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ON THE MAGNETIC PROPERTIES OF HEUSLER'S ALLOYS.

By J. C. McLennan.

SINCE the discovery by Heusler some three years ago that it was possible to prepare alloys of copper, manganese, and aluminium which possessed magnetic properties similar to and comparable in amount with those of cast iron, considerable attention has been paid by a number of investigators[1] to this interesting phenomenon.

Among others Mr. H. F. Dawes, M.A., and Miss L. B. Johnson, M.A., demonstrators in the Physical Laboratory at Toronto, and Messrs. H. A. McTaggart and J. K. Robertson, senior students in the same laboratory have from time to time during the past year, as opportunity offered, studied the properties of some of these alloys which they prepared, and the following paper contains a few notes on the results of their work, which is still being continued by two of them.

In order to prepare samples of the alloys a supply of manganese, copper, and aluminium, sold as chemically pure and free from iron was obtained from Messrs. Eimer and Amend of New York. The

[1] Fr. Heusler, W. Starck and E. Haupt, Verh. der Phys. Ges., 5, p. 219, 1903. Heusler, Starck and Haupt über der ferromagnetischen Aigenschaften von Legierung unmagnetischer Metalle, Marburg, 1904. Gumlick, Ann der Physik, 16, p. 535, 1905. Austin, Verh. der Deut. Phys. Gesell., 6, p. 211, 1904. Fleming and Hadfield, Proc. Roy. Soc., 76, p. 271, 1905. E. Take, Verh. der Deut. Phys. Gesell., 7, p. 133, 1905, Ann. der Physik, Vierte Folge, Band 20, p. 249. Hill, Phys. Rev., 21, p. 335, 1905; 23, p. 498, 1906. Guthe and Austin, Bulletin of the Bureau of Standards, Washington, Vol. 2, No. 2, page 297, Aug., 1906.

metals were melted in an ordinary coke furnace, such as is used in brass foundries, and poured into moulds just as in making brass castings. A graphite crucible was used for the purpose, and in the process the copper was first heated until it reached a molten state, after which the manganese was added to it. When this in turn was melted the aluminium was added, and the molten mass then stirred for a short time with a porcelain rod, after which the crucible was taken from the furnace and the melted metal poured into the moulds.

For a preliminary set of the alloys four castings were made. As Heusler had found that the most highly magnetic alloy contained manganese and aluminium in the proportion of their atomic weights, one casting was made with as nearly as possible this proportion of the two metals. A second was made with a larger proportion of aluminium and two others with smaller proportions of this constituent.

The percentages of the metals used in each of the four castings and the proportions of aluminium to manganese by weight and by atomic ratios are shown in Table I.

Table I.

Number of Alloy.	Composition of Alloys — Percentages.			Ratio of Manganese to Aluminium by Weight.	Atomic Ratio of Aluminium to Manganese.
	Aluminium.	Manganese.	Copper.		
I.	8.0	32.1	59.8	.250	.51
II.	9.7	25.6	64.6	.378	.77
III.	14.3	28.6	57.1	.498	1.01
IV.	15.9	23.9	60.3	.683	1.392

In each casting sufficient material was used to make two cylindrical rods about 20 cm. long, and 8 mm. in diameter, as well as two rings about 7 cm. in diameter, and 2.5 cm. in height. It was thought desirable to make the castings in the form of rings as well as rods, in order to investigate more fully the permeability of each specimen.

In the whole of the operation the greatest care was taken to keep the alloy free from iron in order that there might be none of this metal present to vitiate the results or to cast doubt upon their validity.

The investigations described below include one by Mr. Dawes on the phenomenon of magnetostriction exhibited by one set of the rods, one by Messrs. McTaggart and Robertson on the same phenomenon with the second set of rods, and one by Miss Johnson on the permeability of the alloys cast in the form of rings.

A. Magnetostriction. (Experiments by Mr. Dawes.)

I. *Apparatus.* — The apparatus used in measuring the elongation was, with some changes, modelled after that used by Rhoads[1] in his investigations on magnetostriction in iron. The apparatus is shown in section in the accompanying diagram, Fig. 1. A long hollow solenoid L produced the magnetic field in which the rod to be tested was placed. The lower end of the rod F was screwed into the fixed brass stand H, and the upper end carried a brass rod E. A cylindrical water jacket K placed between the coil and the rod served to keep the latter at a constant temperature. The change of length of the rod was magnified by means of an optical lever. A brass block D carrying a brass pivot indicated by the inverted arrow was clamped to the rod E, and so moved up or down as the rod F was elongated or shortened. A brass tube G which was attached to H at the base of F supported a horizontal projection A. A carried two brass pivots indicated by the second arrow. A lever B rested horizontally between these sets of pivots as indicated. At C a mirror was mounted so that it could rotate about an axis perpendicular to the plane of the paper and attached to A. This mirror was supported in a vertical plane by an attachment resting on the end of B. The brass points rested on agate beds and the axis was jewelled. The image of a scale as seen in C was

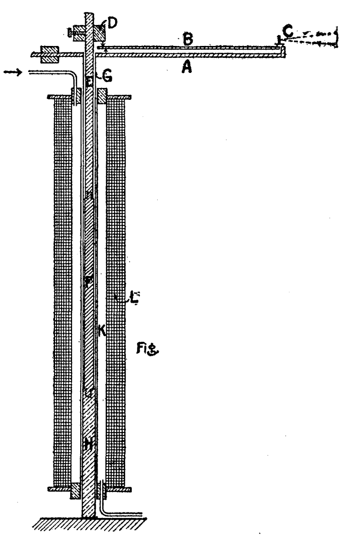

Fig. 1.

