PROCEEDINGS OF

THE ROYAL SOCIETY.

Section A.—Mathematical and Physical Sciences.

On the Effect of Previous Magnetic History on Magnetisation.

By Prof. Ernest Wilson, G. F. O'Dell, and H. W. K. Jennings.

(Communicated by Sir William H. Preece, K.C.B., F.R.S. Received May 4,—Read June 17, 1909.)

Part I.

It is well known that if a piece of iron be subjected to a considerable magnetising force and then be tested for permeability corresponding to a lower force, the permeability so obtained may differ widely from the permeability which would have been obtained had the material been previously demagnetised. The effects of previous history have been studied by a good many experimenters, notably by Searle.*

The object of this part of the present paper is to examine the effect of previous history upon the dissipation of energy by magnetic hysteresis. Suppose in fig. 1 that a piece of iron is carefully demagnetised and that the hysteresis loop No. 1 corresponding to a force H is obtained. This loop is symmetrical about the origin in all respects and its area gives the loss usually referred to in testing work. Suppose that the last value of the force H is positive and that it be increased to a value H_1, reversed a few times, and reduced to zero from its positive value. After re-applying the force H and reversing it a sufficient number of times to produce stability, a loop such as No. 2 will be obtained. As is well known, this loop shows

* See 'Journal of the Institution of Electrical Engineers,' vol. 34, Part 170, p. 55, "Studies in Magnetic Testing," by G. F. C. Searle, F.R.S. *Cf.* also C. W. Burrows, "On the best method of Demagnetising Iron in Magnetic Testing," 'Bull. Bureau o Standards, Washington,' vol. 4, pp. 205—274.

a reduced change of magnetic induction and, consequently, a reduced permeability. Suppose, now, that the iron is carefully demagnetised and that a magnetising force supplied by an independent source is applied very gradually, so that when added to the original force H it gives a force H_3 such that the change of magnetic induction corresponding to a change of the force H is exactly equal to the change observed with loop 2 for the same change of H. The loop obtained will appear as No. 3 in fig. 1. We have

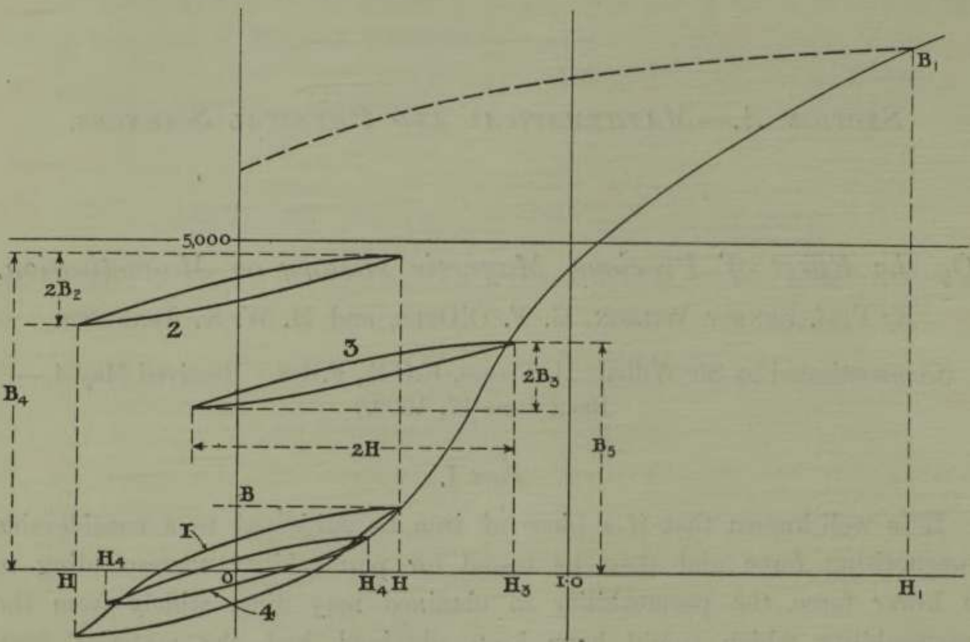

Fig. 1.

