XIX. *Magnetic Qualities of Iron.*

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[Plates 34–41.]

Recent applications of electricity, and especially the extended use of transformers, have added particular interest to the study of cyclic magnetizing processes in iron. It has become a matter of consequence to investigate, in various specimens of metal, not only the amount of the energy dissipated by hysteresis in a magnetic cycle, but the relative amounts under various degrees of magnetization and various intensities of magnetizing force. Other questions arise with regard to the dependence of this loss on the frequency of the cyclic process and on the manner in which it is performed. The experiments to be described in this paper deal mainly with the effects of cyclic variations of magnetizing force. They are intended to contribute some additions to existing data, to answer one or two specific questions, and to exemplify certain more or less novel methods of experimental inquiry. A section at the end of the paper relates to the molecular theory of magnetization, and its adequacy to explain some characteristic manifestations of magnetic hysteresis.

Experiments on Rings, by the Ballistic Method.

In a paper published eight years ago by one of us,* experiments were described in which a piece of soft iron was carried through a numerous series of cycles of magnetization, of graded amplitude, with the object of determining the form taken by the curve of magnetization and magnetizing force during the process of reversal between any assigned limits, and of comparing the work spent in the process with the amplitude of the magnetization. A similar experiment was described for steel. Since then the importance of such information has been recognized by electrical engineers, and some experiments with a similar object have been made by Messrs. Evershed and

* "Experimental Researches in Magnetism." 'Phil. Trans.,' Part II., 1885, p. 523.

VIGNOLES,* and by Mr. C. P. STEINMETZ.† Notwithstanding, however, the increased interest which now attaches to the matter in consequence of its practical bearing, the available data are still meagre. By way of adding to them, we have made a detailed examination of some ten samples of wire and sheet iron, arranged in the form of rings to be operated on by the ballistic method.

In the former tests, referred to above, the method used was to make direct observations with a magnetometer, the samples being then long, straight pieces of wire. When the metal to be examined is in the form of wire, which may be taken long enough to secure practical endlessness, or of rods or bars big enough to be turned down into ellipsoids, the direct magnetometric method is entirely suitable. Several of our samples, however, were to be cut out of plate or sheet metal, such as is now largely used in the manufacture of transformers; and for this reason, as well as because direct measurements were to be made of the heating effect of magnetic reversals (which made ring samples most eligible), the ballistic method was selected, and a somewhat novel form was given to it, to allow points on the cyclic curve to be accurately and conveniently determined by its means.

In the paper already cited, some ballistic observations of magnetic cycles were described, in which the successive points on the cycle were determined by summing the ballistic effect of successive steps, in each of which the magnetic force underwent a small sudden change. This method is, at the best, laborious, and requires great care to avoid the carrying forward and accumulation of errors. The accuracy of each point depends on that of the points before it, though at the end of the process a check may be applied by comparing the ballistic effect of a sudden reversal with the sum of the effects of successive steps. There is an obvious advantage in making the determination of each point independent of the previous readings of the ballistic galvanometer, and, recognizing this, Messrs. EVERSHED and VIGNOLES introduced, in their experiments, the plan of reading each point by a single step from the terminal condition of magnetization represented by one or other extremity of the cycle. They wound their ring with two coils, through one of which a constant current was maintained; through the other coil a current, opposite in magnetizing quality, could be passed, and its strength could be varied up to a maximum which made its ampère-turns just twice the ampère-turns of the other coil. Then, when current flowed in the first coil only, the magnetization had its extreme positive value. By suddenly applying a current in the second coil, it was altered to any value between the positive and negative extremes. The use of two currents is an undesirable complication, especially as the symmetry of the resulting curves depends on the exactness with which the magnetizing effect of the one is adjusted to be, at its maximum, just twice that of the other. We have devised, and used throughout all these experiments, a method which, while requiring only one current and one magnetizing coil, retains the

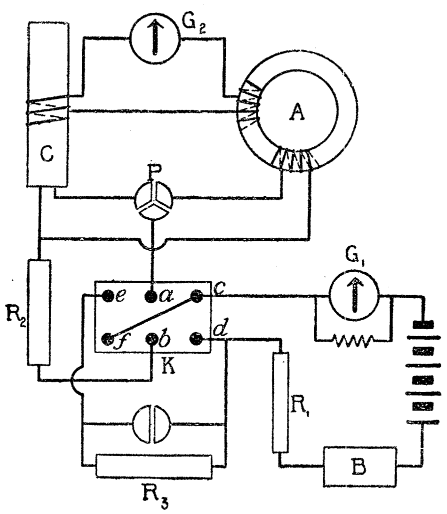
* EVERSHED and VIGNOLES, 'The Electrician,' May 15, 1891.

† STEINMETZ, 'Transactions of the American Institute of Electrical Engineers,' vol. 9, No. 1.

advantage that each point in the cycle is reached by a single step from the end of the cycle.

The diagram (fig. 1) shows the arrangement used.

Fig. 1.



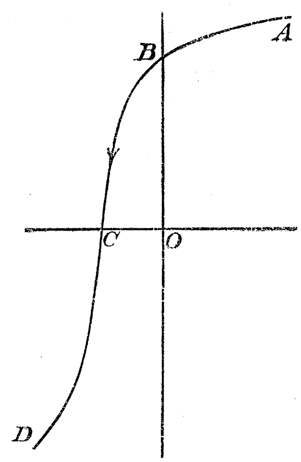
The magnetizing current passes from the battery through the adjustable resistance R_1 and the galvanometer G_1 to a key, K, and thence, through the resistance R_2, to a two-way plug, P, which allows it to be sent either into the magnetizing coil of the ring A, which is the sample under test, or into the primary of a special induction coil, C, which is used for standardizing the ballistic galvanometer. A and C each have a secondary coil; the two secondaries are kept in series with one another, and their circuit is completed through the ballistic galvanometer G_2. A Kelvin balance, B, which is short-circuited when it is not required, serves to determine the constant of the current galvanometer G_1. The key K is a rocker, working in mercury cups, which, when rocked to the left, connects *a* with *e* and *b* with *f*, and, when rocked to the right, connects *a* with *c* and *b* with *d*. In the latter position of the key, the full strength of the magnetizing current is in action, and hence, if the plug P is set so as to send the current into A, the sample is magnetized to a degree which represents one extremity of a magnetic cycle. Between the cups *e* and *d* of the rocking key are a short-circuit plug and also an adjustable resistance, R_3. When this short-circuit plug is inserted, the key K is simply a reversing key, and then, when rocked to the left, it reverses the magnetization of the ring, carrying it at once to the opposite end of the cycle. But when, instead of a short circuit between *c* and *d*, there is a resistance, the rocking of the key to the left applies to the sample a magnetizing current opposite in sign to the primitive current, but less than it in amount, and, consequently, carries its magnetism, not to the end of the cycle, but to a point which falls short of the end by an amount depending on the magnitude of the resistance R_3. The peculiarity of the method is that, by a single movement of the key, the magnetizing current is at

once reduced in amount and reversed in sign.* By giving R_3 a series of values, each movement of the key to the left determines a new point on the curve, while each movement to the right brings back the magnetization to its extreme value. In this way as many points are found as may be required to define that part of the curve which lies between the zero of magnetizing force and its extreme negative value. To find points lying between the positive extreme and the zero of magnetizing force, a different process is adopted. The key is kept to the left, and a sudden reduction of the current (without change of sign) is effected by withdrawing a plug from the resistance box R_2. This gives a point in the first quadrant of the descending curve, and a series of such points are found by selecting successive values of R_2, the magnetization of the sample being, however, restored to its initial full value before each such step.

To make the matter plainer, we may describe the operation of taking a cycle in detail. First, the strength of the magnetizing current was adjusted by selecting a proper number of cells (a storage battery was used throughout) and by means of the resistance R_1, so that the limits of magnetization should have the desired value. At this stage there was no resistance in R_2, and the short-circuit plug between *e* and *d* was in its place. The key K was now rocked back and forth many times to bring the magnetic changes into a thoroughly cyclic state—a precaution especially necessary when only a weak degree of magnetization was in question. The ballistic effect of this reversal was observed, several times over. Then, with the key K leaning to the right, a small sudden reduction of current was made by removing a plug from R_2, and the ballistic effect of this was observed. The plug in R_2 was replaced, the key K rocked back and forth to put the metal through a cycle, and then a second resistance, larger than the first, was suddenly opened in R_2. Operating in this way, a series of points were found for values of the magnetizing force H, lying between the positive maximum and zero. To continue the curve beyond the axis into the region of negative H, the resistance R_3 was adjusted to have, first, a rather high value. The key was then rocked from right to left, the ballistic effect being read; then this resistance was short-circuited; the specimen was taken through its full cycle by rocking the key; R_3 was set to be less than before, and its short-circuit plug was removed, the key was again rocked to the left, and so on. The curve determined by these successive operations was the curve ABCD (fig. 2), in which (ordinates being magnetization and abscissæ magnetizing force) A is the extreme state, always reverted to between each operation and the next; AB is the position determined by plugging out resistances in R_2, and BCD by rocking the key K with successive (lessening) values of R_3. This curve completely defines the magnetic cycle, inasmuch as the return limb

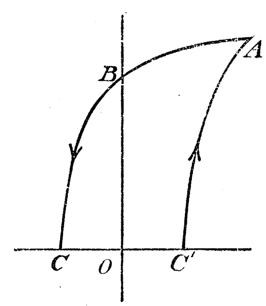
* Since this description was written, a paper has been communicated to the Royal Society by Dr. JOHN HOPKINSON and Messrs. LYDALL and WILSON, in which ballistic experiments are described where the method was essentially the same as that used by us. A single movement of a key reversed the magnetizing current and introduced resistance. ('Roy. Soc. Pro.,' vol. 53, p. 352.)

Fig. 2



is symmetrical with the one sketched. As a matter of convenience in exhibiting the results, the portion CD may be sketched as extending from a point C′ back to the starting point A, as in fig. 3, OC′ being taken equal to OC, and in this way the

Fig. 3.



relations of the rising and falling curve to one another are more clearly shown. There is, of course, no need to draw the other half of the cycle. The ordinate of A is taken as equal to half the magnetic change which occurs on reversal of the full strength of the magnetizing current.

G_1, used in measuring the magnetizing current, was a mirror galvanometer, strongly shunted and provided with a strong controlling field. Its constant in the shunted state was determined daily by means of the Kelvin centi-ampère balance. The ballistic galvanometer was provided with a usual arrangement for applying electromagnetic impulses to stop the swing of the needle. Its readings were reduced to absolute measure by means of the coil C, an air induction coil, whose dimensions were accurately measured, and the coefficient of mutual induction of its coils calculated from them. Its induction was sufficient to give a ballistic deflection of the same order of magnitude as that given by the sample under test. The resistance of the ballistic circuit was not altered throughout an experiment, and the two secondaries were permanently connected in series

The use of the coil C made the magnetic induction, as well as the magnetizing force, depend for its interpretation in absolute measure on the standard furnished by the Kelvin balance. The resistance R_1 was a frame of platinoid wire, wound for these experiments; R_3 was, in the first instance, a liquid slide consisting of amalgamated zinc plates, immersed in a jar containing solution of zinc-sulphate, but in the later experiments we found that a Varley carbon resistance, consisting of a pile of discs adjustable by compression, formed a very convenient substitute, especially when supplemented by short shunts of platinoid for the lower values of R_3.

All the samples tested in this set of experiments were arranged in the form of rings, with a mean diameter, generally, of about 10 centims., and an area of cross-section of from one to two square centims. The magnetizing coil was wound uniformly round the whole ring, in a single layer or in two layers. A few turns of wire, wound outside of that, formed the secondary or induction coil, the number of these turns being chosen so that reversal of the strongest magnetization produced as large a throw as could conveniently be read on the ballistic galvanometer. In several instances pairs of rings were prepared, exactly alike in all respects, for the purpose of making certain special tests which will be described later.

With each sample a series of cycles were determined, generally ten or twelve, beginning with one in which the limiting magnetization was strong, and working down to cycles on which the range was so small that the effects of hysteresis nearly disappeared. In the case of one or two samples a supplementary examination of the smaller cycles was made on a finer scale, by means of another secondary coil with a considerably larger number of turns, while the scale of the current galvanometer was at the same time altered by using a weaker shunt. We shall now give the results of the tests in detail.

Ring I.—In this ring the core was of fine iron wire, insulated by a winding of cotton. The diameter of the wire was 0·02475 centim. It was supplied (by Messrs. Glover) as a specimen of soft iron, but the tests showed that it had either not been softened, or had been insufficiently softened after its last passage through the drawplate, the curve of magnetization presenting, to some extent, the characteristics of those for unannealed metal. Eleven cycles were examined; the results are stated below and are shown by the curves of fig. 4 (Plate 34). The figures give the magnetic force H and the magnetic induction B, both in C.G.S. units.

RING I.—Fine Iron Wire.

Cycle (1).		Cycle (2).		Cycle (3).		Cycle (4).	
H.	B.	H.	B.	H.	B.	H.	B.
18·23	10870	13·01	8840	8·80	6780	6·59	5260
12·12	10220	9·52	8510	7·06	6610	3·76	4880
5·14	8840	7·50	8190	5·87	6450	2·29	4630
2·98	8290	4·58	7690	3·91	6130	1·39	4440
1·61	7620	2·80	7370	2·52	5850	0·78	4200
0	6910	1·55	6990	1·47	5640	0	3900
− 0·67	6890	0	6450	0·65	5370	−0·39	3740
− 1·11	6310	− 0·79	5750	0	5040	−1·11	3310
− 1·48	6040	− 1·30	5420	−0·81	4610	−1·85	2660
− 1·85	5750	− 1·85	4930	−1·48	4170	−2·31	1790
− 2·41	4800	− 2·78	2930	−2·22	3310	−2·78	270
− 2·78	3820	− 3·71	− 430	−2·78	1630	−3·24	−1250
− 3·33	1490	− 4·17	−1630	−3·22	− 110	−3·71	−2280
− 3·89	− 300	− 4·64	−2490	−3·71	−1460	−4·47	−3580
− 4·45	− 1540	− 5·56	−3960	−4·63	−3310	−6·59	−5260
− 5·37	− 3230	− 6·49	−5200	−5·56	−4500		
− 6·48	− 4830	− 8·38	−6670	−6·48	−5370		
− 8·34	− 6580	−13·01	−8840	−8·80	−6780		
−10·18	− 7780						
−18·23	−10870						

Cycle (5).		Cycle (6).		Cycle (7).		Cycle (8).	
H.	B.	H.	B.	H.	B.	H.	B.
4·40	3280	2·91	1410	1·94	560	1·23	270
2·93	3060	2·18	1330	1·24	450	0·73	220
1·94	2900	1·10	1110	0·59	340	0	80
1·24	2760	0·31	870	0	200	0·39	0
0·51	2550	0	760	−0·48	30	0·65	80
0	2360	−0·46	600	−0·74	− 40	0·93	160
−0·43	2110	−0·93	320	−1·02	−150	1·23	270
−1·11	1730	−1·39	50	−1·39	−310		
−1·85	590	−1·85	− 380	−1·67	−420		
−2·31	0	−2·31	− 920	−1·94	−560		
−2·78	−1110	−2·91	−1410				
−3·25	−1980						
−4·40	−3280						

In addition to these, three higher cycles were taken, with limiting values of H and B, as under :—

Limit of H.	Limit of B.
55·8	16640
34·4	14810
25·3	12940

These, however, are omitted from the figure, as they would have required it to be drawn to an inconveniently small scale.

Inspection of fig. 4 brings out one curious feature in the relation of the successive cycles to one another, which, however (as other figures will presently show), is of quite general occurrence. The extremity of each cycle lies outside of the rising curve of the immediately higher cycle, provided there is no very great difference in their ranges of magnetization. It is only when we come down to the lowest cycles, where the steps by which B is reduced from cycle to cycle are relatively great, that this does not happen. It should be remembered that each of these cycles is taken only after a large number of reversals of that particular magnetizing force which determines its range. During these reversals the range became somewhat reduced, especially when the magnetism does not approach saturation.

From these curves, by measuring the enclosed areas, values have been found of the energy dissipated in performing the magnetic cycle, namely, $\int H\,dI$ or, $\frac{1}{4\pi}\int H\,dB$.

RING I.—Fine Iron Wire. Energy dissipated in Cyclic Process of Double Reversal of Magnetism.

Limit of H.	Limit of B.	$\int H\,dI$, ergs.
55·8	16640	24930
34·4	14810	20320
25·3	12940	17130
18·23	10870	13410
13·01	8840	9900
8·80	6780	6420
6·59	5260	4180
4·40	3280	1940
2·91	1410	450
1·94	560	62
1·23	270	18

These results are given graphically in figs. 7 and 8, along with corresponding ones for the next ring.

Ring II. was of steel wire, of nearly the same fineness as the iron wire of Ring I. The diameter was 0·0257 centim., and, like the last, it was insulated throughout with cotton. Eleven cycles were taken in the first instance, as follows :—

RING II.—Fine Steel Wire.

Cycle (1).		Cycle (2).		Cycle (3).		Cycle (4).	
H.	B.	H.	B.	H.	B.	H.	B.
43·91	17680	32·42	16720	21·89	15040	13·66	12070
23·25	16900	19·50	16160	15·02	14680	7·27	11570
15·63	16470	13·93	15870	9·25	14260	3·80	11180
9·69	15900	8·91	15440	5·24	13830	1·83	10960
6·05	15440	5·78	14940	2·79	13430	0	10500
2·31	14830	2·99	14510	0	12820	− 1·36	10040
0	14260	0	13760	− 0·61	12650	− 2·73	9430
− 0·95	13980	− 1·43	13330	− 2·04	12110	− 3·47	9010
− 2·04	13590	− 2·38	13010	− 3·40	11500	− 3·74	8830
− 3·40	12870	− 3·40	12480	− 4·76	10130	− 4·07	8580
− 5·09	11050	− 4·76	11300	− 5·44	7770	− 4·76	7360
− 5·78	8560	− 5·78	8050	− 6·18	4570	− 5·44	4800
− 6·80	4350	− 6·80	3350	− 6·87	920	− 6·12	1950
− 8·16	− 2210	− 8·16	− 3310	− 9·14	− 6270	− 6·80	− 1910
−11·49	− 9270	−10·53	− 8160	−10·19	− 8410	− 8·57	− 6970
−13·59	−11520	−12·27	−10590	−11·56	−10340	− 8·84	− 7820
−16·51	−13400	−17·06	−13830	−13·53	−12190	−10·40	− 9960
−19·44	−14860	−19·91	−14730	−18·01	−14120	−12·10	−11280
−43·91	−17680	−32·42	−16720	−21·89	−15040	−13·66	−12070

Cycle (5).		Cycle (6).		Cycle (7).		Cycle (8).	
H.	B.	H.	B.	H.	B.	H.	B.
10·98	10190	8·91	8190	7·48	6170	6·12	3960
6·51	9840	5·71	7770	5·03	5960	3·40	3680
4·55	9630	3·29	7530	2·58	5600	2·04	3460
2·45	9350	1·77	7320	1·09	5350	0	3060
1·43	9170	0	6890	0	5060	−1·09	2680
0	8810	−1·36	6490	−0·88	4850	−2·04	2350
− 0·34	8770	−2·72	5910	−1·70	4570	−3·40	1470
− 0·68	8700	−3·74	5170	−2·72	4030	−4·08	610
− 1·70	8270	−4·49	4280	−3·40	3600	−4·76	−1390
− 2·72	7840	−5·09	2250	−4·08	2890	−5·44	−3030
− 3·40	7530	−5·44	710	−4·76	990	−6·12	−3960
− 4·08	6920	−6·12	−2680	−5·50	−1900		
− 4·76	5630	−6·80	−5240	−6·12	−4240		
− 5·44	2890	−7·89	−7090	−7·48	−6170		
− 6·12	− 70	−8·91	−8090				
− 6·80	− 3530						
− 7·40	− 5700						
− 8·16	− 7340						
− 9·66	− 9130						
−10·98	−10190						

Cycle (9).		Cycle (10).		Cycle (11).	
H.	B.	H.	B.	H.	B.
4·76	1820	4·08	1180	2·24	360
2·92	1610	1·70	900	0·88	210
1·50	1390	0	610	0	70
0	1110	1·70	110	−1·57	−210
−1·70	610	2·99	− 530	−2·24	−360
−3·40	− 430	4·08	−1180		
−4·08	−1250				
−4·76	−1820				

These results are also shown in fig. 5 (Plate 34), where, however, Cycle 2 and the extremity of Cycle 1 are omitted to avoid overloading the diagram. Cycles 10 and 11 are also omitted. In drawing the curves the points corresponding to the readings actually taken are marked by dots enclosed within circles. They give satisfactory evidence that the method of observation we have used will yield a smooth curve. The curves here have the square-shouldered form, which is often found in steel as well as almost always in *annealed* soft iron. (The absence of this characteristic in Ring I., as well as its comparatively low permeability, was an indication of its being in a somewhat hard state.)