[1] Rhoads, Phys. Rev., Vol. VII., No. 2, p. 65, 1898.

observed by means of a telescope. In order to trace the method by which the change of length was measured, suppose that the rod was slightly elongated relative to the tube *G*. The brass point carried by *D*, would then move upwards, and in consequence the *C*-end of the lever *B* would be allowed to drop. This would cause the mirror to be tilted backwards, and hence cause a change in the scale reading as observed by the telescope. It will be seen that if the change of length was very small, it would be proportional to the change of scale reading, and the proportionality factor could be found by measuring the ratio of the arms of the lever, the distance between the axis of rotation of the mirror and its point of support, and the distance of the scale from the mirror.

In the present experiment a modification was made in the apparatus as used by Rhoads. Formerly a plane mirror was used at *C* and the scale was placed at a distance of about 4 meters from it. This mirror was replaced in these experiments by a concave mirror of one meter radius of curvature, and the scale was placed at a distance from it of one half meter, the focal length of the mirror. By this means the image of the scale was magnified sixteen times its former size and the sensibility, *i. e.*, the change of reading for a given change of length was double that obtained with the plane mirror. A glass scale was used in the telescope instead of a cross hair, and the number of divisions on this scale over which a line of the image moved was taken as the reading. The sensibility of the arrangement was such that a change of reading of one division resulted from a change in length of the specimen of 10^{-5} mm.

II. *Measurements.* — In making measurements the change of scale reading was found for a series of applied fields ranging from about 30 to about 900 C.G.S. units. The strength of the applied field was calculated from the value of the current, and the known dimensions of the coil and the change of length per centimeter was deduced from the scale readings. For each series of readings curves were plotted, the strengths of field, *H*, being taken as abscissæ, and the changes per unit length multiplied by 10^7 as ordinates.

In the first few series of measurements, the readings were taken by applying each field for an instant and then withdrawing it.

By this procedure, an average result was obtained for the effect investigated, but the method was not suitable for bringing out any hysteresis effect which might be present. It was therefore discarded, and the method of increasing the field step by step and then reducing it in the same way was adopted.

It was found that a cycle of readings could be taken in this way in about two minutes.

When the current was kept passing through the coil it might be expected that the heating would effect the change of length. In order to test for errors from this cause, a brass rod was inserted in the apparatus in place of one of the specimens investigated, and a cycle of fields similar to that used in working with the alloys applied to it. As brass is non-magnetic and consequently does not exhibit the phenomenon of magnetostriction, the development of heat by the current and its diffusion into the walls of the water jacket would be followed by the elongation of *G*, Fig. 1, which would produce an apparent shortening of *D*. This test showed that during the time of a cycle of observations no error from heating was introduced.

Elongation curves for each of the four specimens are shown in Figs. 2–5, the corresponding sets of values being given in Table II. Curves 1 and 3 *A* were taken by the first method, the others by the method of cycles.

Table II.

Alloy No. 1.

H	$\frac{dl}{l} \cdot 10^7$	H	$\frac{dl}{l} \cdot 10^7$
33	0	220	.3
50	0	900	.5
130	.1		

Alloy No. 2.

33	0	495	− .5
95	.15	375	− .75
225	.25	335	−1.0
335	.25	286	−1.0
375	.25	225	−1.25
491	−.25	95	−1.5
	−.5		
945	−.25		

Alloy No. 3. Curve A.

22	.25	315	3.8
44	.5	352	4
67	.6	385	4.2
90	.8	435	4.5
124	1.0	456	5.5
192	2.0	980	9
255	2.3		
276	2.5		

Alloy No. 3. Curve B.

33	.5	470	32
56	1.4	385	31
79	4.4	351	30.4
100	8	310	30
143	15	260	29
215	20	215	27.5
260	23.2	143	22.8
310	26	100	19
351	27	79	14
385	27.4	56	9.5
470	27.5	33	5.8
910	33	0	3

Alloy No. 4. Curve A.

33	.5	912	3.2
56	1	475	3
85	1.5	375	3
110	2	357	2.5
143	2.4	320	2.3
220	2.5	275	1.5
275	2.5	221	1
320	2.5	143	.5
385	2.5	110	0
475	2.6	85	−2.5

Alloy No. 4. Curve B.

33	2	490	11.5
56	5.5	400	11.5
90	7.25	332	11.5
111	8.5	221	11
170	9.5	170	11
221	11	110	11
332	11.5	90	10.5
480	11.5	56	10
940	23	33	16
		0	3

III. *Discussion.* — A careful examination of these and the other curves found in the series of measurements showed that three factors entered into the change of length of the bar.

1. When a change was made in the field to which the bar was subjected an almost instantaneous change was made in the length. This change consisted in a lengthening as the field was increased, and a shortening as it was decreased.

2. As the field was decreased there was a certain lag or hysteresis effect so that the length did not have the same value for a given field as the field was approached from above or below.

3. In some cases when the specimen was left in a field for some time there was a continuous shortening. This effect when it existed was very marked in strong fields so that the time for which the specimen was left in these fields had a comparatively great influence on the length. This effect was also observed by Austin in some experiments made by him with these alloys. It does not appear, however, to have been found by him in some measurements he has recently made, in collaboration with Guthe, with other samples of the alloys.

