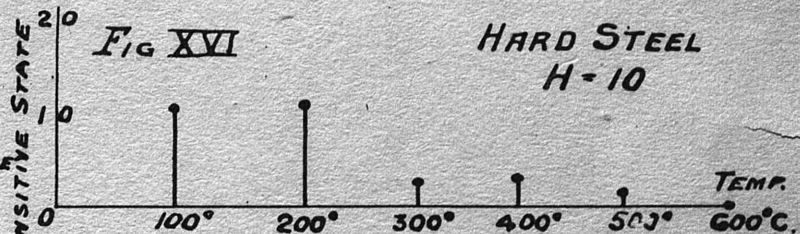


Fig. XVI

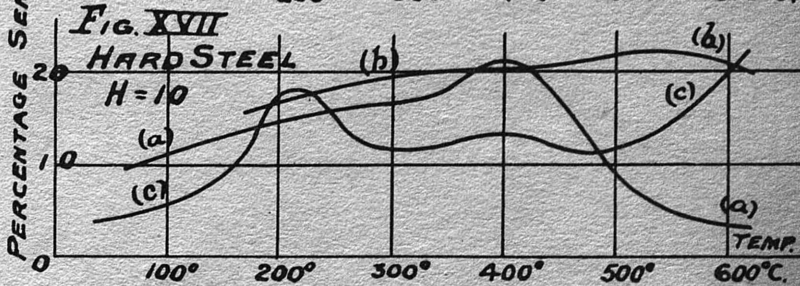


Fig. XVII

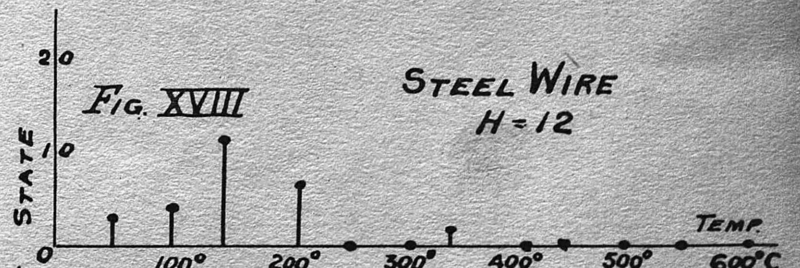


Fig. XVIII

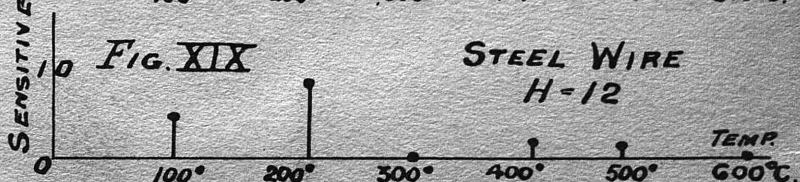


Fig. XIX

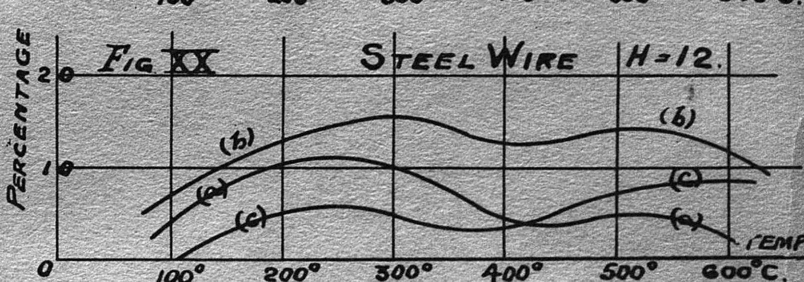


Fig. XX

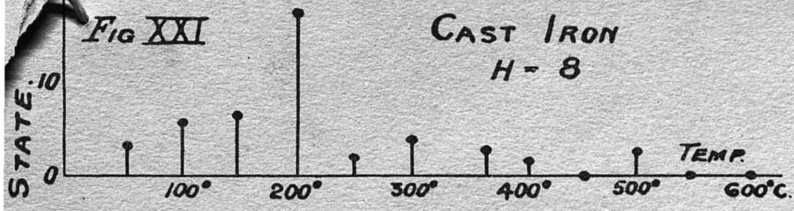


Fig XXI
Cast Iron
H = 8
Percentage Sensitive State
10
0
100° 200° 300° 400° 500° 600°C.
Temp.

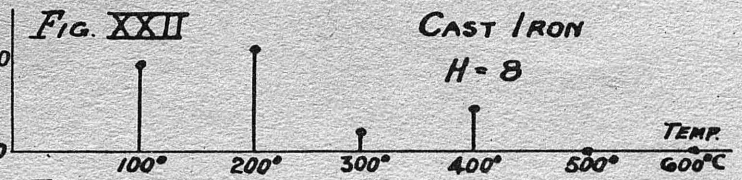


Fig. XXII
Cast Iron
H = 8
10
0
100° 200° 300° 400° 500° 600°C
Temp.

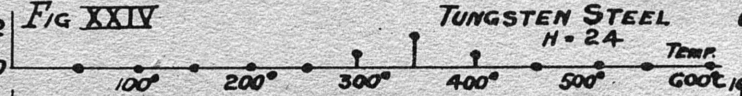


Fig XXIV
Tungsten Steel
H = 24
2
0
100° 200° 300° 400° 500° 600°C.
Temp.


Fig XXV
Tungsten Steel
H = 24
2
0
100° 200° 300° 400° 500° 600C
Temp.

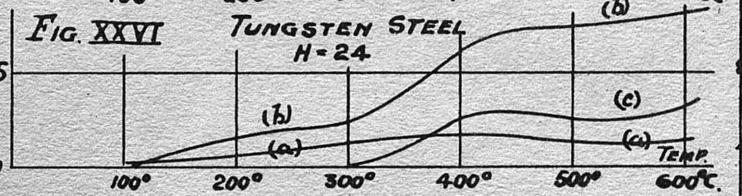


Fig. XXVI
Tungsten Steel
H = 24
5
0
(b)
(a)
(c)
100° 200° 300° 400° 500° 600°C.
Temp.