To test more particularly the action of weak magnetic forces, Ring II. was further taken through a series of low cycles, the sensibility of the apparatus in regard both to ballistic and current measurements having been first increased in the manner already indicated. That is to say, an induction coil of a larger number of turns was now used, and the current galvanometer was less strongly shunted. Five small cycles were observed as follows :—

Ring II. (Small cycles.)

Cycle (12).		Cycle (13).		Cycle (14).		Cycle (15).		Cycle (16).	
H.	B.	H.	B.	H.	B.	H.	B.	H.	B.
3·930	925	3·105	590	2·145	320	1·340	170	0·787	89
2·315	750	1·995	480	1·215	220	0·905	135	0·422	52
1·260	605	1·155	380	0·840	185	0·680	110	0·203	34
0·695	505	0·630	295	0·535	135	0·385	75	0	12
0	395	0·325	245	0	75	0	30	−0·267	−21
−0·265	320	0	195	−0·265	25	−0·160	10	−0·534	−58
−0·535	265	−0·425	125	−0·535	− 10	−0·535	− 35	−0·787	−89
−1·070	130	1·070	− 25	−1·070	−110	−0·800	− 85		
—	− 50	1·605	−160	−1·550	−210	− 1·070	−120		
−2·140	−210	3·100	−590	−2·140	−320	−1·340	−170		
−2·670	−405	2·185	−320						
−2·885	−520								
−3·930	−925								

These, with the exception of No. 15, are drawn out in fig. 6 (Plate 35).

Measuring areas as before we find the energy dissipated in the cycles :—

Ring II.—Fine Steel Wire. Energy dissipated in cyclic process of double reversal of magnetism.

No. of Cycle.	Limits of H.	Limits of B.	$\int$ H dI, ergs.
1	43·91	17680	45770
2	32·42	16720	41320
3	21·89	15040	34330
4	13·66	12070	23460
5	10·98	10190	18100
6	8·91	8090	12820
7	7·48	6170	8300
8	6·12	3960	4310
9	4·76	1820	1130
10	4·08	1180	540
12	3·93	925	307
13	3·105	590	125
14	2·145	320	30
16	0·787	89	1·4

Fig. 7 gives the value of $\int$ H dI for this ring and also for Ring I., in relation to H, and fig. 8 (Plate 36) gives them in relation to B.

Fig. 8a further shows to a larger scale the relation of $\int$ H dI to B in the low-cycle tests of Ring II. It is interesting, as an example of the growth of $\int$ H dI in the region of low magnetic force, when the effects of hysteresis are only beginning to be

felt. The figures show in a striking way how small the loss of energy through hysteresis becomes when the limits of magnetization or of magnetic force are restricted within certain values.

A characteristic of the curves of fig. 5 is the remarkably uniform rate at which B changes with respect to H during a great part of the process of magnetic reversal. After the shoulder of the descending curve has been turned, by applying a sufficiently strong demagnetizing force, the quantity $d\mathrm{B}/d\mathrm{H}$ takes a large and nearly constant value which it retains until a tolerably strong reversed magnetization has been produced. The steep and nearly straight portion of the curve which corresponds to this part of the process has, moreover, nearly the same gradient in all except the smallest cycles. The same characteristic will be found in examples of annealed iron, to be given later, and the gradient in them is of course even steeper than it is here. In the present sample of steel wire (Ring II.), the maximum value of $d\mathrm{B}/d\mathrm{H}$ is about 4950; nearly half the whole magnetic change in the highest cycle occurs at approximately this rate. In some of our soft iron samples $d\mathrm{B}/d\mathrm{H}$ reaches a value nearly three times as great as this.

The amount of demagnetizing force just sufficient to bring the magnetism to zero has been called by HOPKINSON* the *coercive force.* It will be seen from these tests that the coercive force rises progressively as the magnetization is increased. We have measured its values for the cycles of Rings I. and II., and these may conveniently be expressed in relation to the limits of H and of the intensity of magnetization I.

RING I.

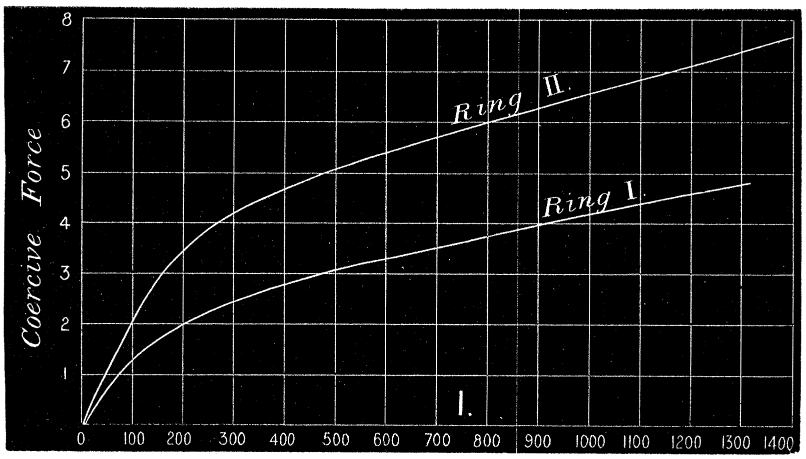
Limits of H.	Limits of I.	Coercive force.
58·36	1320	4·75
35·93	1176	4·55
26·48	1027	4·20
18·23	863	3·84
13·01	703	3·59
8·80	539	3·20
6·59	418	2·88
4·40	261	2·25
2·91	112	1·46
1·23	22	0·36

* J. HOPKINSON, "Magnetization of Iron," 'Phil. Trans.,' 1885, p. 460.

RING II.

Limits of H.	Limits of I.	Coercive force.
43·21	1404	7·71
32·42	1328	7·43
21·89	1195	7·06
13·66	960	6·48
10·98	810	6·00
8·91	643	5·61
7·48	490	5·01
6·12	317	4·28
4·76	145	2·83
4·08	94	1·94
2·14	25	0·45

Fig. 9.



Coercive Force and I. Rings I. and II.

In fig. 9 the coercive force is plotted in relation to I. From this figure it is possible, by extrapolation of the curve, to arrive at a probable estimate of a definite physical constant of the material which forms a good criterion of magnetic hardness, namely, the coercive force which would correspond to the state of magnetic saturation. This, in other words, is the demagnetizing force which would be just sufficient to remove magnetism from a piece which had been magnetized to literal saturation. We know that the saturation value of I. in wrought iron and steel is about 1700.* A conjectural extension of the curves along the straight lines which they follow in the region of strong magnetization shows that the coercive force of saturation is probably about 5·5 in the (rather hard) iron of Ring I., and 8·5 in the steel of Ring II.

* 'Phil Trans,' 1889, A, p. 221.

The next three rings had cores of sheet iron. Ring III. was made up of comparatively thick annular discs which were turned out of discs that had been supplied for the core of a dynamo armature. The mean thickness of the discs was 0·195 centim.; the internal diameter of the annulus was 13·55 centims. and its external diameter 1545 centims. Rings of paper were interposed to prevent the discs from touching one another. The tests showed that this iron compared well with most other specimens in the matter of magnetic softness.

The following cycles were measured :—

RING III.—Thick Sheet Iron.

Cycle (1).		Cycle (2).		Cycle (3).		Cycle (4).	
H.	B.	H.	B.	H.	B.	H.	B.
32·34	15920	21·60	14920	14·62	13730	10·42	12460
22·51	15520	16·66	14660	12·19	13560	9·11	12330
17·23	15190	13·59	14390	10·44	13400	8·12	12130
10·10	14290	8·73	13730	7·29	12900	6·08	11940
5·97	13330	5·47	12860	4·86	12260	4·33	11470
3·30	12220	3·08	11870	2·09	10940	2·70	10940
0	9350	1·37	10670	1·37	10380	1·29	9950
− 1·33	5700	0	9060	0	8950	0	8560
− 1·54	4180	− 0·72	7820	− 0·95	7230	− 0·83	7100
− 1·90	1390	− 1·33	5800	− 1·33	5630	− 1·33	5100
− 2·28	− 1060	− 1·52	4300	− 1·52	4640	− 1·52	3720
− 2·85	− 3720	− 1·90	1390	− 1·90	1390	− 1·90	660
− 3·80	6370	− 2·28	− 1190	− 2·28	− 1330	− 2·28	− 1730
− 4·75	7820	− 2·66	− 2980	− 2·66	− 3120	− 2·66	− 3580
− 5·69	9220	− 3·04	− 4440	− 3·23	− 4970	− 3·23	− 5500
− 6·65	10220	− 3·80	− 6500	− 3·80	− 6570	− 3·80	− 6830
− 7·59	10870	− 4·75	− 8220	− 4·75	− 8230	− 5·69	− 9550
− 9·53	12000	− 5·69	− 9290	− 5·69	− 9350	− 7·59	−11010
−11·30	12740	− 7·59	−10840	− 7·59	−11010	− 8·73	−11670
−18·22	14460	− 9·49	−12000	−10·82	−12660	−10·42	−12460
−24·15	15320	−11·39	−12770	−12·15	−13000		
−25·44	15460	−15·18	−13790	−14·62	−13730		
−32·34	15920	−18·22	−14460				
		−21·60	−14920				

Cycle (5).		Cycle (6).		Cycle (7).		Cycle (8).	
H.	B.	H.	B.	H.	B.	H.	B.
8·05	11340	5·59	9520	4·01	7790	2·89	5830
7·26	11270	4·83	9460	3·42	7700	2·39	5770
6·61	11170	4·03	9260	2·89	7590	1·60	5500
5·17	10940	3·15	9060	2·17	7390	0·95	5230
3·84	10610	2·20	8720	1·48	7100	0	4280
2·51	10150	1·14	8290	0·80	6800	−0·76	3380
1·22	9490	0·61	7990	0·30	6530	−1·14	1930
0·65	8830	0	7130	0	6060	−1·52	− 530
0	8160	−0·76	5940	−0·95	4270	−1·90	−2920
−0·76	6900	−1·14	4740	−1·14	3490	−2·28	−4380
−1·33	4790	−1·52	2090	−1·52	700	−2·66	−5300
−1·52	3260	−1·90	− 900	−1·96	−2020	−2·89	−5830
−1·90	200	−2·28	−3090	−2·28	−3750		
−2·28	− 2260	−2·66	−4540	−2·85	−5600		
−2·66	− 3780	−3·23	−6200	−3·42	−6730		
−3·23	− 5830	−3·80	−7320	−4·01	−7790		
−3·80	− 7100	−4·75	−8660				
−4·75	− 8490	−5·59	−9520				
−5·69	− 9620						
−6·84	−10550						
−8·05	−11340						

Cycle (9).		Cycle (10).		Cycle (11).		Cycle (12).	
H.	B.	H.	B.	H.	B.	H.	B.
2·05	3720	1·32	1360	0·76	400	0·45	170
1·63	3620	0·95	1300	0	140	0	30
1·10	3460	0·68	1160	−0·49	−140	0·42	−100
0·68	3160	0·45	1060	−0·57	−230	0·45	−170
0	2750	0	830	−0·76	−400		
−0·76	1590	−0·57	200				
−1·14	260	−0·76	− 100				
−1·52	−1890	−0·95	− 560				
−1·90	−3380	−1·14	− 960				
−2·05	−3720	−1·32	−1360				

These cycles, with the exception of No. 1, are shown in figs. 10 and 10*a* (Plate 37), where, to avoid confusion, the odd and even cycles are drawn separately. Measurement from these curves of the area, and of the coercive force, gives the following results :—

Ring III.—Thick Sheet Iron: Values of $\int H\,dI$ and Coercive Force.

Number of cycle.	Limits of H.	Limits of B.	Limits of I.	$\int H\,dI$.	Coercive force.
1	32·34	15920	1265	13960	2·10
2	21·60	14920	1187	12050	2·10
3	14·62	13730	1092	10240	2·10
4	10·42	12460	991	8550	2·01
5	8·05	11340	902	7270	1·96
6	5·59	9520	757	5240	1·79
7	4·01	7790	620	3760	1·61
8	2·89	5830	464	2270	1·44
9	2·05	3720	296	1130	1·20
10	1·32	1360	108	230	0·69
11	0·76	400	32	..	0·28
12	0·45	170	14	..	0·12

The values of $\int H\,dI$, in relation to B, will be found plotted in fig. 21, along with corresponding results for other samples of sheet and wire iron.

The next sample to be tested (Ring IV.) was of thin sheet iron, which, like the last, had been supplied to form the core of a dynamo armature. This iron, though supplied for a purpose in which magnetic softness is important, did not compare favourably with the thick sheet of Ring III. The ring was built up of 30 flat annuli, which were turned out of larger punched discs. The thickness of the sheet varied in different discs from 0·044 to 0·050 centim. The external diameter was 10·9 centims. and the internal diameter 8·45 centims., and the mean thickness of the sheets was 0·47 millim. The discs were insulated from one another with paper. Nine cycles were measured in the first instance, and then six small cycles, with a larger induction coil and a more sensitive adjustment of the current galvanometer. The results are given numerically below, and graphically in figs. 11 and 12. The larger cycles, with the exception of the second, are drawn on fig. 11. Fig. 12 exhibits the small cycles. The induction coil used in measuring the large cycles had 12 turns, but in the small cycles a coil with 195 turns was used to give a large magnification of the ballistic readings, the sensibility of the ballistic galvanometer itself being unchanged. The curves of the small cycles have been determined in this instance with particular minuteness, as a study of the behaviour of the iron under reversals of weak magnetizing forces. In the lowest cycle the limits of the magnetizing force are so narrow that the condition is approaching that of quasi-elastic magnetization: there is, however, still a distinct trace of hysteresis.

RING IV.—Thin Sheet Iron.

Cycle (1).		Cycle (2).		Cycle (3).		Cycle (4).		Cycle (5).	
H.	B.	H.	B.	H.	B.	H.	B.	H.	B.
23·61	14720	17·20	13760	12·99	12640	8·89	10880	6·45	9030
15·25	14220	11·33	13420	9·38	12410	7·02	10740	4·63	8830
10·13	13790	8·35	13090	7·26	12170	5·80	10610	3·24	8630
4·97	12960	4·63	12420	4·36	11710	3·78	10280	2·19	8370
2·93	12260	2·76	11890	2·66	11170	2·39	9940	1·33	8100
0	10590	0	10290	1·46	10700	0	8730	0	7430
− 0·68	9990	− 0·68	9660	0	9770	−0·85	7930	−0·68	6830
− 1·19	9320	− 1·36	8750	− 0·73	9100	−1·71	6520	−1·36	5890
− 1·71	8420	− 2·05	6880	− 1·36	8200	−2·39	2650	−2·05	3420
− 2·39	4980	− 2·73	1870	− 2·05	6220	−2·90	− 1020	−2·73	−1250
− 2·90	1370	− 3·41	− 2070	− 2·73	1350	−3·41	− 3750	−3·41	−4460
− 3·41	− 1570	− 4·09	− 4740	− 3·41	− 2520	−4·26	− 6220	−4·09	−6190
− 4·26	− 4690	− 4·78	− 6480	− 4·09	− 5120	−5·15	− 7430	−4·78	−7200
− 5·12	− 6780	− 5·46	− 7880	− 4·78	− 6800	−6·48	− 9300	−5·63	−8300
− 5·97	− 8250	− 6·14	− 8750	− 5·80	− 8470	−7·47	− 9980	−6·45	−9030
− 6·82	− 9250	− 6·82	− 9420	− 6·82	− 9540	−8·89	−10880		
− 8·53	−10720	− 8·53	−10820	− 8·53	−10810				
−10·92	−11840	−10·24	−11760	−10·24	−11670				
−13·65	−12920	−11·94	−12420	−12·04	−12340				
−20·57	−14520	−13·65	−12960	−12·99	−12640				
−23·61	−14720	−17·20	−13760						

Cycle (6).		Cycle (7).		Cycle (8).		Cycle (9).	
H.	B.	H.	B.	H.	B.	H.	B.
4·93	7250	4·01	5710	3·24	4160	2·32	1800
3·78	7120	2·49	5510	2·19	4020	1·36	1670
2·80	6980	1·81	5380	1·63	3920	0·75	1530
1·95	6780	0·85	5080	0·82	3690	0	1270
1·22	6580	0	4640	0	3360	−0·78	800
0	6010	−0·85	4000	−0·73	2790	−1·19	400
−0·82	5310	−1·71	2430	−1·36	1980	−1·36	130
−1·71	3710	−2·05	500	−1·71	1080	−1·71	− 600
−2·39	− 430	−2·39	−1500	−2·05	− 650	−2·05	−1330
−3·07	−3840	−2·73	−3040	−2·39	−2150	−2·32	−1800
−3·75	−5580	−3·07	−4040	−2·73	−3190		
−4·43	−6580	−3·41	−4780	−3·24	−4160		
−4·93	−7250	−4·01	−5710				

RING IV.—continued. Small Cycles.

Cycle (10).		Cycle (11).		Cycle (12).		Cycle (13).		Cycle (14).		Cycle (15).	
H.	B.	H.	B.	H.	B.	H.	B.	H.	B.	H.	B.
1·884	927	1·687	677	1·400	420	1·105	263	0·825	157	0·320	43
1·696	906	1·403	644	1·193	401	0·974	251	0·659	140	0·227	34
1·537	886	1·118	607	0·981	372	0·827	232	0·547	126	0·158	27
1·204	840	0·834	564	0·756	341	0·659	209	0·408	108	0	6
0·882	787	0·551	512	0·518	304	0·470	186	0·232	85	−0·172	−18
0·573	722	0·276	447	0·265	255	0·254	152	0	46	−0·243	−31
0·278	647	0·150	418	0	195	0	98	−0·221	5	−0·320	−43
0·150	610	0	373	−0·221	131	−0·221	49	−0·331	−23		
0	561	−0·221	299	−0·441	59	−0·441	−12	−0·441	−50		
−0·236	470	−0·441	208	−0·662	−29	−0·662	−86	−0·662	−105		
−0·331	429	−0·551	167	−0·772	−80	−0·882	−172	−0·825	−157		
−0·441	380	−0·662	106	−0·882	−129	−0·992	−217				
−0·551	327	−0·772	44	−0·992	−186	−1·105	−263				
−0·662	261	−0·882	−17	−1·105	−249						
−0·772	195	−0·992	−91	−1·213	−319						
−0·882	121	−1·103	−177	−1·400	−420						
−0 992	43	−1·213	−264								
−1·103	−51	−1·324	−363								
−1·213	−154	−1·456	−486								
−1·324	−272	−1·544	−568								
−1·434	−401	−1·687	−677								
−1·544	−552										
−1·654	−693										
−1·783	−824										
−1·884	−927										

From measurement of the curves of figs. 11 and 12, the following values of $\int H\,dI$ and of the coercive force have been determined.

RING IV.—Thin Sheet Iron. Values of $\int H\,dI$ and Coercive Force.

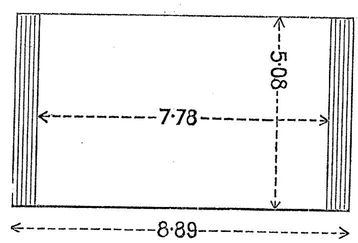
Number of cycle.	Limits of H.	Limits of B.	Limits of I.	$\int H\,dI$.	Coercive force.
1	23·61	14720	1170	16670	2·66
2	17·20	13760	1093	14830	2·56
3	12·99	12640	1005	12670	2·46
4	8·89	10880	865	9750	2·31
5	6·45	9030	718	6940	2·12
6	4·93	7250	577	4980	1·94
7	4·01	5710	454	3440	1·79
8	3·24	4160	331	2220	1·62
9	2·32	1800	143	660	1·20
10	1·884	927	73·6	225	
11	1·687	677	53·7	134	
12	1·400	420	33·3	59	
13	1·105	263	20·9	24	
14	0·825	157	12·4	8	
15	0·320	43	3·4	0·3	

These results are also exhibited, with others, in fig. 21. A reference to fig. 12 will show that the overlapping of one cyclic curve by the next lower curve (corresponding to a slightly narrower magnetic range) is characteristic of low cycles as well as of high ones. The loss of energy in reversal (measured by the area enclosed within the curve) becomes very small, both absolutely and relatively to the magnetization, in the lowest cycles; the molecular movements which constitute magnetization are there approaching the almost perfect reversibility which, as Lord RAYLEIGH has shown, is attained when the range of force is still further reduced.

By way of further illustrating the behaviour of this sample under the weak magnetizing forces of the small cycles, fig. 13 has been drawn to show the total induced magnetism, and also the residual magnetism, in each small cycle, both in relation to H. The figure forms an interesting example of the early stages of the magnetizing process.

