Second Series. *April, 1913.* *Vol. I., No. 4*

THE

PHYSICAL REVIEW.

THE ANNEALING OF STEEL IN AN ALTERNATING MAGNETIC FIELD.

BY H. PENDER AND R. L. JONES.

THE results obtained may be briefly summarized as follows:

1. It has been shown that the treatment of steel by a cyclicly varying magnetic field during its annealing results in a pronounced alteration of its hysteresis loop. The result is to increase largely the permeability at low and moderate inductions with a corresponding increase of the remanent magnetism. The coercive force and the losses are slightly decreased. The maximum value of the permeability was increased as much as 50 per cent. in some cases.

2. The improvement of magnetic quality depends upon the maximum intensity of the force used in the magnetic treatment and shows an approach to a maximum or saturation value when the force is large.

3. The best maximum temperature at which to apply the cyclic treatment has been identified with the critical point Ar_1, about 690° C., on the iron and steel diagram, and through this fact and the evidence of the micrographic studies, it seems very probable that the good results obtained may be ascribed to a preservation of the fineness of the metallographic structure which steel possesses just after it has passed from the non-magnetic to the magnetic condition.

The above results are incomplete but exceedingly suggestive. They point the way to a new line of research on the treatment of steels for electrical purposes and possibly of those for other uses as well. None but magnetic qualities have been observed, but doubtless mechanical characteristics were also affected.

The possible commercial applications of magnetically annealed steel which suggest themselves are numerous. Many forms of direct current apparatus might be decreased in cost by its employment provided the requisite commercial conditions for the treatment could be obtained.

Thus if the fields of direct-current generators and synchronous motors could be made of the material, the weight of iron could be decreased, though not in so large a proportion as the increase of permeability, together with a corresponding decrease in the mean length per turn of

TABLE OF RESULTS.

Sample No.	Maximum Permeability.	Flux Density (C.G.S. Lines per Sq. Cm.) at which Maximum Permeability Occurs.	Permeability at Given Flux Densities (C.G.S Lines per Sq. Cm.).			Iron Loss at Given Flux Densities (Watts per Pound at 60 Cycles).			Explanatory Notes.
			5,000	10,000	12,000	5,000	10,000	12,000	
A	2,620	6,000	2,580	1,900		.490	1.30		Material A as received.
A_1	12,800	8,400	10,200	11,600		.180	.560	.763	Max. temp. 760° C. $H_{max.}=18.5$ from 760° C. to 340° C.
A_2	8,400	7,200	7,730	6,600		.188	.605	.822	Max. temp. 760° C. Annealed plain.
A_3	13,100	8,500	10,500	11,900	6,350	.222	.630	.837	Max. temp. 870° C. $H_{max.}=18.5$ from 870° C. to 160° C.
A_4	9,000	6,850	8,400	7,500	4,050	.236	.662	.876	Max. temp. 870° C. Annealed plain.
A_5	13,500	7,200	11,500	11,300	6,200	.216	.650	.850	Max. temp. 790° C. $H_{max.}=18.5$ from 655° C. to 300° C.
A_6	7,020	6,100	6,780	4,260	1,830				Test on effect of max. temp. of magnetization. Max. temp. 805° C. $H_{max.}=18.5$ on A_7 from 500° C., on A_8 from 625°, on A_9 from 750° C. A_6 had no winding. Mag. current off at 275° C.
A_7	8,370	6,250	7,920	4,870	1,200				
A_8	10,200	7,000	9,100	6,820	3,000				
A_9	9,620	6,700	8,530	5,570	1,760				
A_{10}	3,200	6,600	3,000	2,200					Max. temp. 625° C. $H_{max.}=18.5$ from 625° to 180°.
B	3,330	6,100	3,250	2,400		.558	1.55		Material B as received.
B_1	11,500	7,500	10,400	8,650		.194	.600	.790	Max. temp. 795° C. $H_{max.}=29.6$ from 795° to 400°.
B_2	8,700	6,600	8,040	5,900		.212	.660	.860	Max. temp. 795° C. Annealed plain.
B_3	7,200	5,600	6,980			.240	.680	.870	Max. temp. 765° C. $H_{max.}=69.2$ from 765° to 485°.
B_4	6,530	5,600	6,360			.240	.680	.870	Max. temp. 765° C. Annealed plain.