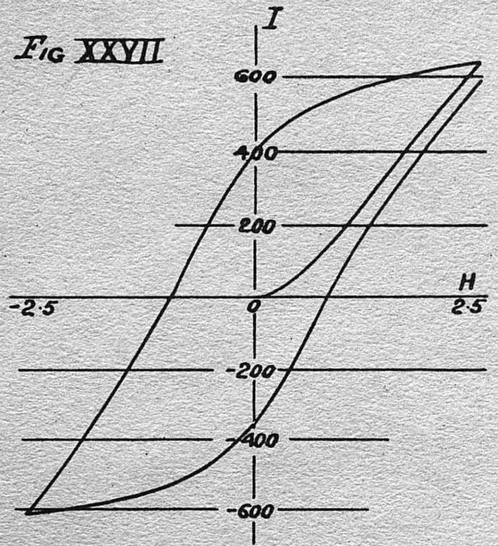


Fig XXVII
I
600
400
200
0
-200
-400
-600
H
-2·5
2·5

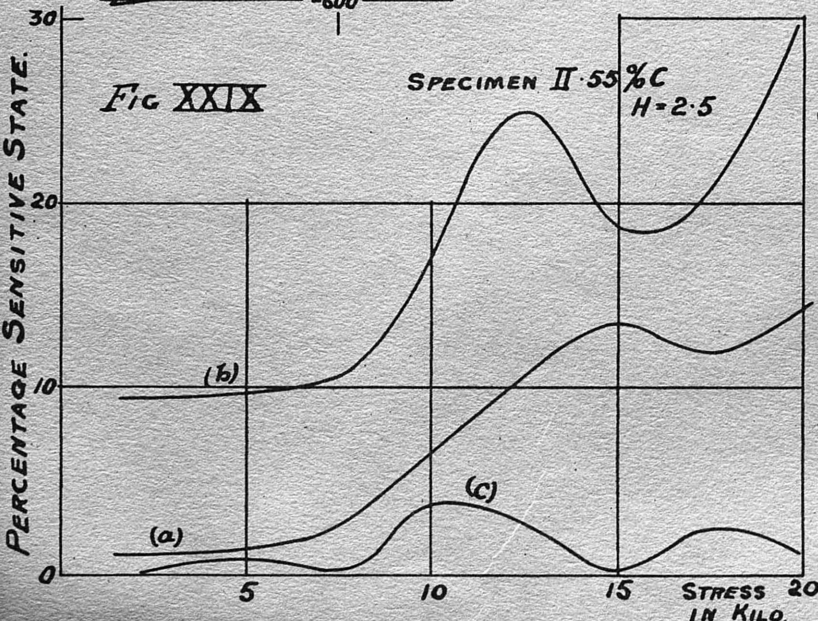
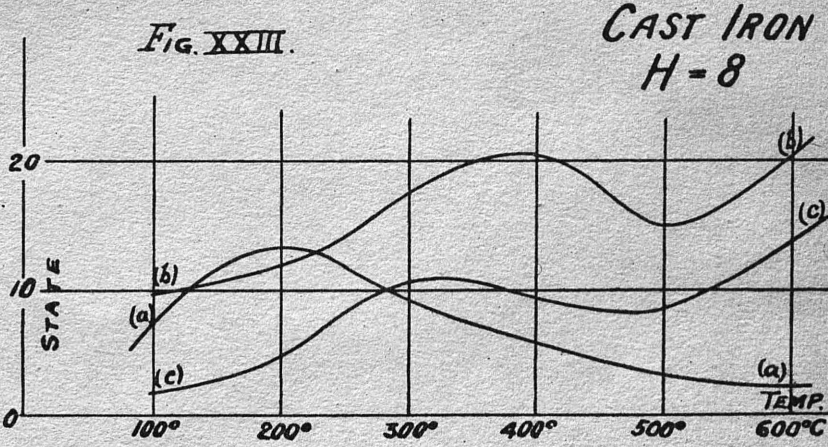


Fig XXIX
Specimen II ·55 % C
H = 2·5
Percentage Sensitive State.
30
20
10
0
(b)
(a)
(c)
5 10 15 20
Stress in Kilo.


Cast Iron
H = 8
Fig. XXIII.
State
20
10
0
(a)
(b)
(c)
100° 200° 300° 400° 500° 600°C
Temp.

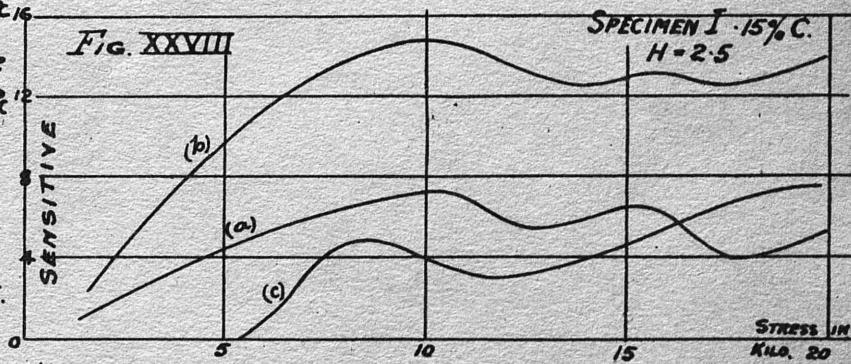


Fig. XXVIII
Specimen I ·15% C.
H = 2·5
Sensitive
16
12
8
4
0
(b)
(a)
(c)
5 10 15 20
Stress in Kilo.

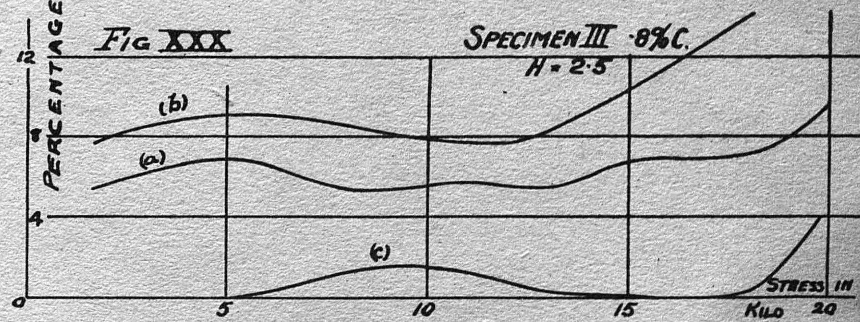


Fig XXX
Specimen III ·8% C.
H = 2·5
Percentage
12
8
4
0
(b)
(a)
(c)
5 10 15 20
Stress in Kilo

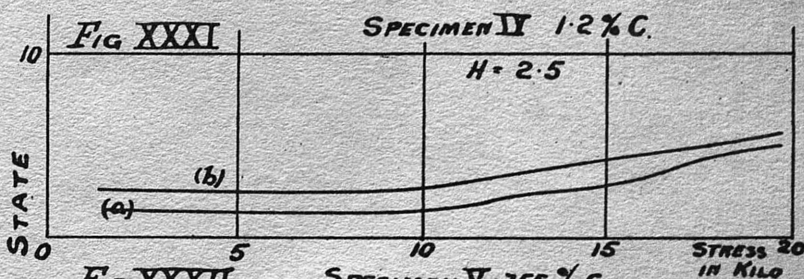


Fig XXXI
Specimen IV 1·2 % C.
H = 2·5
State
10
0
(b)
(a)
5 10 15 20
Stress in Kilo