The next sample (Ring V.) was also of thin sheet iron. It was sent by Mr. PARKER, of the Electric Construction Corporation, as a sample of the iron used in building up the cores of his transformers. This iron is supplied in sheets about 6 feet long and 3 feet wide, and its thickness is 0·367 millim. To make the ring, a strip 2 inches wide and 6 feet long was cut from the sheet, and this was coiled (along with a strip of paper for insulation) into a close spiral of the dimensions shown in the sketch (fig. 14), the

Fig. 14.



Section through Ring V.

ends of the spiral overlapping one another for a centimetre or so. This is a convenient way of giving sheet metal the ring-form suitable for ballistic tests; it is open, however, to the criticism that the bending of the metal is liable to harden it somewhat, especially near both surfaces, and it is possible that this consideration partly explains the comparatively sloping character of the curves (figs. 15 and 15a) obtained with this ring. A similar remark, of course, applies in the case of rings formed by winding soft iron wire.

RING V.—Soft Thin Sheet Iron (used in transformer cores).

Cycle (1).		Cycle (2).		Cycle (3).		Cycle (4).		Cycle (5).	
H.	B.	H.	B.	H.	B.	H.	B.	H.	B.
15·72	12360	12·41	11390	9·15	10120	6·95	8940	5·03	7530
8·43	11420	7·36	10720	6·02	9730	4·99	8690	3·92	7420
5·74	10640	5·23	10170	3·54	9070	3·20	8280	2·75	7120
3·51	9760	3·31	9460	1·96	8360	1·41	7450	1·30	6600
1·62	8720	1·55	8520	0	6760	0	6300	0	5550
0	7230	0	7090	−0·69	5830	−0·69	5420	−0·69	4620
−0·86	5970	−0·69	6160	−1·38	3680	−1·38	3050	−1·38	2140
−1·72	1460	−1·38	4010	−1·72	600	−1·72	−80	−1·72	−880
−2·41	−2560	−1·72	1040	−2·06	−1700	−2·06	−2230	−2·06	−2640
−3·10	−4590	−2·06	−1260	−2·75	−4180	−2·75	−4540	−2·75	−4780
−4·30	−6680	−2·75	−3850	−3·44	−5660	−3·44	−5800	−3·27	−5610
−5·16	−7620	−3·44	−5500	−4·30	−6870	−4·30	−6960	−3·92	−6430
−6·88	−8880	−4·30	−6760	−5·18	−7640	−5·03	−7620	−5·03	−7530
−8·50	−9870	−5·16	−7640	−6·09	−8470	−6·29	−8550		
−11·97	−11370	−6·88	−9020	−7·74	−9400	−6·95	−8940		
−12·76	−11640	−9·90	−10560	−9·15	−10120				
−15·72	−12360	−12·41	−11390						

Cycle (6).		Cycle (7).		Cycle (8).		Cycle (9).		Cycle (10).	
H.	B.	H.	B.	H.	B.	H.	B.	H.	B.
3·68	6100	2·75	4730	2·04	3240	1·27	1210	0·61	220
2·58	5940	2·09	4670	1·30	3080	0·76	1100	0·34	200
1·82	5690	1·55	4480	0·61	2800	0·41	930	0	80
1·20	5440	1·06	4290	0	2360	0	710	−0·34	−150
0	4620	0·67	4070	−0·69	1460	0·34	410	−0·61	−220
−0·69	3680	0	3550	−1·38	−1320	0·69	−50		
−1·38	710	−0·69	2720	−1·72	−2530	1·03	−710		
−2·06	−3350	−1·39	−550	−2·04	−3240	1·37	−1210		
−2·75	−4950	−2·06	−3460						
−3·03	−5280	−2·32	−3960						
−3·68	−6100	−2·75	−4730						

These cycles are shown in figs. 15 and 15*a*. Measuring from the curves we have these results, which will also be found in fig. 21.

RING V.—Soft Thin Sheet Iron. Values of ∫HdI and Coercive Force.

Number of cycle.	Limits of H.	Limits of B.	Limits of I.	∫H dI.	Coercive force.
1	15·72	12366	982	8310	1·92
2	12·41	11390	905	7250	1·87
3	9·15	10120	882	6020	1·80
4	6·95	8940	711	4900	1·71
5	5·03	7530	599	3670	1·62
6	3·68	6100	485	2520	1·47
7	2·75	4730	376	1760	1·42
8	2·04	3240	258	900	1·02
9	1·27	1210	96	180	0·68
10	0·61	220	17	6	0·10

The remaining specimens dealt with in this section of our experiments were of iron wire. In Ring No. VI. the core was of fine cotton-covered wire 0·34 millim. in diameter, which was kindly supplied to us for the purpose of these experiments by a leading firm of manufacturers at the instance of Mr. W. H. PREECE. It was described as Swedish charcoal iron, but the tests show that it was decidedly hard in the magnetic sense, having a rather high coercive force and other characteristics resembling those of mild steel. Six cycles were measured, with results which are given below and graphically in fig. 16.

Ring VI.—Fine Iron Wire.

Cycle (1).		Cycle (2).		Cycle (3).	
H.	B.	H.	B.	H.	B.
12·34	11330	9·14	9430	7·30	7730
6·54	10760	5·45	9070	4·71	7410
3·29	10280	2·44	8540	2·27	7000
1·64	9960	0·61	8140	0·77	6680
0·64	9720	0	7980	0	6480
0	9470	−0·64	7730	−1·28	6030
− 1·31	8910	−1·54	7330	−2·57	5230
− 2·57	8020	−2·57	6360	−3·85	1840
− 3·93	5110	−3·85	3610	−4·50	−1640
− 4·37	2520	−4·37	870	−4·86	−3410
− 5·17	− 1760	−4·88	−2040	−6·12	−6560
− 5·68	− 4180	−5·40	−4460	−6·38	−6880
− 6·41	− 6360	−7·35	−8100	−7·30	−7730
− 9·28	− 9680	−7·71	−8420		
−12·34	−11330	−9·14	−9430		

Cycle (4).		Cycle (5).		Cycle (6).	
H.	B.	H.	B.	H.	B.
6·14	6230	5·03	4220	3·55	1290
3·18	5830	2·85	3940	2·31	1130
1·85	5600	1·72	3690	0·95	850
0	5150	0	3250	0	650
−1·28	4620	−1·28	2760	−1·03	240
−2·57	3810	−2·57	1880	−2·06	− 200
−3·21	2800	−3·21	750	−2·79	− 690
−3·85	100	−3·68	− 950	−3 55	−1293
−4·21	−1520	−4·47	−3290		
−5·27	−5070	−5·03	−4220		
−5·48	−5390				
−6·14	−6230				

RING VI.—Fine Iron Wire. Values of $\int H\, dI$ and Coercive Force.

Number of cycle.	Limits of H.	Limits of B.	Limits of I.	$\int H\, dI$.	Coercive force.
1	12·34	11330	901	16490	4·83
2	9·14	9430	750	12250	4·52
3	7·30	7730	614	9050	4·20
4	6·14	6230	495	6580	3·86
5	5·03	4220	335	3670	3·43
6	3·55	1290	105	490	1·65

The next specimen (Ring VII.) was also of cotton-covered iron wire, of larger diameter than the last, namely 0·975 millim. It turned out to be only moderately soft in the magnetic sense. In addition to the measurements of magnetic cycles, the results of which are given below and in figs. 17 and 17*a* (Plate 39), several other experiments were made with this ring with the view of determining directly the heating effect of magnetic reversals. These will be described in a later part of this paper. The ring had a mean diameter of 9·6 centims., and the net area of section of the iron wire forming its core was 1·00 sq. centim.

Ring VII.—Iron Wire.

Cycle (1).		Cycle (2).		Cycle (3).		Cycle (4).	
H.	B.	H.	B.	H.	B.	H.	B.
37·40	15980	21·73	14340	14·59	12860	10·28	11420
25·65	15490	10·48	13300	8·47	12230	8·21	11130
11·42	13880	5·86	12250	5·18	11580	4·51	10570
3·04	11330	3·38	11370	1·75	10310	1·69	9520
1·58	10610	0·79	9970	0·77	9780	0·39	8670
0·00	9310	0·00	9240	0·00	9130	0·00	8550
− 2·78	− 410	− 0·75	7840	− 0·73	8430	− 0·73	7570
− 3·85	− 5130	− 1·28	7480	− 0·90	7910	− 1·28	6720
− 5·15	− 7740	− 2·14	3820	− 1·71	6050	− 2·14	2860
− 6·97	− 9600	− 3·42	− 3650	− 2·57	520	− 3·00	− 2860
− 9·41	−11070	− 4·71	− 7080	− 3·85	− 5520	− 4·02	− 6290
−13·86	−12710	− 6·84	− 9520	− 5·56	− 8460	− 5·15	− 8190
−22·67	−14600	−10·82	−11670	− 7·72	−10350	− 6·33	− 9430
−24·81	−14860	−21·73	−14340	− 8·68	−10820	−10·28	−11420
−37·40	−14980			−14·59	−12860		

Cycle (5).		Cycle (6).		Cycle (7).		Cycle (8).		Cycle (9).	
H.	B.	H.	B.	H.	B.	H.	B.	H.	B.
7·66	10090	5·61	8520	3·60	5780	2·20	2260	1·05	390
5·56	9840	3·34	8170	1·92	5430	1·07	1960	0·45	260
2·63	9180	1·50	7680	1·28	5270	0·58	1730	0·28	190
0·73	8240	0·71	7350	0·64	4970	0·00	1440	0·00	130
0·00	7770	0·00	6730	0·00	4550	−0·56	880	−0·58	−130
−0·73	6900	−0·73	6020	−0·64	4080	−1·07	230	−1·05	−390
−1·28	6050	−0·98	5620	−1·07	3200	−1·50	− 820		
−2·14	1860	−1·43	4640	−1·71	950	−1·93	−1800		
−3·00	− 3630	−2·14	690	−2·35	−2740	−2·20	−2260		
−4·28	− 7130	−3·00	−4180	−3·00	−4680				
−5·26	− 8170	−4·28	−7130	−3·60	−5780				
−7·66	−10090	−4·53	−7390						
		−5·61	−8520						

RING VII.—Iron Wire. Values of $\int H\, dI$ and Coercive Force.

Number of cycle.	Limits of H.	Limits of B.	Limits of I.	$\int H\, dI$.	Coercive force.
1	37·40	15980	1268	16580	2·81
2	21·73	14340	1140	13390	2·74
3	14·59	12860	1023	11270	2·61
4	10·28	11420	908	8790	2·52
5	7·66	10090	802	7390	2·41
6	5·61	8520	677	5600	2·22
7	3·60	5780	460	3020	1·84
8	2·20	2260	182	650	1·17
9	1·05	390	31	26	0·32

For the last sample on our list (Ring VIII.) we are indebted to Mr. JAMES SWINBURNE, who sent a hank of the soft iron wire used in the cores of his "hedgehog" transformers. The diameter of the wire was 0·602 millim., and its surface was bright. On winding it into a ring with a mean diameter of 2·75 centims., without, in the first instance, taking any steps to secure insulation between neighbouring turns of the bright iron wire, we found that the Foucault currents in the ring were so influential as to make the ballistic tests of it in this condition worthless. In all the previous examples the wire or sheet metal forming the core had been insulated by cotton or paper. The ring was then soaked in a hot bath of boiled linseed oil, which was allowed to penetrate freely to the core—a treatment which, we believe, is similar to that actually followed in the building of the transformers. It appears that this was effective in preventing the Foucault currents from passing from wire to wire. Tests made with the ring in this state, which we shall distinguish as the first state, are shown in figs. 18 and 18*a*. The following are the observed values of B and H in nine graded cycles :—

Ring VIII.—Soft Iron Wire of "Hedgehog" Transformer. First State.

Cycle (1).		Cycle (2).		Cycle (3).		Cycle (4).	
H.	B.	H.	B.	H.	B.	H.	B.
22·23	15600	15·04	14200	11·33	13020	8·62	11690
9·58	14400	7·89	13410	6·72	12550	4·60	11030
4·45	13140	4·05	12530	3·69	11820	1·84	10290
2·16	12130	2·00	11840	1·92	11160	0·75	9830
1·06	11540	0	10140	0·98	10630	0	9300
0	10750	− 1·21	9080	0	9960	− 1·53	7500
− 1·38	9150	− 1·96	7550	− 1·45	8300	− 1·96	6380
− 2·16	7020	− 2·77	1380	− 1·96	7110	− 2·37	3590
− 2·44	4830	− 3·14	− 2080	− 2·40	4190	− 2·75	− 3301
− 2·79	1450	− 3·53	− 4280	− 2·75	800	− 3·14	− 3130
− 3·02	− 550	− 4·34	− 6790	− 3·14	− 2520	− 3·73	− 5980
− 3·34	− 2950	− 4·71	− 8120	− 3·54	− 4780	− 4·32	− 7430
− 3·93	− 5530	− 5·89	− 9520	− 4·15	− 6770	− 5·07	− 8630
− 4·71	− 7520	− 6·88	−10580	− 4·71	− 8040	− 5·91	− 9630
− 5·89	− 9430	− 8·24	−11580	− 5·70	− 9430	− 7·66	−11030
− 7·85	−11310	−12·29	−13310	− 6·68	−10430	− 8·62	−11690
− 9·81	−12500	−15·04	−14200	− 9·69	−12350		
−16·72	−14710			−11·33	−13020		
−22·23	−15600						

Cycle (5).		Cycle (6).		Cycle (7).		Cycle (8).		Cycle (9).	
H.	B.	H.	B.	H.	B.	H.	B.	H.	B.
6·56	10160	5·03	8490	3·65	5950	2·51	2490	1·73	900
3·65	9630	3·14	8170	2·56	5740	1·42	2150	0·82	630
1·57	9030	1·57	7700	1·69	5470	0	1490	0	300
0·90	8760	0	6910	0	4680	1·10	430	0·66	− 30
0	8230	−1·10	5780	−1·10	3480	1·77	− 690	1·18	−360
−0·98	7240	−1·57	4980	−1·77	1960	2·12	− 1020	1·73	−900
−1·38	6710	−2·16	2320	−2·36	− 1630	2·51	− 2490		
−1·96	5120	−2·75	− 2660	−2·87	− 4150				
−2·36	2320	−3·10	− 4650	−3·65	− 5950				
−2·76	− 1530	−3·95	− 6910						
−3·14	− 4190	−5·03	− 8490						
−3·53	− 5780								
−4·13	− 7300								
−4·83	− 8360								
−6·01	− 9630								
−6·56	−10160								

These cycles give the following values of $\int H dI$ and the coercive force :—

RING VIII.—Soft Iron Wire of "Hedgehog" Transformer. First State. Values of $\int H\,dI$ and Coercive Force.

No. of cycle.	Limits of H.	Limits of B.	Limits of I.	$\int H\,dI$.	Coercive force.
1	22·23	15600	1240	15980	2·95
2	15·04	14200	1128	13620	2·89
3	11·33	13020	1035	11890	2·85
4	8·62	11690	930	9780	2·71
5	6·56	10160	808	7820	2·61
6	5·03	8490	673	5850	2·40
7	3·65	5950	474	3500	2·17
8	2·51	2490	198	870	1·47
9	1·73	900	72	130	0·60

The fact that the cyclic curves obtained from the metal in this state had somewhat rounded outlines, and gave values of $\int H\,dI$, which, though by no means exceptionally great, are greater than those given by the softest iron, led us to suspect that the metal had been slightly hardened, either in the manufacturer's hands, or in our coiling it into a ring for testing. Accordingly, we resolved to make another trial after annealing the wire in the coiled up state. The ring (No. VIII.) was stripped of its magnetising coil, and was heated to redness in a forge-fire, after which it was again thoroughly soaked in a hot bath of boiled linseed oil. This treatment, besides removing any hardness that might have been produced by mechanical operations, no doubt had the effect of improving the insulation of the coils from one another, by coating the wire with a film of oxide; and this may have contributed to produce an apparent change of magnetic quality. On rewinding the magnetising coil, the following tests were made with results which differ in a noteworthy way from those of the preceding tests, although the expectation that $\int H\,dI$ would be reduced was not fulfilled.

Ring VIII.—Second State. Soft Iron Wire of "Hedgehog" Transformer after special annealing.

Cycle (1).		Cycle (2).		Cycle (3).		Cycle (4).		Cycle (5).	
H.	B.	H.	B.	H.	B.	H.	B.	H.	B.
23·60	16170	15·25	15490	11·24	14870	8·05	13840	6·15	12640
9·63	15700	7·89	15220	6·74	14660	4·08	13510	3·50	12450
5·77	15450	4·01	14830	3·70	14460	1·81	13330	1·27	12120
3·46	15180	2·04	14570	1·92	14070	0	12720	0	11650
2·12	14970	0	13970	0	13460	−1·50	11470	−1·54	10540
0	14310	− 1·23	13040	− 1·54	12150	−2·16	8480	−2·35	4890
− 1·54	13380	− 1·92	11720	− 2·31	7650	−2·73	1780	−2·89	− 2110
− 2·58	5560	− 2·69	3570	− 2·69	2800	−3·27	− 5160	−3·46	− 6950
− 3·08	− 1060	− 3·27	− 3700	− 3·08	− 2350	−3·85	− 8360	−4·58	−10410
− 3·46	− 4960	− 3·85	− 7880	− 3·47	− 5990	−4·62	−10330	−6·15	−12640
− 3·91	− 8020	− 4·62	−10340	− 4·23	− 9500	−7·05	−13190		
− 4·70	−10410	− 7·05	−13170	− 5·27	−11490	−8·05	−13840		
− 5·77	−12180	−10·82	−14690	− 7·05	−13280				
− 7·74	−13730	−15·25	−15490	− 9·59	−14400				
−12·24	−15180			−11·24	−14870				
−16·17	−15640								
−23·60	−16170								

Cycle (6).		Cycle (7).		Cycle (8).		Cycle (9).		Cycle (10).	
H.	B.	H.	B.	H.	B.	H.	B.	H.	B.
4·66	10940	3·63	8640	2·50	4000	1·92	1390	1·41	660
2·19	10610	1·42	8250	0	3140	0	730	0	260
1·19	10480	0	7780	−1·39	1480	−1·06	− 120	−0·81	− 70
0	10080	−1·54	6310	−1·73	30	−1·35	− 450	−1·41	−660
−1·42	9010	−2·27	1890	−2·07	−2101	−1·92	−1390		
−1·92	7550	−2·87	−4660	−2·50	−4000				
−2·50	1060	−3·63	−8640						
−2·89	− 3570								
−3·66	− 8750								
−4·27	−10140								
−4·66	−10940								

Inspection of these curves (figs. 19 and 19*a*, Plate 40) will show that a result of the special annealing, which the ring received after it was coiled, was to make the stages of the cyclic process be much more sharply differentiated from one another than they were before. In other words, the curves are now exceedingly square-shouldered. The residual magnetism is high, and the rate of descent when reversal of magnetism is taking place is extremely rapid and uniform. dB/dH in the higher cycles is about 13,000 at its maximum, and maintains a value little short of this, while B changes by as much as 20,000.

Fig. 20 has been drawn in further illustration of the magnetic qualities of this ring (Ring VIII. after special annealing). The curves in it show the whole induced magnetism and the residual magnetism (for each cycle) in relation to H. Taking the inclination of a tangent to the former curve drawn through the origin to measure the maximum permeability we find its value to be 2420.

In the same diagram (fig. 20) the curve drawn in broken line shows, in relation to H, the ratios of the residual to the induced value of B in each cycle. This curve rises with a rapid, nearly uniform, gradient (from a point to the right of the origin, since a finite amount of magnetising force may be applied without causing the iron to acquire any residual magnetism). It bends over fast when H is about 2·5, passes a maximum which is not sharply defined, and slowly falls as the magnetism is pushed into the region of saturation. Throughout the steep part of the magnetization curve the difference between the residual and induced magnetisms scarcely increases at all, while B is increasing tenfold. The relation of the residual to the induced magnetism presents, in this and other respects, just those characteristics which the molecular theory (referred to below) would anticipate. In the present instance when the ratio is a maximum the residual induction is 93 per cent. of the induced.