now obtained two loops, Nos. 2 and 3, each having the same change of magnetic induction, and each having the same net change of force H. The change from loop 1 to loop 2 has been brought about by inter-molecular force, whereas the change from loop 1 to loop 3 has been brought about by the application of an externally applied constant force $H_3 - H$. If the effect of inter-molecular force were capable of being exactly equivalent to the externally applied constant force, one would expect to find that the energy required to perform a complete cycle would be the same in each case; that is, the area of loop 2 would be equal to the area of loop 3.

Two rings built up of stampings of Stalloy and Lohys respectively have been experimented upon and have already formed the subject of a communication.* The method of test employs a ballistic galvanometer and has

* See 'Roy. Soc. Proc.,' A, vol. 80, 1908, p. 548. The distinguishing feature of Stalloy is that it contains about 3 per cent. of silicon, and Lohys is a good grade of transformer iron.

already been described.* Each experiment involved the following operations :—

1. The ring was carefully demagnetised by placing it in circuit with an alternator having a frequency of 50,† and gradually reducing the magnetising force to zero from a value of 6 to 9 C.G.S. units, which is much larger than that corresponding to maximum permeability. This operation usually takes a quarter of an hour to perform and when it is subsequently mentioned that the ring was demagnetised it is meant that the above operation has taken place.

2. After reversing a chosen force H about 100 times loop 1 was obtained, and the force left positive and removed.

3. A higher force H_1 was then applied in a negative direction, reversed 50 times and reduced to zero from its positive value. This operation determined the amount of the previous history.

4. The force H was again applied negatively and reversed 200 times. Several values of the total change of magnetic induction corresponding to a reversal of H and to the reducing of H from its positive and negative maximum values to zero were obtained, and if these did not repeat, another 100 reversals of H were applied and so on until stability was obtained.

5. Loop 2 was then obtained and its absolute value B_4 was found as follows :—

The magnetising force was reduced from its positive maximum value H to zero, and the change of magnetic induction noted. The change of magnetic induction produced by applying a positive force much longer than H was measured. This larger force was then reversed twice and the corresponding changes of magnetic induction observed. The same force was then reversed 50 times, after which the changes of magnetic induction were again noted. If these last changes had the same value as the first it was assumed that the absolute value on the B axis was the difference between one-half of the total change produced by reversal of the larger force and the change found originally when the force was increased from zero to its larger value. The absolute value B_4 was obtained by adding the change observed when the force H was originally removed. The ring was then demagnetised.

6. The force H was applied positively, and by aid of a tertiary coil a force H_3-H was applied gradually ; at each step reversals of H were made and the resulting change of magnetic induction noted. About 50 reversals of H were made at each step until the proper value of the current in the tertiary coil was nearly reached ; several hundreds of reversals were then

* See 'Roy. Soc. Proc.,' vol. 53, p. 353, fig. 2.

† See C. W. Burrows, *loc. cit.*

given. Finally, such a value of H_3-H was obtained that the resulting change of induction $2 B_3$ was equal to $2 B_2$.

7. Loop 3 was then observed, care being taken to see that the maximum value of B_3 was the same at the end of test as at the commencement. The absolute value of the loop B_5 was then obtained as before and the ring demagnetised.

The results are plotted in fig. 2, in which the abscissa is the value of H_1, the force applied to obtain previous history, and the ordinate is the difference of the area of loops 2 and 3 expressed as a percentage of the area of loop 2. Each curve corresponds to the reversal of a given value of H which is noted in the figure.