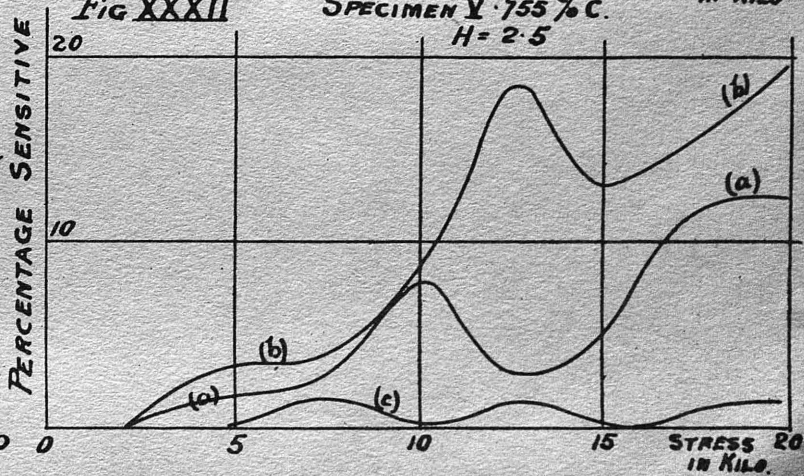
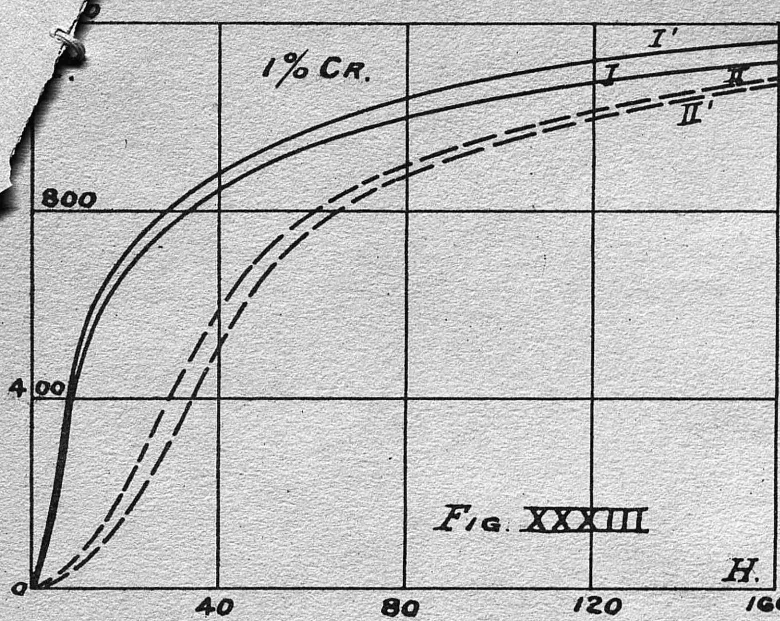
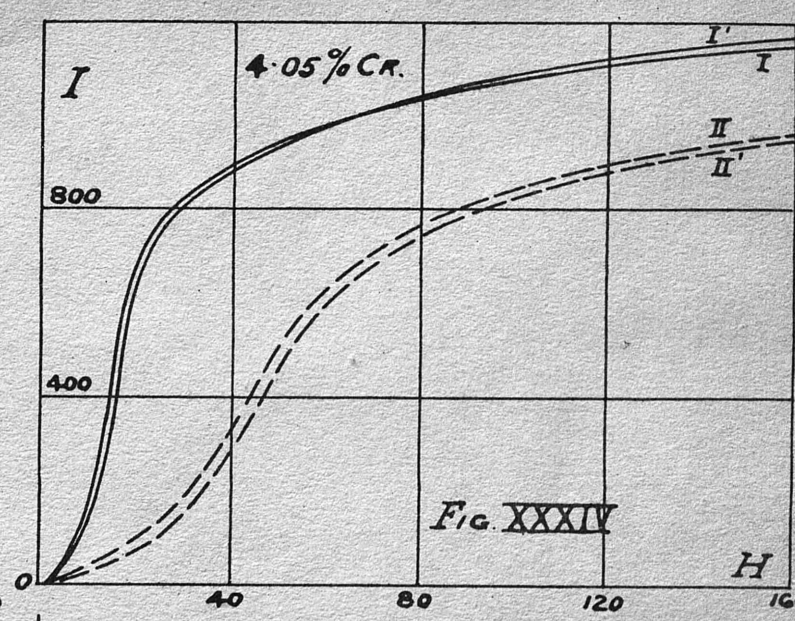
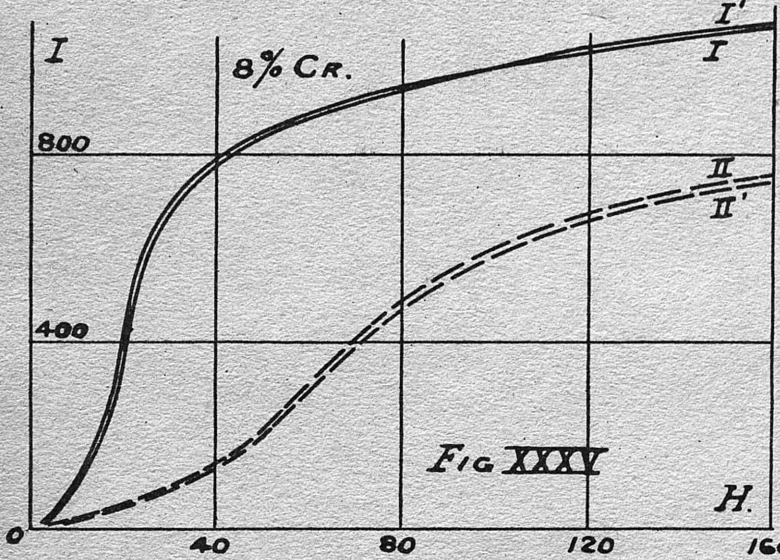
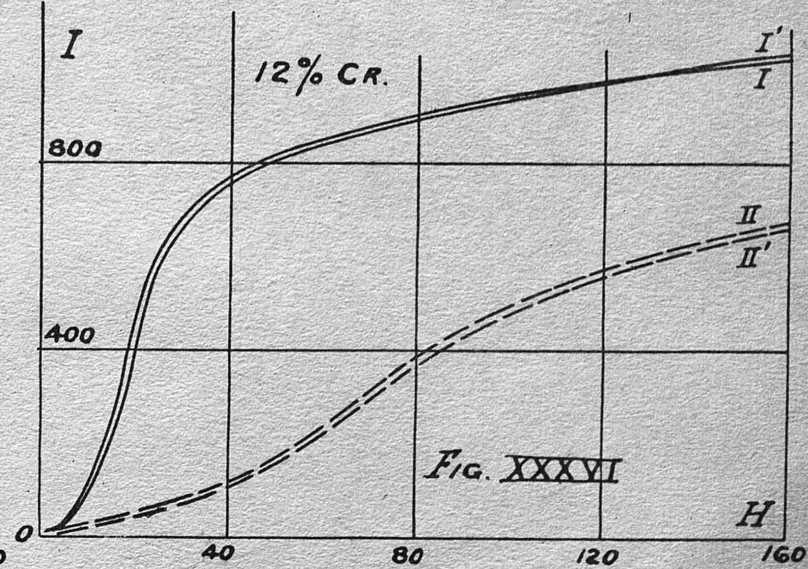


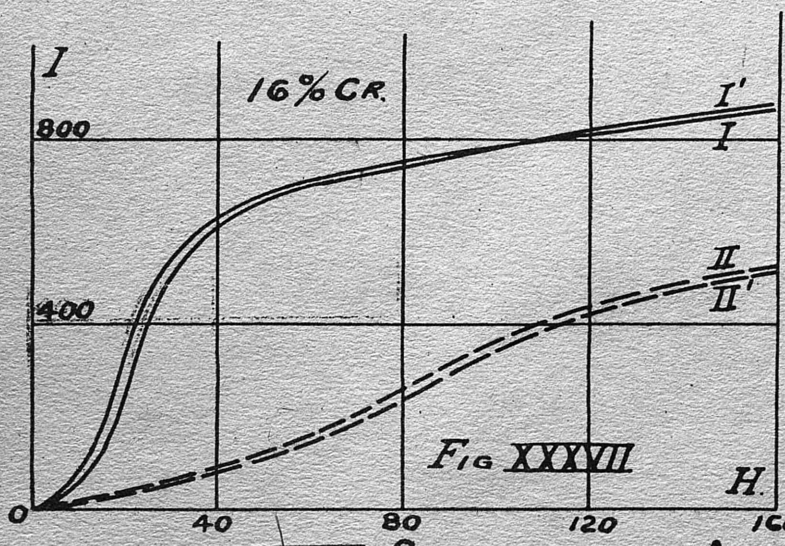
Fig XXXII
Specimen V ·755 % C.
H = 2·5
Percentage Sensitive
20
10
0
(b)
(a)
(c)
5 10 15 20
Stress in Kilo.

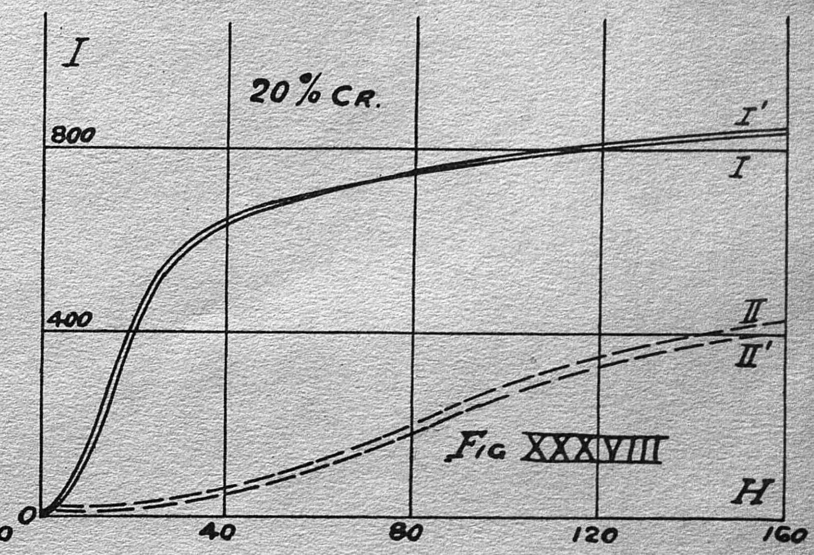












——— SPECIMEN IN ANNEALED CONDITION

- - - - - " " QUENCHED "

I & II TESTED AT ROOM TEMPERATURE

I' & II' " " -190°C.