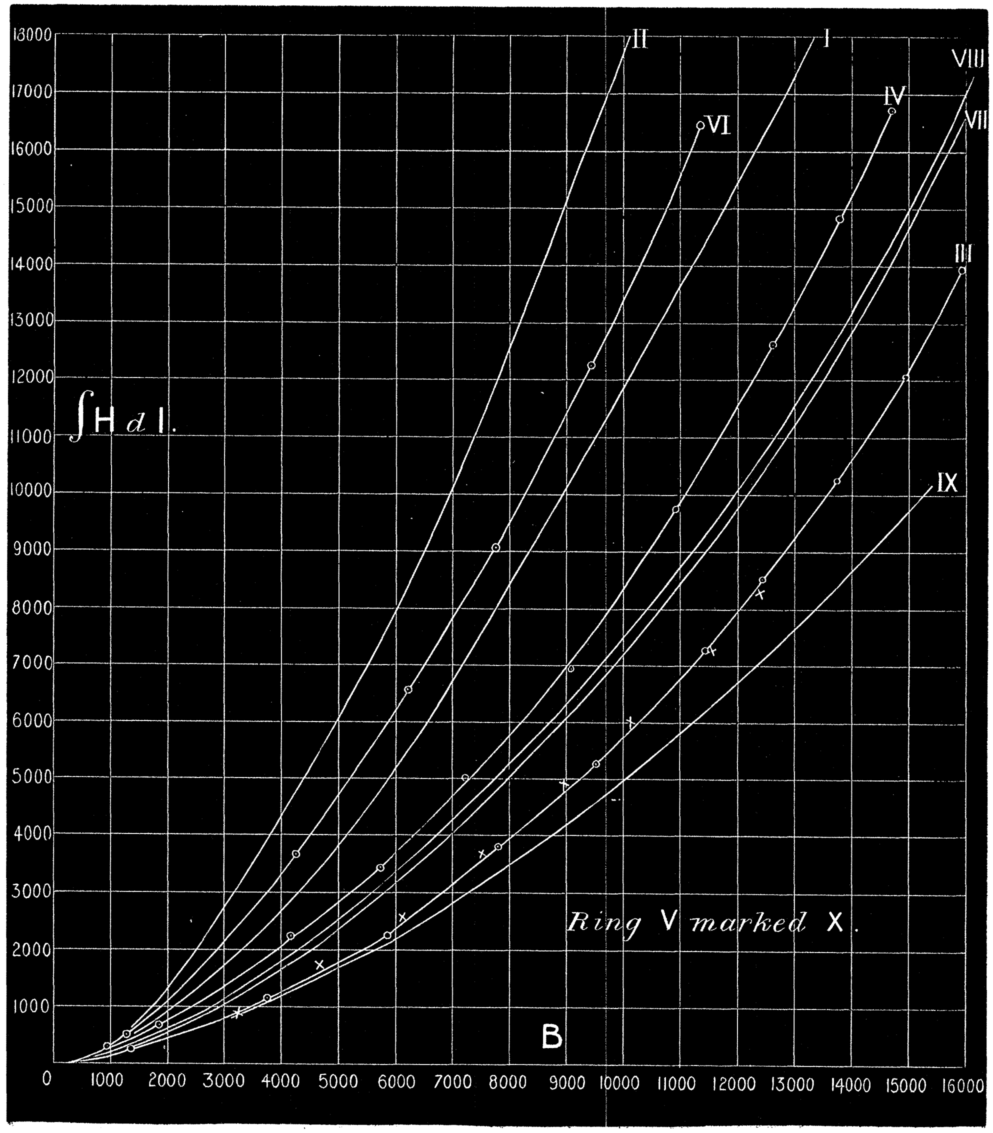
The values of $\int H dI$ and the coercive force for Ring VIII. in its second (annealed) state are as follows :—

RING VIII.—Second state. Soft iron wire of "Hedgehog" Transformer after special annealing. Values of $\int H\, dI$ and coercive force.

No. of cycle.	Limits of H.	Limits of B.	Limits of I.	$\int H dI$.	Coercive force.
1	23·60	16170	1285	17380	2·98
2	15·25	15490	1231	15790	2·95
3	11·24	14870	1183	14800	2·89
4	8·05	13840	1101	12990	2·85
5	6·15	12640	1005	10770	2·73
6	4·66	10940	871	8780	2·56
7	3·63	8640	688	6120	2·44
8	2·50	4000	318	1770	1·71
9	1·92	1390	111	310	1·00
10	1·41	660	53	70	0·70

It will be seen from these figures that the special annealing had hardly any influence on the value of $\int H dI$ and of the coercive force, notwithstanding its very considerable effect in changing the form of the cyclic curves and in improving the permeability. The curve from Ring VIII. in fig. 21 gives the relation of $\int H dI$ to B in this final state. The corresponding curve for the ring in its previous state would, if drawn, be nearly coincident with this one.

Fig. 21.



Curves of ∫HdI and B. Collected results.

For the sake of comparison with these various specimens of iron we add here the values of ∫HdI (copied from 'Phil. Trans.,' 1885, p. 556) obtained in tests made in Japan of a piece of soft iron wire. The method used in the Japanese tests differed from our present method; the specimen was a single straight piece, long enough to be practically endless, and its magnetism was changed slowly and was measured by a magnetometer. We have numbered these old tests IX. for convenience of reference.

IX.—Old tests made in Japan of a Soft Iron Wire.

Limits of H.	Limits of B.	Limits of I.	$\int H\,dI$.
75·2	15560	1230	10040
26·5	13700	1090	8690
7·04	11960	951	6590
6·62	11480	913	6160
4·96	10590	842	5560
3·76	8790	699	3990
3·01	7180	571	2940
2·56	5950	473	2190
1·95	3830	304	1160
1·50	1970	157	410

None of the specimens tested at this time have given so low values of $\int H\,dI$ for the higher cycles, though the values in Rings III. and V. are practically identical with those in the Japanese iron for cycles in which B is less than 4000. The superior magnetic softness of this wire (No. IX.) was further shown by the fact that its coercive force after strong magnetization was 1·75, whereas in all the rings now tested the coercive force exceeded 2. At least one other specimen of wire used in the Japanese experiments was as good.

The comparison suggests a doubt whether all that is possible has yet been done by manufacturers of iron to produce a quality specially suitable for such uses as the construction of transformer cores. The conditions of manufacture which secure low hysteresis appear to be imperfectly known, or, at least, to be less generally recognized than electricians might wish. It must, however, be admitted that with respect to hysteresis losses under the comparatively low intensities of magnetization usual in transformers, the sheet iron of Rings III. and V. is very nearly as good as the wire tested in Japan.

This will be apparent from fig. 21, where the values of $\int H\,dI$ are plotted in relation to B for all the rings, and also for the wire in question (No. IX.). The figure shows in a striking way the extent to which the dissipation of energy in a cyclic magnetizing process may vary in different specimens even of soft iron.

To facilitate comparison, we also give a Table of Numerical Values of $\int H\,dI$, measured from these curves, for the various specimens of iron.

VALUES of $\int H\, dI$.

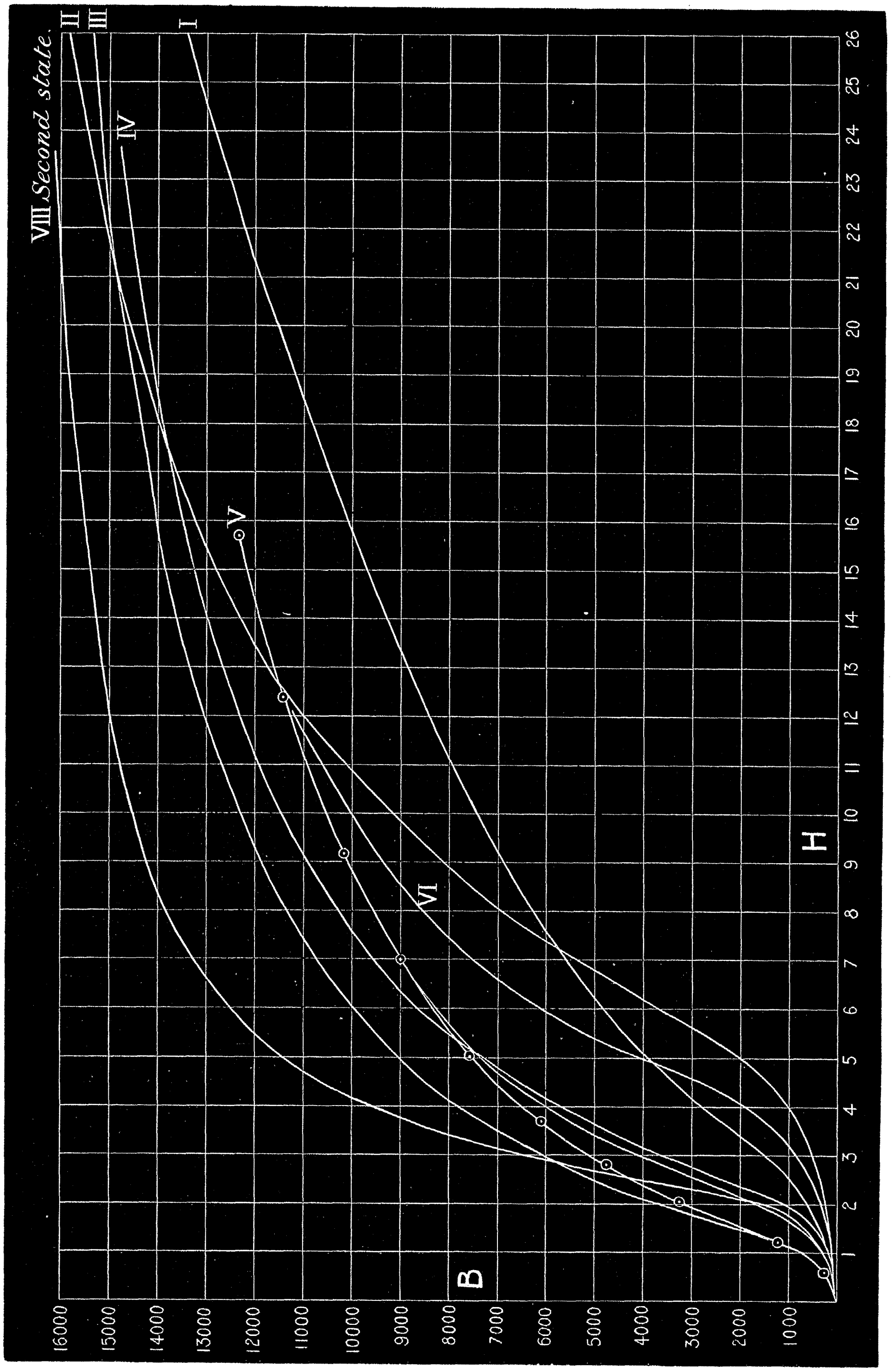
B.	IX.	III.	VII.	VIII.	IV.	I.	VI.
2000	400	420	530	600	750	930	1100
3000	780	800	1050	1150	1350	1700	2150
4000	1200	1260	1670	1780	2030	2600	3300
5000	1680	1770	2440	2640	2810	3800	4700
6000	2200	2370	3170	3360	3700	5200	6200
7000	2800	3150	4020	4300	4650	6600	7800
8000	3430	3940	5020	5300	5770	8400	9500
9000	4160	4800	6100	6380	6970	10100	11400
10000	4920	5730	7200	7520	8340	11800	13400
11000	5800	6800	8410	8750	9880	13600	15600
12000	6700	8000	9750	10070	11550	15400	
13000	7620	9200	11200	11460	13260	17300	
14000	8620	10500	12780	13100	15180		
15000	9730	12150	14600	14900	17300		

The values for Ring V. are nearly the same as for Ring III.

IX. Very soft iron wire (Japanese tests).
III. Sheet iron, 1·95 millim. thick.
V. Thin sheet iron, 0·367 millim. thick.
VII. Iron wire, 0·975 millim. diameter.
VIII. Iron wire (of "Hedgehog" transformers), 0·602 millim. diameter.
IV. Thin sheet iron, 0·47 millim. thick.
I. Fine iron wire, 0·2475 millim. diameter.
VI. Fine wire, 0·34 millim. diameter. Supplied as Swedish charcoal iron.

Again, fig. 22 shows the relation of B to H for the various rings. The values of B are the limiting values in the successive cycles, and are measured, as we have already pointed out, after the corresponding magnetic force has been many times reversed. They are consequently rather lower, especially in the early parts of the curve, than those values of B which a first application of H would produce. Comparing the curves of fig. 22 we see that high maximum permeability does not necessarily imply small hysteresis losses. Ring VIII. with its "square-shouldered" curve has a higher maximum of permeability than any of the other rings, though its hysteresis losses are much greater than those of Rings III. and V. And Rings III. and V. differ decidedly in permeability though their hysteresis losses are as nearly as possible equal. A reference back to fig. 15 will show that the curves exhibiting magnetic cycles may assume a sloping form, implying comparatively little permeability, and yet enclose but small areas. When iron is spoken of as magnetically soft the implication sometimes is that its permeability is high, sometimes that its hysteresis losses are small. The two characteristics are however, in great measure,

Fig. 22.



Curves of B and H. Collected Results.

independent. It is interesting to notice also that the easy slope of some of the soft iron curves in fig. 22 allows them to be crossed by curves for steel, even under moderate magnetizing forces. For instance, a force of 13 *c.g.s.* induces more magnetism in the rather hard steel of Ring II. than in the very soft iron of Ring V. A comparison of permeabilities in respect to any such force as this would furnish no criterion of magnetic softness. It may, however, be added that the specimens which are soft in the sense of having small hysteresis losses excel in permeability in the initial stage of the magnetizing process. Compare, for instance, the relative permeabilities of the rings when B is say 1000: it will be seen that the order in which they stand in regard to smallness of hysteresis loss, and in regard to permeability, is at this stage the same. If softness is to be judged by the B-H curve it is clear that the early portion of the curve is the best guide.

In a paper read before the American Institute of Electrical Engineers* on the "Law of Hysteresis," Mr. C. P. STEINMETZ has discussed certain experiments on the relation of $\int H\,dI$ to B, and contends that the empirical formula

$$\int H\,dI = \eta B^{1\cdot6},$$

where η is a constant factor, is in good agreement with the results of experiment. From the figures Mr. STEINMETZ gives, and from those which our own experiments supply, it appears that within a certain range of values of B this formula may be taken as giving a fairly close approximation to the real value of $\int H\,dI$. As an empirical formula of the kind is of use to designers of transformers, we have been at some pains to examine how nearly and within what range a formula of this type may be taken to represent the facts. It will suffice to refer to one example in some detail.

Taking Ring IV. (thin sheet iron) for which we have a numerous and very consistent series of determination of $\int H\,dI$, extending from $B = 43$ to $B = 14,720$, we have tested the constancy of the index ϵ in the formula

$$\int H\,dI = \eta B^{\epsilon}$$

by plotting log B in relation to log $\int H\,dI$.

From $B = 2000$ to $B = 8000$, the curve obtained in this way is a good straight line giving the value 1·475 for the index ϵ, and 0·01 for η. When B is about 8000 the inclination of the line changes, and from $B = 8000$ to $B = 14,000$ we again obtain very nearly a straight line giving $\epsilon = 1\cdot70$ and $\eta = 0\cdot00134$.

Again, the measurements obtained from the small-cycle tests of Ring IV., show that from $B = 200$ to $B = 500$ the curve of log B and log $\int H\,dI$ is very closely a straight line, giving $\epsilon = 1\cdot9$.

Where B is above 500 the gradient of the line gradually changes. Taking the

* 'Transactions of the Institute,' Jan. 19, 1892, vol. 9, p. 3.

region from B = 500 to B = 1000 the value of ϵ is 1·68, while from B = 1000 to B = 2000 it is 1·55.

From these results it is clear that no formula of the type under consideration, with a constant index ϵ, will serve to represent the results within anything like the limits of experimental accuracy. The index begins by being 2 or nearly 2 (a result which follows also from Lord RAYLEIGH's experiments*): in the ring referred to, this decreases to about 1·47 in the region of high permeability, and then increases again to 1·7 when the "wendepunct" is passed. The changes in the index, indeed, correspond to the passage from one to another of the familiar successive stages in the process of magnetization: comparatively high values of the index are found first in the initial stage of low permeability, and again in the stage of strong magnetization when the permeability is reduced by the approach towards saturation, while in the intermediate stage where the curve of B and H is steep the index is decidedly low. The well-marked changes of gradient curve which characterize the magnetizing are accompanied by scarcely less well-defined changes on the part of the index ϵ and the factor η, in the empirical formula devised by Mr. STEINMETZ.

While, therefore, a formula of this type cannot be admitted to have any physical significance, it may still be serviceable in giving rough approximations for the purposes of the electrical engineer. Though the formula is by no means to be accepted as an equation to the actual curve of $\int H\,dI$ and B, the curve which it gives by a suitable choice of index ϵ and factor η lies fairly close to the actual curve, intersecting it at an intermediate point as well as at two extremes. And it is the case that an index of 1·6, or a number approximating to that, gives a curve lying generally in the neighbourhood of the true curve throughout the range of B which is of most practical importance. In the case of our Ring IV., for instance, the formula

$$\int H\,dI = 0{\cdot}0034\,B^{1{\cdot}6}$$

give values of $\int H\,dI$ which are nowhere (within the range of these experiments) so grossly divergent from the truth as to unfit them for use in calculations connected with transformer design. Thus we have :—

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

B.	Actual value of $\int H\,dI$.	Value calculated from the above formula.
150	7	10·3
300	31	31
500	80	71
1,000	256	215
2,000	750	650
4,000	2,030	1,970
6,000	3,700	3,780
8,000	5,820	5,980
10,000	8,340	8,540
12,000	11,550	11,430
14,000	15,200	14,630

The divergence is becoming considerable at the top of the range, but elsewhere the agreement is fair. It should, however, be observed that if we wish to make the curve given by the empirical formula coincide with the real curve throughout any short part of its range, other, and often very different values must be given to ϵ and η. Thus, if the part from $B = 2000$ to $B = 8000$ only is considered—a part which includes those values of B which are usual in transformer cores—the formula

$$\int H\,dI = 0{\cdot}01\,B^{1{\cdot}475}$$

will express the results very much more closely. For example:—

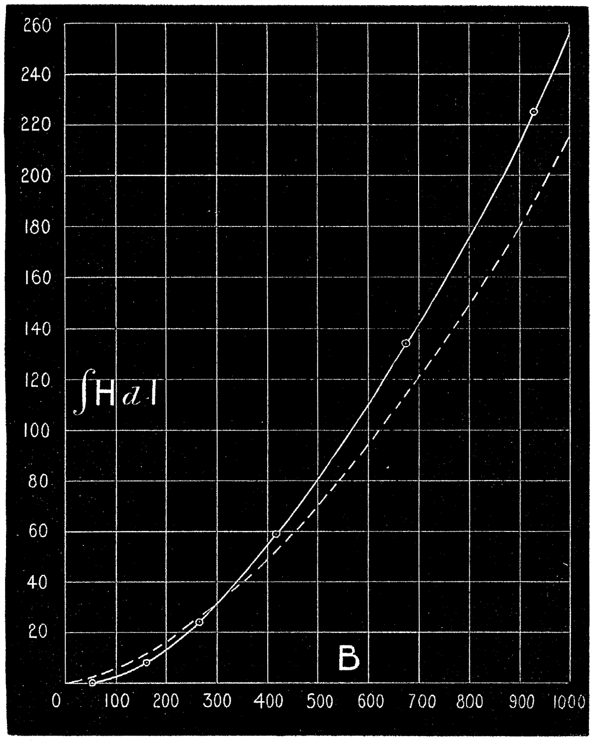
B.	Actual value of $\int H\,dI$.	Value calculated from the expression $0{\cdot}01\,B^{1{\cdot}475}$.
2,000	750	740
3,000	1,350	1,345
4,000	2,030	2,060
5,000	2,820	2,860
6,000	3,700	3,740
7,000	4,650	4,690
8,000	5,800	5,720

Throughout this not inconsiderable range of magnetization (the region, namely, of high permeability) the agreement is good, but other empirical constants are required to fit the earlier, and again the later parts of the curve.

In further illustration of the point, we add a curve (fig. 22), showing the actual values of $\int H\,dI$ in relation to B for the low cycles in the tests of Ring IV., and on the same diagram a dotted line is drawn, to show the value found for Mr. STEINMETZ' formula, namely, $\eta B^{1{\cdot}6}$, the constant η being taken as $0{\cdot}0034$, since that value best accords with the tests of Ring IV. throughout the whole range of magnetization. It will be evident from the diagram that this early portion of the curve is not even approxi-

mately expressed by the formula in question. The character and extent of the divergence is, perhaps, more obvious from inspection of the curve, than from comparison of the numbers which have been given above.

Fig. 23.



$\int H\,dI$ and B for the low cycles of Ring IV. The dotted line represents values of $0{\cdot}0034\,B^{1{\cdot}6}$.

Experiments on the Heating Effect of Reversals of Magnetism.

In another section of our experiments direct measurements were made of the amount of heat generated by reversals of magnetism.

Some of the rings employed in the tests which have just been described were again used in these experiments, and under precisely the same conditions.