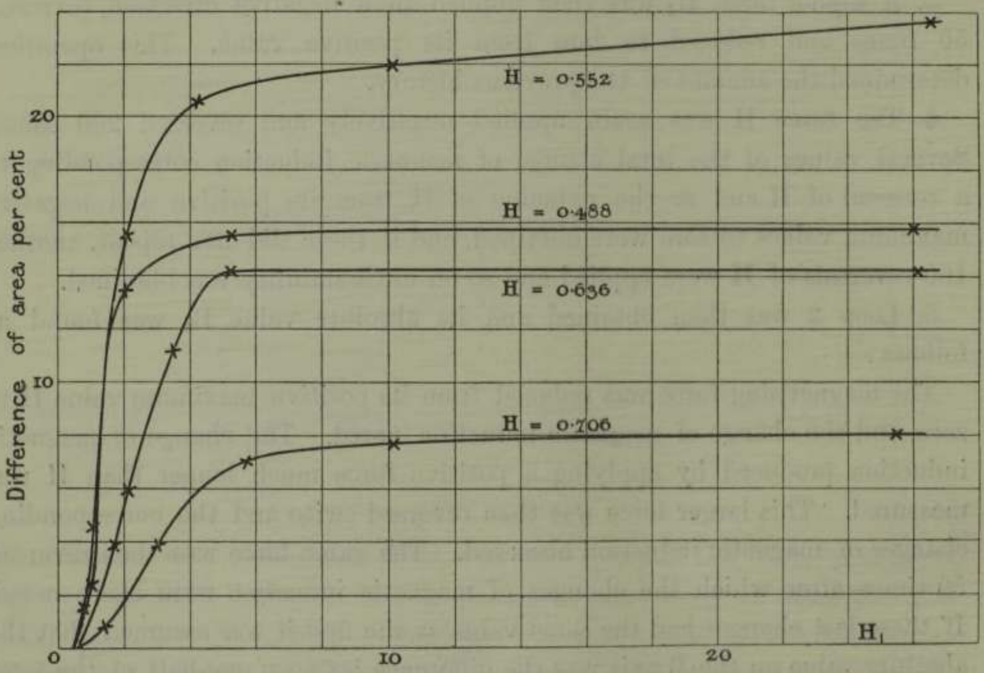

Fig. 2.

In fig. 1 the symmetrical loop 4, corresponding to a force H_4, has a value of magnetic induction equal to B_2 or B_3.

In a large number of cases the changes of magnetic induction for loops 2 and 3 respectively are equal. In others, where there is a small difference, the area of loop 3 has been corrected by an application of Steinmetz' law. Fig. 3 has been taken from fig. 2 and shows the relation between the percentage difference of area and the values of H for a given previous history H_1.

It will be noticed in fig. 2 that of the chosen values of H the intermediate value 0·552 gives the largest ordinate.

The conclusion arrived at is that iron may be in one or other of two states according to treatment. In each state it gives exactly the same change of magnetic induction for the same change in the magnetising force, and yet the

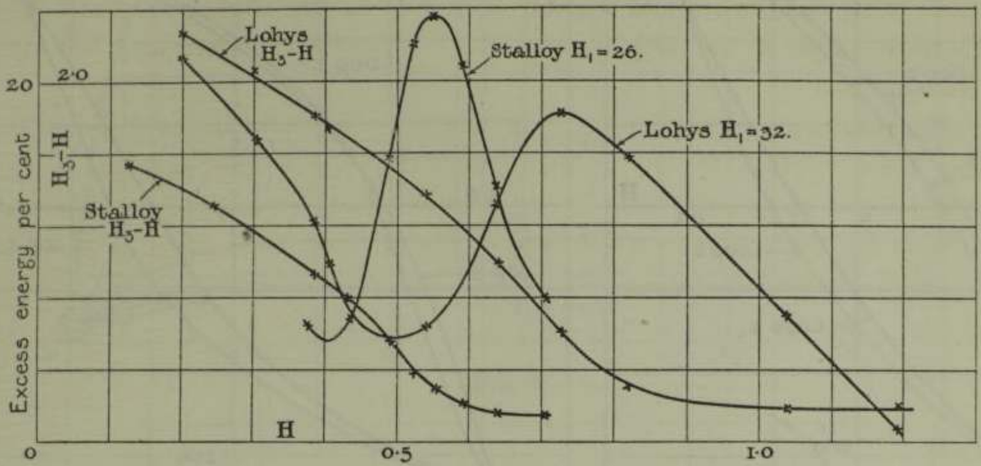

FIG. 3.

