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VIII. The magnetic properties of the alloys of iron and aluminium—Part I

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VIII. *The Magnetic Properties of the Alloys of Iron and Aluminium.*—PART I. *By* S. W. RICHARDSON, *D.Sc., late* 1851 *Exhibition Research Scholar; Lecturer and Demonstrator in Physics at the University College, Nottingham**.

CONTENTS.

§ I. THE INTRODUCTION.

THE experiments made by Hopkinson† on alloys of iron and nickel led to such striking results that the author thought that experiments of the same nature on other alloys of iron might contribute some interesting facts to our knowledge of Magnetism. Accordingly a series of experiments were undertaken on some alloys of iron and aluminium. An account of the earlier experiments on these alloys, performed at the Cavendish Laboratory during the years 1897 and 1898, is given in this paper; the later experiments being reserved for a subsequent communication.

The alloys were made to the author's order by the British Aluminium Company. Considerable difficulty was experienced at first in obtaining satisfactory specimens, the ones first made being very brittle and liable to split when smartly struck. This was no doubt due mainly to rapid cooling. After taking suitable precautions against this, however, sufficiently durable specimens were obtained—unless the amount of aluminium approached 30 per cent., in which case the alloys gradually disintegrated to fine powder with the evolution of acetylene gas.

The specimens actually investigated contained 3·64, 5·44, 9·89, and 18·47 per cent. of aluminium respectively. The first was comparatively soft and could easily be turned in a lathe; but the other three (in which the carbon was in the combined form) were extremely hard, and it was found impossible to cut them with ordinary tools. The rings used in the experiments were obtained by casting the metal into a disk and boring out the central part of this by means of a rotating copper tube fed with emery-powder and oil.

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* Communicated by the Physical Society: read October 27, 1899.

† 'Proceedings of the Royal Society,' December 1889, January and May 1890.

The experiments made extend over temperatures ranging from −83° C. to +900° C.

To obtain the low temperatures, the specimen, wound with primary and secondary coils, was immersed in an ether bath surrounded by a cooling medium of either ice and salt or carbon-dioxide snow. The ether bath was connected with a water-pump, by means of which rapid evaporation could be set up, and the ether thus cooled below the temperature of the surrounding medium.

The carbon-dioxide snow was obtained from Guinness's brewery, Dublin, and was sent over in a barrel packed with cowhair. Although the journey took three days, the loss due to evaporation was comparatively small, being not more than one quarter of the whole amount. While working with the carbon-dioxide snow the experiments were continued throughout the night, and on one occasion the author conducted an experiment for 36 consecutive hours.

The high temperatures were obtained by means of Fletcher's improved muffle-furnace, furnished with a governor to regulate the supply of gas to the furnace. In later experiments, however, the alloys have been heated electrically by an arrangement similar to that used by Morris* in his experiments on the magnetic properties of iron. This method has been found to be in every respect superior to the furnace method.

The temperatures were deduced from the resistance of the secondary coil, which was of platinum wire, and was wound next to the ring.

The chief results obtained from the experiments recorded in this paper may be summed up generally as follows:—

(1) The alloys behave magnetically as though they consisted of two distinct media superposed.

(2) The general roundness of the curves and their lack of abruptness near the critical point seem to indicate that the alloys are heterogeneous in structure. A similar lack of abruptness near the critical point will be seen in the curves obtained by Hopkinson for nickel-iron alloys.

(3) The permeability decreases with rise of temperature near the critical point until a minimum value is reached, when further rise of temperature produces very slight diminution, if any, in the permeability.

Morris† has shown that in the case of iron we have a remanent permeability after passing the critical point (which result has since been corroborated by Hopkinson ‡).

(4) The experiments suggest that the maximum value of

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* Phil. Mag. Sept. 1897.

† *Loc. cit.*

‡ 'Proceedings of the Royal Society,' 1898.

the permeability for an alloy containing 10 per cent. of aluminium is reached at about −90° C.

(5) An alloy containing 18·47 per cent. of aluminium has a critical point of about 25° C., and gives no indication of temperature hysteresis. This alloy probably has a maximum permeability at a temperature much below −90° C.

§ II. THE MAGNETIC MEASUREMENTS.

Theory of the Method.

The ring of metal X (fig. 1) whose magnetic properties are to be investigated is wound with a primary P_2 and a secondary S_2. The primary is connected in series with a battery B, the primary P_1 of a standard mutual inductance coil Y, an adjustable resistance R, a reversing-key K, and a Weston's ammeter A.

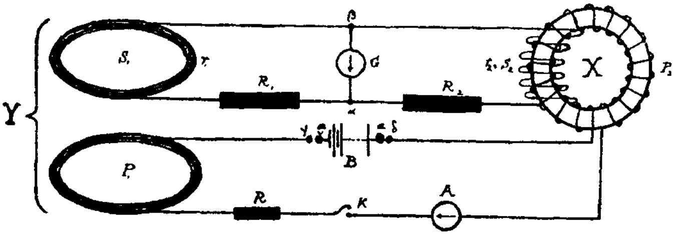
The secondary S_2 is connected in series with the secondary S_1 of the standard mutual inductance-coil Y, and two adjustable noninductive resistances R_1 and R_2.

One terminal of a galvanometer is connected with the point α between R_1 and R_2, and the other terminal with the point β on the opposite side of the bridge.

The secondaries are connected up so that the flows generated in them on reversing the primary are opposed in the branch $\alpha\,\beta$.

The resistances R_1 and R_2 are adjusted until on reversing the primary circuit no *quantity* of electricity passes through the galvanometer.

Fig. 1.



Then, if

B = the induction in the ring X,

σ = the mean sectional area of the ring,

N = the number of turns in the secondary of ring (S_2),

r_2 = the resistance of S_2,

r_1 = „ „ of S_1,

M = the mutual inductance of Y,

γ = the value of the steady current in the primary circuit;

we have

$$\frac{B\times\sigma\times N}{R_2+r_2}=\frac{M\gamma}{R_1+r_1},$$

or

$$B=\frac{M}{\sigma\times N}\,\frac{R_2+r_2}{R_1+r_1}\gamma^*.$$

And if

H = the field strength in the ring X,
n = the number of turns in the primary of X,
d = the mean diameter of the ring,

$$H \doteqdot \frac{4n}{d}\gamma.$$

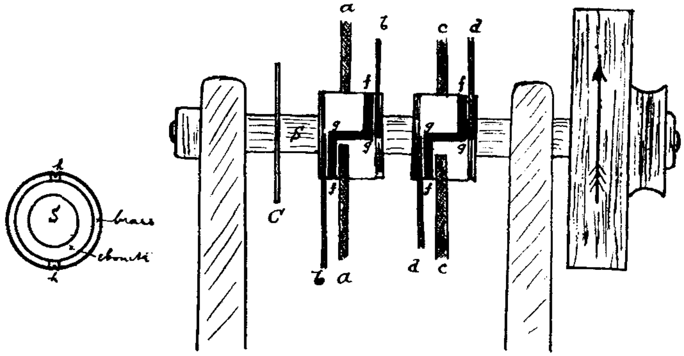
Note.—This is the condition for no quantity through the galvanometer. The condition for no current through the galvanometer cannot be satisfied owing to the variability of the permeability with the field strength. It will, however, be seen later that this did not materially affect the experiments.

Practice of the Method.

The sensitiveness of the method was increased by means of a secohmmeter making about 3 alternations per second.

The secohmmeter D, a diagram of which is shown in fig. 2, consisted of two ebonite rings fitted on to a steel axle S. To each ebonite ring was attached externally a cylindrical brass ring divided along the black lines *f*, *f*.

Fig. 2.