Sample No.	Maximum Permeability.	Flux Density (C.G.S. Lines per Sq. Cm.) at which Maximum Permeability Occurs.	Permeability at Given Flux Densities (C.G.S. Lines per Sq. Cm.).			Iron Loss at Given Flux Densities (Watts per Pound at 60 Cycles).			Explanatory Notes.
			5,000	10,000	12,000	5,000	10,000	12,000	
B_5	5,980	5,900	5,860	4,280	2,430				Test of effect of intensity of magnetization.
B_6	6,870	6,000	6,720	4,430	2,330				Max. temp. 800° C. At 700°, $H_{max.}=.46$ on B_5,
B_7	7,760	6,700	7,320	5,500	2,880				1.85 on B_6, 5.53 on B_7, and 18.5 on B_8.
B_8	9,300	7,200	8,350	7,300	4,000				Mag. current off at about 400° C.
C_1	12,100	9,100	9,200	12,000	9,980	.420	1.28	1.73	Max. temp. 835° C. $H_{max.}=18.5$ from 835° C. to 200° C.
C_2	9,000	8,100	7,600	8,700	7,500	.440	1.32	1.78	Max. temp. 835° C. Annealed plain.
C_1'	10,900	9,700	7,500	10,750	9,500	.400	1.21	1.60	C_1 after aging at 100° C. for 865 hours.
C_2'	8,400	9,200	6,400	8,300	7,350	.438	1.29	1.68	C_2 after aging at 100° C. for 865 hours.

the winding and a consequent increase in copper efficiency. The power factor of transformers, induction motors, and alternating-current series motors could be improved, and the constancy of ratio of instrument transformers could be increased by employing magnetically annealed metal.

DETAILS.

There is very little published information on the annealing of steel for electrical uses, a subject of great commercial importance. The mechanical properties of metals, however, as dependent upon their microscopic structure have been the subject of extensive research. In the case of steel especially, metallographists have much information showing relations between the microscopic structure and grain size, and the tensile strength, elastic limit, and percentage elongation at fracture.[1] The structure of a metal, although it depends partly upon its chemical composition, may be largely modified by heat treatment. The arrangement of the chemical or metallographic constituents and the size of the *grains* in a steel depends partly on the elevation of the maximum temperature above the principal critical point and partly on the rate of cooling. There is practically no information available on the relations between

[1] Howe, H. M., Iron, Steel, and Other Alloys, page 217 et seq.

the electrical and magnetic properties and the *grain* size, and such information as is available connecting them with the metallographic structure is scattered and meager. Hence rules for annealing are qualitative and unsatisfactory.

The use of a magnetic field as a formative force during the structural arrangement of iron particles has not been entirely unsuggested. In the old experiment of Beetz, recalled by Ewing, a small constant magnetic field acted along the axis of the cathode of an electrolytic cell containing a solution of an iron salt. The iron deposited was strongly magnetic and practically saturated. More recently the work of Maurain[1] and of Gans[2] has thrown further light on the subject. The former found that a field of ten to fifteen gausses acting on the cell was sufficient to saturate the electrolytically deposited iron and that the resulting product had a hysteresis loop which was almost a rectangular parallelogram. Gans has also studied the peculiarities in the hysteresis loop of iron electrolytically deposited in a magnetic field.

The fact that a magnetic field might have a similar effect on the structural formation which takes place with the heat treatment of steel appears to have attracted no serious consideration. A single reference to such a possibility occurs in a discussion before the American Institute of Electrical Engineers,[3] where Mr. P. A. N. Winand states that he once tried to magnetize bar magnets by quenching them while under the influence of a steady magnetizing force. He thought that the magnets were slightly better than those obtained by the common method, but decided that the difference was not sufficiently great to warrant fuller investigation.