The form of the curve arising from a cycle of readings on a given specimen would depend, therefore, on the relative importance of

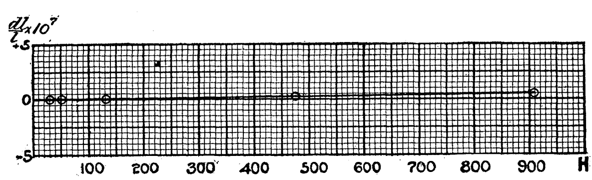

Fig. 2.

these three factors. In the early stages of an increasing field there would be no effect from (2) and that from (3) would be small so that the initial portions of the elongation curve would correspond to the change of length arising from the first source. In each of the curves shown, this part of the curve exhibits the same character. The curve rises slowly in the very weak fields and then in fields extending from about 50 to 200 units quite rapidly. In still higher fields the rise becomes smaller and tends to a maximum value.

In the case of alloy No. 2, Fig. 3, it will be seen that while the actual changes were small compared with those in alloys No. 3 and No. 4, the third factor was of more importance than the first, with

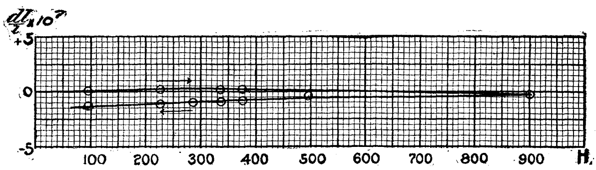

Fig. 3.

the result that in the higher fields the bar diminished a little below its original length. This was also observed in the case of alloy No. 1, although it is not shown in the curve as the experimenter failed to keep a record of his measurements.

In curves 3, *B* and 4, *B*, Figs. 4 and 5, this cause of change of

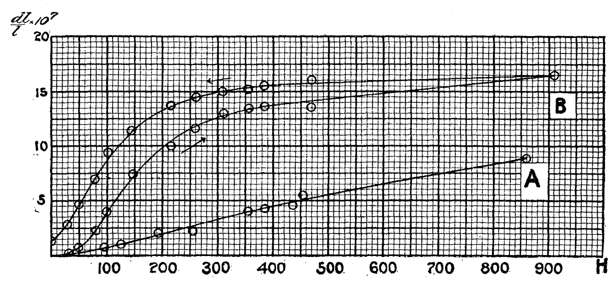

Fig. 4.

length was not sufficiently great to make the return half of the curve cut the forward half, *i. e.*, to overcome the hysteresis effect. But if the strong fields had been left on a little longer this would probably

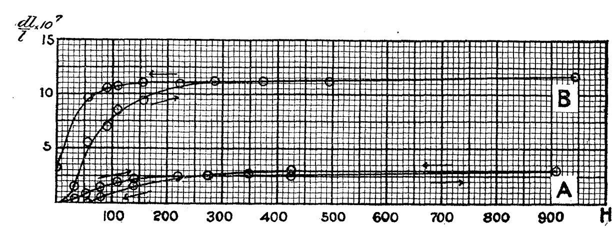

Fig. 5.

have been the case and there would have been a final resultant contraction. An example of this effect is shown in 4, *A*, Fig. 5, where the return portion of the curve crosses the forward initial portion and consequently masks the presence of the hysteresis effect shown in 4, *B*.

In Figs 4 and 5, curves *A* represent the elongation obtained with two of the alloys when magnetized for the first time, and curves *B*, in the same figures represent the elongations obtained with the same rods after they had been magnetized and demagnetized several times, and then allowed to lie undisturbed for about thirty hours.

This increase in the elongation has not hitherto been observed, and it may possibly be connected with the increase of permeability observed by Starck and Haupt,[1] Gumlich,[2] Hill[3] and others with these alloys when they were heated for some time to a moderate temperature, such as a 110° C. after being cast. It may possibly, too, point to changes in the constitution of the alloy analogous to those marking the recovery of iron from overstrain observed by Muir,[4] on heating strained iron bars for short periods in boiling water.

Considering the curves as a whole it will be seen that the elongation increased with the percentage of aluminium, present in the alloy, the maximum elongation, curve *B*, Fig. 4 being obtained with the alloy in which the manganese and aluminium were present in the proportions of their atomic weights.

The maximum elongation in this case, it will be seen, was 16 ten-millionths or about one third the maximum for iron.

The effect of higher percentages of aluminium is shown in Fig. 5, curve *B*, where the maximum elongation was 11.75 ten-millionths.

Chemical analyses of the alloys have not as yet been made, but if the constituents of the different samples of the alloys can be taken to have the same relative proportion as the metals from which they were cast, these results would go to show that the maximum elongation was obtained with alloys containing the same proportions of manganese and aluminium as were found by Heusler to give the highest permeability.

[1] Deutsch. Phys. Gesell. Verh., 5, 12, pp. 224–232, June, 1903.

[2] Electrotech. Zeit., XXVI., 9, Mar., 1905.

[3] Hill, Phys. Rev., Vol. XXIII., No. 6, p. 498, 1906.

[4] Phil. Trans. Roy. Soc., London, Vol. 193, pp. 1–46, Series A.

B. Magnetostriction. (Experiments by Messrs. H. A. McTaggart and J. K. Robertson.)

In the experiments made with the first set of rods a very marked difference was observed in the elongations obtained with alloys Nos. 3 and 4, when magnetized for the first time, from what was obtained with them after they had been magnetized and demagnetized several times. This result pointed to the existence of an unstable equilibrium among the molecules of newly cast specimens of the alloys, and it forms a corroboration of the opinions of other experimenters who have arrived at the same conclusions from their observations on the changes in permeability of the alloys produced by variations in temperature.