Close to the edges of the brass rings were grooves. In these grooves fitted contacts of copper gauze *b*, *b*, *d*, *d*. Two other pairs of contacts of copper gauze *a*, *a*, *c*, *c*, pressed against the central portions of the brass rings. The contact

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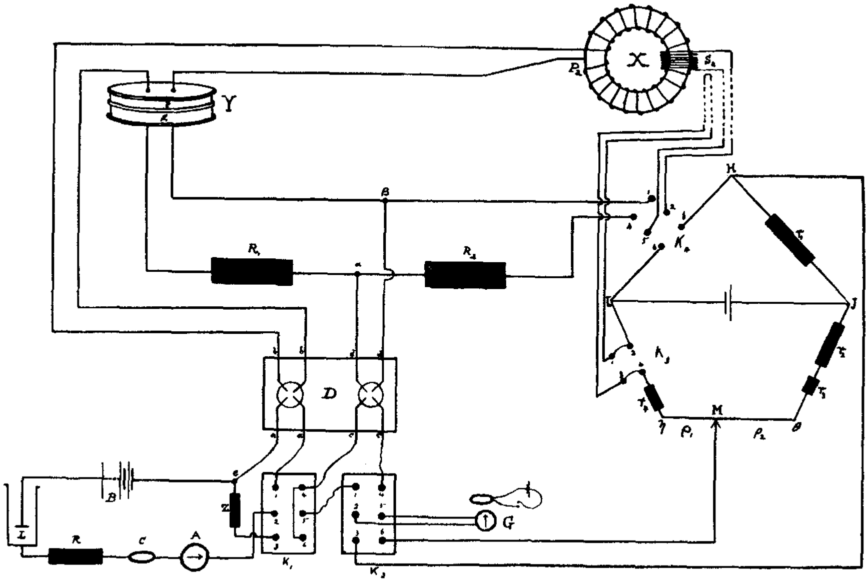
* *Cf.* Maxwell, vol. ii. p. 395.

pieces *a*, *a*, were connected to the two terminals of the battery B, *vide* figs. 1 and 2, and the two terminals *b*, *b*, to the points γ, δ, in the primary circuit (fig. 1). It will be seen that at each half revolution of the secohmmeter the current in the primary circuit was reversed.

The contact pieces *c*, *c* were connected to the two terminals of the galvanometer G (figs. 1 and 3), and *d*, *d* to the points α, β in the secondary circuit. The secohmmeter was driven by a small motor, and the contacts were arranged so that the galvanometer connexions were reversed immediately before the reversal of the battery. The direction of rotation is shown be the arrow (fig. 2).

Pieces of ebonite were fitted into the spaces *g g* to allow the central contacts to pass smoothly over them. In time the insulation becomes impaired owing to the continuous deposition of brass on the ebonite. To prevent this, V-shaped grooves *h*, *h* were cut in the ebonite, and thus the continuity of the deposit was broken. These grooves were scraped out from time to time during the experiments.

Fig. 3.



The Branch Circuit.—To prevent the heating of the primary coils due to the passage of the current for any lengthened period a branch circuit Z (fig. 3), whose resistance was equal to that of the primary coils, was made use of.

The brushes *a a* of the secohmmeter D were joined to the mercury cup 1 of the rocker K_1 and to the point *e* respectively. This rocket serves the double purpose of throwing the current in and out of the primaries and of obtaining a zero. This second purpose is considered under a separate heading. The three arms of the rocker on either side are soldered together. In the initial position the points 2 and 3 are connected up, and the current flows through the branch circuit Z. On reversal, the points 1 and 2 are joined, and the current then flows through the primaries of X and Y.

The Galvan meter.—The resistance of the galvanometer finally used in the experiments was about 7 ohms. It was made as sensitive as possible. A weighted needle was used in the first experiments, but was afterwards discarded as it was found that the gain in steadiness was more than outbalanced by the loss of sensitiveness. The needle was never absolutely at rest, owing to the difference of the time constants in the two secondaries, and the variability of that of X. This effect was not sufficient to prevent the detection of a deflexion of $\frac{1}{2}$ millim. on the scale. The scale was read by means of a telescope placed at some distance from the galvanometer. The mutual inductance Y was placed with its axis vertical, and at such a distance from the galvanometer as not to disturb the needle.

To obtain a Zero.—The mercury cups 4 and 6 in the key K_1 are connected. On reversing the rocker, the galvanometer is first cut out and then reconnected. The lengths of the legs of the rocker are such that the current is reversed *before* the galvanometer is reconnected. If the rocker be turned over slowly, the spot of light moves off continuously from the zero.

The Mutual Inductance.—The coil Y was wound with one primary and three secondaries. The values of the mutual inductances for the separate secondaries were $9{\cdot}04 \times 10^6$, $7{\cdot}014 \times 10^5$, and $4{\cdot}536 \times 10^5$ respectively. It was hence possible to vary considerably the value of the mutual inductance used in the experiments. The values given above were determined by comparison with a standard coil whose mutual inductance had been carefully calculated.

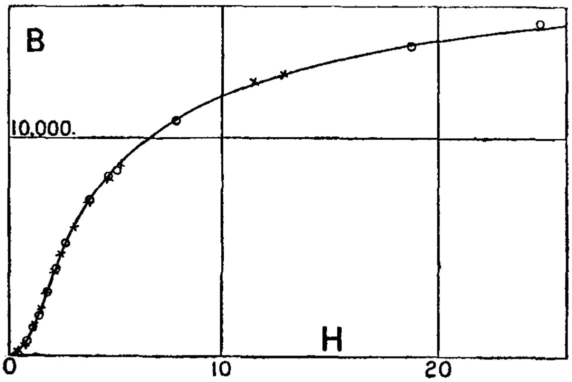
Comparison with the Ballistic Method.—It was thought desirable to compare the results obtained by this method with those obtained from one of the methods in common use. For this purpose a laminated iron ring was wound with primary and secondary coils and was compared with the standard inductance $(=9{\cdot}040 \times 10^6)$, first by the Ballistic Method and secondly by the Balance Method.

The values of the induction obtained in the two sets of experiments are given below.

Ballistic Method.		Balance Method.	
H.	B.	H.	B.
0·97	644	0·52	160
1·24	1,285	0·92	553
1·49	1,870	1·30	1,421
1·85	2,990	1·56	2,190
2·20	4,050	1·81	2,895
2·70	5,230	2·17	3,905
3·90	7,230	2·50	4,730
4·69	8,170	3·13	5,960
5·08	8,470	3·84	7,075
7·82	10,850	4·76	8,150
18·80	14,230	5·40	8,790
24·80	15,150	11·38	12,690
		12·87	13,020
		26·50	15,230

These results are plotted in fig. 4, the ballistic reading being indicated thus ○, and the balance readings thus ×. It will be seen that the two series of results agree with one another within the limits of experimental error.

Fig. 4.



Eddy Currents.—As the rings used in the experiments were not laminated, the question of the influence of the eddy currents set up in them on reversing the primary became an important one.

In J. J. Thomson's Recent Researches, the case of a cylinder placed in a uniform magnetic field which is suddenly destroyed is considered, and it is shown how the total induction in the cylinder at any time t after the magnetic force is destroyed can be calculated if we know the value of $\frac{4\pi\mu a^2}{\sigma}$, where μ and σ are the permeability and specific resistance of the material of the cylinder and a is its radius. We can make use of this result to form an approximate idea of the speed at which the secohmmeter might be driven without materially affecting the magnetic measurements.

The greatest permeability for alloy No. 1, which is the most permeable of the three specimens considered in this paper, was 680. If we take a as 0·6 cm. and σ as 20,000 (the temperature being 380° C.) $\frac{4\pi\mu a^2}{\sigma}=0{\cdot}15$. A comparison with the table on p. 357 ('Recent Researches') will show that in this case the total induction will have diminished to 1 per cent. of its original amount in 0·1 of a second.

Hence we see that the number of alternations per second in the experiments on this alloy should be less than 10 per second, in order that the results may be relied upon to 1 per cent.

In general the secohmmeter made about 3 alternations per second. It could easily be seen whether, in any given case, the eddy currents were affecting the measurements, by obtaining a balance and then allowing the speed of the secohmmeter to increase.

The effect of eddy currents would be shown by the balance being disturbed.

Care was taken, during the experiments, that the speed of the secohmmeter should in all cases be less than that at which this occurred.

§ III. The Determination of the Temperature.

The resistance of the secondary of the ring (which was of platinum wire and was wound next to the ring) was taken as a measure of the temperature. Thick platinum leads were connected to the secondary close to the ring, and after passing out of the box containing it dipped into mercury cups suspended in an oil-bath. From these cups copper wires passed to the key K_4 (fig. 3), by means of which the secondary could be connected at will to either the magnetic bridge or the wire bridge. Side by side with the platinum leads were placed compensating leads. These were cut from the same specimen of wire as that used for the leads to the secondary, and also dipped into mercury cups suspended in the oil-bath. Copper wires of the same resistance as those connected to K_4 joined these cups with the key K_3.