The method employed (a short account of which was published in 'The Electrician' of October 9, 1891) depended on the use of two exactly similar rings, one of which had its iron core subjected to magnetic reversals, while heat was developed in the other by the passage of a steady electric current. This steady current was adjusted until the rate at which heat was generated by the current in one ring became the same as the rate at which heat was generated by reversals of magnetism in the other ring, equality of temperature as between the two rings being tested by means of a thermoelectric circuit with a pair of junctions, one embedded within the core of each ring. The current which was used to magnetize the one ring passed also round the

other, in a coil which had the same dimensions as the magnetizing coil of the first ring, but which was wound non-inductively. Hence, whatever heating effect the magnetizing current had on one ring, it also had on the other, though one ring only became magnetized. Both rings were subjected to precisely the same thermal influence, except that in the active ring the magnetism of the core was periodically reversed, and in the inactive ring a special heating current was used to balance the heat generated in the other by these magnetic reversals. The arrangements were in all cases such that the inactive ring could be made magnetically active and *vice versâ*, without any change in the winding or structure of the rings, by merely changing the electrical connections of the divided coils which were wound in identical fashion on each. In those of the experiments that dealt with rings which had a core of insulated iron wire, the heating current was caused to pass through the wire of the core itself in the inactive ring—a particularly satisfactory arrangement, inasmuch as the heat generated by this current in the inactive ring was then distributed throughout the core in just the same way as the heat generated by magnetic reversals in the active ring. In experiments dealing with sheet metal cores a special coil was wound as close as possible to the core of the inactive ring to take the heating current.

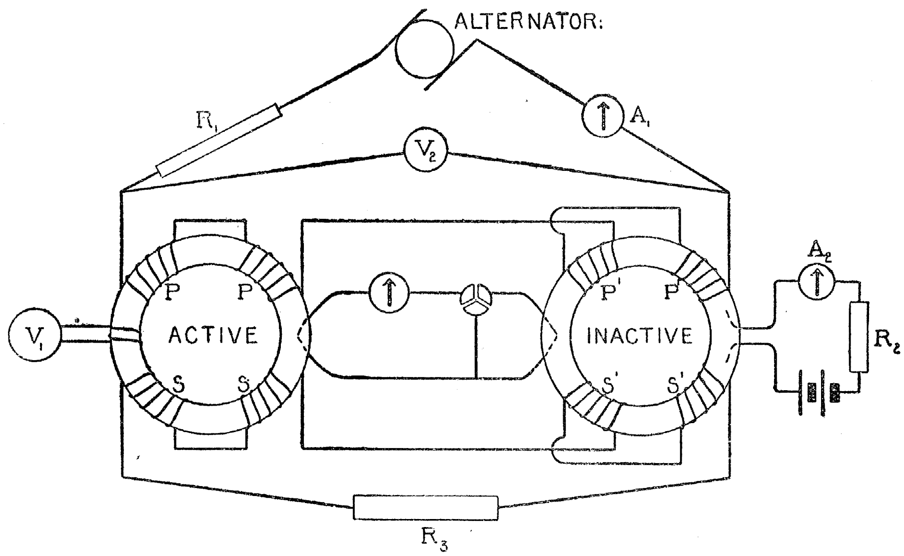
This method of measuring the heat due to magnetic hysteresis by securing a thermal balance between two rings, alike in all respects, was originally devised to give an answer to the question whether, when a transformer is in action, the heating of the core through magnetic hysteresis is the same when the transformer is "loaded," or when it is not; in other words, whether the taking of current from the secondary coil has any influence on the amount of heat generated in the core, the limits of magnetization and the frequency of the reversals being unaltered. Independent experiments by Professor RYAN, Mr. MORLEY, and Professor AYRTON, on the efficiency of transformers, had apparently agreed on showing a marked reduction in the loss of energy due to magnetic reversals when the "load" was put on. Adding a secondary coil to each of our rings to make it into a transformer, we applied the above balance method to compare the rate of magnetic heating when the secondary was open with the rate when the secondary was closed through a low resistance, so as to apply a heavy "load," arrangements being at the same time used to keep the magnetic range and frequency unchanged. The result was that no change could be detected in the rate at which heat was produced by the reversal of magnetism when the "load" on the secondary coil was varied from nothing to an amount greatly in excess of any "load" used in practical transformers.* The conclusion being of this negative kind, a very short account of the experiments will suffice.

The electrical connections are shown in fig. 24. On each ring of the pair a primary coil was wound in two layers, and a secondary coil, also in two layers. In each coil

* Since these experiments were made (and briefly published in 'The Electrician' of Dec. 4, 1891), later tests of transformers, by Professor FLEMING and others, have borne out our conclusion that the amount of "load" has no influence on the waste of energy through magnetic hysteresis

the two layers had the same number of turns, and the number was the same on both rings. The two layers, both of primary and of secondary, could be connected either inductively or non-inductively. They were each wound uniformly round the whole of the ring. On one ring they were connected inductively, and were respectively in series with the non-inductive primary and secondary of the other ring. Hence all direct thermal action of primary and secondary currents was the same for both rings. The magnetic reversals were caused by passing through the primary circuit the current from an alternating dynamo, which could be run at various speeds, and the strength

Fig. 24.



of this current was adjusted, by means of a liquid rheostat, R_1, in its circuit, to secure that the magnetization should have the same limiting value when the secondary circuit was closed (through the resistance R_3) as when it was open. To test the constancy in the limit of magnetization, a voltmeter, V_1, of special construction was used, which was connected to a special induction coil of a few turns wound on each ring. The voltmeter was of the hot wire type; it consisted of a piece of very fine platinum wire, stretched between supports, but deflected sideways, after the manner of the wire in Professors PERRY and AYRTON's voltmeter, by a light spring pulling transversely in the middle of the wire's length. The middle portion of the wire stood in the field of a microscope, and its transverse movements were read on a micrometer scale in the eye-piece. This was found to form a very convenient means of reading alternating electromotive forces of one or two volts and under. Owing to the small section of the wire and the freedom from friction which was secured by having no mechanical indicating gear, the instrument responded quickly and exactly to change of electromotive force, and allowed the necessary adjustment of the primary alternating current to be made with great nicety. In most of the experiments a Cardew voltmeter, V_2, was also connected across the terminals of the primary circuit. Its response to small changes was much less rapid

and certain, but its absolute graduations furnished a convenient means of estimating the intensity of magnetization from the amount of back electromotive force.

The heating due to magnetic reversals in the active ring was determined by seeing what strength of steady current in the core of the inactive ring would maintain a balance in the thermo-electric circuit. The heating current was adjusted, by means of R_2, so that, after both rings had been brought to the same temperature, the two temperatures remained equal while both rose. The thermo-electric junctions were connected to oppose each other through a sensitive galvanometer, but an alternative connection could be made in which one junction only acted on the galvanometer, so that the temperature of the ring might be estimated at any stage in the experiment. It was necessary, in fact, to record the temperature of the ring from time to time, to allow for change in the resistance of the iron wire forming its core.

The following will serve as an example of the readings taken. It refers to an experiment upon a pair of precisely similar rings, one of which was the Ring VII. of the tests already described. The core consisted of iron wire, insulated with cotton. The frequency in this experiment was 133 periods per second, and the greatest value of B was about 7500.

(*a.*) With secondary open :—

Heating current, in ampères.	Reading of Cardew voltmeter.	Resistance of iron core.
0·75 (too strong)	22	5·85
0·65 (too weak)	22	to
0·7 (balance)	22	5·90

(*b.*) With secondary closed through a low resistance :—

Heating current, in ampères.	Reading of Cardew voltmeter.	Resistance of iron core.
0·75 (too strong)	$24\frac{1}{2}$	5·80
0·65 (too weak)	to	to
0·7 (balance)	24	5·90

The reading of the microscope hot-wire voltmeter was the same in both parts of the experiment, the difference in the Cardew readings being due to the greater volume of magnetizing current that was required when the secondary circuit was closed. It will be seen that no difference could be detected in the amount of balancing current necessary to maintain equality of temperature. Other experiments gave confirmatory and quite conclusive results. One more may be quoted :—

Frequency 69 periods per second. Greatest value of B about 13500.

(*a.*) Secondary open. Balancing current 236 on arbitrary scale.

(*b.*) Secondary *short-circuited*. Balance with current between 231 and 244.

The heating effect of reversals is, of course, due to Foucault currents, as well as to magnetic hysteresis. An attempt was made to compare the total heating effect, measured directly by reference to the balancing current in the inactive core with the value of $\int H\,dI$ as found in the preceding experiments, with the view of estimating the influence of Foucault currents. But the value of such a comparison depends on our being able to estimate the maximum of magnetization in the cycle, and this is by no means a simple matter. The observed electromotive force gives the mean value of $(dB/dt)^2$, and to calculate B from this it is often assumed that the mode of variation of B may be treated as simply harmonic, in which case we should have

$$\text{Maximum B} = \frac{10^8 . E}{\pi n \, NA \sqrt{2}},$$

where E is the observed electromotive force in a coil of N turns, the area of curve-section of the iron being A and the frequency n. But even if the magnetizing force were simply harmonic it is otherwise with B, whose increment and decrement is largely affected by magnetic hysteresis. The relation of maximum B to mean $(dB/dt)^2$ could be determined if the form of the curve of B and t were known. Recent experiments—amongst others, those of Dr. JOHN HOPKINSON and Messrs. WILSON and LYDALL,* in which B as well as dB/dt has been determined as a function of t in a ring submitted to alternating magnetic forces—exemplify how wide the variation from a sine-function is likely to be. In view of this consideration, and of the fact that no such data were at hand in the case of our own tests, we have not followed up this method of directly measuring the heat produced by reversals.

EXPERIMENTS MADE WITH THE MAGNETIC CURVE TRACER.

When the magnetism of a piece of iron is reversed rapidly more work is spent than when the reversal takes place slowly. Whether all the extra work done in the former case is to be set down to Foucault currents is, perhaps, an open question ; there may be a genuine time-lag in the process of magnetization, independent of the effect of Foucault currents, though not readily distinguishable experimentally from their effect. This quasi-viscosity, distinct from Foucault-current effects, will, if it exists, require higher values of H to be applied than would otherwise be necessary when any assigned limits of B are to be quickly reached. At high speeds of reversal the curve which shows the relation of the externally applied magnetizing force to B becomes swelled out and encloses a larger area, corresponding to the greater amount of work then done, whether in generating Foucault currents or in overcoming this other possible source of quasi-viscous resistance. That an increased amount of energy is expended is clear from experiments of the kind which have just been referred to,

* 'Roy. Soc. Proc.,' 1893.

even if the exact interpretation of these results is somewhat doubtful through uncertainty as to the value of B. Direct evidence of the change in form of the B—H, or rather B-current, curve is furnished by the magnetic curve-tracer.

This instrument, which was exhibited by one of us at the Edinburgh meeting of the British Association (1892), draws the magnetic curve by giving to a small mirror two component motions, one (horizontal) proportional to the magnetizing current and the other (vertical) proportional to the magnetism of the metal under examination. The metal is arranged to form a magnetic circuit which is complete except for a narrow gap between a pair of opposed poles. In this gap a wire is tightly stretched, through which a constant current passes. The wire consequently sags up or down in the gap as the magnetism of the circuit varies, and this gives movement in altitude to the mirror. At the same time, the varying magnetizing current passes through another similar wire tightly stretched between the poles of another magnet. The magnetism of this second magnet is kept constant, and hence the sagging of its wire depends on the varying strength of the current which the wire carries, namely, the magnetizing current of the other magnet. This gives azimuthal movement to the same mirror. A spot of light reflected from the mirror to the screen consequently traces out the curve of magnetism and magnetizing current. The movements are so deadbeat that with a light mirror and tightly stretched wire a magnetic cycle of double reversal may be traversed ten times or even twenty times per second without material distortion from the inertia of the working parts. The variation of magnetizing current must not, however, be sudden, and to secure this a commutator is used in which a revolving boss carrying two zinc plates turns within a cylinder containing a weak solution of zinc sulphate, in which there are two other (fixed) plates of zinc. As the revolving pair of plates reverse their position between the fixed pair, the potential of a battery connected to the fixed plate becomes reversed on the revolving pair, and from them the current is taken to the magnetizing coil.*

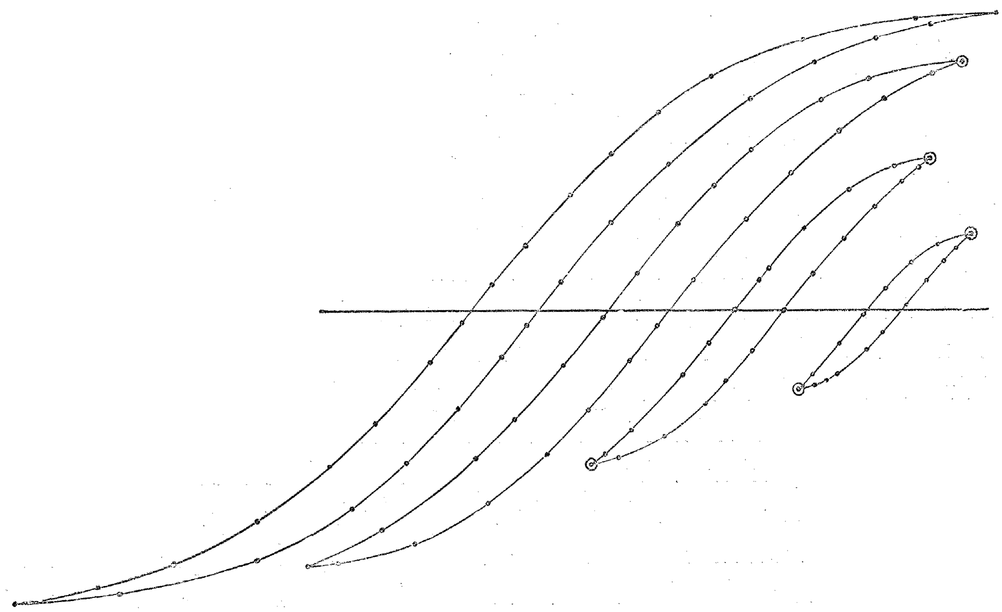
By the slow manipulation of a rheostat of any form the magnetizing force may be carried throughout any desired series of changes and the character of the corresponding process of magnetization be studied. The instrument affords a ready means of testing the comparative magnetic quality of given samples of metal. It also allows features in the magnetizing process to be examined which it would be difficult to observe in other ways. We have made a number of experiments with it, some of which may be cited as showing the application of a novel method in magnetic research, and also as bearing incidentally on points that have been already spoken of in connection with the ballistic tests.

Fig. 25 gives the curves drawn by the magnetic curve tracer in a series of tests of a pair of bars built up of soft thin sheet iron. Four cycles are shown, the magnetizing current having had as extreme values three, two, one and one-half ampères respec-

* For diagrams and description of the magnetic curve tracer, see the 'Electrician' of May 26, 1893.

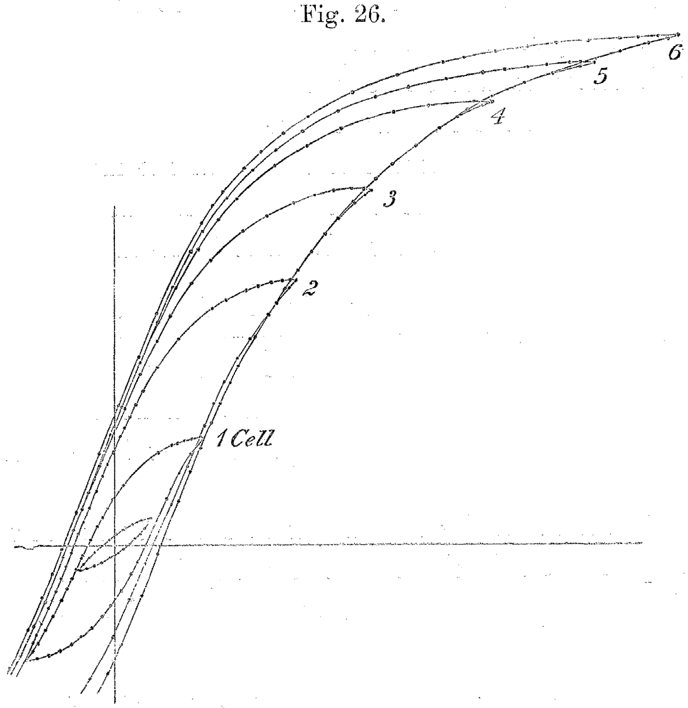
tively. The zero was shifted a little before each cycle to separate the curves. Here the changes of current took place slowly, a pause being made at each of the marked points to allow the position of the reflected spot of light to be noted. The curves are sheared over to the right in consequence of the gap in the magnetic circuit under

Fig. 25.



Cyclic magnetization of soft iron shown by the magnetic curve tracer.

Fig. 26.

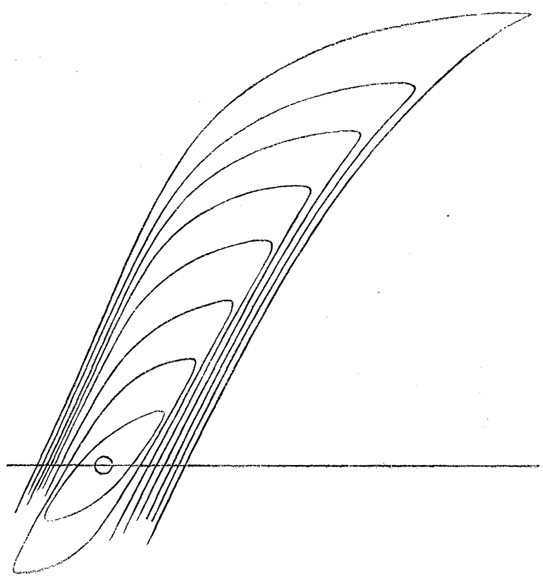


test. The areas of these curves, which are not affected by this shearing, when plotted in relation to B are found to lie on a smooth curve of the type drawn in fig. 21.

Fig. 26 is another test of the same class, made with a different curve tracer and with other iron. Here the successive cycles are shown in their natural relation to one another, without change of zero, and it will be seen that they show well a feature which was referred to in the ballistic tests, namely the projection of the extremities of each cyclic curve over the rising limb of the cycle next above it. Many other examples of curve-tracer tests might be cited as confirming this observation.

Fig. 27 is closely related to fig. 26. It shows a group of curves taken in immediate

Fig. 27.



succession to the group of fig. 26, the iron, the instrument, and the condition of the experiment being in every way the same, except that in fig. 27 the cycles were gone through comparatively fast—at the rate of $3\frac{1}{2}$ cycles per second—whereas in fig. 26 the process was quite slow. The rounded corners and increased wideness of these curves should be noticed. Their increased area shows that more work is here being done on the iron, the effect probably—at least in great part—of Foucault currents. The main portion of the magnetic circuit consisted, in this instance, of well laminated metal, but thick solid pole pieces were used.

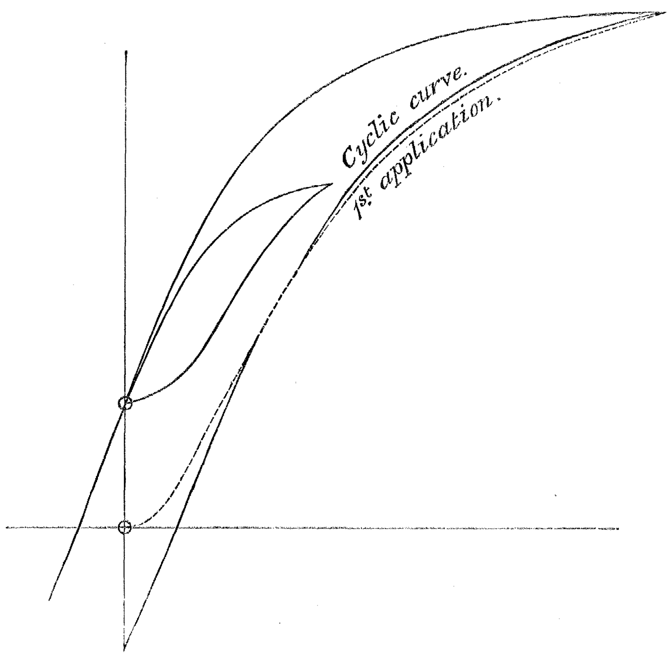
The curves of fig. 27 were recorded by marking with a pencil the luminous line described upon the screen in the periodic repetition of each cycle. In fig. 28, where the results of a group of tests with a different instrument are shown, the curves were automatically recorded by allowing the spot of light to fall on a sensitive plate.* In all except the last figure in this group each cycle was gone through in about half

* We are indebted to Mr. A. G. DEW SMITH for these photographic records.

a second—the commutator being driven uniformly by means of a small electric motor —and the exposure lasted during some twenty to thirty cycles. The curves, therefore, give good evidence of the constancy with which the movement repeats itself. In the last figure in the group of fig. 28 the commutator was slowly turned by hand, and two minor loops were superposed on the main cycle.