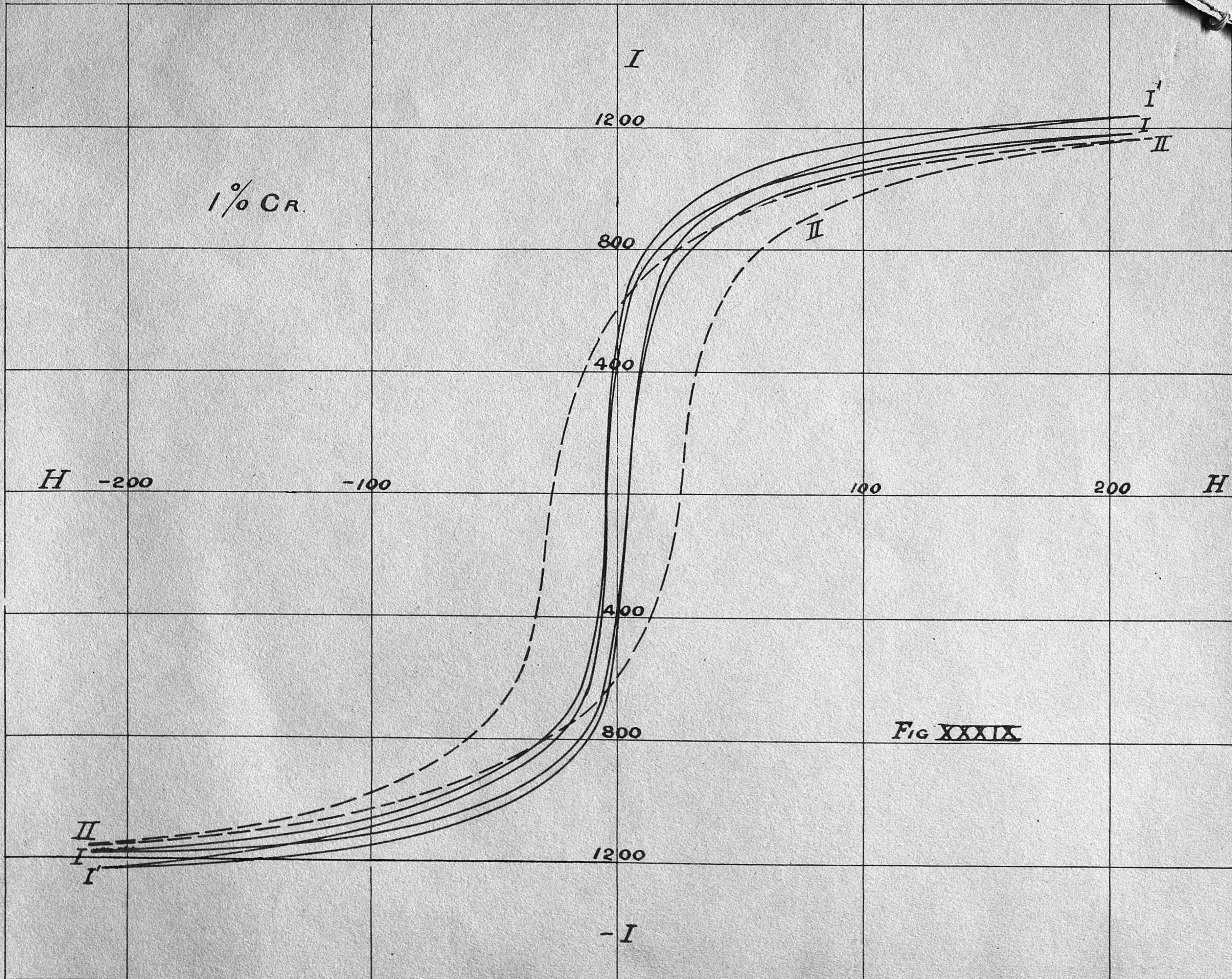
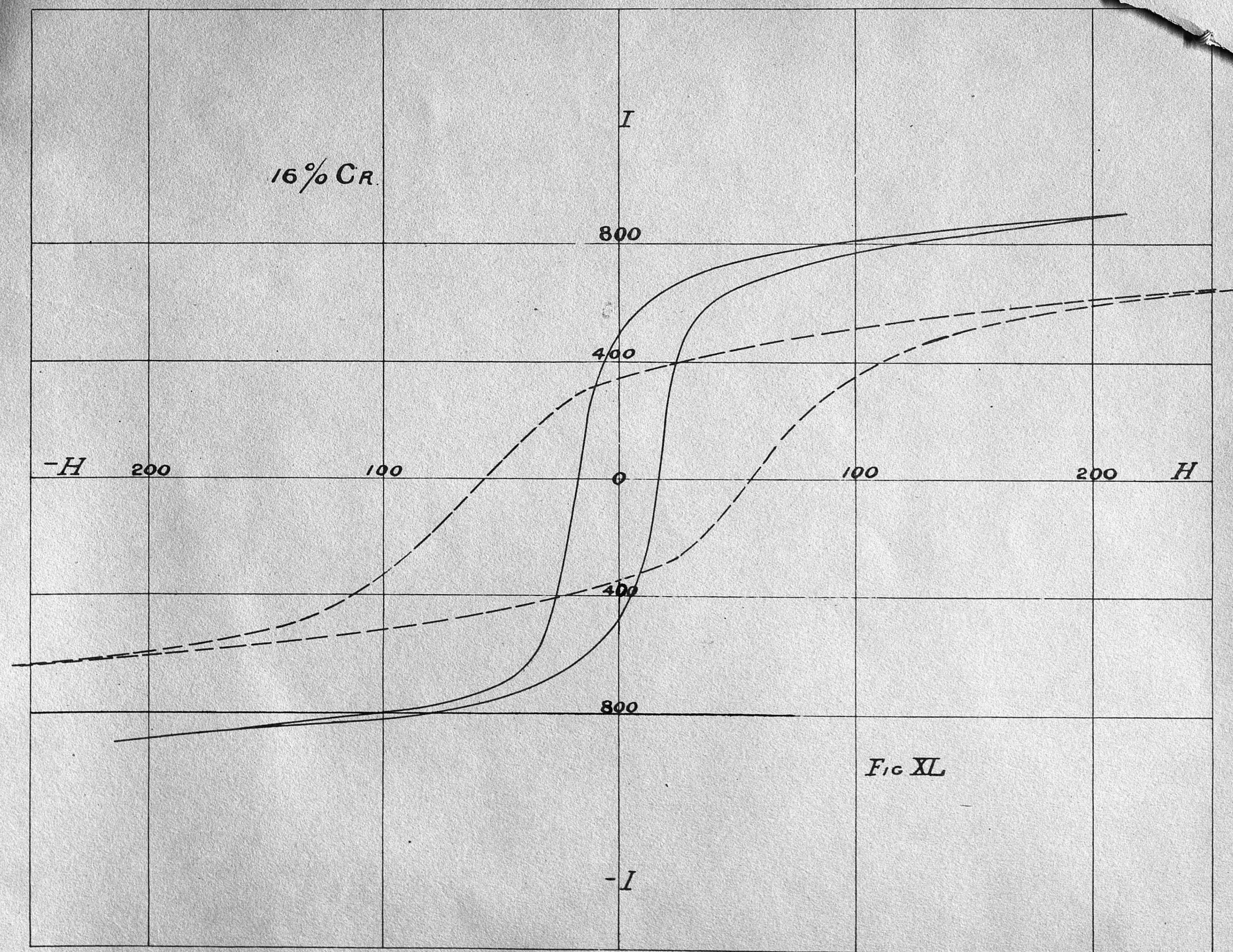