The object of the oil-bath was to maintain the junctions of platinum and copper at the same temperature, and thus get rid of thermoelectric currents.

The leads were protected from direct heating by the furnace by means of a thick sheet of asbestos.

The resistance-bridge H L M J was so arranged that the resistance of the secondary could be obtained directly from one observation.

This end was gained by the following device:—

The resistance of the arm HJ was made equal to 1001 ohms.

The resistance of MJ consisted of three parts, r_2, r_3, and ρ_2. r_2 was a resistance of 1000 ohms; r_3 consisted of coils of tenths of an ohm; and ρ_2 was part of the bridge-wire $\eta\theta$.

The resistance of the whole wire $\eta\theta$ was slightly greater than 1 ohm. Hence, by taking the proper plugs out of r_3, the resistance of ρ_2 and r_3 could be made together equal to one ohm to within one-twentieth of an ohm; *i. e.*, the resistance of the arm MJ is equal to 1001 ohms to within a twentieth of an ohm. To obtain a reading, the secondary and galvanometer are switched on to the wire-bridge by means of the keys K_4 and K_2, and r_4 and ρ_1 are adjusted until there is a balance [with $MJ \doteq HJ$].

When this is the case the resistance of the secondary is given by

$$r_t = r_4 + \rho_1.$$

The compensating leads are connected to the arm LM by the key K_3.

The resistance of different lengths of the bridge-wire having been previously tabulated, the resistance of the secondary could be read off directly from the scale.

The temperature t of the ring of alloy was obtained from r_t by means of Callendar and Griffiths's well-known formula

$$t = 100\frac{r_t - r_0}{r_{100} - r_0} + \delta\left[\left(\frac{t}{100}\right)^2 - \frac{t}{100}\right],$$

r_{100}, r_0 being the values of r at 100° C. and 0° C. respectively, and δ having been obtained from observations in the vapour of boiling sulphur.

[To obtain the resistance of the secondary and leads together, the mercury cups 2 and 4 in the key K_3 were joined by a thick copper wire. Then we have, when balance has been obtained as before,

$$r_t + \text{leads} = r_4' + \rho_1'.]$$

As the secondary is outside the ring whose temperature is required, care is necessary to insure that the temperature of the ring does not materially lag behind that of the thermometer.

To avoid the error due to this cause as far as possible, readings were only taken when the temperature was practically stationary.

The close agreement of the results obtained under different conditions shows that the temperature of the ring could not have been greatly different from that of the secondary. As it was impossible to read the magnetic bridge and the resistance bridge simultaneously, the time of each observation was recorded. A time and temperature curve was plotted, and from this the temperature at the time of taking a magnetic observation was inferred.

§ IV. METHODS USED FOR VARYING THE TEMPERATURE AND FOR INSULATING THE COILS.

(1) *Experiments at High Temperatures.*

Asbestos paper was used as an insulator in these experiments. The specimen of paper used was obtained from Bell & Sons and was of a very superior quality. After heating to a white heat and subsequently cooling, the discoloration was very slight—the paper then having a faint yellow tinge. The paper also held well together after heating, and showed no signs of crumbling. The amount of carbonaceous matter present must have been very much less than that contained in the paper usually found in the market.

The paper was cut into strips of about 1 cm. width.

A double layer of this paper was wound next to the ring. Outside this the platinum secondary was wound, a double layer of paper being twisted round the wire during winding; this thickness of paper being again doubled for the first and last wind. The primary was of copper wire insulated in the same way as the secondary, a double layer of paper being wound between the primary and secondary.

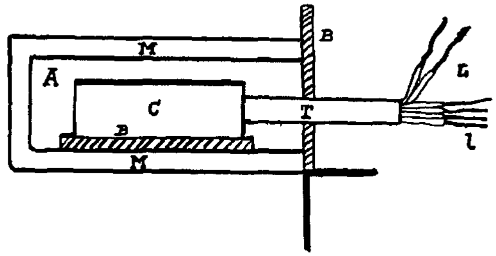
The ring when wound was placed in a copper box, to which a copper tube of about 8 inches in length was attached.

The box was placed in the muffle of a Fletcher's "Improved Muffle" Furnace, being separated from direct contact with it by means of a thick pad of asbestos board. The mouth of the muffle was closed with another piece of asbestos board, through a hole in which the tube attached to the box passed.

This copper tube, through which the leads passed, served the double purpose of protecting them from the action of the furnace gases and at the same time of maintaining the temperature round them comparatively steady.

The arrangement of the apparatus is shown in fig. 5.

Fig. 5.



M = muffle.
A = air-space.
C = copper box.
T = copper tube.

B, B = asbestos board.
L = primary leads.
l = secondary and compensating leads.

A small governor was connected up between the main gas-supply in the laboratory and the furnace. By this means the pressure of the gas at the furnace was kept constant.

The insulation-resistance between the primary and secondary was tested from time to time during the experiments. It was found to be always greater than 500,000 ohms.

(2) *Experiments at Temperatures between* 0° C. *and* 50° C.

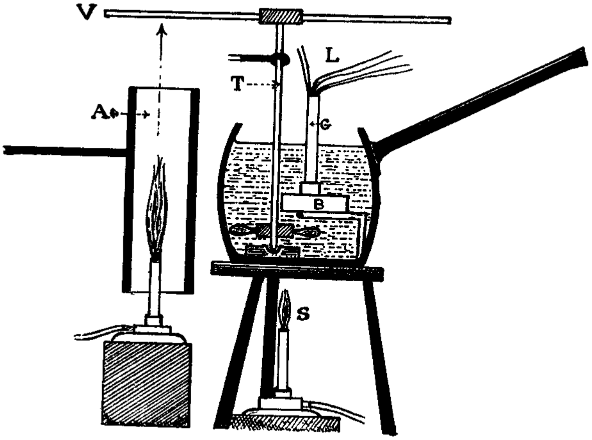
The ring was placed in a thin-walled copper box, which it almost completely filled. A piece of copper tubing of about one inch in length was fastened to one side of the box, and to this was attached a piece of glass tubing of about one foot in length, through which the leads passed. The glass tube was attached to the brass one by means of a joint made with Thomas's alloy. This alloy melts at about 75° C. and expands considerably on solidifying. If a piece of glass tubing is placed concentrically within a brass tube of somewhat greater diameter, and the melted alloy is run into the clear space between the two tubes, a very good mechanical air-tight joint is obtained. A glass tube is used to carry the leads in preference to a metal one, as it is desirable to prevent, as far as possible, the passage of heat between the cavity containing the ring and the external air.

In working at temperatures much below zero this precaution was found very necessary.

The general arrangement of the apparatus is shown in fig. 6. The box containing the ring was placed in a vessel of water which was heated from below by a bunsen-burner. The water was automatically kept in movement by means of a stirrer driven by a current of air passing through an asbestos cylinder and impinging upon a wind-wheel V.

To obtain temperatures between that of the atmosphere and that of ice, the source of heat was removed and small pieces of ice were added to the water from time to time until the desired temperature was obtained.

Fig. 6.



V = wind-wheel.
T = stirrer.
B = copper box.
G = glass tube.

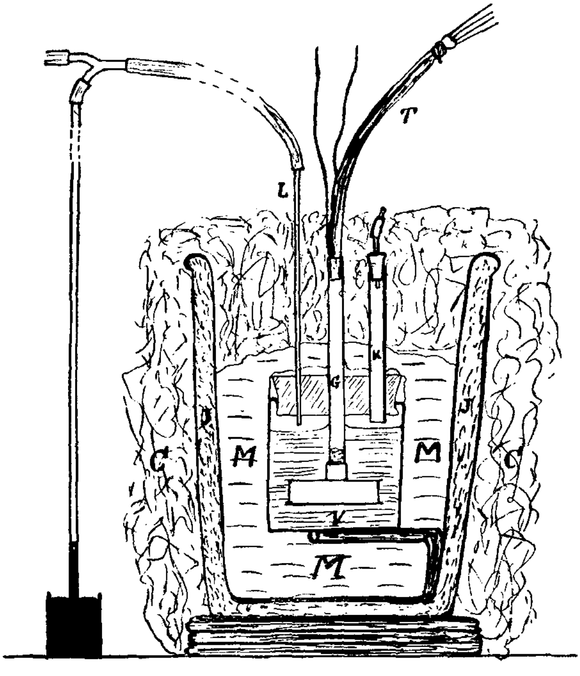
L = leads.
S = source of heat.
A = asbestos cylinder.