Fig. 29 is another test made at the same time, and on the same metal as the tests of figs. 26 and 27. It shows a small loop superposed on a main cycle, and also a curve (drawn in broken line), which is the magnetization curve starting from zero, taken after the metal had been reduced to neutrality by the process commonly known as "demagnetizing by reversals"—namely by numerous reversals of a gradually

Fig. 29.



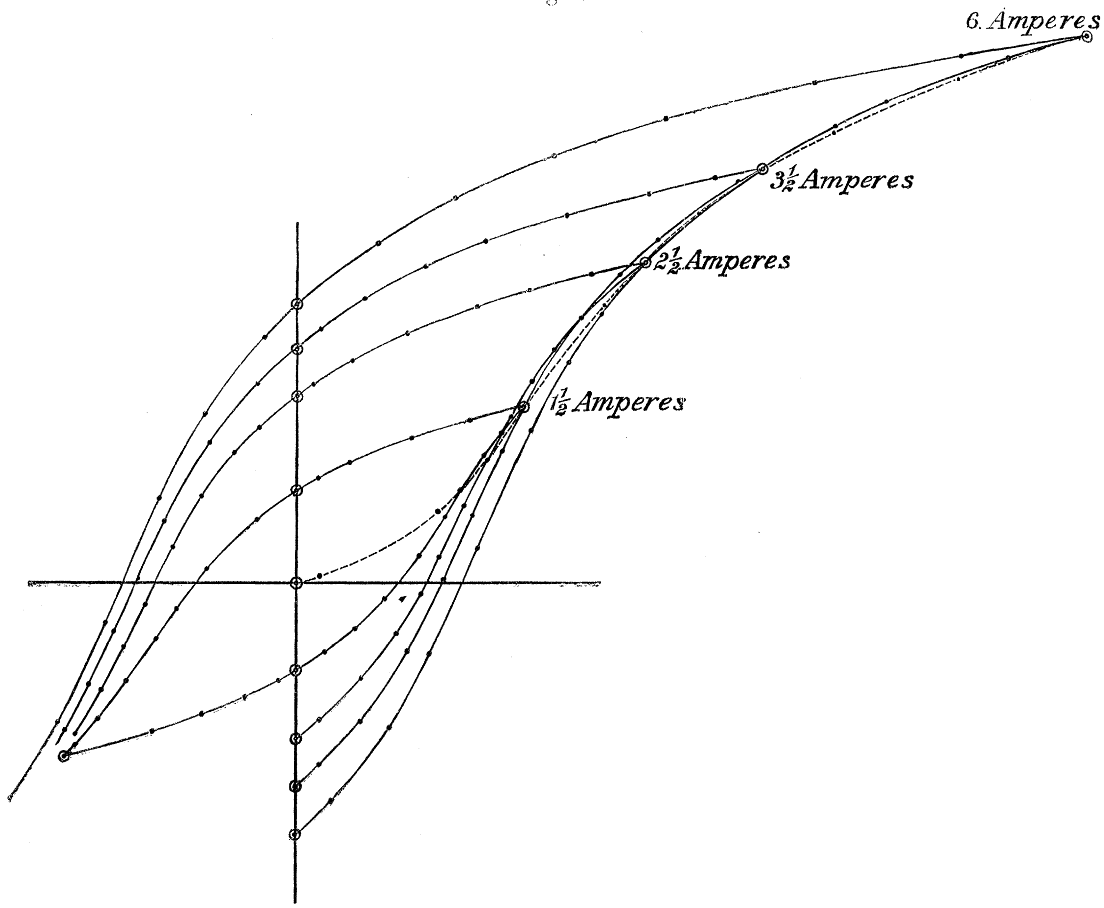
diminishing magnetic force. Here is found a feature which was first remarked, we believe, by Dr. JOHN HOPKINSON, namely, that in magnetizing from the neutral state the curve crosses the rising limb of the cyclic curve. The same feature has been looked for, and always found, in many other curve-tracer tests.

This crossing is in agreement with the fact already noticed, that the extremity of one cyclic curve projects beyond the rising limb of a higher cycle. For, after a piece has been put through the process of "demagnetizing by reversals," the magnetizing curve starting from zero passes, as nearly as we can judge, through the projecting extremities of the cycles. Hence it lies outside of the upper part of the rising limb of any cyclic curve.

Fig. 30 gives a further illustration of these remarks. It shows a magnetic curve-tracer test of moderately hard steel, the dotted curve being obtained by magnetizing

from zero, after the process of demagnetizing by reversals had been performed. This line will be seen to pass through the extreme points of the several cyclic curves, which thus overlap one another in the manner already described.

Fig. 30.

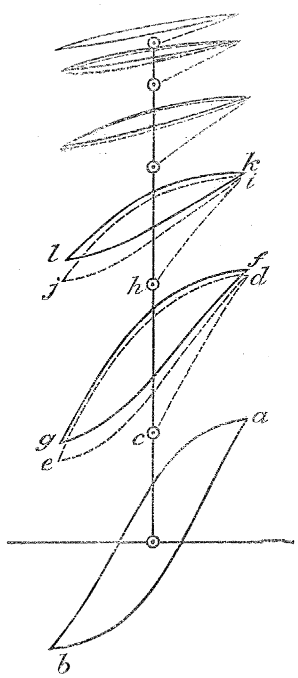


Cyclic magnetization of steel, shown by the magnetic curve tracer.

Fig. 31 is a study in superposed magnetizations in soft iron. Here the magnetic curve tracer was arranged with two independent magnetizing coils upon the magnetic circuit under examination. One of these was used to apply a cyclic variation of magnetic force, while the other was used to apply a steady force of greater or less intensity, on which the cyclic force could be superposed. For brevity, we may distinguish the two circuits as P and Q. In the first place, after the iron had been demagnetized by reversals, the current in Q was applied, and was reversed repeatedly between equal positive and negative values, there being, at the time, no current in P. This gave the usual cyclic curve *ab* (fig. 31), from which it will be seen that the magnetizing force then applied by Q was comparatively small. Then (the piece having been again demagnetized) a current was set up in P, which brought the magnetism up to a value represented by the point *c* in the figure. This current in P being now kept

constant, the current in Q was applied. This gave the line *cd*; then the current in Q was reversed, giving the dotted line *de*, and re-reversed. Finally, after several reversals of the current in Q, the process of reversal gave the closed figure shown by the full line *fgf*. Next (the current in Q having been stopped), the steady current in P was increased to a value which brought the magnetism up to *h*. Then the application and reversal of Q's current gave the lines, *hi*, *ij*, *jk*, the cycle finally settling down after several reversals into the form shown by the full lines, *klk*. The same description applies to each of the loops which are seen higher in the diagram. The highest ones lie in what is often called the region of saturation. Throughout all these successive

Fig. 31.

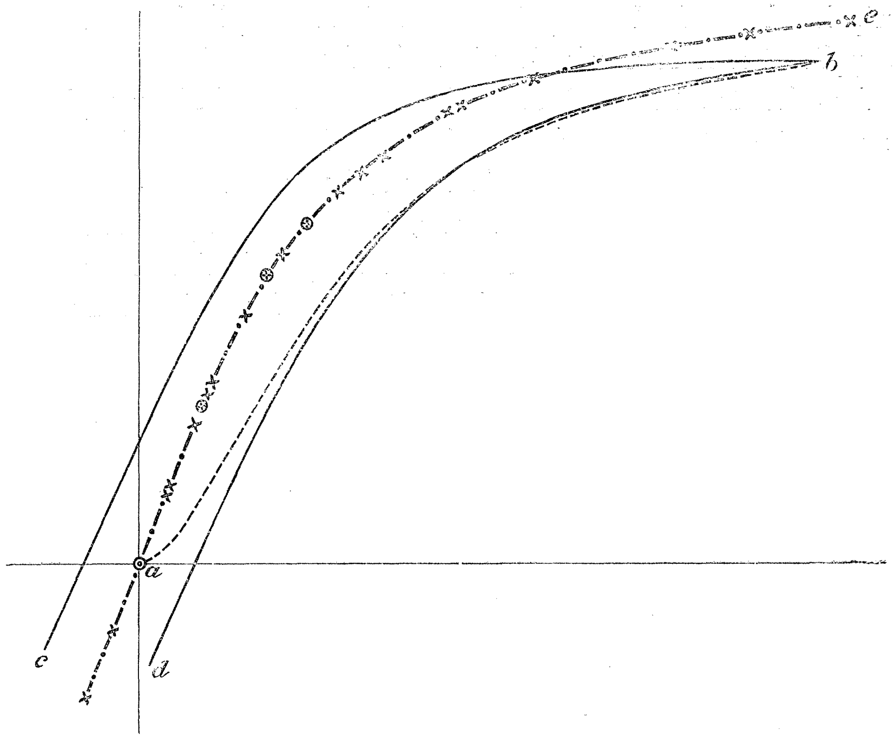


operations the current in Q, whose reversal formed the loops, had the same extreme value. The experiment shows how, as might be expected, the reversals of a given magnetizing current produce less and less magnetic change as the total magnetism is increased. It also illustrates one of the minor consequences of magnetic hysteresis, namely, that a periodic force, applied in addition to a constant force, does not immediately produce cyclic effects; it is only after several repetitions of the reversal that the curves become closed. During the interval of "accommodation" (to use the term which has been applied in other instances where the same feature occurs in the phenomena of magnetization) the mean value of the magnetism is rising, as a consequence, one may say, of the molecular shaking which is involved in the process of reversal.

A more striking example of the influence of the molecular shaking which is brought

about by reversals of a magnetizing force will be found in the experiment of fig. 32.

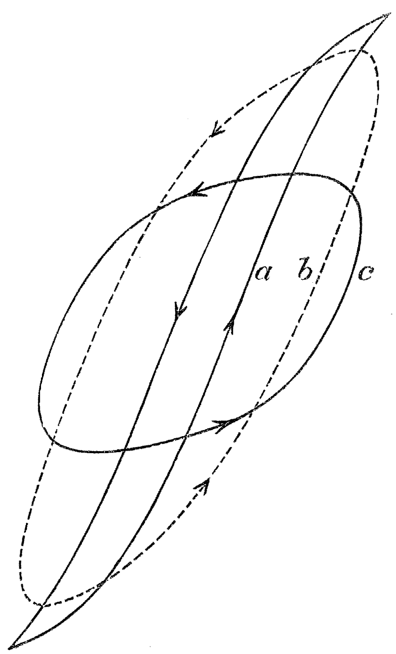
Fig. 32.



This experiment, like the last, was made with a magnetic curve-tracer in which the metal under examination had two independent magnetizing coils wound on it. Through one of these, Q, a current was passed which, when acting alone and carried through a cycle of values, gave the usual curve *abcd*, the dotted line *ab* being obtained after the metal had been neutralized by reversals in the usual way. Next the current in Q was brought to some steady value and a violent molecular shaking was produced by rapid reversals of a current in P which, starting with a rather high value, was gradually reduced to zero while a rapid reversing key in its circuit was kept in motion. It would be inappropriate to call this process by the accustomed name (of "demagnetising by reversals") inasmuch as its effect was to leave the iron more or less strongly magnetized in consequence of the existence of the constant magnetizing force due to the current in Q. The maximum magnetizing force produced in this process of reversals by the current in P was about equal to the maximum force which was excited by the current Q at the extreme point *b* of the curve. Reversals of a force beginning with this high value and decreasing to zero gave the metal so thorough a molecular shaking up that the magnetizing effect of the steady current became, under their influence, almost wholly independent of the previous magnetic history of the piece. In other words the effects of hysteresis nearly disappeared. The points marked thus + in fig. 32 were obtained in this way. They represent the relation of

B to the magnetizing force after reversals of an auxiliary force had been used to produce violent molecular agitation. Some of the points are marked thus ⊕, and in these cases the process of magnetic shaking was performed after the steady current had been so manipulated as to lead to a point on the descending limb of the ordinary cyclic curve : the application of reversals then brought the magnetism down to the marked value. On the other hand the points marked + were reached by applying reversals to raise the magnetism from a point on the ascending limb of the main cycle. It will be seen that the points marked ⊕ lie as nearly as possible on the same smooth curve with those marked +. That is to say, the effects of hysteresis are obliterated by this method of agitating the metal even more completely than they are obliterated by mechanical vibration in soft iron.* Ascending and descending limbs alike become merged on the single curve *ae*.

Fig. 33.



Magnetic curve-tracer curves for soft iron bars.
(*a*) Cycle performed slowly.
(*b*) Period of cycle 3 seconds.
(*c*) Period of cycle 0·43 second.

Reference has been made above to the evidence of time-lag in magnetization which the magnetic curve tracer furnishes. It is in the softest iron that these are most apparent, and especially when the pieces under test are solid or imperfectly laminated. When solid rods of soft iron are used, three quarters of an inch or so in diameter, the

* Compare a corresponding experiment in which tapping was found to make the ascending and descending limbs of the magnetic cycle approach coincidence, 'Phil. Trans.,' 1885, Part II. p. 564–566.

movements of the mirror of the curve traces take place as if it were controlled by a dash-pot, or were immersed in a viscous fluid. Even a comparatively slow gradual change in the magnetizing current is followed, after it ceases, by a continued creeping of the reflected spot of light lasting for some seconds,* and, when a cycle of reversal is performed at even a very moderate pace, the curve assumes a wholly different form from that which would correspond to a quite slow process. This is illustrated by fig. 33, where (*a*) is the curve taken quite slowly for a pair of soft iron rods 1·9 centim. in diameter, and (*b*) and (*c*) show the results when the period of a cycle was 3 seconds and 0·43 second respectively.

The influence which even the lower of these speeds has on the form of the curve is extraordinary. The maximum of the magnetizing current is nearly the same in all three curves (owing to the self-induction of the magnetizing coil it is a little less in the faster cycles, but enough non-inductive resistance was put in the circuit to make this difference small). It will be seen that the effect of time-lag in lowering the maximum of magnetization (namely, the maximum of the mean magnetization taken over the cross-section of the rods) is enormous; the effect of change in frequency being most noticeable when the period is comparatively long. Again, the influence of time-lag in augmenting the work spent in magnetic reversals is conspicuous, and here, again, it is remarkable how great this influence is at very moderate speeds of reversal. The exact form which the curve takes at any assigned speed will, of course, depend on what particular function of the time the applied electromotive force is caused to be, as a consequence of the exact form of the commutator plates and other conditions of the experiment. In the present case it appeared that the applied electromotive force was made to vary rather quicker near its mean values and rather less quick near its extreme values than would have been the case had it been a simple harmonic function of the time.

It is noticeable that the area of the curve increases at first and finally decreases as the frequency is increased. In other words, with a given maximum of magnetizing current the work expended in reversals is a maximum, per cycle, for some one frequency. This, of course, results from the fact that at higher frequencies the magnetization fails to penetrate sufficiently into the interior of the bar.

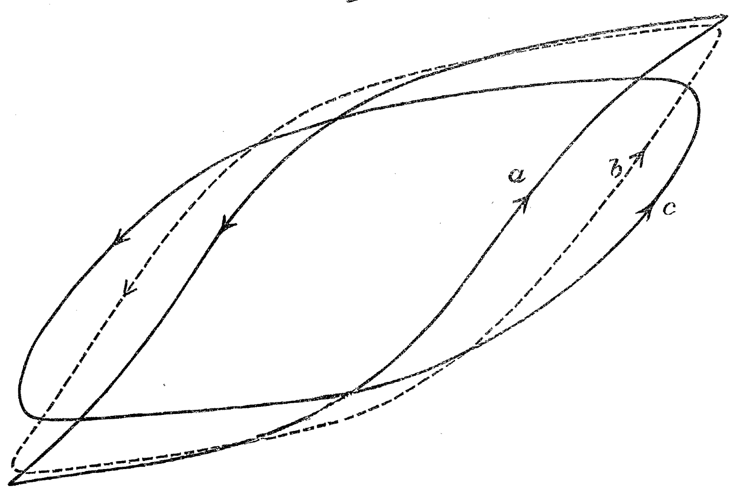
In steel these phenomena are much less apparent than in soft iron, but they take place to some extent. Fig. 34 shows the results of a similar experiment made with a pair of bars of tool steel of the same dimensions as the iron rods of fig. 33. Here again (*a*) shows the effects of perfectly slow reversal, while (*b*) and (*c*) are cycles performed in periods of 3 seconds and 0·6 second respectively. In both of these experiments (figs. 33 and 34) the cycles marked (*b*) and (*c*) were produced by using an electric motor to drive the commutator, regularity of speed being essential to steadiness of the figure, especially at the slower speeds.

Whether these manifestations of time-lag in magnetization are entirely explicable

* Compare the direct magnetometric observations described in 'Roy. Soc. Proc.' June 20, 1889.

by reference to Foucault currents is not easy to answer. It appears possible that another cause may contribute to produce time-lag. In the upsetting of a group of molecular magnets time is needed for the disturbance to gradually spread from the point, or points, where the mutual controlling forces which produce equilibrium are first overcome. Let a group of pivotted compass needles, for example, be subjected to a gradually augmented deflecting magnetic force; the first to yield will in general be some outlying member; its yielding will reduce the stability of its neighbours, and the disturbance spreads to them and from them to others. In a bar of iron we may conceive the molecules next the surface to be less strongly controlled than those in the interior, and to be, therefore, more likely to act as origins of disturbance when the equilibrium is upset by application of magnetizing force. From this point of view, the greater amount of surface a mass of iron presents the more quickly it is likely to take up the full amount of magnetic induction proper to any applied magnetic force, and hence in laminated iron the influence of time-lag should be less conspicuous

Fig. 34.



Magnetic curve-tracer curves of steel.
(*a*) Cycle performed slowly.
(*b*) Period of cycle 3 seconds.
(*c*) Period of cycle 0·6 second.

than in a solid piece. To distinguish an effect of the kind here suggested from the effect of Foucault currents is evidently difficult, since both effects depend on the metal being tested in relatively large solid masses. A possible experiment might be arranged in which a rod built up of a number of concentric cylinders should be compared with an equal rod of the same iron built up of a number of sectors parted by radial planes. Both modes of lamination would reduce whatever part of the time-lag is due to the cause just suggested, but the second mode only would be effective in preventing Foucault currents.

It is clear from the experiments of fig. 33, and even those of fig. 34, that ordinary ballistic tests are liable to serious error when the specimen tested is a solid bar of any

considerable section, especially when the material is soft iron, unless the ballistic galvanometer has a much longer period than is usual. The need of insulation, as well as lamination, is well exemplified by the case of Ring VIII., described above at p. 1008.

EXPERIMENTS WITH GROUPS OF PIVOTTED MAGNETS.

The remainder of our experiments relate to the molecular theory of magnetic induction discussed in a former paper by one of us.* It was there shown that, if we adopt WEBER'S view that the molecules of a magnetizable metal possess magnetic polarity, the phenomena of hysteresis and other prominent characteristics of the magnetizing process follow as consequences of the control which the molecular magnets exert on one another by their polar forces. Thus, in the application of magnetic force to an unmagnetized piece, the molecular magnets are at first deflected stably, and in this stage there is no hysteresis. But when the force is sufficiently increased certain molecules are deflected so far as to become unstable, and a breaking up and re-arrangement of molecular groups supervenes. Finally, after this process has occurred throughout the piece a third stage is entered on, when further stable deflections through a small range bring about the completely "saturated" state. Hysteresis is found whenever any of the molecules pass from one stable configuration to another through a phase of instability, and this transition, being mechanically irreversible, involves a dissipation of energy. It was shown that this conception of molecular structure gave an explanation of very many known facts regarding the magnetic quality of iron and steel, and that some of these may be effectively illustrated by means of a model consisting of a group of small magnets pivotted like compass needles on fixed centres, and placed near enough to one another to allow their mutual polar forces to be strongly felt.

