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PHYSICAL REVIEW.

THE EFFECT OF THE FIBROUS STRUCTURE OF SHEET IRON ON THE CHANGES IN LENGTH ACCOMPANYING ITS MAGNETIZATION.

By Edward Rhoads.

General Description of the Phenomenon.

THE subject of the change in dimensions which a piece of one of the magnetic metals undergoes when magnetized is of considerable interest as offering a possible help in the effort to get a closer insight into the nature of magnetism. That there is such a change was discovered by Joule in 1847. The subject has since been studied by many observers, notably by Bidwell and Nagaoka, and as a result we have a good knowledge of the manner in which the changes follow the application of magnetizing force, accompanying the magnetization.

The case which has been most studied is the change in length in the direction of uniform magnetization, as in a long thin cylinder magnetized by a uniform field in the direction of its length or a cylindrical shell magnetized in the direction of its circumference. With such a piece it is found that, in iron, the length at first increases as the magnetic force increases, the change being proportional to the square of the magnetization. Somewhat after passing the point of maximum permeability, however, the length reaches a maximum, and as the field is increased still further a shortening of the piece takes place. This shortening is proportional to the increase of field until quite high fields are reached when it becomes less in proportion, and finally the bar assumes a minimum length which it maintains in all higher fields. The maximum elongation does not exceed five millionths of the whole length nor the contraction twelve millionths. They differ widely according to the quality, hardness, etc., of the specimen, and are especially dependent, as shown below, upon the "grain." But for any one specimen, as long as its other properties are not altered, the changes are always the same under the same conditions.

Nickel differs from iron in that it never shows any elongation but contracts even in the weakest fields. Cobalt shows a contraction in weak fields followed at higher fields by an elongation which still continues in the highest fields that have been applied to it.

If, instead of continuing to increase the field from any point, it is decreased, the lengthening or shortening which the bar was undergoing is in general reversed but shows a hysteresis effect. That is to say, if the bar was lengthening with increasing field, then when the field begins to decrease it will shorten, but this shortening will not be as rapid in proportion to the change of field as the lengthening was. In looking at the curves representing cyclic change of length it is well to bear in mind that the change in length, unlike the magnetization, is independent of the sense of the magnetizing force which causes it. Thus in taking a cyclic magnetization curve when the field has been reduced to zero, and is being increased in the opposite direction, the magnetization is first reduced to zero and then begins to *decrease* below zero. The change of length on the other hand first becomes zero, and then begins to *increase* again. Hence the relation which the two curves bear to each other stands out more clearly if we imagine the lower half of the magnetization curve drawn above the line of zero magnetization instead of below.

Connection Between the Magnetization and the Changes in Length Produced by It.

The most striking feature of this relation is the fact that the field at which the minimum change of length is reached is the same as that in which the magnetization becomes zero, *i. e.*, the coersive force. Also it appears, as already mentioned, that in low fields the change of length shows a close proportionality to the square of the magnetization. The proportionality, however, is not exact, as is at once evident from the fact that the bar does not quite regain its original length even when the magnetization has become zero. It is possible that this, together with the closely allied fact shown by Nagaoka that the factor of proportionality is different in the ascending and descending curve, may be due to a hysteresis effect in the action of the apparatus used, or to mechanical hysteresis in the specimen. If this be the case it may be that the change of length is rigidly a function of the magnetization; or in any case of both the magnetization and the field, of which in weak fields the term containing the magnetization squared becomes all important. But until this is shown, the fact remains that, all other things being equal, the length may still be different under the same magnetization arrived at differently. So all that can be said is that the magnetization and change of length both follow from the same causes, but that apparently neither is rigidly connected with or due to the other.

In the language of the molecular theory this might be expressed by saying that changes in length result from changes in the grouping of the molecular magnets, which changes may or may not result in producing in each group an excess pointing in any direction, *i. e.*, producing a state of magnetization. The extent to which these changes in the grouping may take place without affecting the magnetization is well shown in a recent paper by Fromme.[1]

It is not the object of this paper to discuss the connection between the magnetic change in length and the magnetization; but since both quantities separately have been plotted against the field in the experiments about to be described, it seemed necessary to say this much to show the reason why. And in passing I may perhaps add that I think the very interesting question of this connection might be successfully attacked by taking sets of progressively graded cyclic curves for both phenomena plotted to the magnetizing force and taken between identical limits. Lines could then be ruled on both parallel to the axis of zero field so that, by picking out their points of intersection with the curves, new curves could be drawn

[1] Fromme, Wied. Ann., Vol. 61, p. 55, 1897.

representing the relation between the change of length and magnetization at various constant fields.

PLAN OF THE EXPERIMENT.