(3) *Experiments at Temperatures below Zero.*

The same box and attached tube was used as in the last series of experiments. It was found that, at the low temperatures used, ice formed to the thickness of a centimetre or more along the metal leads, owing to the condensation of the moisture in the air, and thus the insulation was endangered.

To overcome this difficulty the following arrangement was adopted (fig. 7). The secondary and compensating leads were surrounded by an indiarubber tube T, the free end of which was carefully closed. Some portion of this tube passed down into the glass tube G. This was then filled with melted paraffin. By this means the access of moisture to the leads was confined to that in the indiarubber tube, and the formation of ice upon them was almost entirely stopped. The closing of the glass tube also prevented the circulation of air between the surrounding atmosphere and the interior of the box, and the consequent heating of the ring. The box containing the ring was placed in the centre of a thin-walled metal vessel V, which was closed with a tightly-fitting bung through which the glass tube G passed. The vessel V was of about a pint and a half capacity, and was filled with ether, which was introduced through the tube K. The vessel was connected with a water-pump and manometer by means of another tube L. It was thus possible, by the rapid evaporation of the ether, to cool the ring below the temperature of the surrounding medium, and by regulating the evaporation to vary the temperature at will. The bung was covered with melted paraffin before commencing an experiment, to insure air-tightness. The vessel V was placed in the cooling medium M contained in the large stone jar J, which rested on a thick pad of flannel. The whole arrangement was surrounded with a quantity of cotton-waste C. The cooling medium used in these experiments was either a mixture of ice and salt, or carbon-dioxide snow.

Fig. 7.



§ V. THE DATA OBTAINED, AND SOME REMARKS UPON THEM.

Alloy No. I.

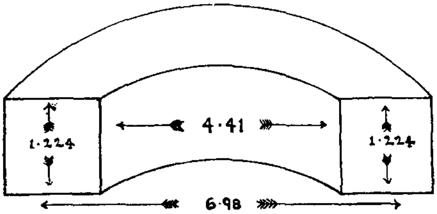
The first alloy investigated contained 3·64 per cent. of aluminium.

This alloy, in which the carbon was mostly in the form of graphite, was comparatively soft, and could easily be turned in a lathe. The other alloys, in which the carbon was mostly in the form of combined carbon, were harder than the hardest steel.

A complete analysis of this alloy, as supplied by Mr. Dawe, is as follows :—

Aluminium	3·64 per cent.
Combined Carbon . .	0·09 „
Graphite	2·40 „
Silicon	2·89 „
Sulphur	0·007 „
Phosphorus	1·086 „
Manganese	0·301 „
Copper	0·112 „
Chromium	traces.
Iron (by difference) . .	89·47 per cent.
	100·00

Dimensions of Ring.



External diameter = 6·98 cms.
Internal „ = 4·41 „
Mean „ = 5·695 „
Thickness = 1·224 „
Mean section = 1·57 sq. cms.

Other data.

Turns in Primary = 87
Turns in Secondary = 61
Mutual Inductance used in these experiments. = $1 \cdot 155 \times 10^6$.

The following readings of the induction were obtained for different temperatures, the maximum field reached at each reversal being maintained constant during any series of observations.

In the tables

B stands for the induction, in C.G.S. units.
T „ „ temperature, in degrees centigrade.
H „ „ field-strength, in C.G.S. units.

Curve (1). H=12·22.

T.	B.	T.	B
15	3850	435	3130
276	3855	438	3020
315	3855	450	2970
328	3855	476	2885
375	3855	493	2820
386	3855	525	2760
410	3720	540	2690
415	3630	557	2610
428	3240		

Curve (2). H=7·39.

T.	B.	T.	B.
15	2945	415	2730
230	3090	418	2625
268	3215	428	2575
297	3280	437	2550
365	3380	473	2475
392	3335	500	2425
400	3250	510	2390
408	3025	580	2000
412	2780	600	1850

Curve (3). H=4·09.

T.	B.	T.	B.
14	1640	410	2195
147	1735	423	2070
218	1945	425	2055
242	20 0	437	2055
297	2275	440	2045
330	2400	450	2030
348	2520	459	2020
372	2600	463	2010
392	2595	467	1995
400	2525	498	1945
		527	1760

Curve (4). H=3·12.

T.	B.	T.	B.
14	1115	397·5	2070
168	1230	410	1790
217	1360	427	1675
242	1460	433	1670
280	1605	440	1660
320	1785	446	1650
342	1945	452	1650
353	2005	462	1645
363	2055	474	1610
380	2115	482	1580
390	2115	525	1405
[397	2110]	579	488

Curve (5). H=2·20.

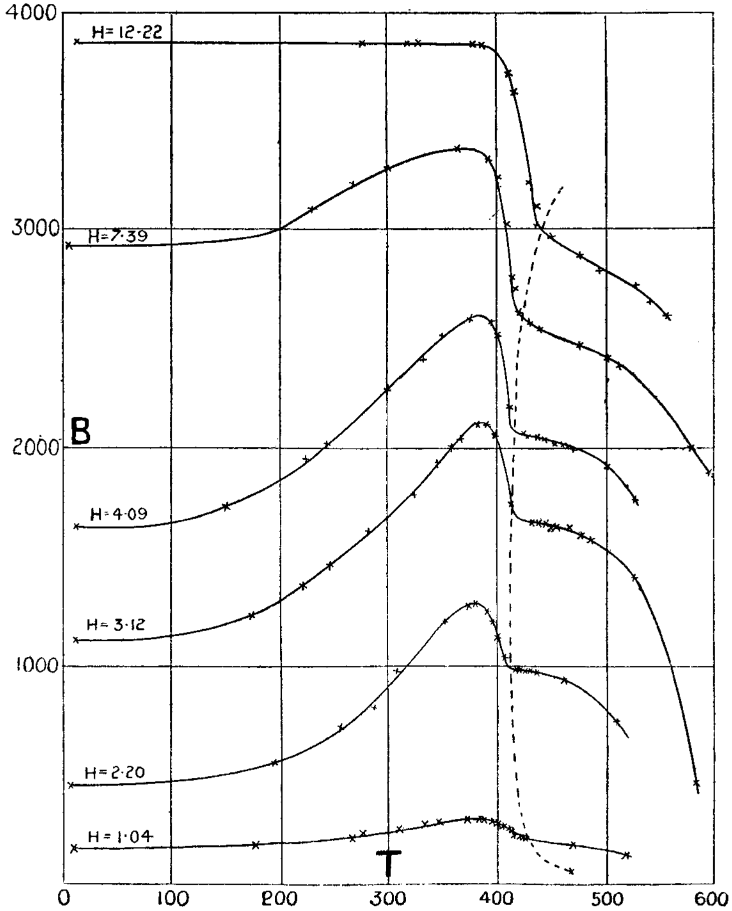
T.	B.	T.	B.
14	455	394	1220
195	562	400	1110
253	729	406	1045
283	816	413	997
305	963	415	997
350	1210	420	994
375	1290	424	994
380	1300	431	994
390	1260	460	955
		507	765

Curve (6). H=1·04.

T.	B.	T.	B.
14	168	397	282
173	185	400	274
260	219	405	265
273	239	408	252
305	253	411	240
328	274	412	231
343	286	417	219
375	295	421	215
387	295	423	202
390	290	467	181
		515	140

Curve (7).	H=0·49.			Curve (8).	H=1·96.		
T.	B.	T.	B.	T.	B.	T.	B.
14	67·7	400	91·0	15	367	585	219
172	75·9	426	81·5	305	736	624	67
230	83·3	434	73·1	345	895	693	18
247	86·3	443	67·2	435	714	785	3·4
300	92·7	462	61·0	457	714	888	3·4
315	96·0	469	59·1	483	681	943	3·4
365	101·0	516	50·8				
390	98·6	535	48·2				
		544	43·4				

Fig. 8.