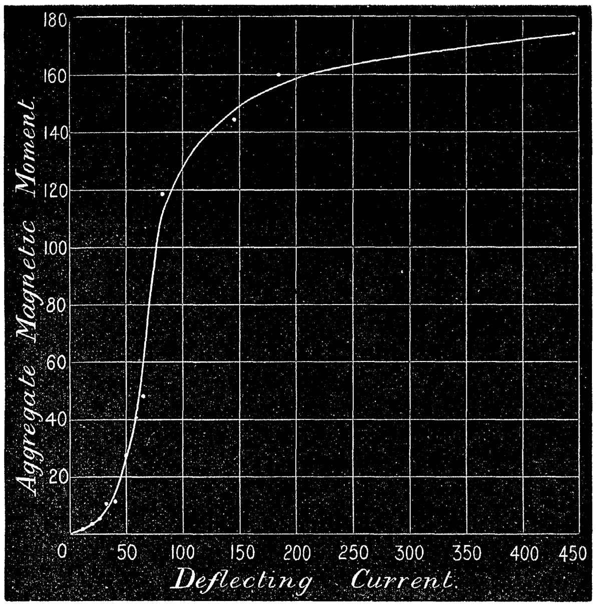
In further elucidation of this theory, we have made a number of experiments with such a model. In some of them as many as 130 little magnets have been used. These were cut out of sheet steel. They were mostly lozenge-shaped, and were about an inch long and half an inch wide, but some were smaller; each had a central recess punched in it to form a socket for the supporting pivot, which was an inverted drawing-pin with a sharp point. The pins were stuck through a sheet of paper to hold them at the desired distance apart, and the paper was laid on a horizontal sheet of glass which stood between a pair of coils, through which current was passed to produce a deflecting magnetic field. Two layers of such magnets were generally used, one above the other. The aggregate magnetic moment of the group was measured by means of a mirror magnetometer, which was furnished with an adjustable compensating coil to neutralize the direct effect of the current in the two field-coils of the model.

The group having been well stirred up and allowed to settle in the absence of

* "Contributions to the Molecular Theory of Induced Magnetism," 'Roy. Soc. Proc.,' vol. 48, p. 342 (June, 1890).

directing force, the current in the coils was slowly increased by means of a liquid rheostat, and galvanometer readings of it were taken, along with magnetometer readings of the aggregate moment. The numbers (with arbitrary scales) are given below, and are drawn as a curve in fig. 35. The highest value of the current was

Fig. 35.



Curve showing the behaviour of a group of 130 pivotted magnets subjected to increasing directive force.

strong enough to bring the group of magnets to a configuration approaching "saturation." It will be seen that the three stages of the magnetizing process are well reproduced in the behaviour of the model, and, notwithstanding the limited number of "molecules" which took part in the operation, the readings lie fairly well on a smooth curve, which has all the general character of the curve of magnetization in actual iron.

Current.	Moment.	Current.	Moment.
0	0		
4	0	58	41
10	1	63	48
17	3	83	119
26	5	145	145
33	11	184	160
41	11	447	174
50	28		

In the same way fig. 36 shows the results obtained in carrying a group of pivotted magnets through a complete cycle, by double reversal of the directing field, after the cycle had already been gone through once or twice. Fig. 37 shows an immediately succeeding experiment on the same group, designed to illustrate the formation of small

loops by the removal and reapplication of magnetic force. In these operations the behaviour of the model agrees in all respects with that of a magnetic metal.

Fig. 36.

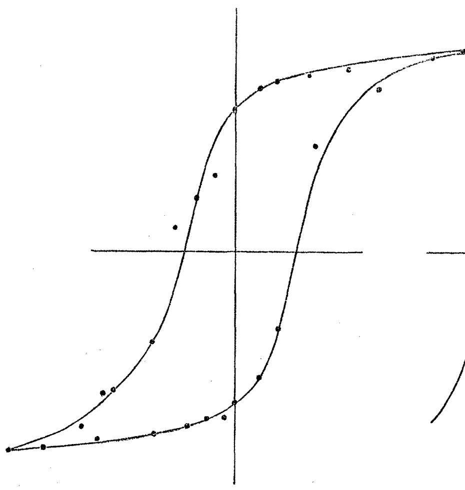
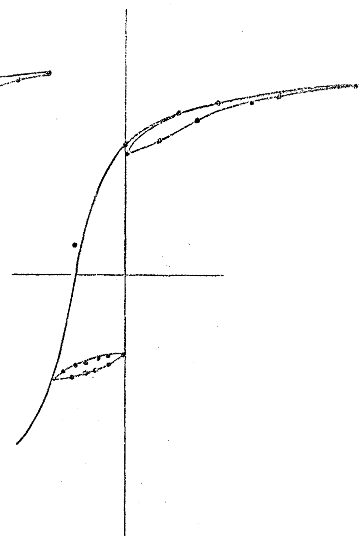


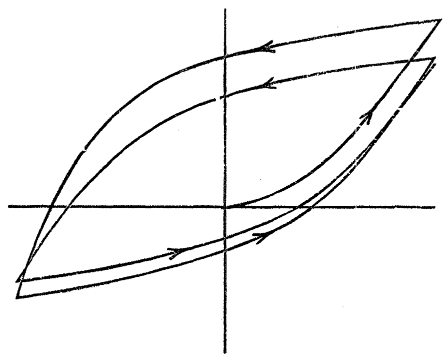
Fig. 37.



Cyclic processes in a group of pivotted magnets.

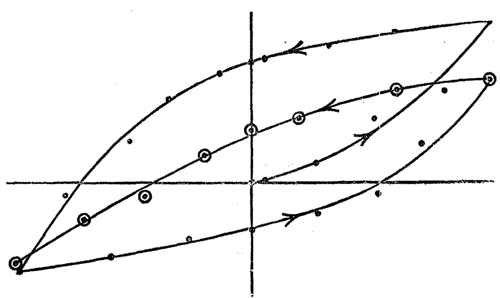
The same close correspondence is found even in less obvious features of the magnetizing process. This is illustrated in figs. 38, 39, and 40.

Fig. 38.



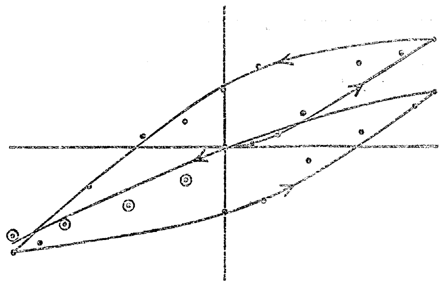
Magnetisation of steel.

Fig. 39.



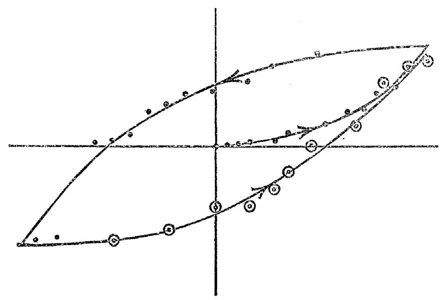
Corresponding process in model.

Fig. 40.



When a piece of previously unmagnetized iron or steel is acted on by a magnetic force sufficiently strong to carry the metal to the stage of high permeability, but not strong enough to make it approach saturation, and this force is then caused to vary between equal positive and negative values, it is found that the first application induces more magnetism than is induced by subsequent applications, and that the changes of magnetism do not become cyclic until the force has been several times reversed. And during this gradual approach towards a cyclic *régime* the range through which the magnetism varies between its positive and negative extremes becomes reduced. These effects of hysteresis are well shown by fig. 38, which is copied from a former paper,* and represents a test of a piece of annealed steel.

Fig. 41.



The same phenomena occur in the model, provided the little magnets have been previously shaken up and allowed to settle in the absence of any directing field : a condition which may be supposed to correspond with the annealing of the solid metal. Fig. 39 is a characteristic instance. It represents a test of the same group of pivotted magnets as was used in figs. 36 and 37. After all effects of earlier deflecting fields had been eradicated by shaking up the group, a rather weak directing force was applied, first to the positive side, and then this was reversed three times. At the third reversal the changes of aggregate moment on the part of the group had become nearly cyclic, but with a range of variation which was decidedly less than that indicated by the first application of the field. Corresponding results were found in another

* 'Phil Trans.,' 1885, Plate 61, fig. 28. See also fig. 26 on the same plate.

experiment where the first application of the field was towards the side called negative.

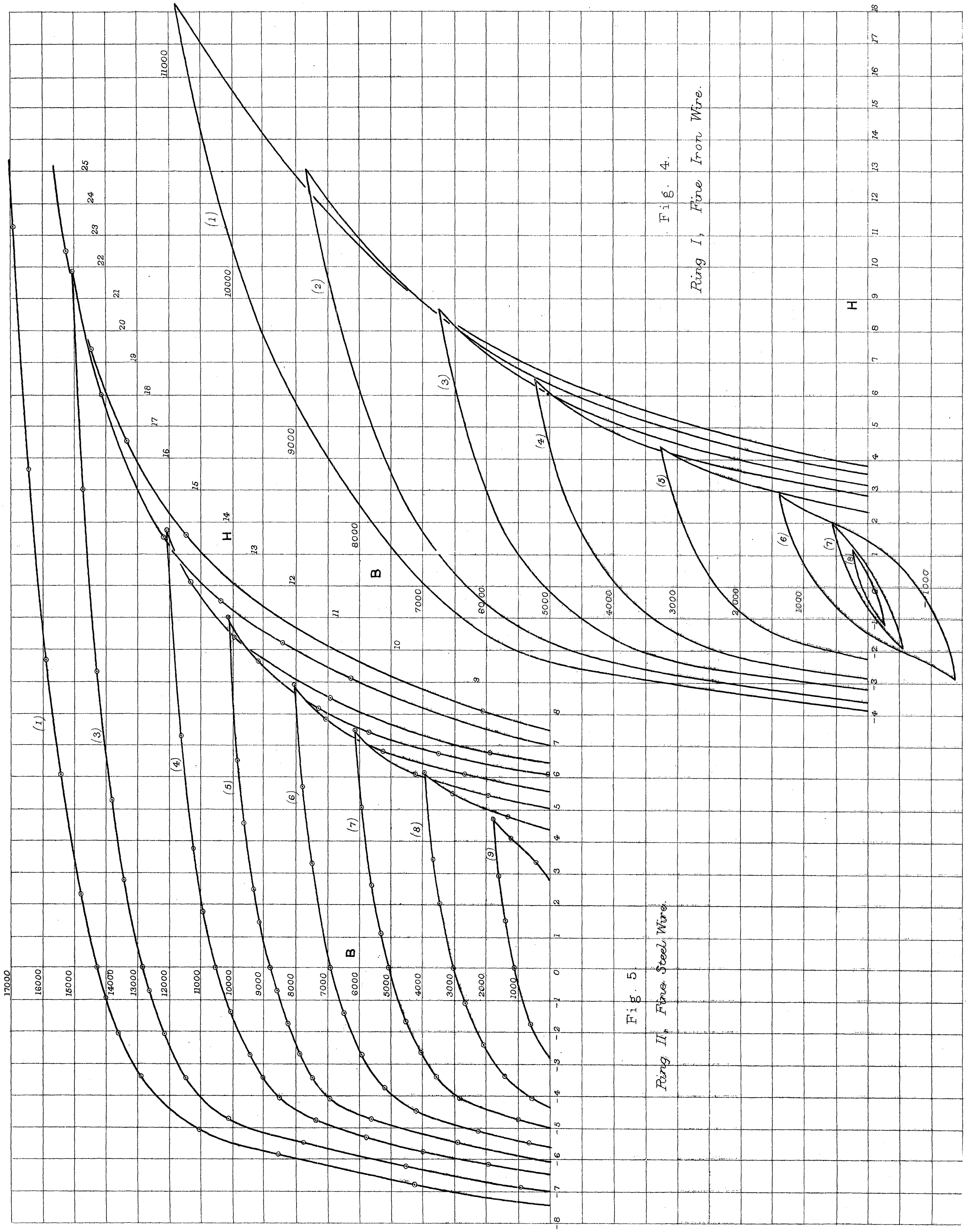
Again, using a model in which there were only 36 magnets, notes were made of the position assumed by each member of the group when the directing field was (1) applied, (2) reversed, (3) re-reversed, and so on. It was seen that the configuration assumed in the first application was not reproduced in the third, nor that of the second in the fourth. But the fifth application made all the members of the group take up the same position as they took in the third, and again the sixth agreed with the fourth.

Further, tests of iron and steel show that if we have to deal, not with a previously unmagnetized piece but with a piece on which the process of "demagnetizing by reversals" has been performed, the phenomena which have just been described are not found, or, at least, are much less conspicuous than in virgin metal.

They reappear after the primitive state is reproduced by annealing. In this respect the molecular state of iron which has been demagnetized by reversals of a strong magnetic force (diminishing to zero) differs from that of a piece which has been demagnetized by annealing—or even, it may be added, by mechanical vibration.*

The same difference is found in the behaviour of the model after the two corresponding kinds of preliminary treatment. If a neutral initial state has been arrived at by a casual stirring up of the little magnets, the model behaves in the way shown in fig. 38. On the other hand, if the neutral state has been produced by repeated reversals of a strong deflecting field, very slowly performed, so as not to throw the group into general agitation, and gradually reduced in range to zero while the reversals go on, the displacements of the magnets under a subsequently applied weaker field are found to fall at once into a cyclic *régime* when the field is reversed. An example of this is given in figs. 40 and 41, which show experiments made with a group of 120 magnets. In fig. 40 the magnets had been shaken up to begin with, and, in consequence, when the magnetic field was applied the displacements were not at once cyclic. Fig. 41 shows the behaviour of the same group under precisely the same changes of deflecting field after the process of "demagnetizing by reversals" had been used to bring the group into a neutral state. Here we find a cyclic *régime* established at once, and as near an approach to symmetry in the curve as a model with a limited number of magnets can well be expected to show. Observations made on such a model are necessarily somewhat rough, and too much stress must not be laid on particular features of the curves. But in several repetitions of these experiments the same general distinction has always been apparent in the behaviour of the model after one and the other mode of preliminary treatment, a distinction which, as we have seen, forms a striking analogue to what is observed in actual iron or steel.

* In illustration of this difference, reference may be made to figs. 26 and 27 in Plate 61, 'Phil. Trans.,' 1885.



West, Newman, lith.

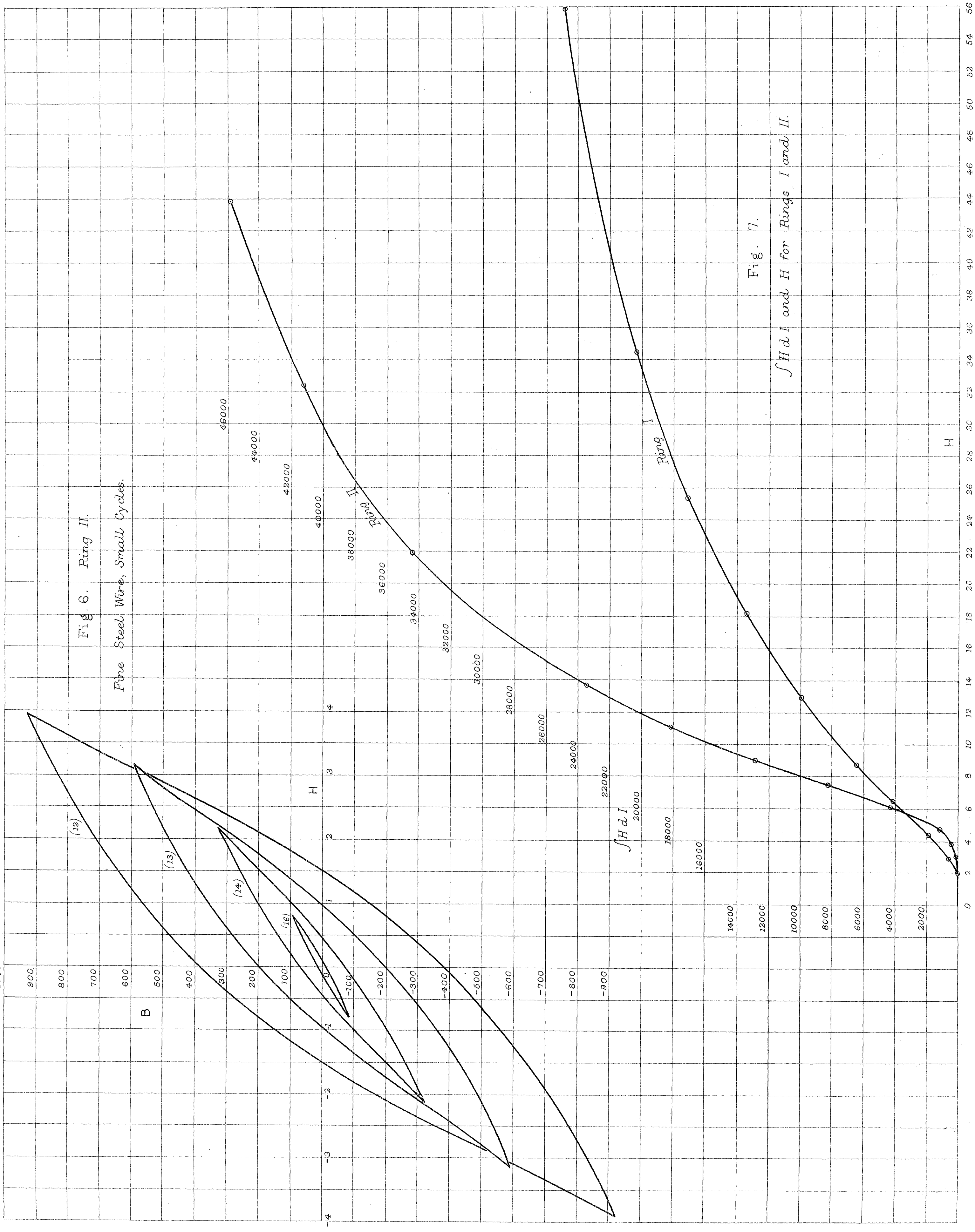
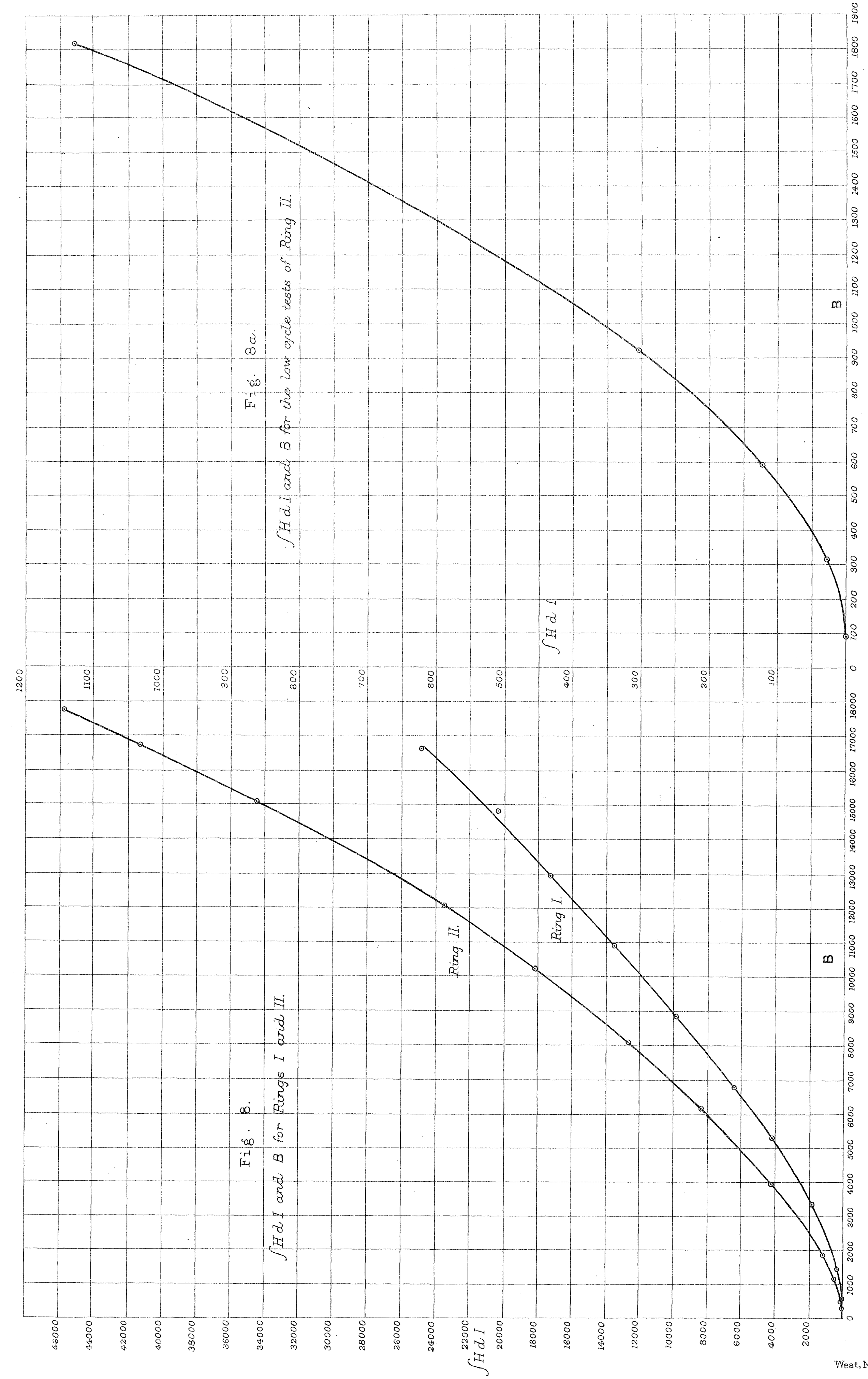


Fig. 6. Ring II.
Fine Steel Wire, Small Cycles.
(12)
(13)
(14)
(16)
B
H
Fig. 7.
∫H d I and H for Rings I and II.
Ring I
Ring II
∫H d I
H



West, Newman lith.