Fig XXXIX


16% Cr.
I
800
400
0
400
800
-I
-H
200
100
100
200
H
Fig XL

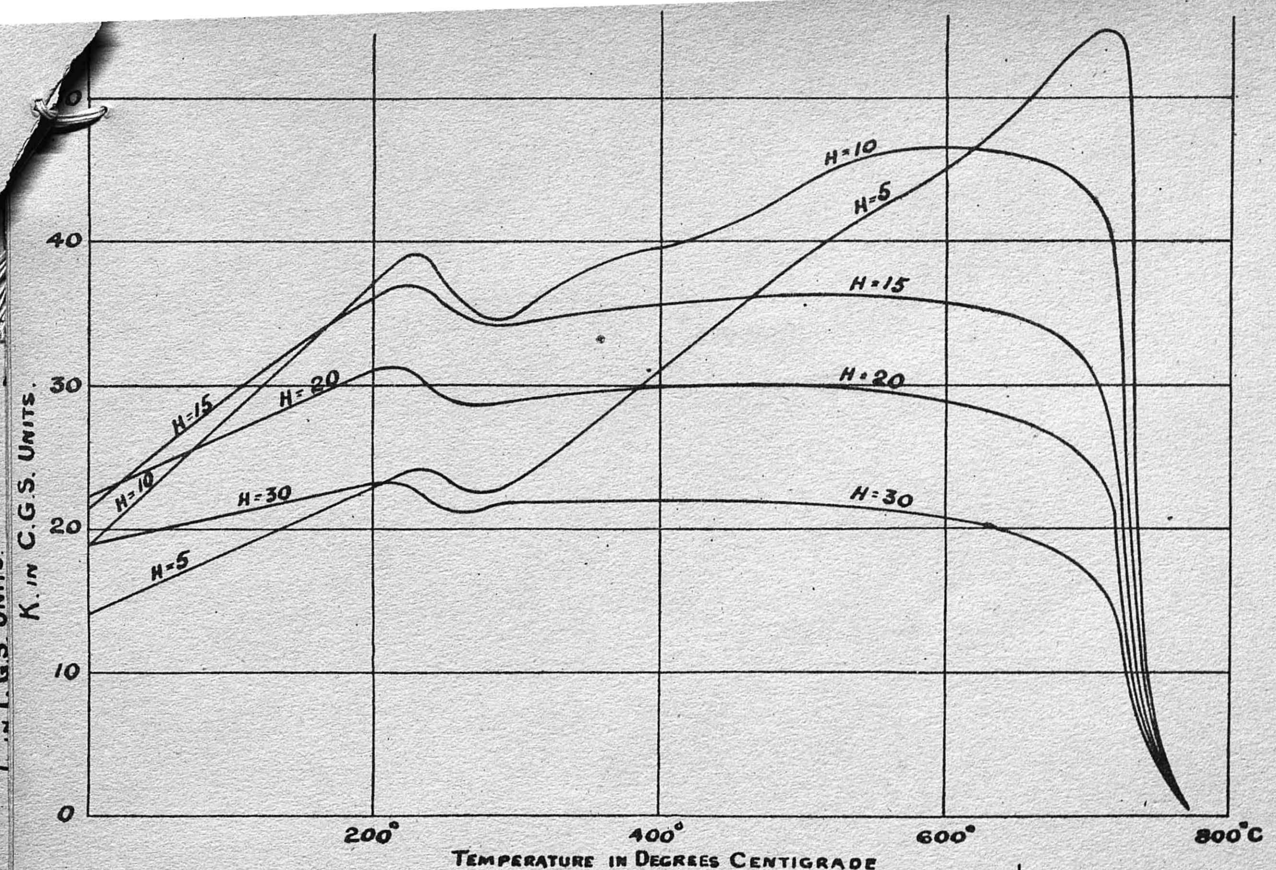


Fig IV Specimen of High Carbon Steel.

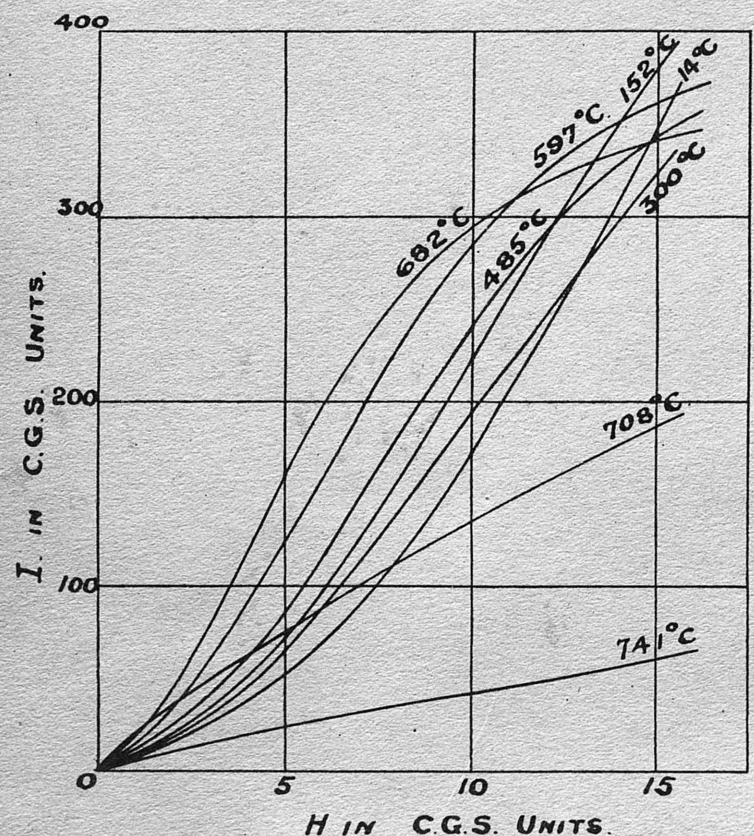


Fig V. Specimen of Medium Carbon Steel

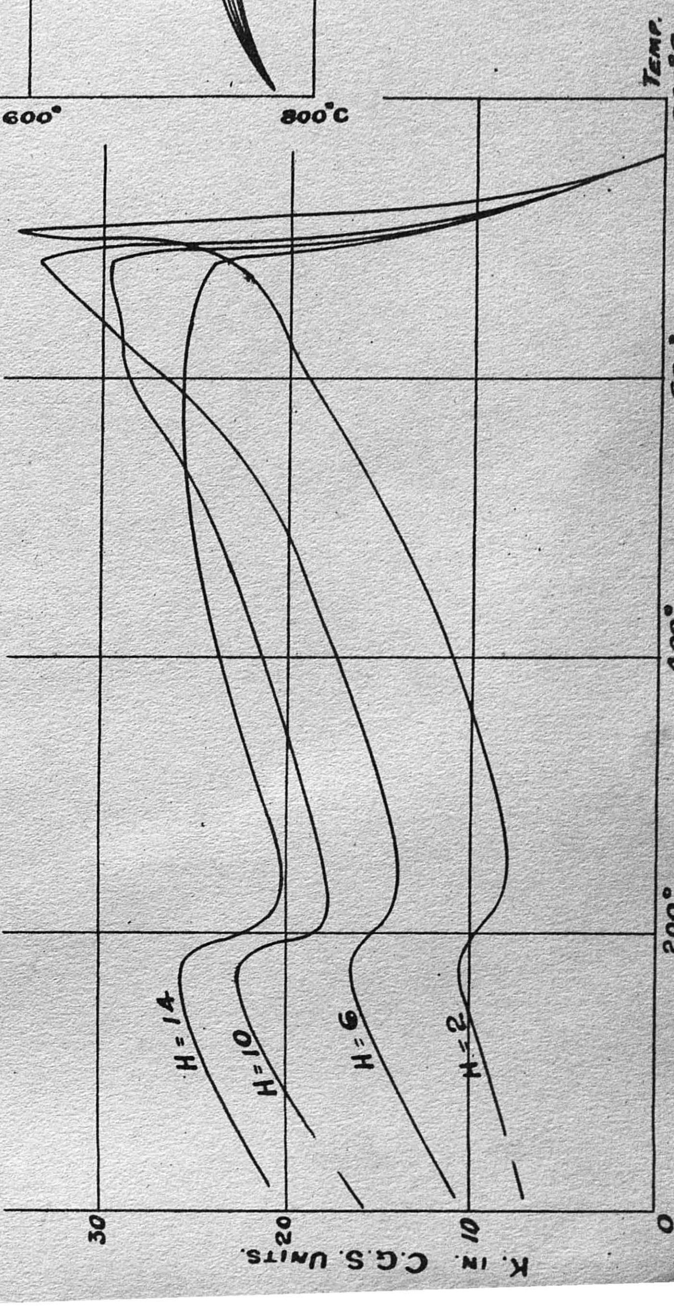


Fig VI Specimen of Medium Carbon Steel.