This paper reports a method of annealing steel by which its permeability may be permanently increased by an amount considerably greater than that possible by heat treatment alone. The method consists in subjecting the metal to a cyclicly varying magnetic force during the period of slow cooling from a temperature above the recalescence point. The result manifests itself by a change in the shape of the hysteresis loop, as well as by an increase in its ordinates. The remanent field is considerably increased and the coercive force slightly decreased, *i. e.*, the loop becomes more erect and slightly narrower.

The work at first undertaken was along the line suggested in the opening

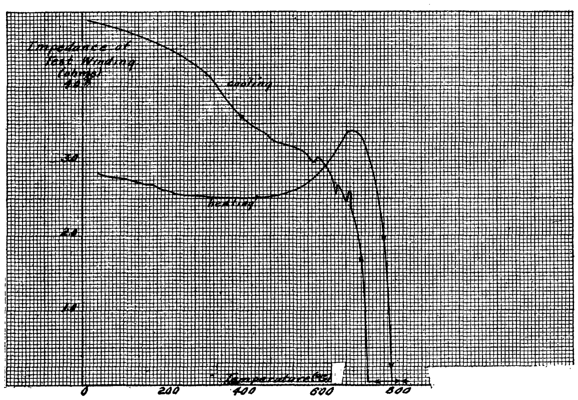
[1] Maurain, C., "Magnetic Deposits Formed in a Magnetic Field," Comptes Rendus, CXXXI., 410 (1900).

[2] Gans, R., "Magnetic Properties of Iron Electrically Deposited in a Magnetic Field," Phys. Zeit., XII., 911 (1911).

[3] Guthe, K. E., "The Influence of Heat Treatment on the Magnetic Properties of Steel and Iron," Trans. A. I. E. E., XIV., 57 (1897).

paragraph. Its plan included a study of the effect of the maximum annealing temperature and of the rate of cooling upon the electric properties and microscopic structure of such silicon steels as are used in electrical manufacture. Early in the work it was desired to have a simple method of detecting the point at which the principal critical temperature or point of magnetic transformation is reached in the heating and cooling.

This temperature, Ar_2 in the equilibrium diagram of iron-carbon alloys, is usually determined by means of the evolution of heat which takes place at that point due to chemical transformations. The fact that a marked change of magnetic permeability also occurs here suggests the use of this phenomenon as a means of the determination. A specimen carrying an asbestos insulated magnetizing winding was placed in the furnace and through the winding a 60-cycle alternating current of 4 amperes constant effective value was maintained during the heating and cooling. The data showing the temperatures and corresponding impedances are shown in Fig. 1. The impedance is approximately pro-



An attempt to determine the transformation point A_2 by a magnetic method.

Fig. 1.

portional to the permeability, since the resistance of the magnetizing winding was low. The plot indicates with a precision of a few degrees the point at which the magnetic property was lost and that at which it was regained. It also has a peculiarity worthy of note.

In the experiments of Hopkinson[1] and Morris[2] on permeability at high

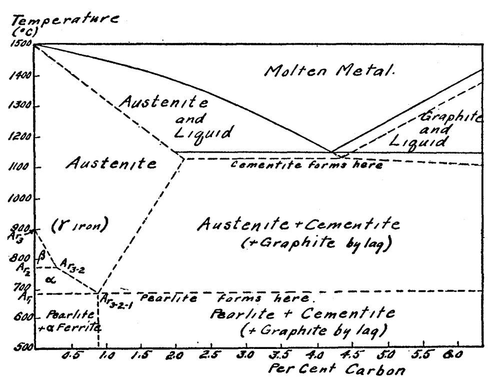
[1] Hopkinson, J., "Magnetic Properties of Iron at High Temperatures," Phil. Trans. (1889), 443.

[2] Morris, D. K., "On the Magnetic Properties and Electrical Resistance of Iron as Dependent upon Temperature," Phil. Mag. (5), XLIV., 213 (1897).

temperatures, all the curves of permeability and temperature approach zero temperature in a general horizontal direction. On the other hand the curve obtained here shows a marked improvement in permeability as the sample cooled to room temperature. Apparently this could be explained only on the assumption that the alternating magnetic field exercised a pronounced influence on the beneficial structural changes which accompanied the annealing, and the circumstance was deemed worthy of further examination. The effect was confirmed by further experiment and this led on to an investigation which precluded the original plan of work. Certain interesting and suggestive results were obtained which this paper aims to present.