energy required to effect the cyclical change is different in the two cases. The magnitude of the effect depends upon the value of the reversed force and the value of the force producing previous history. In all cases where there is a difference in the energy dissipated, the iron requires more energy when in the state following the application of a larger force to produce previous history.

With regard to the relative shapes of the loops it may be remarked that when the unsymmetrical loop No. 2 is plotted about an origin common with loop No. 3, the difference in area is brought about in the following manner. In all cases within the limits of the experiment the right-hand side of loop No. 3 lies within the right-hand side of loop No. 2. With regard to the left-hand side of the loops it may be remarked that when the previous history is *large* for a comparatively small value of H, loop No. 3 lies wholly inside loop No. 2. As the value of H is increased for large previous history this effect is ultimately reversed. When the previous history is *small*, the left-hand side of loop No. 3 is wholly outside that of loop No. 2. Figs. 4 and 5 show the effects for a large previous history, and fig. 6 for a small previous history. Fig. 7 is interesting as it shows the relation between the required force due to the tertiary coil H_3-H and the previous history force H_1. Each curve has marked upon it the corresponding value of H. Fig. 8 shows the relation between the absolute values B_4, B_5 (see fig. 1) and previous history force H_1. It will be noticed that they are similar to those in fig. 2. Fig. 9 shows the relation between the absolute values B_3, B_4, and

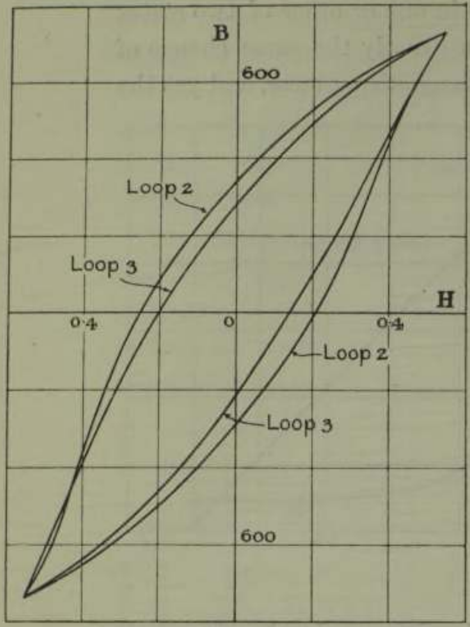

FIG. 4.

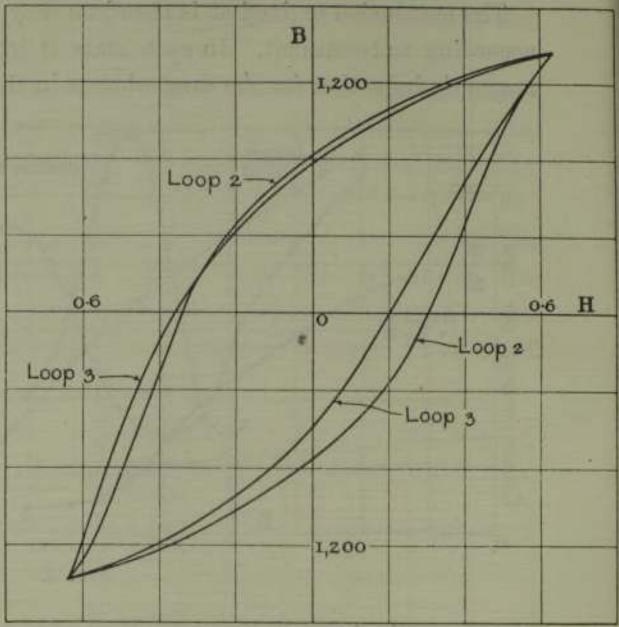

FIG. 5.