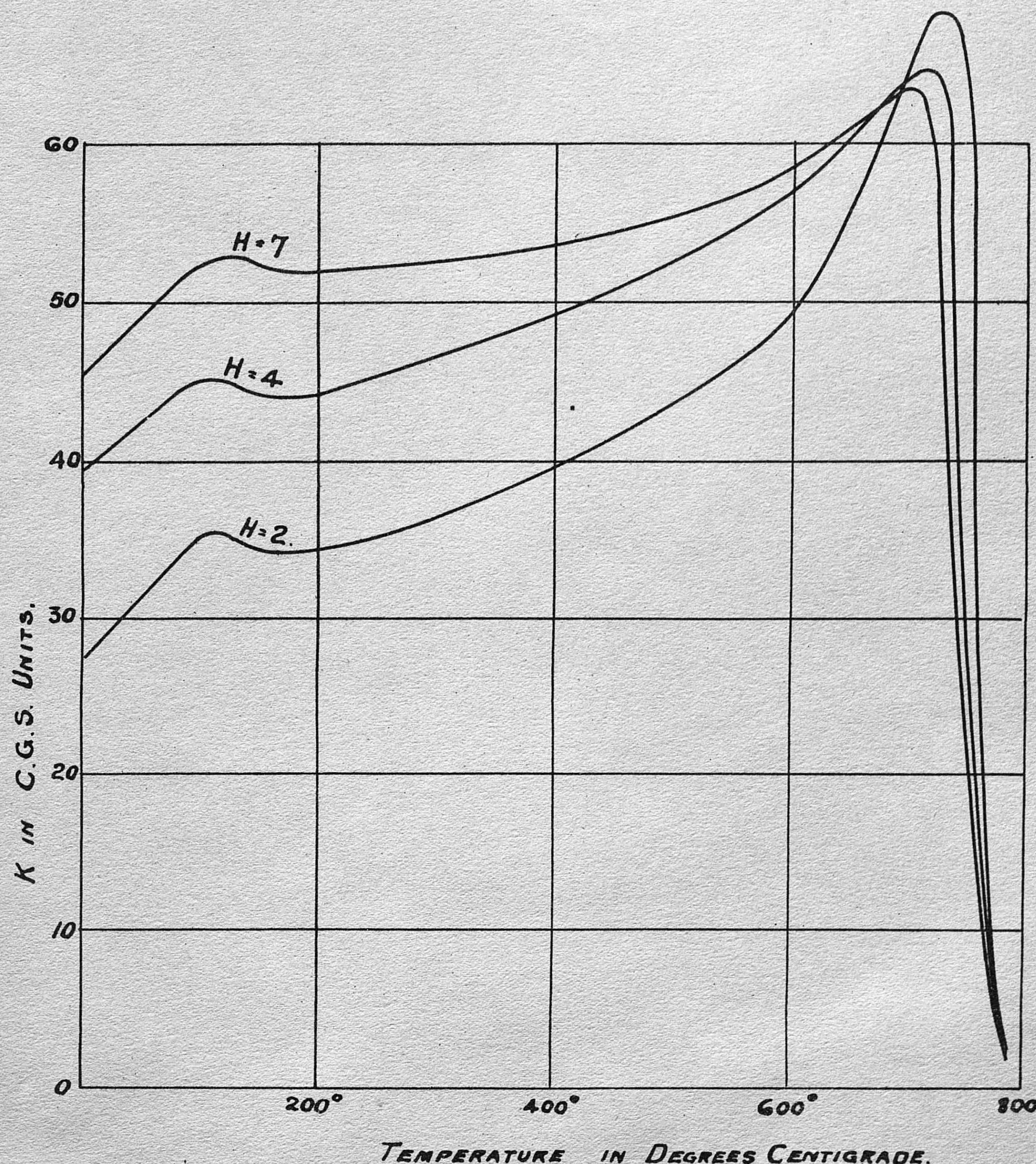


Fig VII Specimen of Low Carbon Steel.

Fig III Specimen of High Carbon Steel.