Methods of Study.

Any study of heat treatment may best be based on the equilibrium diagrams of iron alloys. In all commercial steels carbon is an important constituent, and the transformation diagram of the iron-carbon system is the one best known. The work of Guertler and Tamman[1] on the iron-silicon system shows that for all alloys containing less than about 20 per cent. silicon the mass consists of a solid solution of iron silicide in iron with no critical point below 1200°. Hence in spite of the fact that the samples studied are low in carbon, the iron-carbon transformations are



The carbon-iron equilibrium diagram. (Howe.)

Fig. 2.

probably of considerable importance in the structural changes accompanying annealing.

The essential portions of the iron-carbon diagram are reproduced in Fig. 2, which shows transformation temperatures for different percentages of carbon during cooling from the molten condition. Here we

[1] Guertler, W., and Tamman, G., "On the Compounds of Iron with Silicon," Zeit. für Anorg. Chemie, XLVII., 163 (1905).

are interested simply in the left-hand edge of the diagram, since the samples used are all of low carbon content. Above 900° C. the mass consists of austenite, a solid solution of carbon in iron in the gamma form. At about 900° C. the gamma iron changes to the beta form and the austenite passes into a transition stage to which the name martensite has been given. This transformation point is known as Ar_3. That at which the beta allotropic modification changes to the alpha form, about 770° C., is called Ar_2. Alpha iron is magnetic, while beta and gamma iron are non-magnetic. Hence Ar_2 is the magnetic transformation point. Finally, the temperature where the alpha ferrite and the cementite (Fe_3C) begin their segregation to form the composite lamellar structure known as pearlite, is called Ar_1. This temperature is about 690° C. Two transition stages have been distinguished between martensite and pearlite, and to these the names troostite and sorbite have been given. The former is probably the structure of a tempered steel. The sorbitic stage represents the condition where most of the metal has been transformed into ferrite and cementite but where the two have not yet formed the pearlitic structure. It is probably an ultramicroscopic mixture of ferrite and cementite particles. As the cooling continues slowly to room temperatures, the tendency is for the ferrite and cementite to segregate and form interstratified layers of the two materials. This composite pearlite is the characteristic structure of a slowly cooled steel as ordinarily annealed. The microscope is commonly used as an aid to metallographic research and studies have been made of polished sections of several of the samples in investigating the structural transformations and the resulting changes in properties.

The steel used in this research consists of two kinds of silicon alloy sheets such as are used in transformer manufacture. In addition, two samples, C_1 and C_2, of low-carbon dynamo steel were used. Analyses of the former materials as given by the manufacturers are as follows:

	Nos. *A*.	Nos. *B*.
Carbon	.06	.09
Manganese	.13	.17
Phosphorus	.04	.05
Sulphur	.02	.03
Silicon	3.46	3.95

The samples were in the form of hollow squares 3 in. in internal diameter and 5 in. in external diameter. Each sample contained one hundred sheets and weighed about 6½ lbs.

The heat treatment was carried out by means of an electrical resistance furnace in which several samples could be treated at once. The inside of the furnace consisted of a nine-inch iron pipe closed at the bottom and about 15 in. tall. The walls were ¼ in. thick and the furnace chamber had an iron cover. The furnace pot was first covered with a layer of thin mica sheets. The resistance winding was double, each element consisting of 20 turns of nichrome resistance ribbon (3/16 in. $\times$ .005 in.) and was wound on the mica under considerable tension. The use of simply a thin layer of mica to insulate the winding from the furnace walls reduced the temperature gradient, and the form of the resistor material gave a large area of contact on the surface of the furnace. Over the winding about ¼ in. of a paste of magnesium oxide and water was put on and securely bound in place with asbestos tape. The whole was then surrounded with a pipe cover and placed in a sheet iron cylinder 24 in. in diameter, and of about the same height. The space of about 6 in. beneath the furnace and between it and the walls of the container were filled in with ground pipe cover, of the ordinary 85 per cent. magnesia variety. When a run was made the top of the furnace was covered to about 6 in. with the same material.