The experiments described in this paper have for their object the determination of the effect which the grain, or fibrous structure of sheet iron due to the rolling process by which it is made, exerts on the magnetic changes in length and on the magnetization. Both the subject and the method of studying it were suggested by Professor Rowland. Two strips 3 cm. wide and 91.5 cm. long were cut from a long sheet of transformer iron 0.035 cm. thick. Four were cut across the plate and two along the plate, as shown in the central diagram in Fig. 2. These strips were bent into tubes around a brass bar and measurements were made of the change in a length of 62.9 cm. of each when subjected to gradually increasing and decreasing uniform fields between limits of about 60 C.G.S. Two specimens, one of each kind, were annealed and curves taken as before. Besides this, one specimen of each kind was examined for change of length in increasing fields up to 915 C.G.S. and Young's modulus of elasticity was measured for one of each.

The sheet from which all the specimens were cut was 274 cm. long by 91.5 by .035 cm. thick. It was obtained for me by Dr. Ames through the kindness of Mr. A. L. Rohrer of the General Electric Company, who stated that it represents probably as good a quality of iron for use in armatures as is in the market.

THE APPARATUS AND PRECAUTIONS NECESSARY.

The apparatus for measuring change in length was a modification of that which has been used in this laboratory for several years past and has been several times described.[1] In the figure it is shown in section except the upper part which is in elevation. It consists of a long, hollow solenoid *A*, water jacketed on the inside, which stands vertical. Within this is hung the specimen tube *B*, with a shorter brass tube *C* around its middle which is clamped to it at the lower end by two set-screws *E*. Inside the specimen tube about as far from its upper end as the clamp is from the lower, a

[1] More, loc. cit. Gallaudet, loc. cit. Brackett, loc. cit.

short brass bar D is screwed. This bar has a tongue running up inside the tube, and ending in a stirrup formed by the little steel knife edge F. The brass tube also has an arm G extending out

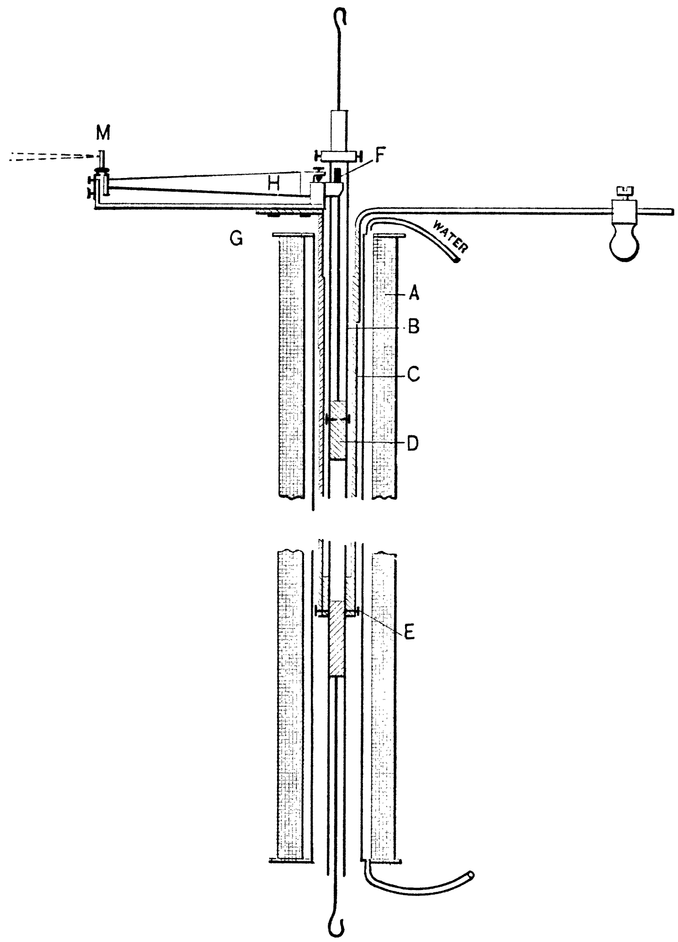

Fig. 1.

the end of the solenoid and a lever rests by means of a knife-edge on a little steel table carried by it, and passes beneath the knife-edge in the stirrup. The other end of the lever extends outwards, and its motion is accurately determined by means of the tilting mirror shown at M, and a telescope and scale.

The whole arrangement must hang free of the solenoid by a suspension which transmits no vibrations, for the magnifying power is so great (about 25,000) that the slightest vibration spoils the definition. When hung directly from a weight of about 60 pounds, which in turn was hung by a strong brass coiled spring from a bracket near the ceiling, the scale was usually blurred out except at night. The vibrations seemed to be very small, probably almost sound vibrations, and they still came down even when the spring was suspended by a cotton rope passing over rubber and cotton pads. But when the apparatus was suspended from this system by means of a number of thin rubber bands all vibration effects were done away with, even though the whole building was strongly shaken. I mention this particular because it is customary to make measurements of this kind only at night, a very inconvenient and unnecessary practice.