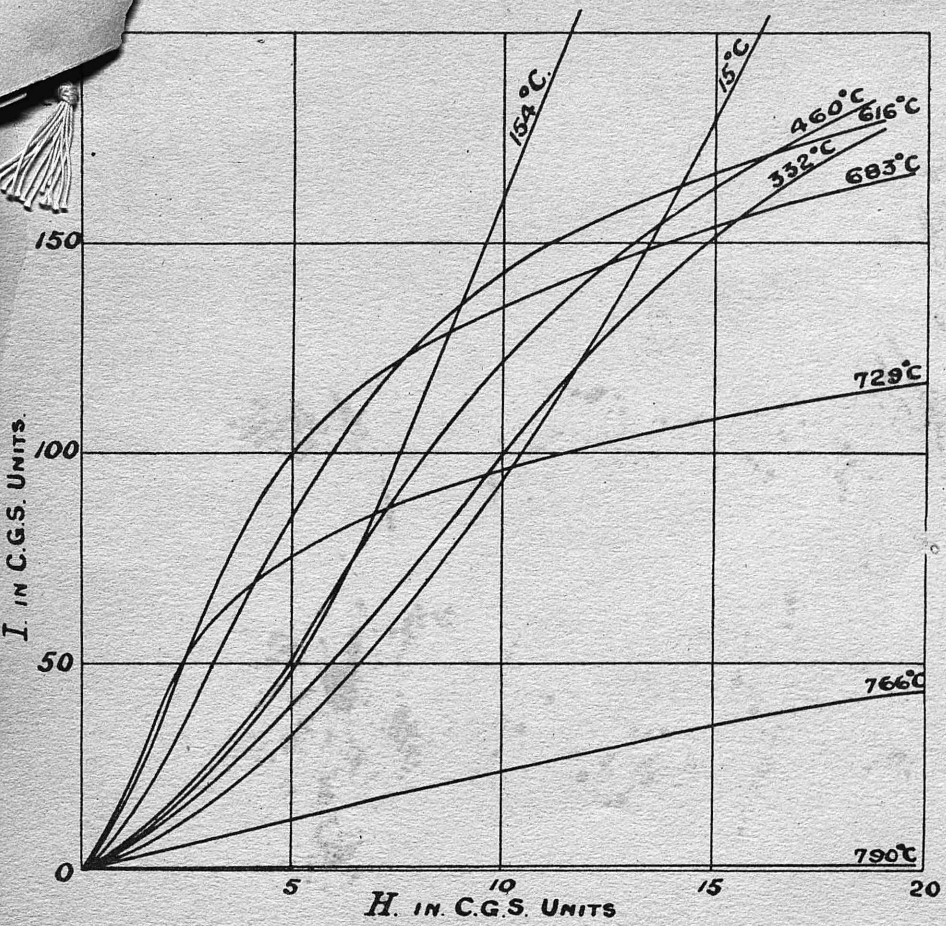


Fig. I Specimen of Cast Iron

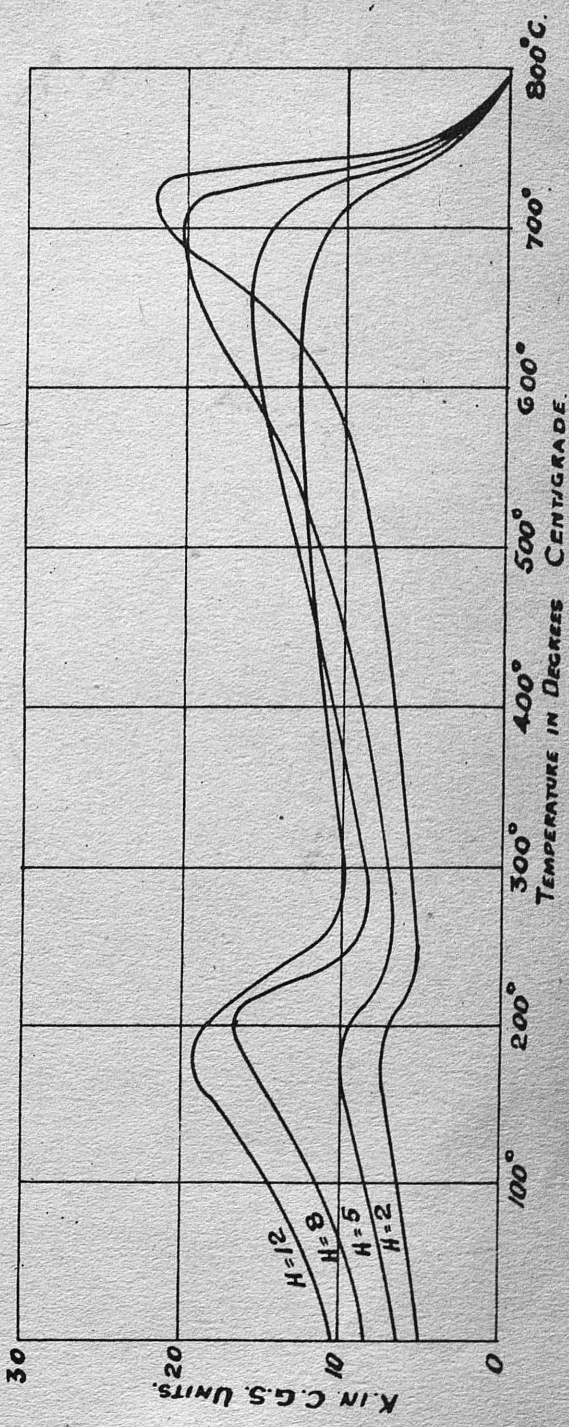


Fig II Specimen of Cast Iron.

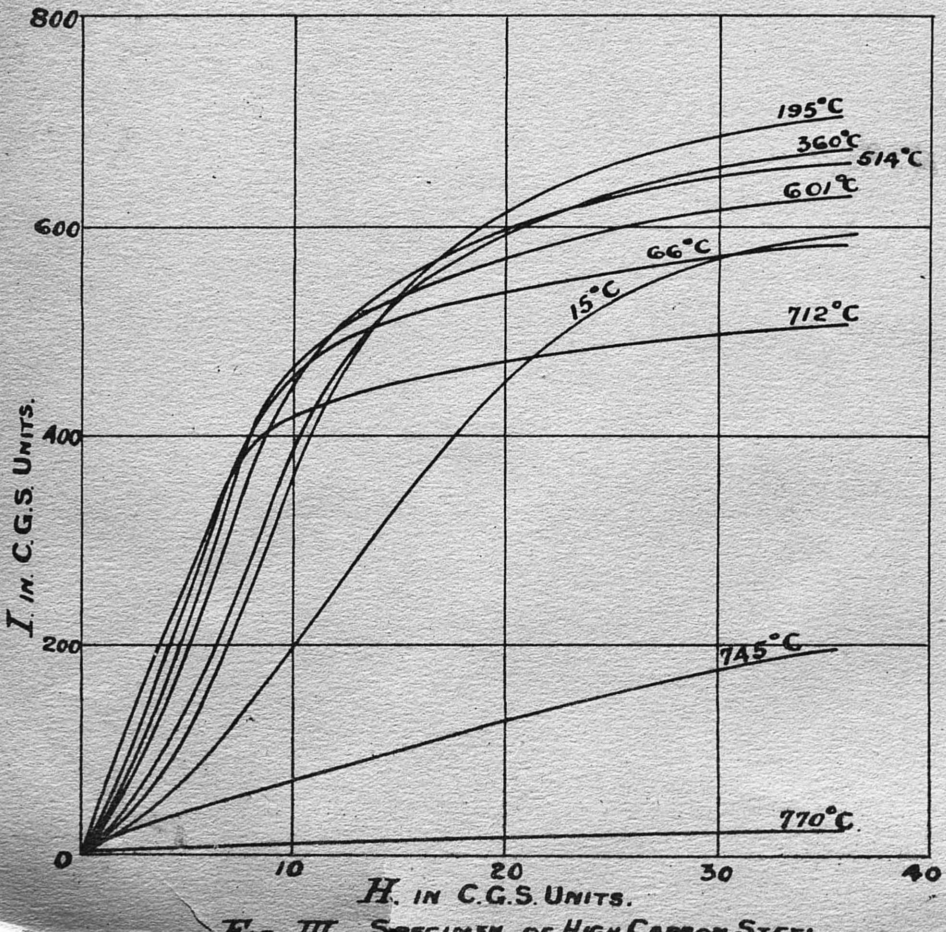
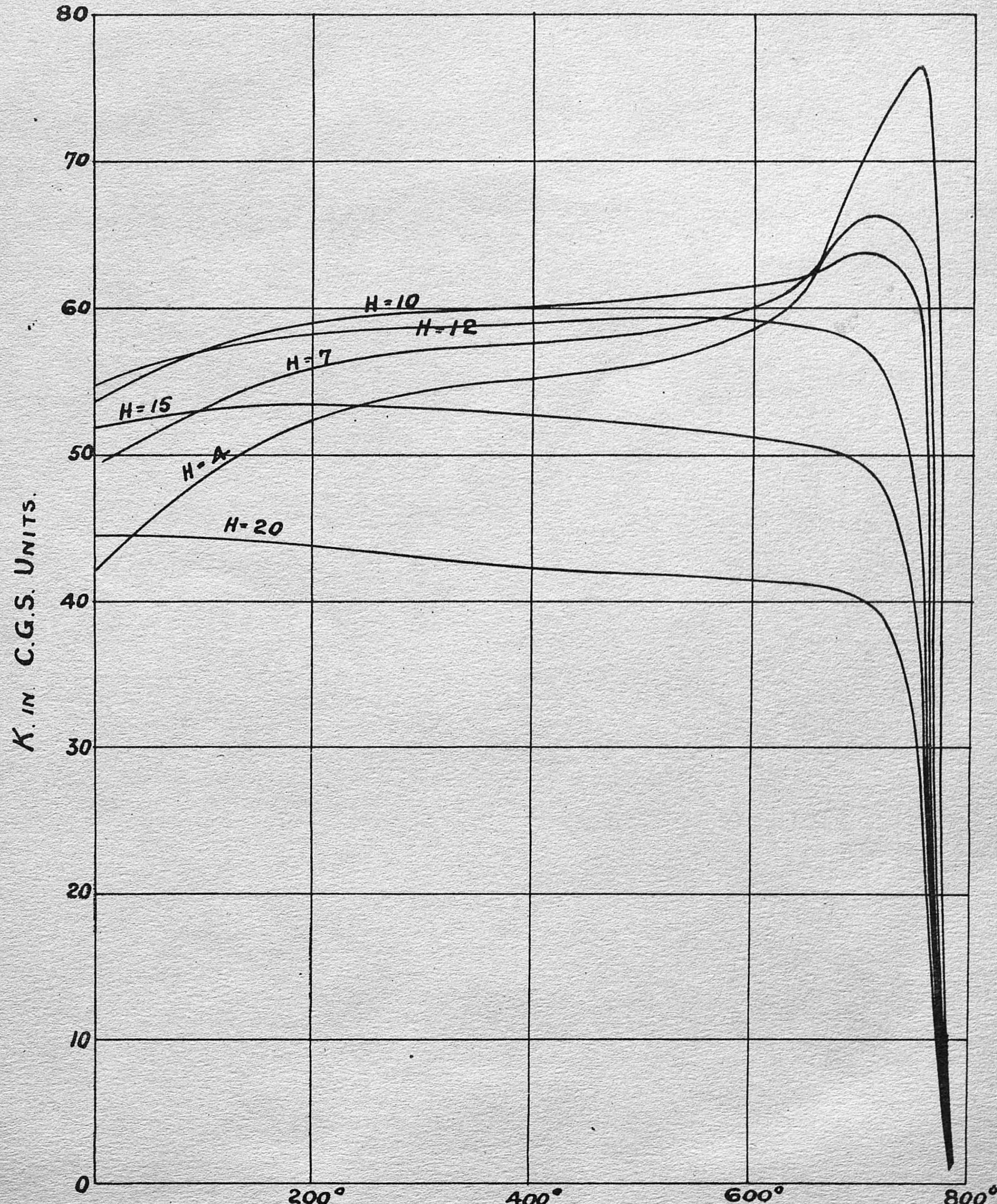


Fig III Specimen of High Carbon Steel.