The furnace took about 2 kw. maximum power. Four specimens could receive heat treatment simultaneously and the heating period necessary was about 8 hours.

The temperatures were measured by means of a platinum-platinum-iridium thermocouple and a Hartmann & Braun recording pyrometer. The thermocouple was enclosed in a quartz tube which was bound to the iron of one of the samples under treatment.

The application of an electromagnetic field to magnetize a specimen during its annealing necessitated that each specimen carry an insulated winding. An asbestos-covered stranded copper wire was used for this purpose. As a further precaution each specimen had its edges covered with folded mica strips and was wound with asbestos tape before receiving its winding. Each winding could be used but once owing to the deterioration of its insulation.

The magnetic testing of the specimens was carried out with the aid of a special testing transformer of which the specimen formed the core. This device had hinged coils, thus expediting tests by making it unnecessary to wind each specimen. Two primary coils of ten turns each enclosed two opposite sides of the hollow square sample and two secondary coils of forty turns each, the other two sides. Permeability measurements were made with direct current, a form of ballistic galvanometer being used to measure the induction.

The hysteresis and eddy current losses were measured at 60 cycles by supplying an alternating current to the magnetizing winding and measuring the power used in the specimen by means of a wattmeter. A diagram of connections is shown in Fig. 3. The induction was calculated from the induced voltage as obtained from the corrected reading of the voltmeter. The loss measurement was obtained by subtracting from the wattmeter reading the total losses of the secondary circuit. No separation of the hysteresis and eddy current losses has been made.

The generator used as a source of supply was a Mordey inductor alter-

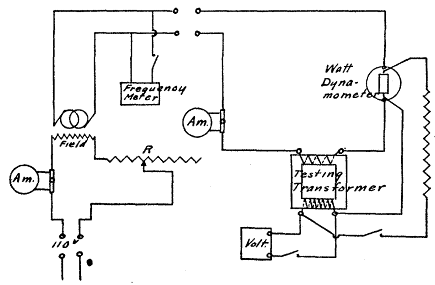


Diagram of connections for magnetic testing with alternating current.

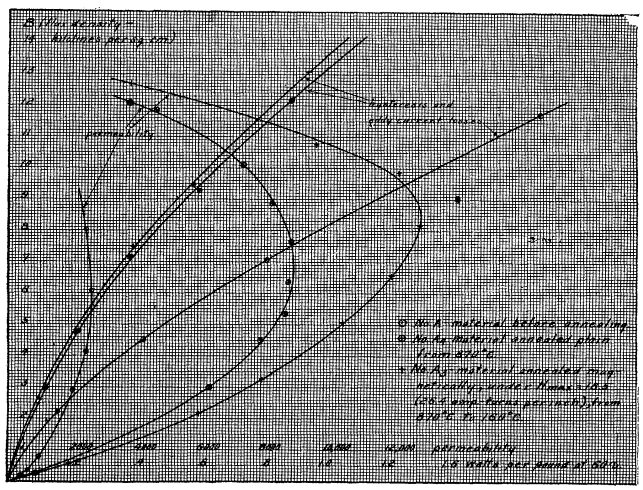
Fig. 3.

nator, giving a wave form which closely approximates a sinusoid. The generator was sufficiently large as to be only lightly loaded by the testing current, and the resistance of the primary circuit was small, the voltage of the alternator being controlled by a large variable resistance in its field circuit. In order to keep the magnetizing current low, specimens of large cross-section, and hence of low reluctance, were used. These conditions all tend to secure a sine wave of induced flux in the specimen under test.

Experimental Investigation.