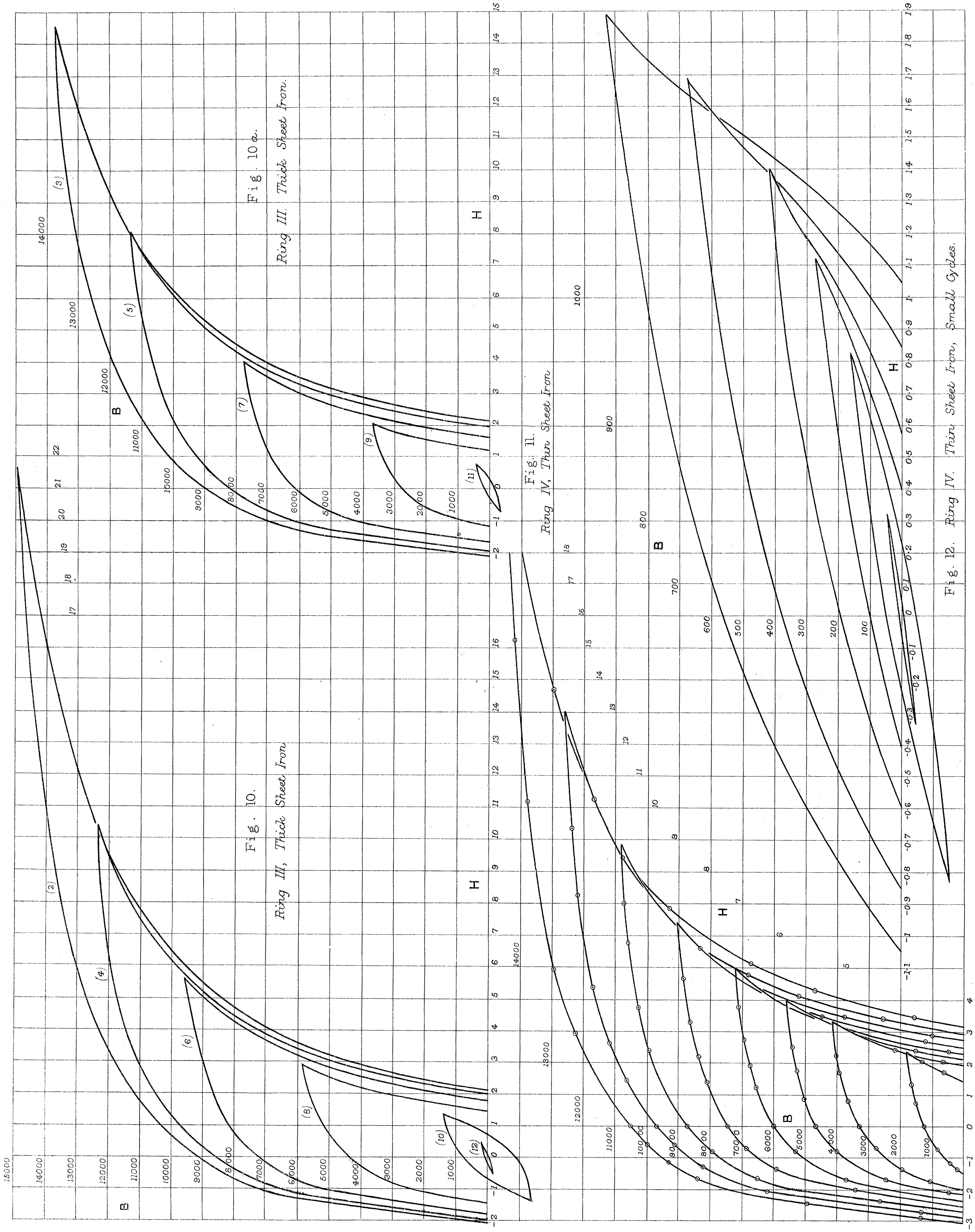


Fig. 10 a.
Ring III. Thick Sheet Iron.
Fig. 10.
Ring III, Thick Sheet Iron
Fig. 11.
Ring IV, Thin Sheet Iron
Fig. 12. Ring IV. Thin Sheet Iron, Small Cycles.

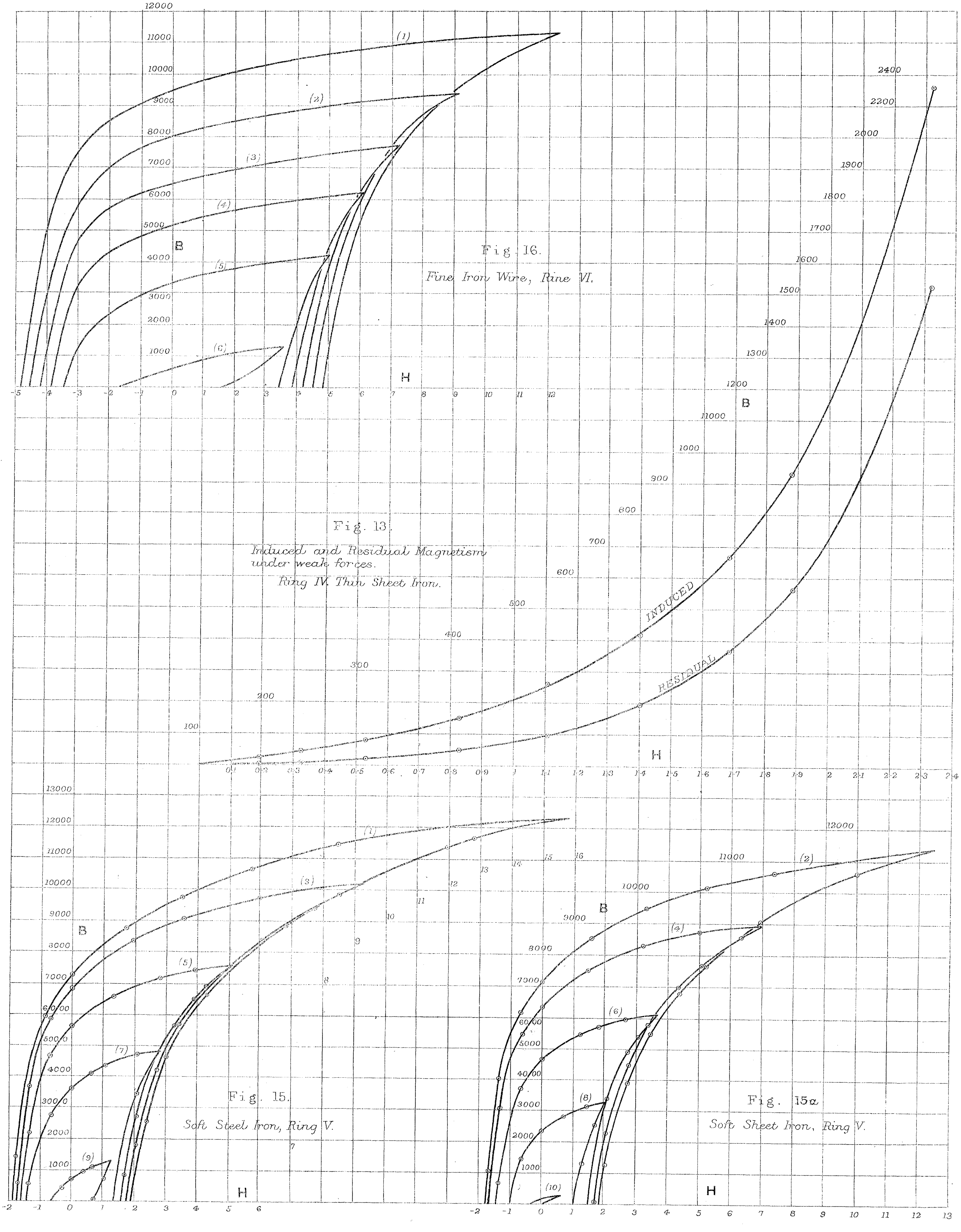


Fig. 16.
Fine Iron Wire, Ring VI.
B
H
Fig. 13.
Induced and Residual Magnetism under weak forces.
Ring IV. Thin Sheet Iron.
INDUCED
RESIDUAL
B
H
Fig. 15.
Soft Steel Iron, Ring V.
B
H
Fig. 15a
Soft Sheet Iron, Ring V.
B
H

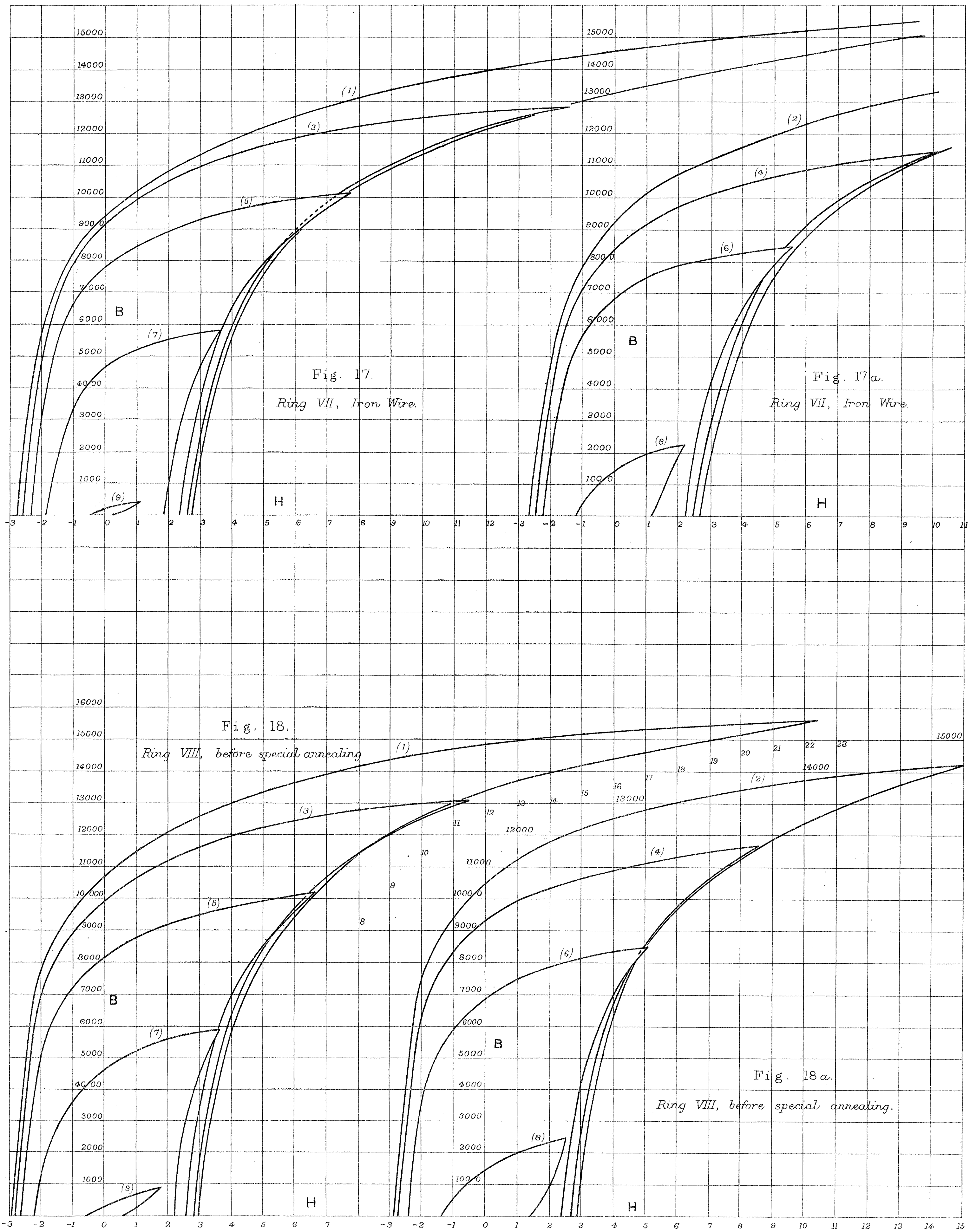


Fig. 17. *Ring VII, Iron Wire.*

Fig. 17 a. *Ring VII, Iron Wire.*

Fig. 18. *Ring VIII, before special annealing.*

Fig. 18 a. *Ring VIII, before special annealing.*

West, Newman, lith.

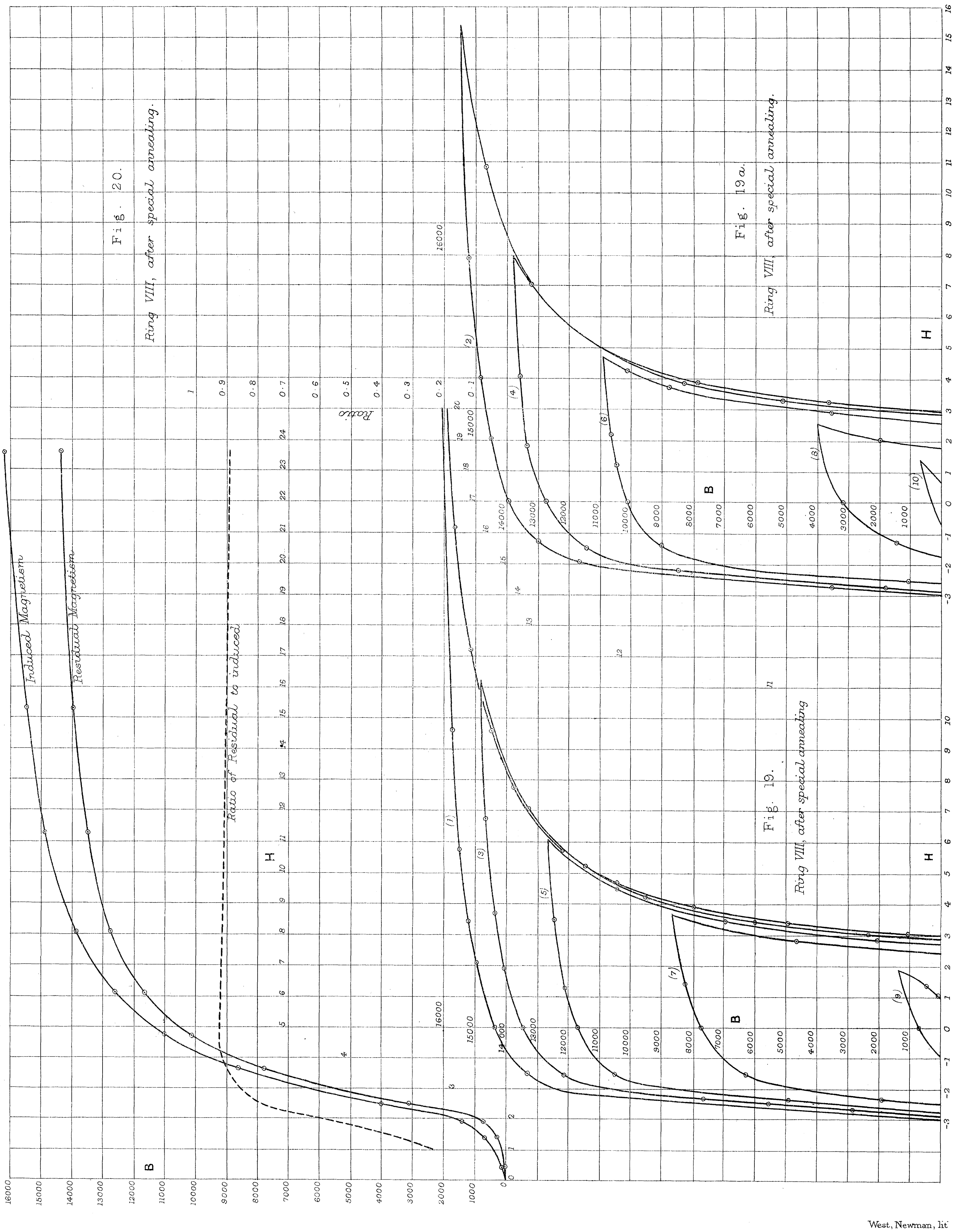


Fig. 20.
Ring VIII, after special annealing.
Induced Magnetism
Residual Magnetism
Ratio of Residual to induced
Ratio
H
B
Fig. 19a.
Ring VIII, after special annealing.
Fig. 19.
Ring VIII, after special annealing

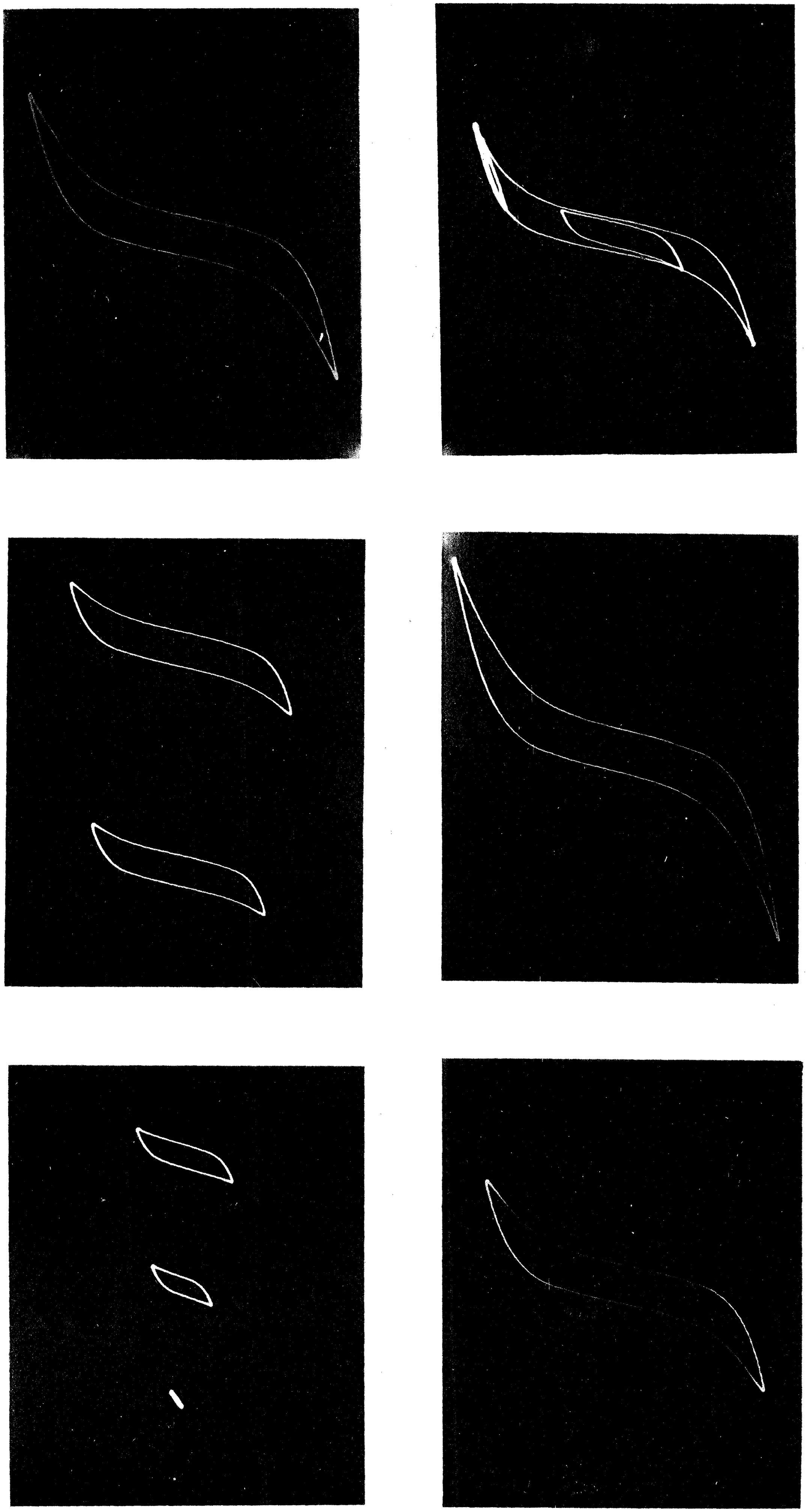


Fig. 28.—Photographic Records by the Magnetic Curve Tracer.

West, Newman imp.

Fig. 28.—Photographic Records by the Magnetic Curve Tracer.