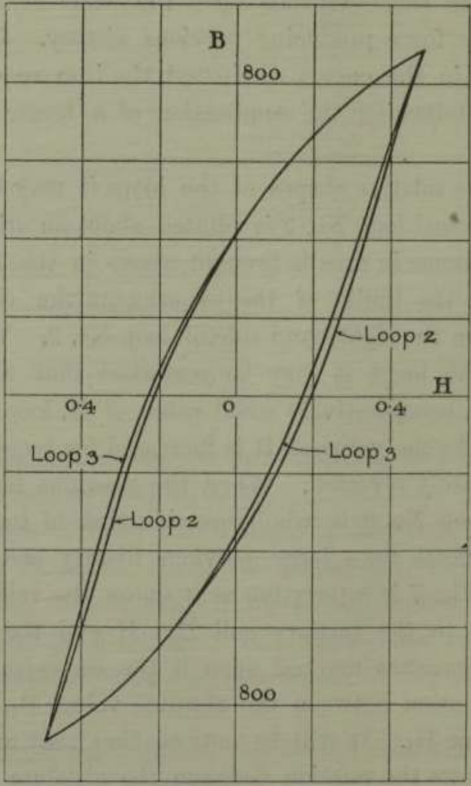

FIG. 6.

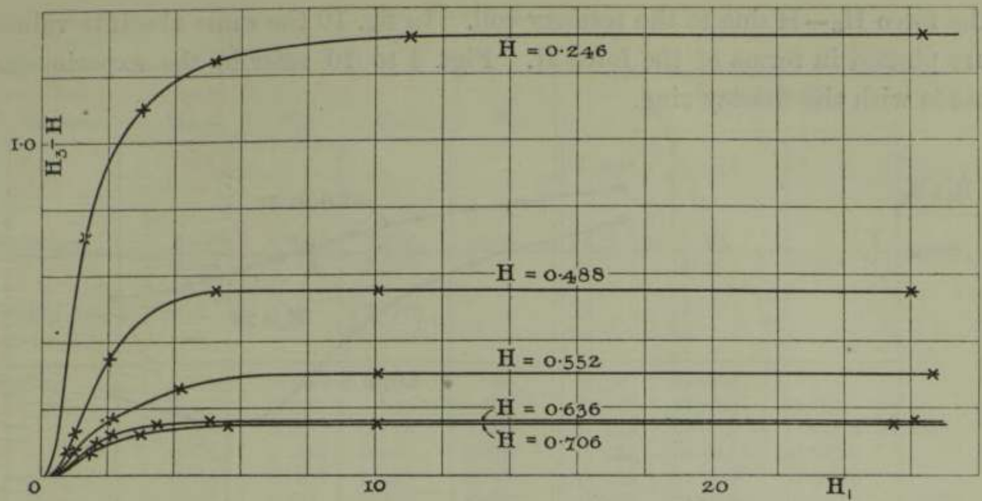

FIG. 7.