These results are plotted on fig. 8 and on fig. 10. The curves obtained show that the maximum value of the induction

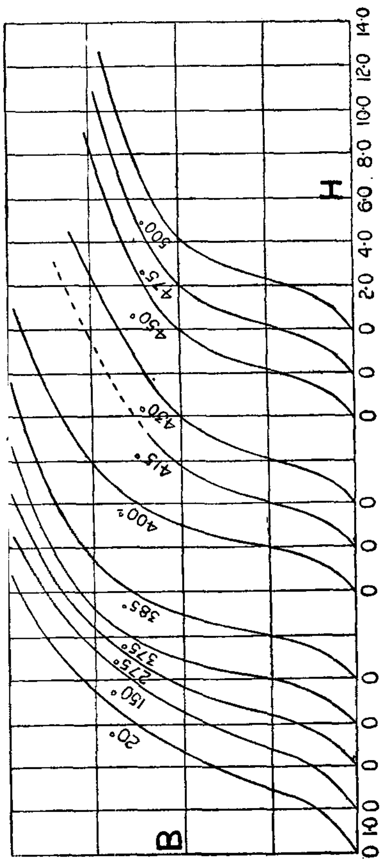


Fig. 9.

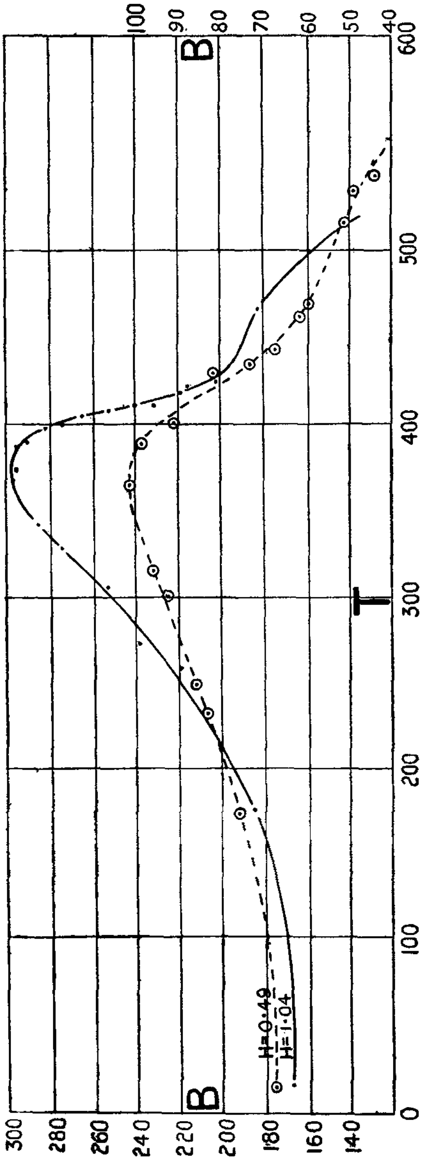


Fig. 10.

is reached at about 380° C. For the next 40° or so the curves are very steep, this steepness indicating a comparatively sudden change in the permeability of the alloy. This steep part of the curve is followed by a very flat part extending over about 100°, for which range of temperature the permeability remains almost constant. This flat part is followed by a steep part extending to about 600°, when the curve begins to bend round again, finally becoming parallel to the axis of temperature at about 750° C.

Fig. 11.

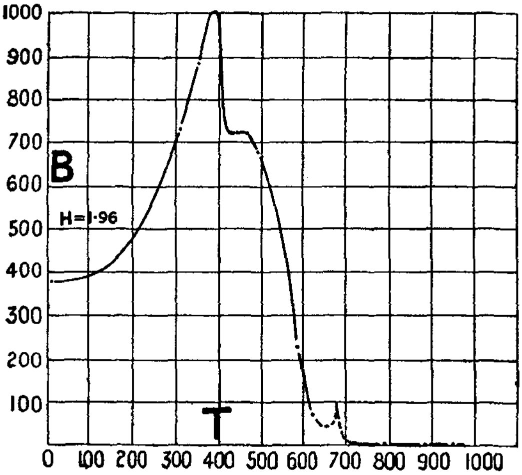
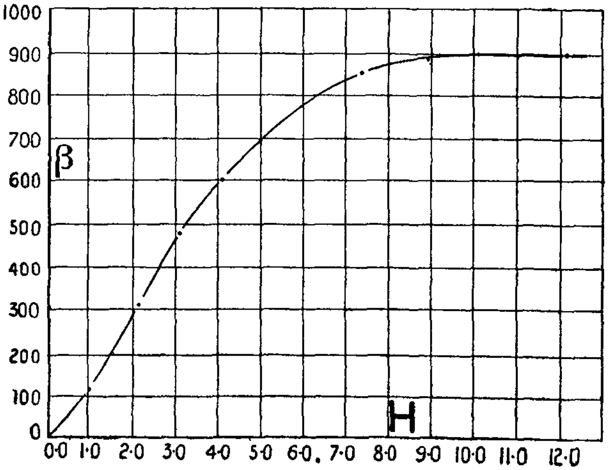


Fig. 12.



This temperature was taken as the critical temperature for the ring of alloy.

At about 660° C. the curve develops a sharp point indicating an abrupt increase in the permeability followed by an equally abrupt decrease. This point will be discussed more fully in Part II.

It will be noticed that there are no sharp points in the curves at the temperatures of maximum and minimum permeability as might be expected to be the case if we were dealing with a substance of uniform consistency. This general roundness suggests that the alloy is heterogeneous in structure, the roundness being due to the different constituents reaching their maximum and minimum values at slightly different temperatures.

A complete curve, showing all the changes of induction with increasing temperature, is shown on fig. 11.

The relatively great steepness of the curve between the temperatures of 385° and 420° (about) is well shown in this figure.

This general form of curve was found to be common to all the alloys experimented on.

In all cases there is a very sudden change in the induction after passing the temperature of maximum induction, followed by a flatness extending in the case of the alloy containing 10 per cent. of aluminium over a considerable range of temperature, after which the curves again become steep.

It was thought that it would be interesting to ascertain whether the magnitude of this sudden change was in any way connected with the strength of the field.

To do this it is easy to select the temperature at which the induction is a maximum, as this is fairly well marked, and is about 380° C. The temperature at which the sudden change ceases does not, however, appear to be the same for all fields. The temperature 450° was arbitrarily chosen as that from which to measure the termination of the sudden change. The difference of B between these two temperatures is for shortness referred to as β.

The following values were obtained for β :—

H.	B at 380°.	B at 450°.	β.
12·22	3860	2960	900
7·39	3375	2520	855
4·09	2630	2030	600
3·12	2130	1650	480
2·20	1300	990	310
1·04	300	187	113

T=20° C.

H.	B.	H.	B.
12·22	3850	3·12	1120
7·39	2940	2·20	470
4·09	1640	1·04	168

T=150° C.

H.	B.	H.	B.
12·22	3850	3·12	1190
7·39	2970	2·20	510
4·09	1740	1·04	178

T=275° C.

H.	B.	H.	B.
12·22	3850	3·12	1580
7·39	3230	2·20	810
4·09	2170	1·04	235

T=375° C.

H.	B.	H.	B.
12·22	3855	3·12	2110
7·39	3380	2·20	1300
4·09	2620	1·04	298

T=385° C.

H.	B.	H.	B.
12·22	3850	3·12	2130
7·39	3360	2·20	1300
4·09	2630	1·04	296

T=400° C.

H.	B.	H.	B.
12·22	3820	3·12	2040
7·39	3250	2·20	1110
4·09	2520	1·04	278

T=415° C.

H.	B.	H.	B.
12·22	(3630)	3·12	1680
7·39	2700	2·20	990
4·09	2080	1·04	225

T=430° C.

H.	B.	H.	B.
12·22	3200	3·12	1670
7·39	2570	2·20	990
4·09	2050	1·04	197

T=450° C.

H.	B.	H.	B.
12·22	2960	3·12	1650
7·39	2530	2·20	980
4·09	2030	1·04	187

T=475° C.