Another troublesome influence which has always to be considered in such work is the variation of temperature. For rough experiments changes of length arising from this cause may be separated from those due to magnetization by simply taking a reading on the length-scale before, and immediately after, making a known change in the magnetizing current. Since the change in length with the temperature shows itself by a steady and comparatively slow drift of the scale, while the magnetic change is almost instantaneous, this affords a means of separation. For more accurate work there are two methods available. Either the effects of temperature changes may be eliminated by compensation or the temperature may be maintained constant. I found the latter more convenient, though there is also partial compensation or rather over-compensation in the apparatus, for what is really measured is the change in relative length of the brass and iron tubes. This causes an apparent contraction of the iron of about 60×10^{-7} of the whole for an increase of $1°$ C., so that in order to have no greater errors than $.5 \times 10^{-7}$ the temperature must not vary more than $0°.01$ C. and this in spite of the heating of the magnetizing solenoid. The tap water was found to be not at all constant; so it was heated to a temperature about equal to that of the room by an arrangement on the principle of Ostwald's regulator. After passing this it entered a large barrel supported near the high ceiling, from which it could be drawn off through the water jacket. The water was usually kept running in and out for several hours before a curve was taken. Then the supply was turned off, and the barrel well stirred; after which the water would continue to run out through the jacket for an hour or two without varying more than 0°.01. The regulator got to working so well toward the end of the time that the supply did not need to be turned off at all. The water jacket could not prevent the heat due to high currents from finding its way through in the course of time, but by hurrying over the higher fields in taking the cyclic curves trouble in them was avoided. For the very high currents used in taking the curves given in Fig. 5, the change of length with the time after turning on the current was carefully measured; and it was found to take so long for the heating to begin that there was no trouble in getting at least one reading first. It took only a moment to take a reading; for, the current being continuously increased, there was no vibration of the lever. After each reading a current was passed in the opposite direction, the whole apparatus was allowed to cool down for a while, and the next reading could be taken using the maximum length as a reference point.

Before taking each curve the specimen was demagnetized by an alternating current. The vertical component of the earth's field was roughly compensated for in the later experiments by a single layer of wire outside the magnetizing coil, through which a constant current was kept flowing. When the alternating current was passed, an outstanding field of one tenth of the vertical component was found to reverse the strongest previous magnetization.

If there is a strong initial magnetization in the specimen before a cyclic change of length curve is taken, the cycle will not be symmetrical. A small initial magnetization, however, affects the first ascending branch of the curve only. Such slight lack of symmetry as is shown in the curves here given is, in all probability, due either to this cause or to temperature changes.

Magnetization curves for each specimen were taken under exactly the same conditions as change of length curves, often several of each alternately on the same specimen. The electrical connections were made as follows: A coil of 1,200 turns of fine wire, wound on a paper tube, was placed over the specimen tube before insertion in the apparatus. This coil was put in circuit with a Rowland D'Arsonval ballistic glavanometer of 1,000 ohms resistance and complete period of 16 seconds, also a standardizing coil wound on a long solenoid, and a reversing switch. For damping, the galvanometer could be disconnected by touching a rocking mercury switch which put in circuit with it a coil in which a magnet slid. The galvanometer was often standardized during the course of the experiments and was found not to alter sensibly. The torsional rigidity of its suspension ribbon must, however, have somewhat decreased during the taking of a curve, for in each case the magnetization apparently reached a slightly higher value the second time the maximum field was applied; but the change was too small to be observed in standardizing. The throws as read were reduced to arc, added up, corrected for the induction through the empty secondary, and lastly reduced to absolute units. The magnetizing solenoid had in its circuit a reversing switch, an iron wire rheostat and a German silver rheostat of about 240 ohms resistance fitted with a mercury connection board so arranged that a copper sulphate resistance could be placed in parallel with each step so as to continuously cut it out or include it.

The current in the solenoid was at first gradually increased from zero by increasing the resistance in a German silver shunt across its terminals, the steps of which were continuously included by the method referred to. When all the shunt resistance had been put in and it had been disconnected, the current was further increased by cutting out the 240 ohms series resistance. This arrangement made it possible to hold the current accurately constant at any value and then rapidly, but continuously change it to another at which it would also remain constant till again changed. It is made necessary by the use of the ballistic galvanometer for taking step by step curves with gradual change of field, and was suggested to me by Dr. Bliss. The circuit could either be connected with the storage batteries, of which twenty-five cells in good condition were used, or with the alternator. For the very high currents used in taking the curves shown in Fig. 5 two direct current generators and a number of cells were placed in series giving 300 volts. The solenoid was of No. 18 copper wire wound in seven layers, 84 cm. long and 10.5 ohms resistance and gave 45.7 C. G. S. units of field per ampere. The currents were measured by Weston standard ammeters of appropriate capacity.