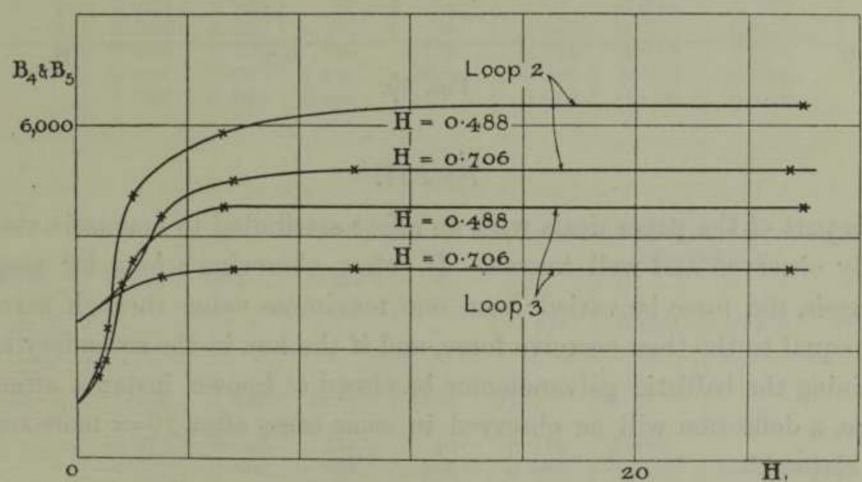

FIG. 8.

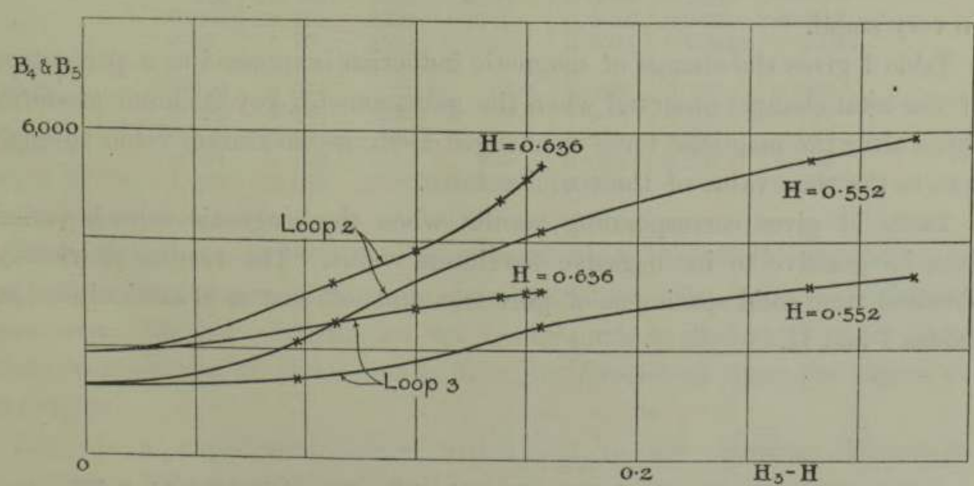

FIG. 9.

the force H_3-H due to the tertiary coil. In fig. 10 the same absolute values are plotted in terms of the force H. Figs. 4 to 10 refer to the experiments made with the Stalloy ring.

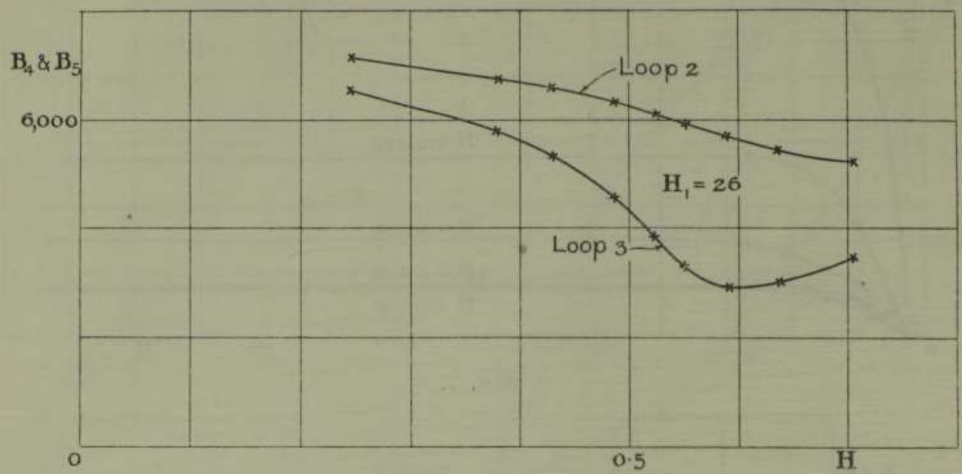

FIG. 10.