H.	B.	H.	B.
12·22	2870	3·12	1610
7·39	2480	2·20	910
4·09	2000	1·04	176

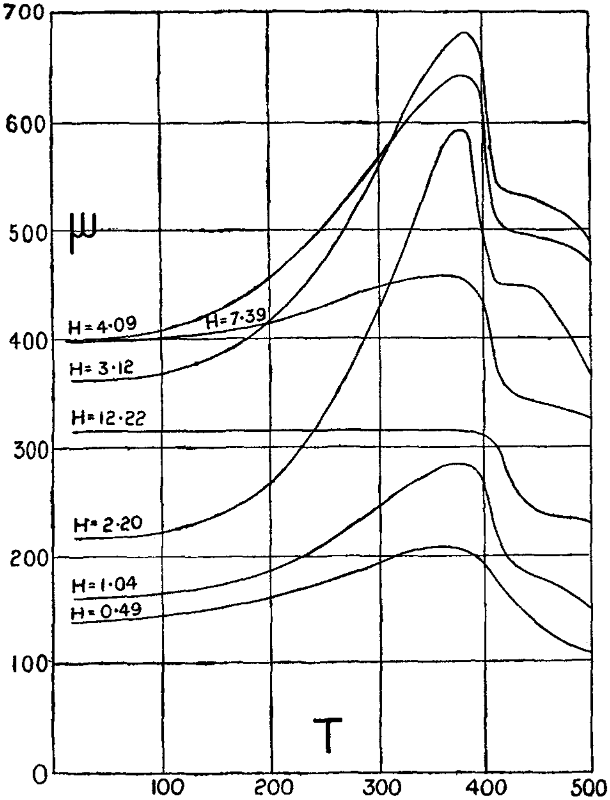
T=500° C.

H.	B.	H.	B.
12·22	2820	3·12	1530
7·39	2420	2·20	810
4·09	1940	1·04	156

These results are plotted on fig. 12. The curve obtained is very similar in general shape to a B and H curve, and does not differ materially in shape from the analagous curves for the next alloy considered. The changes of the induction with temperature are, in fact, of the same nature as those we should obtain if we were dealing with two rings of different compositions superposed one upon the other.

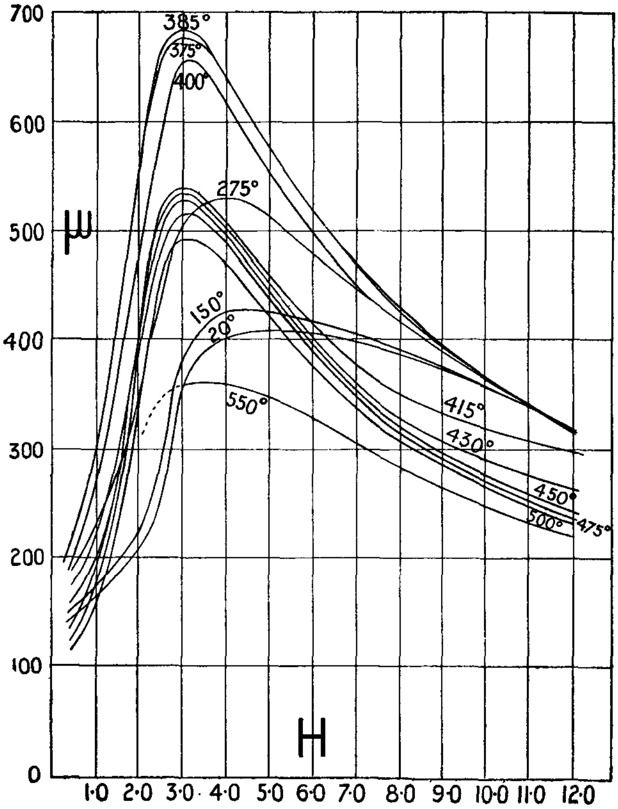
The B and H curves shown on fig. 9 were obtained from the readings given in the Table on p. 140.

Fig. 13.



On figs 13 & 14 are shown the curves connecting (1) the permeability and temperature when the maximum field reached at each reversal is maintained constant, and (2) the permeability and field-strength when the temperature is constant. The greatest permeability is reached at 380° C. for fields of about 3·0 C.G.S. units, but the increase in permeability between 20° and 380° is greatest for fields of about 2·2 C.G.S. units. The curves are more rounded in general outline both for high and low fields than for fields of medium strength.

Fig. 14.



The values from which these curves were obtained are given below (Table opposite page).

Alloy No. II.

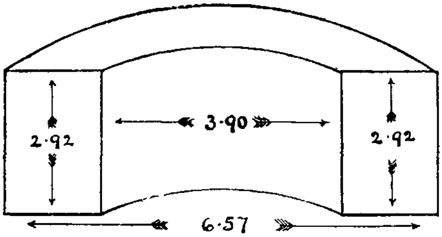
This alloy contained about 10 per cent. of aluminium. It was too hard to be cut by ordinary tools. The molten metal was cast into a ring of 6·57 cms. external diameter, and 2·92 cms. thick. The ring was subsequently cut into two by means of a diamond wheel, and an analysis was made of the upper half.

T.	H.	μ.	T.	H.	μ.
20°	12·22	315	150°	12·22	315
	7·39	398		7·39	402
	4·09	401		4·09	425
	3·12	359		3·12	382
	2·20	214		2·20	232
	1·04	161·5		1·04	171
	0·49	139		0·49	151
275°	12·22	315	375°	12·22	316
	7·39	437		7·39	457
	4·09	530		4·09	640
	3·12	507		3·12	675
	2·20	368		2·20	591
	1·04	226		1·04	286
	0·49	184		0·49	206
385°	12·22	315	400°	12·22	313
	7·39	454		7·39	439
	4·09	643		4·09	616
	3·12	683		3·12	654
	2·20	591		2·20	505
	1·04	285		1·04	267
	0·49	204		0·49	192
415°	12·22	297	430°	12·22	262
	7·39	366		7·39	348
	4·09	508		4·09	501
	3·12	539		3·12	535
	2·20	450		2·20	450
	1·04	216		1·04	189
	0·49	173·5		0·49	155
450°	12·22	242	475°	12·22	235
	7·39	342		7·39	336
	4·09	496		4·09	489
	3·12	529		3·12	516
	2·20	446		2·20	414
	1·04	180		1·04	169
	0·49	135		0·49	118
500°	12·22	231	550°	12·22	217
	7·39	327		7·39	298
	4·09	474		3·12	359
	3·12	491			
	2·20	368			
	1·04	150			
	0·49	110			

Analysis of upper half (by Mr. Dawe).

Aluminium	9·89
Combined Carbon	2·80
Graphite	traces
Silicon	2·75
Sulphur	traces
Phosphorus	0·57
Manganese	trace
Copper	nil
Chromium	nil
Arsenic	nil
Iron (by difference)	83·99
	100·00

Dimensions of Ring.



External diameter	6·57 cms.
Internal "	3·90 "
Mean "	5·23 "
Mean thickness	2·92 "
Mean section	3·88 sq. cms.

Other data.

Turns in Primary	63
Turns in Secondary	36

Standard Mutual Inductance used$=1{\cdot}155 \times 10^{6}$.

The curves connecting B and T (H=const.) for this alloy are shown on figs. 15 and 16.

A study of these curves in conjunction with the corresponding ones for the Alloy No I leads to the conclusion that the maximum value of the induction is probably reached at a temperature of about −90° C. The great change in the induction between this temperature and +100° C. is very striking, the value at 100° being about one-quarter of that at −90° C., and about one-half of that at 20° C.

The curves show for weak fields a second maximum between 300° and 400°, after which the induction falls off to a minimum value at about 460° when the permeability $\doteq$ 1·7. All the methods for varying the temperature (*vide* § IV.) were called into requisition in the experiments on this alloy. The method used in obtaining each series of observations is indicated above the series in the tables given below.

Fig. 5.