TEMPERATURE IN DEGREES CENTIGRADE.

FIG VIII SPECIMEN OF SOFT IRON.

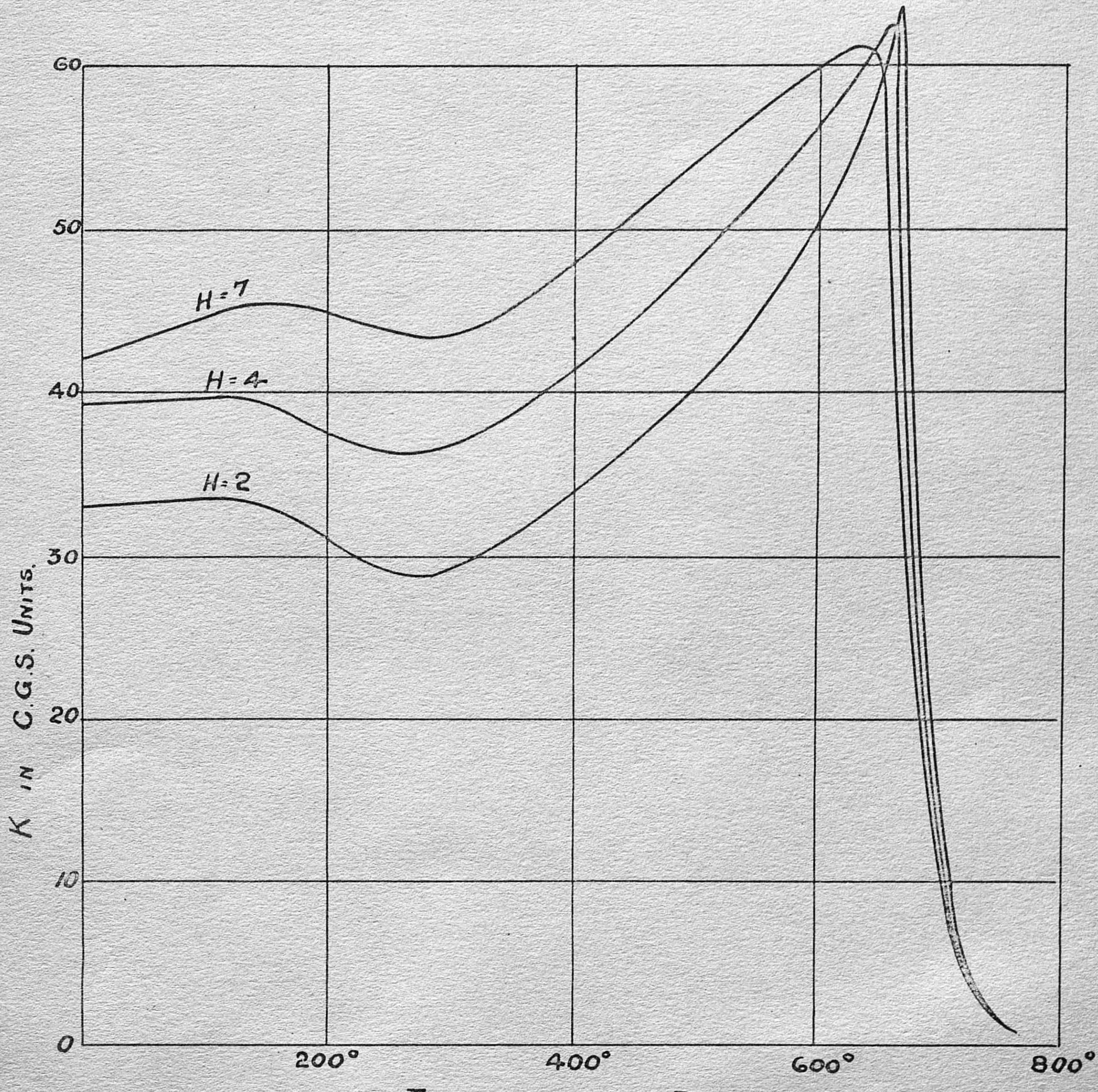


FIG. IX SPECIMEN OF ALUMINIUM STEEL.

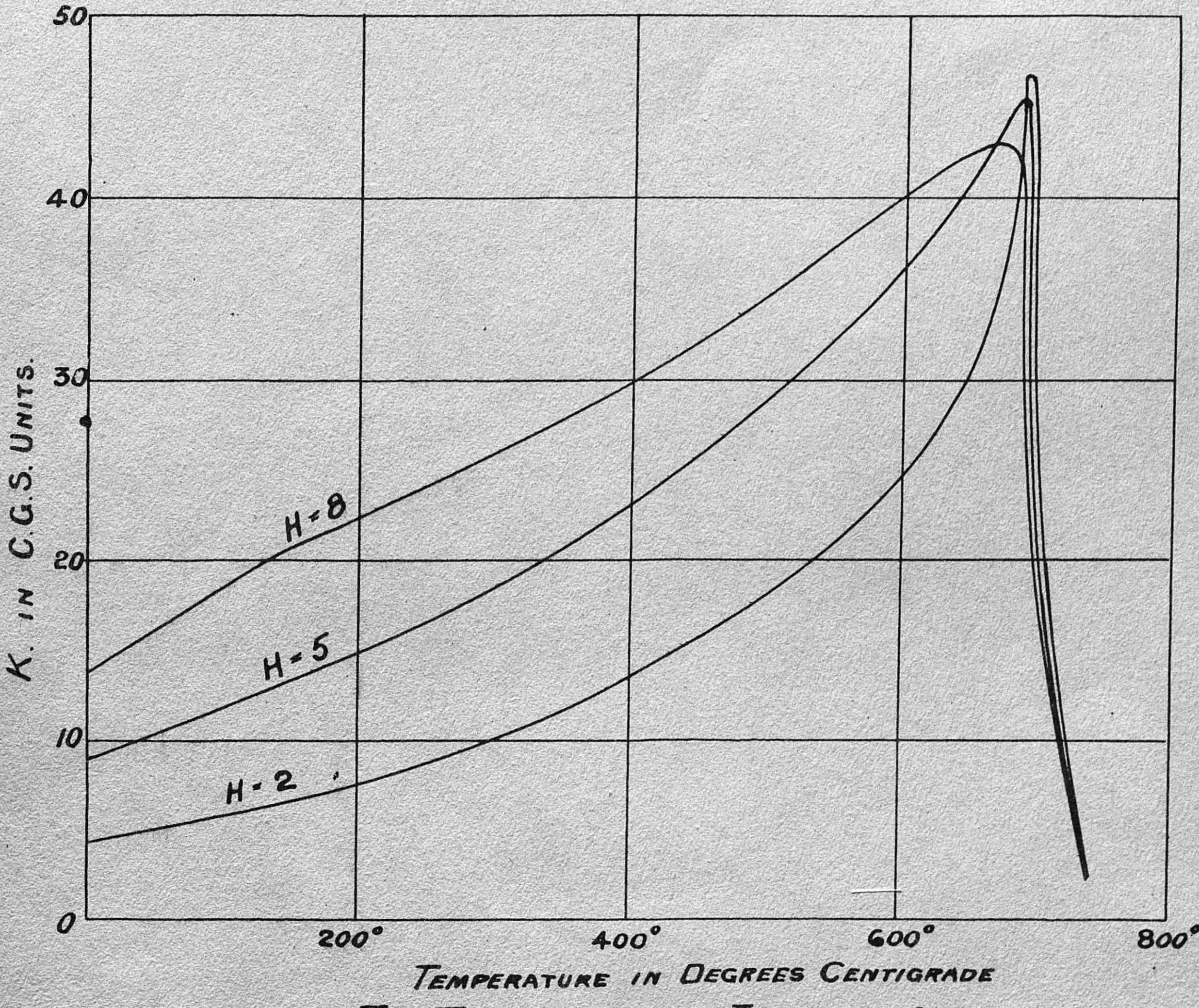


Fig X Specimen of Tungsten Steel.