Part II.

This part of the paper deals with an effect attributed to magnetic viscosity already observed and well known. If, when observing a loop for magnetic hysteresis, the force be varied from one maximum value through zero to a value equal to the then coercive force, and if the key in the secondary circuit containing the ballistic galvanometer be closed at known instants after such change, a deflection will be observed in some cases after 10 or more seconds have elapsed.*

This effect has been examined in the present cases and has been found to be very small.

Table I gives the change of magnetic induction (expressed as a percentage of the total change) observed when the galvanometer key is closed at stated times after the magnetic force is changed from its maximum value through zero to the then value of the coercive force.

Table II gives corresponding results when the magnetic force is varied from its positive to its negative maximum value. The results previously obtained from solid specimens of pure iron and soft cast steel are included in Tables I and II.

* See 'Roy. Soc. Proc.,' vol. 62, p. 371 ; also 'The Electrician,' vol. 55, p. 792.

Table I.

Material.	H_{max}.	H_0.	B_{max}.	B_0.	Percentage change of magnetic induction after			
					1 sec.	5 secs.	10 secs.	20 secs.
Pure iron ……	1·003	0·620	3,770	3100	14·8	0·28		
	9·24	1·13	15,270	—	29·7	2·1	0·31	
Soft cast steel	98·0	1·0	17,100	—	20	3		
	—	—	—	—	24	2		
Stalloy ………	0·212	0·040	184	40	0·23	0·084		
	0·415	0·150	650	258	0·11	0·033	0·016	
	0·666	0·37	2,115	1360	0·039	0·012	0·0075	0·0025
	0·935	0·485	3,875	2850	0·031	0·010	0·0059	
	0·945	0·496	3,790	2747	0·029	0·010	0·0058	
	2·77	0·70	9,200	6850	0·021	0·0050	0·0026	0·0013
Lohys ………	0·200	0·044	97·4	24·4	1·76	0·314	0·126	
	0·385	0·140	264	93	0·850	0·151	0·058	
	0·638	0·290	746	378	0·378	0·115	0·054	
	0·821	0·450	1,510	895	0·166	0·078	0·053	
	1·193	0·635	3,660	2830	0·052	0·026	0·018	

Table II.

Material.	H_{max}.	H_0.	B_{max}.	B_0.	Percentage change of magnetic induction after			
					1 sec.	5 secs.	10 secs.	20 secs.
Pure iron ……	1·003	0·620	3770	3100	21·1	0·17		
Stalloy ………	0·212	0·040	184	40	0·111	0·034		
	0·415	0·150	650	258	0·048	0·015	0·0077	
	0·666	0·37	2115	1360	0·015	0·0047	0·0031	0·0014
	0·935	0·485	3875	2850	0·0094	0·0035	0·0018	
	0·945	0·496	3790	2747	0·0086	0·0032	0·0017	
	2·77	0·70	9200	6850	0·0021	0·00068	0·00024	
Lohys ………	0·200	0·044	97·4	24·4	0·885	0·157	0·062	
	0·385	0·140	264	93	0·407	0·082	0·029	
	0·638	0·290	746	378	0·139	0·047	0·029	
	0·821	0·450	1510	895	0·064	0·028	0·022	
	1·193	0·635	3660	2830	0·019	0·0071	0·0042	

From the above experiments it appears that the effects attributed to magnetic viscosity are much more pronounced in solid than in laminated specimens. Further experiments are being made to discover how far these effects in a material of given composition are dependent upon the degree of lamination.

The above experiments were carried out in the Siemens Electrical Engineering Laboratory, King's College, London.