Table III.

H	$\frac{dl}{l} \cdot 10^7$	H	$\frac{dl}{l} \cdot 10^7$
	Alloy No. 2.		
235	0.8	300	−0.8
370	1.7	218	−1.7
531	2.5	155	−2.5
675	2.5	0	−3.3
440	0		
	Alloy No. 3.		
55	1.6	580	13.3
96	3.3	376	12.5
130	4.2	255	10.8
198	6.6	202	10
255	8.3	155	8.3
272	9.2	118	6.6
376	10.8	75	4.2
474	12.5	0	−1.6
	Alloy No 4.		
32	4.2	255	15.8
62	8.3	180	15
96	10.8	125	14.2
145	12.5	84	12.5
202	14.2	55	10
250	15	40	8.3
355	15.8	10	4.2
474	16.7	0	0
595	17.1		

It seemed desirable to investigate this point more closely, and therefore a set of measurements was made by the above mentioned senior students on the elongations of the second set of rods cast at the same time as those used by Mr. Dawes. Before proceeding with this however, a set of readings was taken with the rods used by the latter to see whether any change had taken place in them in the six months interval during which they had been laid aside. The results of their measurements are given in Table III. and represented graphically by the curves in Figs. 6–8.

With alloy No. 1 no elongation whatever could be observed by them. With alloy No. 2, Fig. 6, the general form of the curve they obtained is similar to that given in Fig. 3, by Mr. Dawes, although the maximum elongation they obtained in increasing fields and the maximum shortening in decreasing fields was greater than that observed by him with this specimen.

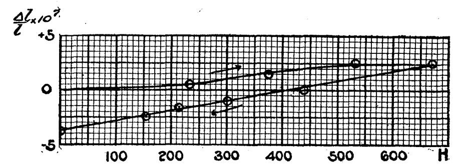
Fig. 6.

Their results with alloy No. 3, Fig. 7 show the presence of the three effects pointed out in the first set of measurements, the hysteresis and the shortening being clearly marked. The maximum

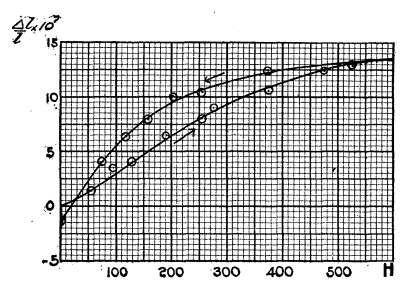
Fig. 7.

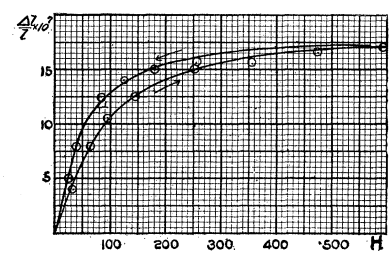
Fig. 8.

elongation obtained by them with this specimen corresponded to a field of 600 units and is slightly less than that obtained in the first tests for the same field.

With alloy No. 4, Fig. 8, the elongation was about 50 per cent. greater than that shown in Fig. 5. In both curves there exists a well marked lag, but in the later measurements, the rod returned to its original length whereas in the earlier ones it showed an elongation when the field was removed.

It is evident from these measurements that considerable modifications must have taken place in the structure of the alloy in the interval which elapsed between the two tests, and that the lapse of time is a factor as well as changes in temperature and magnetization in producing alterations in the molecular groupings in the alloy.

TABLE IV.

Alloy No. $2A_1$.

H	$\frac{dl}{l} \cdot 10^7$	H	$\frac{dl}{l} \cdot 10^7$
0	3.3	445	2.9
174	3.3	330	2.9
425	3.75	284	2.5
745	4.1	180	1.7
670	3.75	104	0.8
635	3.3		

Alloy No. $2A_2$.

118	0.8		
280	1.7		
705	2.1		
425	1.7		
155	0.8		
0	0		

Alloy No. $3A_1$.

42	2.5	910	27.5
86	8.3	600	25
138	12.5	405	23.3
180	15	320	21.7
215	16.7	280	20.8
312	20	215	19.2
390	21.7	121	15
460	22.5	75	8.3
545	24.2	42	5.8
705	25	0	4.2
890	26.7		

TABLE IV.—*Continued.*

Alloy No. 3A_2.

50	2.5	705	20.8
75	4.2	880	22.5
104	6.7	635	20.8
125	8.3	405	19.2
155	10	270	16.7
185	12.5	175	12.5
238	14.2	104	8.3
320	16.7	60	4.2
398	18.3	0	0
495	19.2		

Alloy No. 3B_1.

53	1.7	740	23.3
80	4.2	592	22.5
110	5.8	425	20.8
138	8.3	370	20
192	12.5	326	19.2
225	14.2	284	17.5
277	16.7	255	16.7
348	18.3	208	15
372	19.2	174	12.5
458	20.8	118	8.3
565	21.7	68	4.2
610	22.5	0	1.7

Alloy No. 3B_2.

55	1.7	545	21.7
85	4.2	390	20.8
134	8.3	348	20
187	12.5	327	18.3
275	16.7	255	16.7
390	19.2	187	12.5
480	20.8	125	8.3
665	22.5	68	4.2
760	23.3	0	0

Alloy No. 4A_1.

112	3.3	565	7.5
208	4.2	452	7.5
270	5	320	7.5
362	5.8	215	7.5
390	6.7	103	6.7
478	6.7	0	5
705	7.5		

TABLE IV.—*Continued.*

Alloy No. 4A_2.