In order to confirm the effect of a cyclicly varying magnetic field during annealing, Nos. B_1 and B_2, after being annealed together from 950° C., were prepared for test. The former was wound with asbestos-insulated wire and placed in the furnace with the latter. Both were then heated to 795° C. and slowly cooled. During the cooling B_1 had an alternating magnetic field of maximum value $H = 29.6$ (42.2 ampere-turns per inch) impressed upon it down to 400° C. Upon testing, it showed a maximum value of permeability about 33 per cent. higher than that of B_2 and slightly lower losses. The result was confirmed by a similar run on Nos. A_1 and A_2. A consideration of the method of experiment shows that the only difference in the treatment of the two samples other than that of the magnetic field is the possibility of more even cooling due to the

I^2R loss in the magnetizing winding. As a final test two runs were made in which the unmagnetized sample had a non-inductive winding of the same number of turns as that of the magnetized specimen. The windings of the two specimens were connected in series, and both occupied the same relative positions in the furnace. Under these conditions, the only possible difference in treatment is that due to the magnetizing field. The results of these two tests are those given for Nos. B_3 and B_4 and for Nos. A_3 and A_4. A_3, which was magnetized during its cooling, has a maximum permeability of over 13,000, about 45 per cent. greater than that of No. 8 and slightly lower losses. The permeability and loss



Permeability and loss curves after plain and magnetic annealing.

Fig. 4.

curves of Fig. 4 show the results obtained with A_3 and A_4 and may be taken as typical of these preliminary tests.

In order to determine whether or not as great an improvement in magnetic quality might be looked for in the magnetic annealing of other sorts of steel, two samples of a low carbon dynamo steel were given a treatment similar to that of the other samples. These are Nos. C_1 and C_2. C_1, which was annealed under $H = 18.5$ (26.4 ampere-turns per inch) from 835° C. down to 200° C., showed an increase of permeability over that of C_2 of about the same per cent. as the other samples.

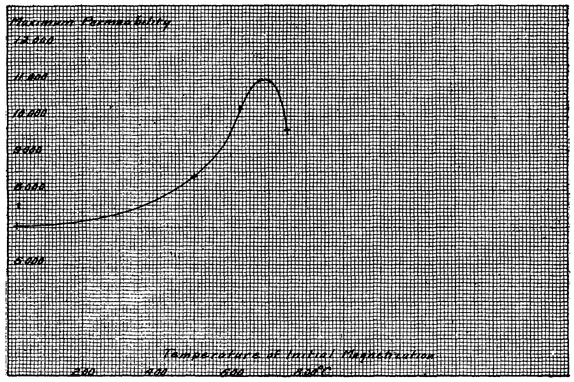
The phenomenon of aging is now of course well recognized in the behavior of iron, and in carbon steels operating under working temperatures an increase of 50 per cent. or more in losses with a corresponding decrease of permeability, is not uncommon. This is due to a gradual alteration of the structure of the iron caused by the prolonged exposure to the moderate temperature of operation. Silicon steels have the important advantage of being non-aging. It is well recognized among metallographists that the presence of silicon stimulates the transformations which take place during annealing, and in this fact is probably to be found the reason for the stability of silicon steels as regards aging.

The fact of the aging phenomenon suggested, however, that the newly effected improvement of magnetic quality might prove only temporary under working conditions. To test this Nos. A_1 and A_2 and Nos. C_1 and C_2 were placed in an aging oven maintained at a temperature of 100° C. and their magnetic properties tested at intervals over a period of about six weeks. A_1 and A_2 show scarcely any decrease in permeability or increase in losses. In the case of C_1 and C_2 about the usual amount of aging was observed. Each showed a decrease in permeability but the percentage improvement of the magnetically annealed sample was about the same after aging as before. This test indicates that the improvement in properties is just as permanent as that due to ordinary annealing.

Experiments were next undertaken to study the best temperature limits of the alternating magnetic treatment. The method of studying the effect of a maximum temperature at which magnetic treatment is applied, was to place several samples wound with an equal number of turns of asbestos-insulated wire in the furnace and turn the current on the samples at different points on the cooling curve. Thus, after heating a number of samples up to a point a little above the principal critical point, the current would be turned on the first sample at 700° C., on the second at 650° C., on the third at 600° C., and on the fourth at 550° C. When all the samples were in circuit they were connected in series so that the same current flowed through the winding of each. The current was maintained constant by means of an external resistance.

The results shown by Fig. 5 were obtained. They indicate that the best effect of the magnetizing field is to be obtained if the field is impressed at a point on the cooling curve of about 690° C. Referring to the transformation diagram, we see that this temperature seems to correspond to the transformation point Ar_1 where pearlite begins to be formed.