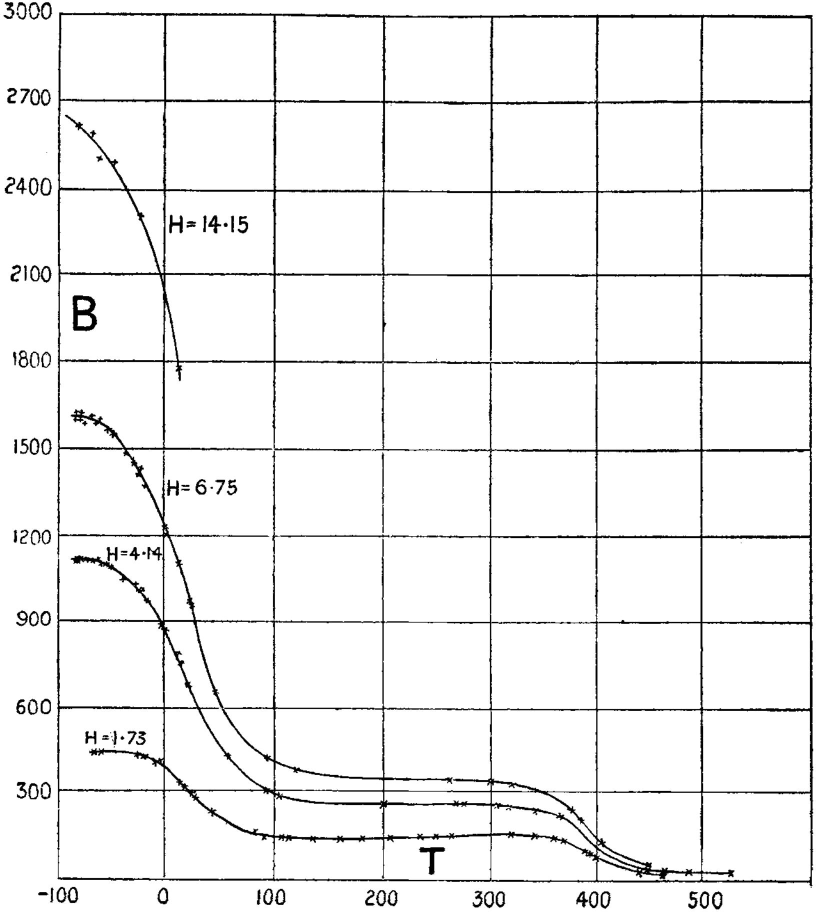
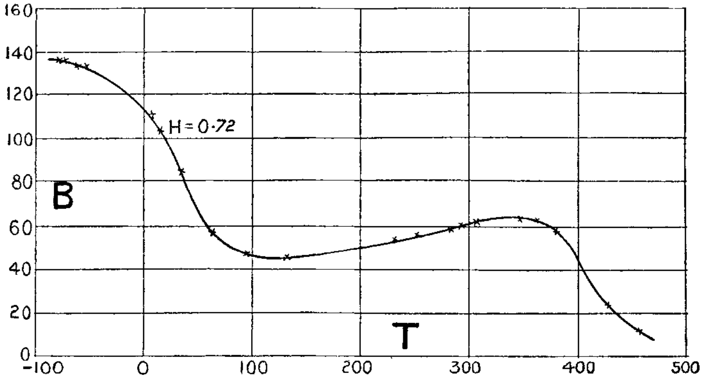

3000
2700
2400
2100
1800
1500
1200
900
600
300
B
H= 14·15
H= 6·75
H=4·14
H=1·73
T
-100
0
100
200
300
400
500

Fig. 16.


160
140
120
100
80
60
40
20
0
B
H=0·72
T
-100
0
100
200
300
400
500

Data obtained from Experiments at High Temperatures

H.	T.	B.	H.	T.	B.
6·75	12	1099	6·75	321	303
	22	951		377	232
	45	641		385	192
	93	404		404	113
	120	359		448	33·4
	263	328		486	12·9
	300	314			
4·14	14	745	4·14	309	238
	57	419		320	232
	90	300		342	219
	104	276		366	206
	200	254		448	24·3
	270	250		461	14·6
	277	245		525	7·0
1·73	13	313	1·73	88	133
	22	282		106	128
	40	223		112	128
	80	148		250	136
	132	125		359	127
	160	126		367	122
	181	127		389	89·5
	207	131		392	74·6
	236	135		398	64·5
	263	136		439	13·5
	320	137		460	5·5
	341	135			
0·72	14	105	0·72	292	59·0
	34	85·5		307	60·4
	62	55·3		343	61·8
	93	45·0		362	61·3
	131	45·2		379	57·7
	230	52·3		427	23·7
	250	55·0		454	10·1
	281	57·7			

Data from Experiments in Ether Bath surrounded by a mixture of ice and salt.

H.	T.	B.	H.	T.	B.
6·75	− 2	1242	4·14	− 6	880
	−20	1370		−20	966
	−26	1405		−26	1000
1·73	−10	393			
	−20	420			
	−25	425			

Data from Experiments in Ether Bath surrounded with CO_2 snow (First Series).

H.	T.	B.	H.	T.	D.
14·15	−80	2620	14·15	−48	2485
	−68	2590		−22	2260
	−61	2500		+13	1775
6·75	−81	1612	6·75	−61	1587
	−80	1612		−51	1550
	−77	1603		−23	1422
	−68	1600		+11	1103
4·14	−82	1106	4·14	−62	1094
	−80	1106		−53	1082
	−78	1117		−24	1002
	−69	1102		+11	775
1·73	−69	434	1·73	+10	321
0·72	−79	137	0·72	−62	133
	−79	137		−54	133
	−77	137		+ 9	111

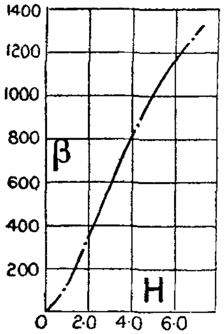
Data obtained from Experiments in Ether Bath surrounded by CO_2 snow (Second Series).

H.	T.	B.	H.	T.	B.
6·75	−83	1595	6·75	−38	1477
	−80	1595		−29	1443
	−75	1587		− 1	1207
	−66	1580		+20	960
	−55	1560			
4·14	−80	1110	4·14	−42	1040
	−76	1110		−29	1020
	−67	1105		− 3	860
	−56	1090		+20	673
1·73	−65	434	1·73	− 6	393
				+20	294

β for this alloy represents the difference in the values of the induction at (1) −90° C., and at (2) the temperature of the lowest point reached by the B and T curves between 100°

and 200° C. The results are given below, and the curve obtained from them is shown on fig. 17.

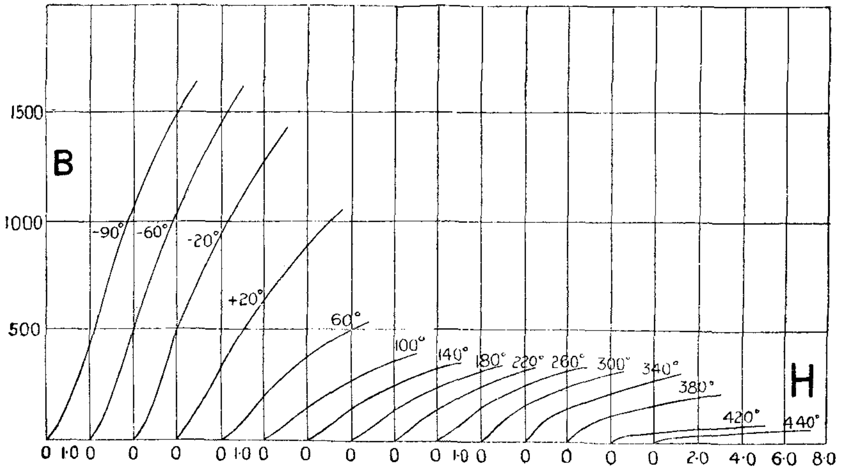
Fig. 17.



The curve obtained is similar in general form to a B and H curve.

H.	β.	
6·75	(1600 – 340)	1260
4·14	(1110 – 250)	860
1·73	(435 – 130)	305
0·72	(138 – 44)	94

Fig. 18.



The B and H curves at constant temperature, shown on fig. 18, were obtained from the following readings :—

T = −90° C.		T = −60° C.	
H.	B.	H.	B.
6·75	1605	6·75	1583
4·14	1110	4·14	1095
1·73		1·73	435
0·72	138	0·72	134

T = −20° C.		T = + 20° C.	
6·75	1385	6·75	990
4·14	968	4·14	675
1·73	420	1·73	285
0·72	123	0·72	100

T = 60° C.		T = 100° C.	
6·75	533	6·75	390
4·14	400	4·14	280
1·73	175	1·73	130
0·72	57	0·72	45

T = 140° C.		T = 180 °C.	
6·75	350	6·75	338
4·14	255	4·14	248
1·73	125	1·73	125
0·72	45	0·72	47·5

T = 220° C.		T = 260° C.	
6·75	335	6·75	330
4·14	255	4·14	250
1·73	130	1·73	135
0·72	50·5	0·72	55·5

T = 300° C.		T = 340° C.	
6·75	320	6·75	295
4·14	245	4·14	225
1·73	140	1·73	135
0·72	60·5	0·72	63

T=380° C.		T=420° C.		T=440° C.	
H.	B.	H.	B.	H.	B.
6·75	218	6·75	68	6·75	45
4·14	160	4·14	50	4·14	30
1·73	105	1·73	30	1·73	15
0·72	57	0·72	28	0·72	14

Alloy No. III.