50	1.7	362	2.9
110	2.5	255	2.5
362	3.3	118	2.5
552	3.4	70	2.1
610	3.4	42	1.25
590	2.9	0	0

The measurements made with the duplicate set of rods are given in Table IV., and curves representing them are given in Figs. 9, 10, 11, 12, 13, and 14. For convenience in description the rods used in this investigation are designated as No. 1, *A*, No. 2, *A*, No. 3, *A*, and No. 4, *A*, and where subscript figures are used, for example in No. 3, A_1, and in No. 3, A_2 they represent the first and second tests respectively made with the specimen. Alloy No. 3, *B* is a rod of another casting made over a year ago from the same metals and with the same proportions as the pair No. 3 and No. 3, *A*.

With No. 1, *A* no elongation was observed which accorded exactly with the behavior of the twin rod No. 1.

With No. 2, *A*, Fig. 9, the results obtained were very similar to those obtained with rod No. 2. Curve No. 2, A_1 represents the elongations obtained with the first magnetization. As the field was

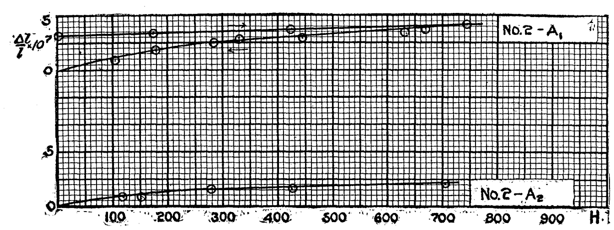

Fig. 9.

gradually increased to 750 units the rod steadily lengthened, and as the field was decreased the rod shortened, and finally when the field was removed entirely it remained slightly shorter than its original length. It was then repeatedly magnetized and demagnetized and afterwards put through the usual cycle of fields. The curve No. 2, A_2 represents its behavior after this treatment. The rod as will be seen had assumed a steady state, and the upward and downward curves coincided exactly. No hysteresis action or shortening under high fields was observed.

With alloy No. 3, *A* the measurements made with the first magnetization are given in Fig. 10. Here it will be seen a lag was

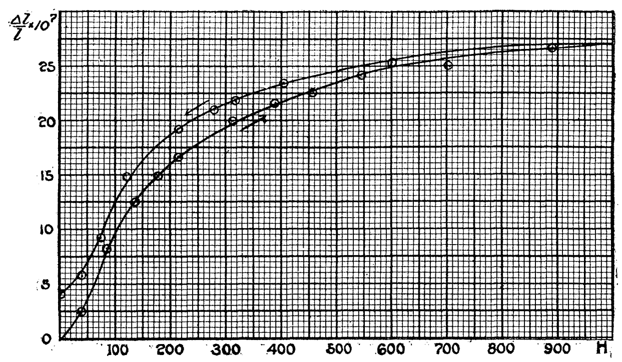

Fig. 10.

obtained in the return portion of the cycle, the rod ending with a slightly greater length than it had originally.

Curve No. 3, A_2, Fig. 11, shows its behavior after being repeatedly magnetized. Here again a lag was observed in the return

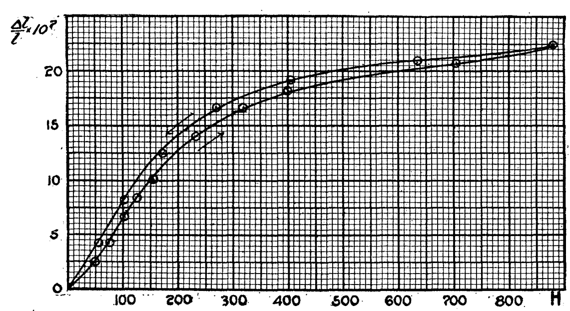

Fig. 11.

portion of the cycle, but the shortening referred to under heading No. 3 page 455 had entirely disappeared, so that the initial and final lengths of the rod were the same.

The first and second tests with alloy No. 3, *B* are shown in Figs. 12 and 13. Here again it will be seen, precisely the same behavior was obtained as with No. 3, *A*. As with the latter a lag was again observed in the return portion of the cycle and a final lengthening of the specimen occurred. In the second tests, Fig 13, made after

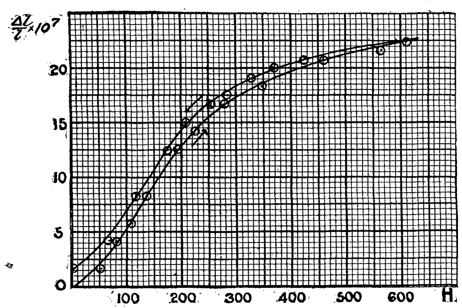

Fig. 12.

repeated magnetizations, this change of length disappeared, and the rod after being put through its cycle returned to its original length.

With alloy No. 4, *A*, the behavior was exactly the opposite of that obtained with No. 2, *A*. In the initial test, No. 4, A_1, Fig. 14, the rod steadily lengthened as the field was increased to 700 units

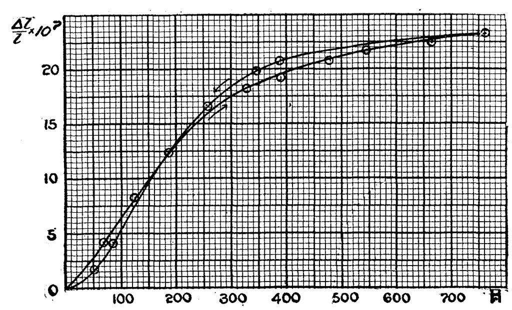

Fig. 13.

and afterwards as the field was decreased a lag occurred and the rod ended somewhat longer than it was at the commencement of the cycle. After it had been repeatedly magnetized and demagnetized it was again put through a cycle, and curve No. 4, A_2 was obtained. Here again the values in the downward portion of the cycle coincided exactly with those obtained in the forward portion and no lag and no shortening was observed.