From the dimensions of the specimens it will be seen that their length is about 500 times the diameter of a wire of the same cross section, so the demagnetizing force of the ends is inconsiderable. To vertify this fact a coil of ten thousand turns of very fine wire wound on a glass tube was placed inside a specimen tube and connected to the galvanometer. Then a large current was reversed in the magnetizing solenoid. The resulting throw was compared with that given when the specimen tube was removed while everything else remained the same. The ratio of the whole throw to the increase is the ratio of the whole field to the demagnetizing field due to the ends. Both this experiment and a rough calculation pointed to about ⅛ of a C. G. S. unit of demagnetizing field for an intensity of magnetization of 1000 lines per sq. cm.

Description of Curves Taken.

The first two specimens examined were numbered 1 and 3. Their position in the plate is shown in Fig. 2 in the central diagram. The

Table I.

Changes in length and intensity af magnetization, of Specimen No. 3, *unannealed; in cyclic field.*

H	$\frac{\Delta l}{l} \times 10^7$	H	$\frac{\Delta l}{l} \times 10^7$	H	$\frac{\Delta l}{l} \times 10^7$	H	$\frac{\Delta l}{l} \times 10^7$
1.737	.51	46.16	44.59	1.51	12.78	50.27	43.19
2.194	1.53	54.84	43.70	0	6.13	54.84	42.93
3.428	5.11	41.13	46.25	1.05	2.30	36.56	45.74
5.027	10.22	36.56	46.77	1.37	2.04	23.54	46.00
9.140	22.49	25.135	47.02	1.83	2.55	17.59	44.47
16.45	36.80	16.45	44.47	3.20	6.13	9.14	36.03
22.48	41.91	9.14	36.29	4.84	11.24	6.31	29.13
36.42	45.23	5.347	26.58	9.14	23.51	3.84	21.46
41.13	45.23	3.153	18.91	16.91	36.80	0	6.13
				23.35	41.91	1.14	2.04
				36.01	44.47	1.74	1.92
				41.13		1.87	2.04
				45.70	43.96	2.70	3.58
						4.25	8.69

TABLE I.—*Continued.*

H	I	H	I	H	I
1.92	354	17.59	1338	9.05	740
2.70	519	9.14	1229	17.55	936
3.75	696	4.52	1073	30.66	1039
4.94	822	1.92	919	54.84	1110
9.14	1074	0	702	31.21	1062
17.37	1276	1.19	299	17.55	1004
29.70	1382	1.87	30	9.14	899
54.84	1453	3.11	264	3.15	683
30.80	1401	4.16	422	0	400
				1.37	8.5
				3.02	594
				4.94	863
				10.96	1190

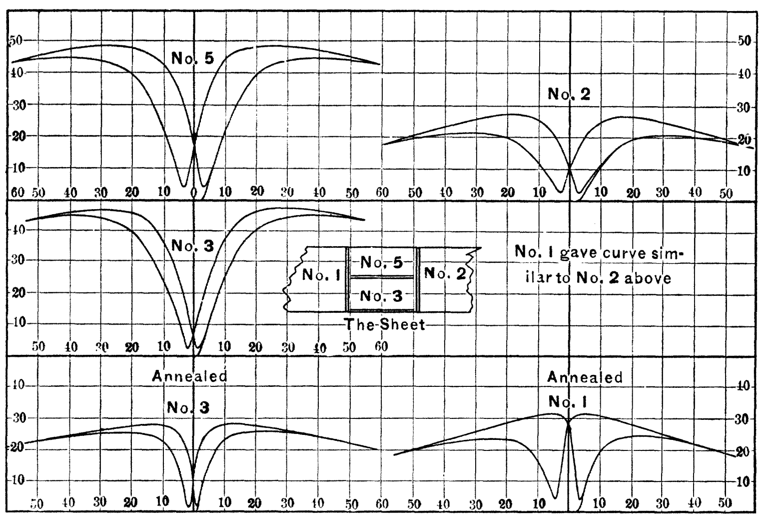

Fig. 2. Cyclic change of length curves for specimens cut out as indicated in the central diagram.

Ordinates = ten millionths of the length.
Abscissas = magnetic field c. g. s.

change of length cycle for No. 3 is plotted on the same sheet, the values being given in Table I. That for No. 1 is not given. As it was exactly like No. 2 taken later except that the coercive force was about 1 C. G. S. unit greater and the retentiveness very slightly

Table II.