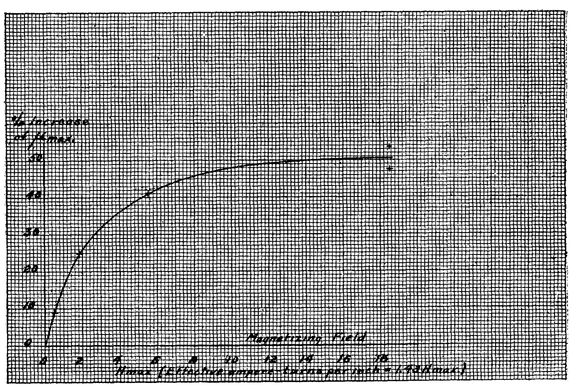
One sample, No. A_{10}, was heated to a temperature of about 600° C. and cooled from that temperature under a magnetizing force of 18.5 (26.4 ampere-turns per inch). Only a very slight improvement in magnetic quality, as compared with that of the other tests, was obtained. This tends to indicate that the critical temperature must be exceeded in order to benefit from the magnetic treatment.



Effect of initial temperature of magnetization on the maximum permeability. Max. temperature of heat = 800° C. Magnetizing force (H max. = 18.5) ceased at 275° C.

Fig. 5.

A study of the effect of various intensities of maximum magnetization yielded the results shown by Fig. 6. The result is what might have been expected from our theories of magnetism and shows that there is a saturation value for the improvement in permeability due to increasingly strong field. This test was made in the following way: A number of samples wound with different numbers of turns and having their windings con-

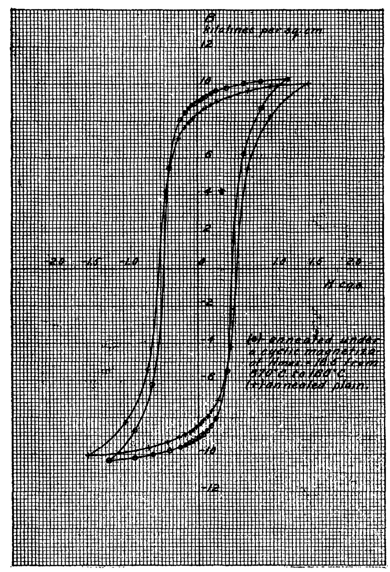


Effect of the magnitude of the annealing magnetizing force on the increase in max. permeability. Max. temperature of heat = 830° C. Magnetizing force on from 750° C. to 200° C.

Fig. 6.

nected in series, were placed in the furnace and after heating to about 800° C. were slowly cooled under a magnetizing force which in the case of each sample was proportional to its turns. The upper two points of the curve were obtained from two samples, treated under as nearly identical conditions as to heat and cooling as possible (Nos. A_1 and B_8) although their treatment was not simultaneous with that of the others. The curve indicates that under the given conditions of maximum temperature and rate of cooling, the maximum percentage increase of permeability, to be obtained by magnetic treatment over that by plain annealing, is about 50 per cent. This is no indication that a larger improvement is not possible under more favorable conditions of temperature treatment and point of application of the magnetizing force on the cooling curve. However, the same shape of curve for the effect of the strength of the magnetizing field in increasing the permeability would doubtless be obtained.

Such a large increase in permeability as is evidently obtained by appropriate magnetic treatment without a corresponding decrease in eddy-current losses and hysteresis, is somewhat surprising. Hysteresis loops taken with a fluxmeter for samples (1) after plain annealing, (2) after magnetic annealing, are shown by Fig. 7. The effect of the treatment has evidently been to increase the permeability of the silicon steel at moderate and low flux densities without a corresponding increase at the higher densities. It is noticeable that the value of the remanent flux is increased with a slight decrease in the coercive force. Thus although the permeability in moderate fields is much greater after the treatment, the area of the hysteresis loop is only slightly lessened. The effect seems to be rather an increase in the power factor than an improvement in losses.



Effect of magnetic annealing on the shape of the hysteresis loop.