In the measurements with these rods, the greatest elongation was obtained with samples No. 3, *A* and No. 3, *B*. With them the maximum elongation observed was about 22.5 ten-millionths which is somewhat greater than that obtained with the specimen No. 3 where the maximum elongation obtained was 16 ten-millionths.

The maximum elongation obtained with rod No. 4, *A* was somewhat less than that obtained by Mr. Dawes with rod No. 4. With the former specimen the maximum elongation was about 3 ten-millionths while that obtained with the latter was over three times as great. This discrepancy was very likely due to a difference in the composition of the two rods which should be brought out by a chemical analysis of the specimens. It is interesting to note that with both sets of rods the maximum elongation was obtained when the composition of the alloy was approximately the same as that of the specimens which were found by Heusler to give the highest permeability.

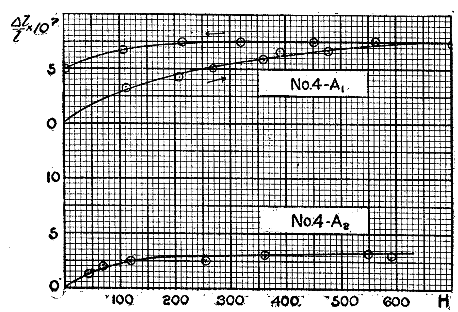

Fig. 14.

Summarizing the results of the two measurements it would appear that the structure of the alloys when freshly cast is very unstable, and that it undergoes a rapid change under repeated magnetizations and a slower change under the lapse of time.

In their experiments on magnetostriction Guthe, and Austin state that no after-effect either in expansion or in contraction was observed even with the strongest fields, whereas Austin in his first communication refers very definitely to the observation of such an effect in his measurements. The explanation probably is that in the first investigations the rods were in the same condition as those with which the initial tests described in this paper were made; while in the later investigation the rods tested (which were obtained from Dr. Heusler) had very likely been subjected to such conditions prior to the test as to bring them into the stable condition.

III. PERMEABILITY. (EXPERIMENTS BY MISS L. B. JOHNSON.)

During the period covered by the experiments on magnetostriction, a series of measurements was made by Miss L. B. Johnson on the permeability of the four alloys. Two rings had been made at each casting, in addition to the two rods mentioned above, and with these the experiments on permeability were carried out. The magnetization was measured by the ballistic method, by reversing the magnetizing force, and the arrangement of apparatus was similar to that used by Ewing and Klaasson.[1]

TABLE V.

Designation of Ring.	Height.	Thickness.	Mean Diam.	Cross Section.	Turns in Primary.	Turns in Secondary.
No. I.	1.56 cm.	.881 cm.	6.59 cm.	1.374 sq.cm.	155	100
No. II.	1.47 "	.855 "	6.615 "	1.256 " "	153	100
No. III*a*.	2.44 "	.623 "	6.98 "	1.516 " "	150	50
No. III*b*.	2.37 "	.68 "	6.87 "	1.61 " "	115	50
No. IV*a*.	2.39 "	.703 "	6.86 "	1.684 " "	157	50
No. IV*b*.	1.447 "	.838 "	6.64 "	1.212 " "	136	46

TABLE VI.

Alloy No. I.

H	B	μ	H	B	μ
1.39	1.39	1.0	14.40	18.7	1.3
2.82	4.01	1.4	28.22	37.8	1.3
3.93	5.35	1.3	37.63	50.8	1.3
7.52	10.7	1.4	86.45	78.9	1.3

TABLE VII.

Alloy No. II.

H	B	μ	H	B	μ
.814	1.464	1.7	17.5	27.8	1.5
1.66	2.92	1.7	42.5	68.8	1.6
4.99	8.78	1.7	69.3	106.8	1.5
8.55	13.17	1.5			

[1] Phil. Trans., Vol. CLXXXIV., A, p. 987, 1893.

TABLE VIII.

Alloy No. IIIa.

H	B	μ	H	B	μ
.68	6.442	9.3	17.1	201	11.6
1.8	17.1	9.8	28.3	332.8	11.7
4.4	46.1	10.3	36.9	364	9.8
7	71.2	10.1	42.9	413.8	9.6
11.9	129.8	10.8	59.3	483.1	8.1

The dimensions of the rings which have been designated as I., II., III*a*, III*b*, IV*a*, IV*b* for the purpose of identifying them with the rods which were denoted by the same numbers, are given in Table V. The table also contains the number of turns in the primary and secondary coils of each ring.

TABLE IX.

Alloy No. IIIb.

H	B	μ	H	B	μ
.99	4.596	4.6	11.24	70.17	6.2
1.45	9.138	6.3	23.4	160.8	6.8
2.04	11.42	5.5	30.81	221.5	7.1
3.08	18.27	5.9	50.75	352.1	6.9
6.01	34.26	5.7			

The first set of measurements was made with the rings, just as they were cast, and the results are given in Tables VI., VII, VIII., IX., X., XI. The permeability curves are given in Fig. 15.

TABLE X.

Alloy No. IVa.