Values of intensity of magnetization of Specimen No. 1, unannealed in cyclic field.

H	I	H	I	H	I	H	I
1.65	54	33.36	1355	4.35	104	11.88	970
1.83	66	18.97	1305	6.50	446	5.70	877
3.34	255	12.02	1254	11.88	762	3.20	799
4.52	450	6.50	1178	18.83	914	0	622
9.64	937	3.66	1097	33.36	1036	1.83	390
18.83	1193	0	894	55.75	1116	2.83	110
33.36	1320	1.60	696	33.36	1068	3.79	231
55.75	1401	3.61	93	18.97	1016	6.50	757
						11.88	1096

Table III.

Changes in length and intensity of magnetization of Specimen No. 2, unannealed.

H	$\frac{\Delta l}{l} \times 10^7$	H	$\frac{\Delta l}{l} \times 10^7$	H	$\frac{\Delta l}{l} \times 10^7$	H	$\frac{\Delta l}{l} \times 10^7$
2.33	.05	11.88	25.86	14.72	17.75	7.86	18.66
4.11	1.52	99.55	25.00	35.97	21.29	3.20	10.39
6.19	5.07	4.20	20.28	45.70	20.28	0	3.55
9.51	10.75	1.83	13.31	59.41	17.75	1.83	2.94
16.91	17.75	0	10.04	35.65	23.73	3.24	3.04
22.85	20.28	1.37	5.07	18.65	26.46	4.71	5.07
38.85	20.69	2.74	2.53	12.80	26.36	9.46	12.17
59.41	17.29	4.11	5.07	9.51	25.35	22.39	20.79
24.22	25.60	7.86	10.14		23.42		
18.28	26.36	9.51	12.47				

Table III.—*Continued.*

H	I	H	I	H	I	H	I
1.74	67.2	9.50	1064.0	9.37	845	0	710
3.20	276.8	3.20	922.6	18.28	1040	.82	592
4.25	470.4	1.83	859	52.78	1203	1.78	374
6.63	696.0	0	714	59.41	1211	2.33	106
9.37	841.6	.87	597	52.56	1202	3.20	128
18.28	1040.0	1.78	373	18.28	1118	4.39	422
53.01	1203.2	2.33	108	9.50	1058	6.63	698
59.41	1219.2	3.15	125	3.20	918	9.37	854
52.60	1206.4	4.34	414				
18.28	1124.8	6.63	690				

greater, it has not been thought worth while to reduce to absolute units and plot. The magnetization curves for these two specimens are given in Fig. 3 and in Tables I. and III. The initial magnetization shown is due to the fact that the earth's field was not compensated for during the previous demagnetization. The initial length, *i. e.*, zero of change of length, has been corrected in the case of No. 3 for this.

The very marked difference between the cycles for these two specimens is apparent. They differ in the maximum length reached, in the field in which it is reached, in retentiveness, in coercive force, and the differences are similar in the magnetization curves. But it

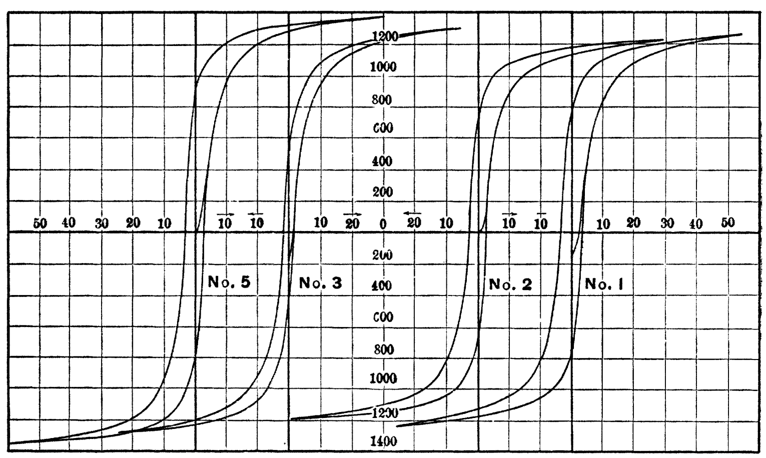

Fig. 3. Cyclic magnetization curves for specimens cut out as indicated in diagram in Fig. 2.

Ordinates = lines of magnetization per sq. cm.
Abscissas = magnetic field c, g. s.

might well be objected that merely chance differences in the specimens would account for this, especially as one comes wholly from the edge of the plate while the part of the other which is examined comes from the middle. Therefore specimens 2 and 5 were cut out and examined; the results are plotted in the same figure (2), and given in Tables III. and IV. Number 2 showed, as stated, almost identical changes in length with No. 1; so it seems fair to assume that any other specimen cut parallel to them from the space between

TABLE IV.