The third alloy investigated contained 18·47 per cent. of aluminium. It was exceedingly hard. The molten metal was cast into a disk, and a hole was bored through the central part of this by means of the emery cylinder. The critical temperature was found to be about 25° C.

The experiments give no evidence of temperature hysteresis—the B and T curves obtained with rising temperatures being identical with those obtained with falling temperatures.

The great similarity between these curves and the latter part of those for Alloy No. II. (*e.g.* the part above 200° C.) leads to the conclusion that the maximum value of the induction is probably attained at a temperature much below any reached in the experiments.

The curves on fig. 19 (p. 153) show that the values of the induction obtained in the experiments on this alloy can, in the main, be relied on to $\frac{1}{10}$ of a line.

The largest induction observed during the experiments was about 21·5 lines, and the smallest about 2·4 lines.

The greatest permeability was equal to 3·7.

As in the case of the other alloys, there is a remanent permeability after the critical temperature is passed; its value is about 1·5. A curve connecting the temperature and time during cooling did not indicate an evolution of heat on passing the critical point.

As, however, the cooling took place in the air, the test is not sensitive, and this result cannot be regarded as of much value.

The temperature of the alloy during the experiments was regulated by the methods 2 and 3 described in § IV.

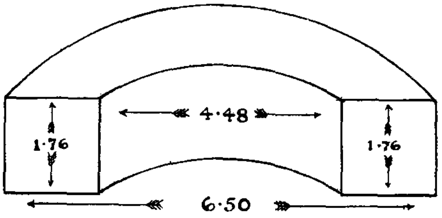
Dimensions of Ring.

External diameter	6·50 cms.
Internal ,, ...	4·48 ,,
,, thickness	1·76 ,,
Mean Section	1·78 sq. cms.

Other data.

Turns in Primary	82
Turns in Secondary	37

Standard Mutual Inductance used = $4{\cdot}536 \times 10^5$.



Analysis (*by Mr. Dawe*).

Aluminium	18·47 per cent.
Combined Carbon	1·56 „
Graphite	0·10 „
Silicon	1·47 „
Phosphorus	0·651 „
Manganese	0·25 „
Chromium	0·00 „
Copper	traces
Iron (by difference)	77·50 „

I.—Experiments with Rising Temperature.

H.	T.	B.	H.	T.	B.
6·11	6	13·1	1·63	7·0	3·6
	8	12·5		8·5	3·4
	20	10·0		19·5	2·7
	37	9·1		37·5	2·5
	51·5	8·6		51·5	2·4
	43 (Temp. falling)	9·0		43 (Temp. falling)	2·4
3·56	6·5	7·6			
	8·5	7·3			
	19·5	5·8			
	37·5	5·4			
	51·5	5·2			
	43 (Temp. falling)	5·4			

II.—Experiments with Falling Temperatures.

H.	T.	B.	H.	T.	B.
6·11	43	9·0	1·63	42	2·4
	26	9·5		26	2·5
	10	11·8		10	3·2
3·56	43	5·4			
	26	5·4			
	10	6·9			

III.—Experiments in Ether Bath, surrounded by CO_2 snow.

H.	T.	B.	H.	T.	B.
6·11	-83	21·0	1·63	-83	5·5
	-80	20·9		-80	5·5
	-78	20·9		-79	5·5
	-74	21·0		-74	5·4
	-63	21·2		-64	5·5
	-50	21·5		-54	5·5
	-31	21·4		-35	5·5
	-14	19·0		-15	5·0
	+ 1	15·2		0	3·9
	21°·1	9·6		21°·1	2·6
3·56	-83	12·1			
	-80	12·0			
	-78	12·1			
	-74	12·0			
	-63	12·2			
	-53	12·4			
	-33	12·3			
	-14	10·9			
	+ 1	8·8			
	21°·1	5·6			

These results are plotted as fig. 19.

The B and H curves shown as fig. 20 were obtained from the following readings:—

H.	B. T=-80°.	B. T=-40°.	B. T=0°.	B. T=40°.	B. T=50°.
6·11	21·0	21·6	15·5	9·0	8·7
3·56	12·0	12·0	8·8	5·4	5·4
1·63	5·5	5·5	4·0	2·4	2·4

It is not proposed at this stage to enter at length into a consideration of the explanation of the observed phenomena; but it is interesting to notice that the characteristic B and T

Fig. 19.

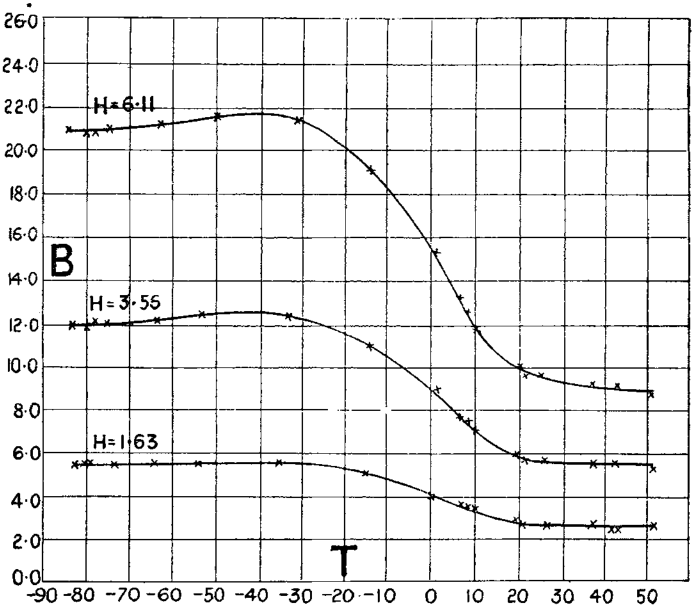
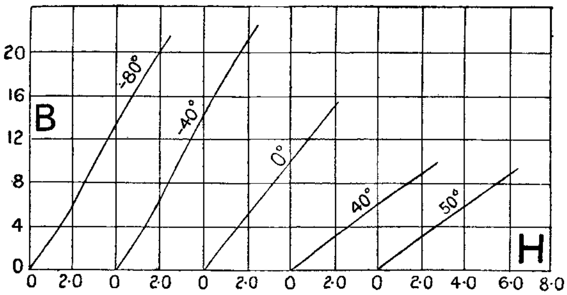


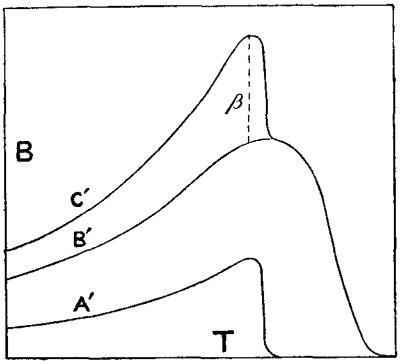
Fig. 20.



curve is of the same form as that which would be given by the superposition of two media of different constitution, as for instance crystals in a solidified mother-liquid. That this is so can easily be seen by the consideration of the following diagram.

Suppose, for instance, A′, B′ are the curves obtained by plotting the parts of the induction contributed by each medium independently against the temperature for any given value of H; then the curve C′ obtained by adding the ordinates will represent the observed B and T curve for the alloy in question.

Fig. 21.



The value of β for this curve, which approximates to the maximum value of the ordinate of the curve A′, would then be connected with H by a curve similar to a B and H curve.

This result is in agreement with the curves actually obtained from the experiments.

It is intended very shortly to publish an account of some further experiments on the changes of hysteresis as the temperature rises, and on the behaviour of the alloys during cooling.

In conclusion, the author's best thanks are due to Mr. Dawe, F.I.C., Chemist to the Ebbw Vale Ironworks, for his kindness in making the very complete analyses of the alloys, and to Prof. J. J. Thomson for suggestions and encouragement during the progress of the work.

University College, Nottingham.