H	B	μ	H	B	μ
.2745	13.1	48.1	8.692	565.7	65.1
.5032	30.5	58	16.47	933.9	56.7
1.464	96.1	65.6	34.31	1487.2	43.3
2.379	157.2	66.1	45.29	1724.08	38
4.575	314.5	68.7	69.54	2072.3	29.8

TABLE XI.

Alloy No. IVb.

H	B	μ	H	B	μ
.0379	3.108	82	16.45	1366.93	83.0
.147	13.67	92.9	27.14	2113.44	77.8
.452	49.72	110	34.55	2257.76	65.4
1.192	136.75	114.7	41.77	2424.24	58
2.467	279.72	113.3	51.00	2548.4	49.8
3.331	360.52	108.2	55.93	2586.4	44.4
5.264	535.81	101.7	80.61	2735.04	33.8
7.81	739.70	94.7	92.13	2735.04	24.6

From these it will be seen that Alloys IVa and IVb showed the highest permeability. Alloys I. and II. were but feebly magnetic, and Alloys IIIa and IIIb only slightly so.

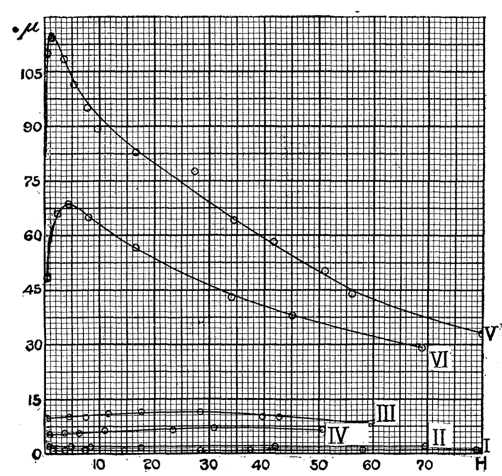

Fig. 15.

It had been expected that the permeabilities of the rings would give an indication of the relative permeabilities of the corresponding rods used in the measurements on magnetostriction. The very considerable difference in the permeability of the two rings No. IVa and No. IVb, which were made at the same casting, showed, however, that even different portions of the same casting did not exhibit the same magnetic properties, and that before any definite comparisons could be made, it was necessary to make a chemical analysis of each of the specimens tested. This difference in magnetic properties was also very marked with alloy No. III. The rods of this casting gave the greatest elongation, while the rings, as the figures show, possessed but a small permeability. Guthe and Austin[1] have pointed out that the greatest elongation was obtained by them with rods which possessed the greatest permeability and as some experiments which are now being made on the permeability of the rods No. III. show that they possess a very much higher permeability than that exhibited by the rings, this conclusion is very probably correct.

TABLE XII.

Alloy No. IIIa.

H	B	μ	H	B	μ
.73	8.59	11.9	17.1	309.2	17.9
1.28	15.03	11.7	27.5	440.1	15.9
1.97	25.77	13	36.1	541.1	14.9
6.4	94.4	14.7	46.4	674.3	14.5
6.8	105.2	15.3	64.5	751.6	11.6
8.5	138.2	16.2	91.1	843.9	9.2
11.5	196.5	17			

Alloy No. IVa.

H	B	μ	H	B	μ
.164	9.83	59.9	8.88	758.02	85.3
.814	65.33	80.5	16.4	1187.42	72.4
1.41	121.02	85.8	34.31	1857.5	54.1
2.33	203.15	87.1	43	2090.1	48.8
4.3	415.05	96.7	71.32	2402.6	33.6
6.03	538.26	89.2			

Alloy No. IVb.

H	B	μ	H	B	μ
.7621	10.567	13.9	24.38	528.22	21.6
1.258	28.172	16.3	31.24	654.99	20.9
3.35	56.34	16.4	44.2	795.85	18
6.09	116.2	19	58.68	993.06	16.9
9.9	211.29	21.3	86.11	1253.6	14.55
15.24	352.15	23.1			

[1] Loc. cit.

In addition to the initial tests just described, some measurements were also made on the changes in the permeability produced by continued heating.

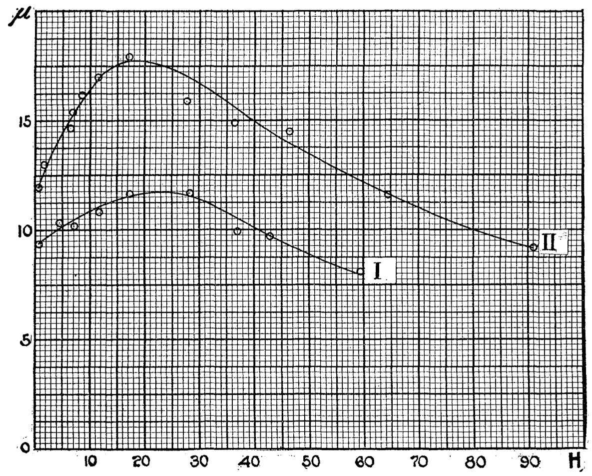

Fig. 16.

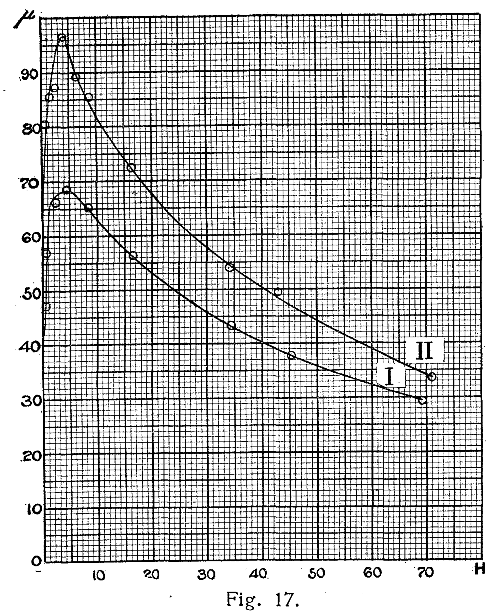

Fig. 17.