Change in length and intensity of magnetization of Specimen No. 5, unannealed.

H	$\frac{\Delta l}{l} \times 10^7$	H	$\frac{\Delta l}{l} \times 10^7$	H	$\frac{\Delta l}{l} \times 10^7$	H	$\frac{\Delta l}{l} \times 10^7$
2.79	12.68	59.41	47.66	6.86	32.96	9.51	27.88
3.66	7.61	23.86	48.11	9.37	38.03	6.40	17.75
4.57	3.40	16.00	47.66	14.40	41.47	3.66	17.34
7.77	5.58	9.55	43.50	18.28	43.60	0	7.61
9.19	12.68	4.57	39.04	23.81	44.72	1.78	4.06
13.71	21.24	2.29	32.14	37.93	44.62	2.47	3.09
18.26	32.85	0	.51	59.41	43.35	4.02	4.06
22.85	38.03	.37	1.57	32.45	48.67	5.94	9.63
28.33	41.83	1.78	4.06	23.99	47.66	7.50	15.21
36.56	44.51	3.20	15.62	18.28	44.51	9.60	21.80
45.70	42.99	4.57	20.28		35.24		

TABLE IV.—*Continued.*

H	I	H	I	H	I	H	I
1.78	70.3	31.53	1303.5	4.34	411	9.46	1212
3.15	264.6	14.17	1232.6	6.63	744	3.20	1059
4.25	467.6	9.37	1175.1	9.28	938	0	855
6.58	728.0	3.20	1032.1	18.19	1184	.87	751
9.23	921.3	0	825.2	31.62	1294	1.78	556
23.76	1222.3	.87	720.2	52.10	1359	2.33	256
52.33	1339.2	1.78	530.5	59.41	1377	3.15	39
59.41	1335.4	2.33	232.5	52.05	1365	4.34	363
52.10	1343.6	3.15	58.4	23.76	1302	9.37	926

would show the same. Number 5, cut from the middle of this space in the other direction, showed a maximum length equal to that of No. 3, and occurring in the same field. It seems, therefore, that the difference in the maximum change of length and the field in which it is reached must be due to differences in the direction of the grain. The differences in hysteresis and coercive force, however, seem to be merely dependent upon the position of the specimen in the plate. The coercive force of specimen 5 is the mean of that of specimens 1 and 2. That of specimen 3, on the other hand, bears no relation to any of the others. Its location in the sheet was well outside the limits of the parts of 1 and 2 which were examined, and the actual structural appearance of this part was quite different from that at the center. The surface was darkened with oxide and seemed more close-grained. The magnetization curves for these specimens are plotted in Fig. 3.

After specimens 1 and 3 were measured, they had been wrapped together in asbestos and annealed in a combustion furnace at a red heat. They became covered with dark oxide but showed no red, and did not seem badly burned, though the area was considerably reduced; and therefore the value to be used in computing the absolute values of the intensity of magnetization is a very uncertain quantity. The curves representing their change of length are plotted on the same sheet with the others; the magnetization curves in Fig. 4; and the values given in Tables V. and VI.

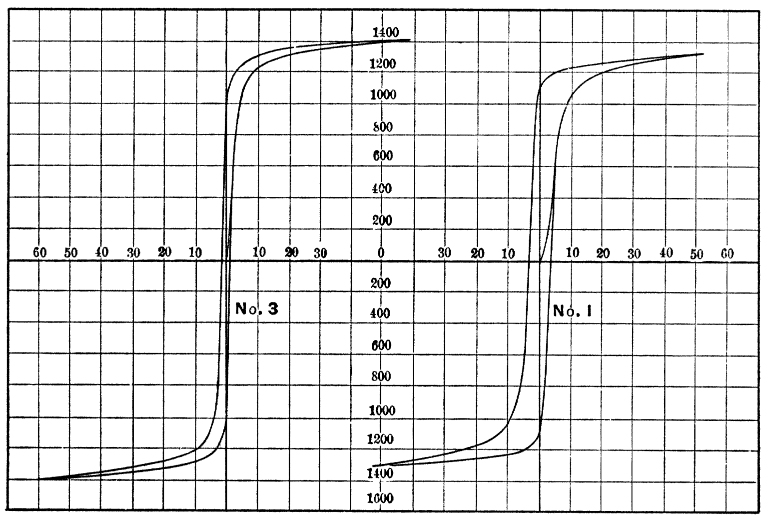

Fig. 4. Cyclic magnetization curves for Numbers 3 and 1, annealed.
Ordinates = lines of magnetization per sq. cm.
Abscissas = magnetic field c. g. s.

An increase in the retentiveness is noticeable in every curve, but the coercive force does not seem to be much affected by annealing. Specimen 3 annealed had a slight initial magnetization which was not corrected for. It is probable that this causes the whole cycle as drawn to be a little too close to the base line. From the fact that the average of the ascending and descending curves for Nos. 1 and 3 when annealed are similar, it might seem as if annealing had removed the effects of the grain. To test this Nos. 2 and 5 were annealed. Though well wrapped up in asbestos paper and placed in a larger iron tube, they were badly burned—yet did not seem to be well annealed, for No. 2 showed the same curve as before with only a slight increase of retentiveness ; while No. 5 had its maximum increase of length greatly diminished and changed so as to take place in a lower field. Consequently, it compared with No. 2 almost as No. 2 had compared with it before annealing. This

TABLE V.

Changes in length and intensity of magnetization of Specimen No. 1, annealed.

H	$\frac{\Delta l}{l}\times 10^7$	H	$\frac{\Delta l}{l}\times 10^7$	H	$\frac{\Delta l}{l}\cdot 10^7$	H	$\frac{\Delta l}{l}\times 10^7$
2.285	0	2.285	11.50	12.43	30.29	3.20	31.39
3.20	.38	3.67	4.56	9.60	30.93	1.37	30.57
3.67	1.014	4.57	5.07	7.77	31.18	0	28.65
4.57	3.30	6.40		5.03	31.44	1.83	17.75
6.85	11.15	7.77	12.68	3.20	31.30	2.79	8.61
9.37	17.75	9.51	16.22	1.78	30.81	3.67	5.07
18.46	24.34	16.91	23.02	0	28.39	4.57	4.81
22.85	24.47	22.85	24.08	.914	23.93	4.57	5.58
31.22	23.70	31.99	23.63	11.47	30.67	5.94	8.86
56.21	18.25	56.21	18.35	7.77	31.33	7.77	13.18
32.46	24.84	32.36	25.35	4.57	31.44	9.46	16.73
22.85	27.63	20.57	28.39				

TABLE V.—*Continued.*

H	I	H	I	H	I	H	I
.82	21	34.74	1288	1.79	866	18.72	1249
1.74	74	53.47	1345	2.38	424	9.50	1222
2.38	154	32.13	1308	3.20	31	3.20	1191
3.20	286	14.22	1260	4.52	505	0	1134
4.43	555	9.50	1245	6.81	857	1.83	840
6.76	890	3.20	1214	9.45	1019	2.38	393
9.42	1058	0	1151	18.28	1178	3.20	80
14.17	1169	.86	1093	53.93	1318	4.47	562

TABLE VI.

Change in length and magnetization of Specimen No. 3, annealed.

H	$\frac{\Delta l}{l} \times 10^7$	H	$\frac{\Delta l}{l} \times 10^7$	H	$\frac{\Delta l}{l} \times 10^7$	H	$\frac{\Delta l}{l} \times 10^7$
1.33	.51	4.02	5.07	9.14	27.89	6.85	27.89
2.29	5.07	5.99	12.68	6.85	27.28	3.67	27.13
4.11	12.68	9.19	18.25	3.66	24.34	1.83	24.34
6.85	19.42	16.00	22.46	1.83	20.28	.91	20.28
9.28	22.36	20.57	25.55	0	9.89	0	16.22
13.25	24.84	27.42	25.86	1.37	1.52	.91	9.89
18.28	25.81	31.53	25.76	2.29	2.03	1.46	22.05
23.58	25.86	60.78	25.35	.91	1.27	17.37	25.25
41.13	23.83	31.53	20.28	1.46	1.52	22.85	25.35
59.41	20.28	22.85	25.96	2.29	5.07	41.13	23.32
23.76	27.38	19.19	27.38	4.11	12.68		19.77
18.28	27.89	13.25	27.84	9.16			
13.71	28.04	9.37	28.09				

TABLE VI.—*Continued.*

H	I	H	I	H	I	H	I
.82	157	9.37	1364	3.10	836	9.37	1230
1.74	592	3.20	1295	6.58	1099	3.20	1162
3.10	966	0	1019	9.23	1160	0	892
4.20	1110	.46	760	26.96	1258	.46	642
9.19	1285	.82	424	52.10	1333	.82	287
23.58	1384	1.38	21	60.78	1350	1.38	176
58.50	1470	1.74	370	52.10	1336	1.74	521
23.72	1413	2.33	679	18.19	1265	2.33	829

seems to agree with Bidwell's experiments on sheet iron rings. Changes in diameter and width were observed by him for both the hard and the annealed state; and he found that the annealing had a great influence on the former, but scarcely any on the latter. Assuming that the direction in which the plates passed through the rolls was the same as the circumference of the ring into which it was made it will be seen that the difference in the effect of annealing with changes parallel to and across the field may arise from the fact that these happened to be also parallel to and across the grain. The difference due to the grain in the changes under high fields is shown in the two curves in Fig. 5. They were taken when the specimens were unannealed.