Examples of these measurements with alloys No. III*a* and No. IV*a* and No. IV*b*, are given in Table XII.

The values of the permeability of alloy No. III. were obtained when the specimen had become cool after being heated to 107° C. and kept at this temperature for 40 hours. A permeability curve repre-

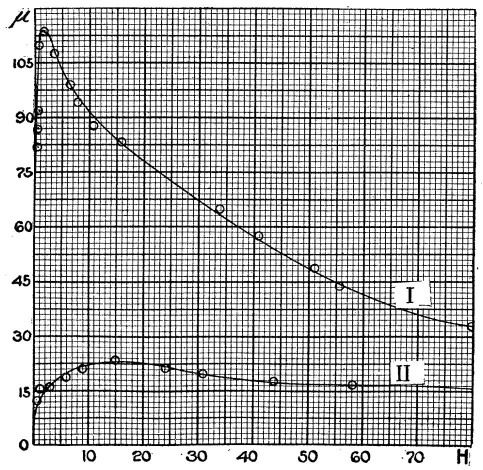

Fig. 18.

senting the results is given in Fig. 16, and a comparison with the curve made in the initial test which is plotted in the same figure shows that although the magnetic properties of the specimens were

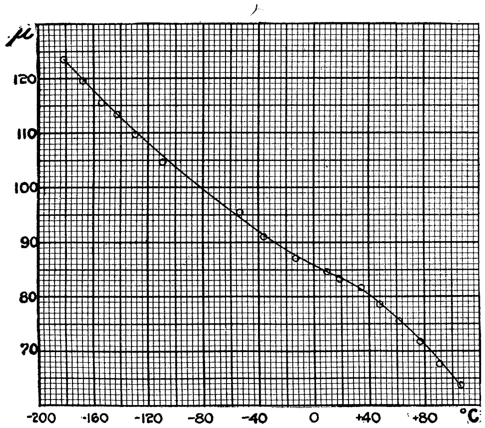

Fig. 19.

not very marked the heating nevertheless produced a very considerable increase in the permeability.

This increase in the permeability is also shown by the numbers for alloy No. IV*a*. Curve I., Fig. 17, shows the permeability of the alloy in different fields when freshly cast, and curve II. its permeability in the same fields after it had been repeatedly heated up to 100° C. and cooled to the temperature of liquid air.

The results obtained with alloy No. IV*b* show the effect of raising the alloy to a red heat and then allowing it to cool slowly. This specimen in the initial tests showed the highest permeability of all the rings, but after being treated as described a very considerable decrease in the permeability ensued. Curves I. and II. represent respectively the initial and final tests with this specimen.

In the interval between which the results with alloy IV*a* recorded in Fig. 17 were obtained, this specimen was examined under a constant magnetizing force of 3.934 C.G.S. units for temperatures ranging from – 182° C. to 105° C. The temperatures were estimated from variations in the resistances of a platinum wire wound round the ring between the primary and secondary coils. The results of these measurements are given in Table XIII. and a curve representing them is given in Fig. 19.

TABLE XIII.

Alloy No. IVa. $H=3.934$ C.G.S. units.

Temperature.	B	μ	Temperature.	B	μ
−182	487	123.7	0	338.5	86
−169	471.8	119.9	8.2	334.2	84.9
−154	454.3	115.4	19.6	327.6	83.2
−143.5	445.6	113.2	35.3	321.1	81.6
−131	432.5	109.9	48	308.8	78.5
−110.5	410.6	104.3	63.1	297	75.5
−53	375.7	95.4	69	288.3	73.2
−46	364.8	92.7	76.4	281.8	71.6
−36	358.2	91	91.6	266.5	67.7
−13.5	342.9	87.1	105	521.21	63.8

The permeability, it will be seen, showed a steady increase as the temperature was lowered.

The results of these various tests, it will be seen are in accordance with the observations of other investigators, who have found that the permeability of these alloys can be considerably increased by continued heating at moderate temperatures.

The results obtained with alloy No. IV*a* lends support to the view expressed by Hill, that when these alloys are raised to a temperature higher than the transformation point, and then cooled, they possess a permeability which is largely determined by the temper ature from which the cooling took place. This alloy when cooled from the melting point as curve I., Fig. 18, shows, possessed a permeability very much higher than that which it had when cooled from a red heat.

This suggests a parallel between the behavior of these alloys and those studied by Heycock and Neville.[1] In their investigations it was found that the structure of an alloy at any temperature could be ascertained very closely by suddenly chilling it from that temperature. It is possible that these alloys under varying conditions of temperature, may pass through different phases, some of which may be magnetic, and others not. From the general results of the present investigations it is evident that the magnetic properties of the different alloys are intimately associated with their molecular structure, and since the structure of an alloy at any temperature can be ascertained by rapid cooling from that temperature, it is possible that the magnetic properties of the alloy may also be investigated by the same procedure. The results obtained by Hill and other investigators would seem to point in that direction.

Physical Laboratory,
University of Toronto, December 20, 1906.

[1] Rapports Congrès Int. de Phys., Paris, 1900, p. 131.