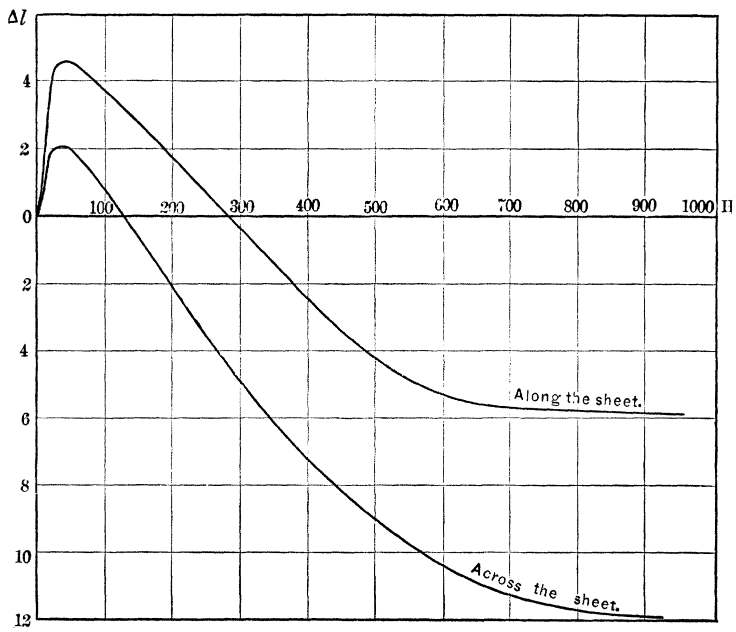

Fig. 5. Change of length curves with increasing magnetic field.
Ordinates = millionths of the length.
Abscissas = magetic field.

Young's modulus of elasticity was also measured for these two specimens and was found to be the same for both within the limit of accuracy of the measurement, about 1%. Magnetization did not seem to affect it. In dynes per sq. cm. the value was 172×10^{-11}.

It is clear from these results that the changes in volume which take place in iron wire, sheet iron, etc., when magnetized, may be due to the fibrous structure of such iron. So that it seems that we have no reason to think that an isotropic specimen would show any such change. Whether it would or not remains to be proved.

I wish here to express my thanks to Professor Rowland, who suggested this experiment to me and to Dr. Ames for his very kind interest and supervision of the work.

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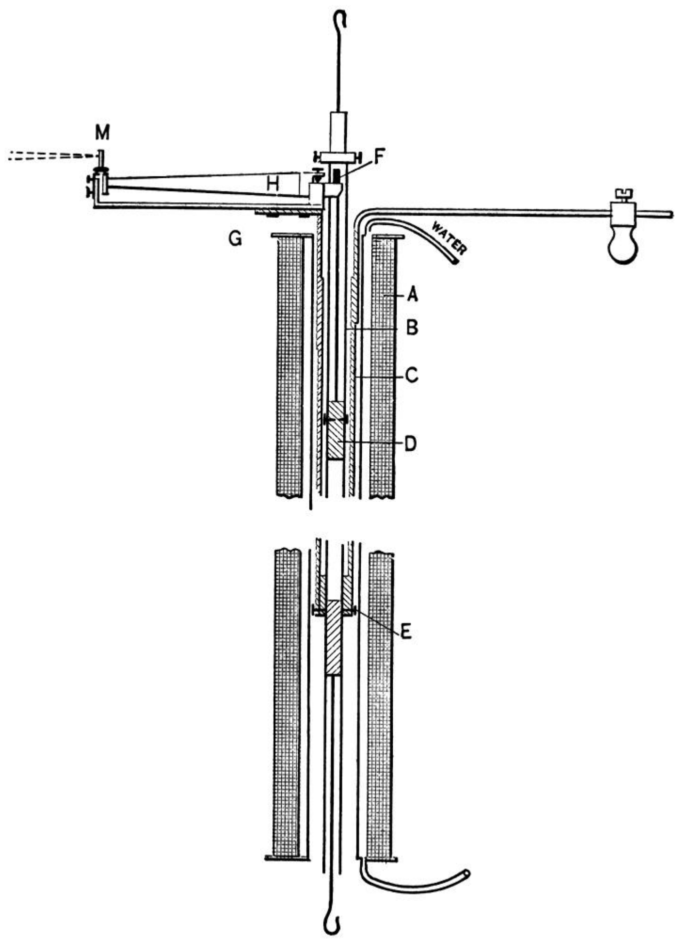

Fig. 1.