Fig. 7.

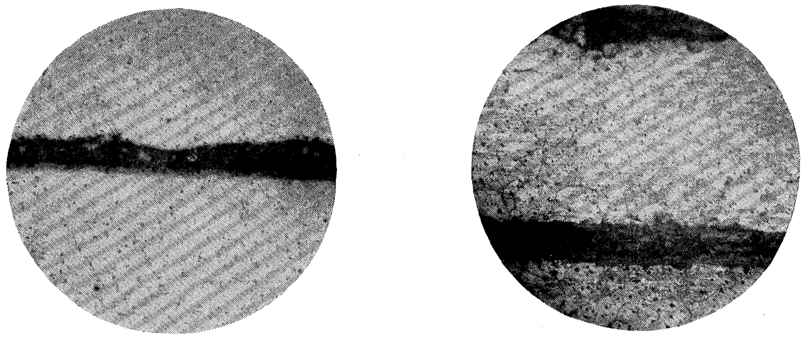
The data for Nos. C_1 and C_2 indicate that in the case of a carbon steel the treatment described would result in a larger improvement at higher flux densities than in the case of the silicon steel. A study of the shape of the permeability curves of all the different samples shows that the magnetic treatment shifts the point of maximum permeability toward higher flux densities, thus giving the largest increases in permeability in the range of flux densities used in the design of transformers. In the case of carbon steels the improvement is sufficiently marked, even up to densities such as are used in generating machinery, to be worthy of consideration. The accompanying table gives a summary of the magnetic data obtained.

A micrographic study of several of the specimens has been made in order to see if any connection might be traced between the effect of the magnetic treatment and the metallographic structure. The results of this study are shown by the micrographs of Figs. 8 and 9, which are but two of a number of specimens. Those specimens which were annealed under a magnetizing force seem to show a more homogeneous structure than those which were annealed plain. The micrographs of the etched sections show the grain size of corresponding samples to be about the same and give no further light as to structural difference due to magnetic annealing. The grain of the etched sections has been found, by the investigations of various metallographists, to be a function of the maximum temperature of the heat treatment and the grain structure to undergo a marked change at the transformation point Ar_1.

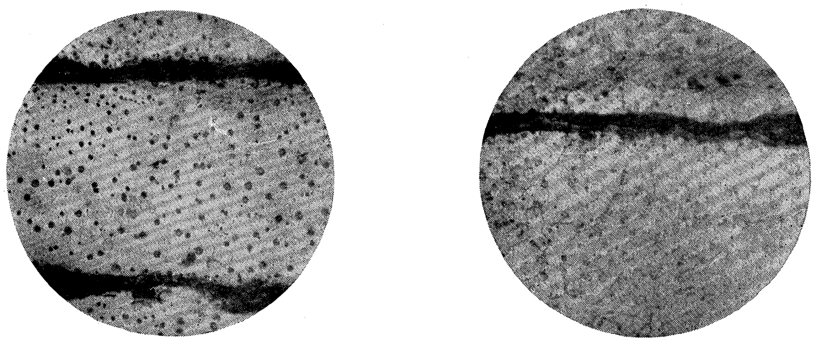
Structural Hypothesis.

A slight consideration of the molecular theory of magnetism in its relation to the structural forms of steel offers an apparent explanation for the results that have been obtained. Considering the case of a low carbon steel and again referring to the iron and steel diagram, we see that the point Ar_2, where iron regains its magnetic properties on cooling, comes at about 770° C. Just below this point steel shows a remarkably high permeability, especially for low magnetizing forces, and it seems not at all improbable that this characteristic is due to the very fine structure which the sorbitic steel possesses at this point of its heat history. As the cooling progresses further and Ar_1 is reached, the sorbite is gradually transformed into a conglomerate structure containing pearlite with some excess magnetic ferrite. Pearlite is a lamellar structure consisting of curving layers of alpha ferrite and cementite, and under the higher power microscope appears as in Fig. 10. The dark layers of highly magnetic ferrite are partitioned off by interstratified bands of lower permeability cementite. Pearlite always occurs in the constant proportions of about six parts by weight of ferrite to one of cementite.

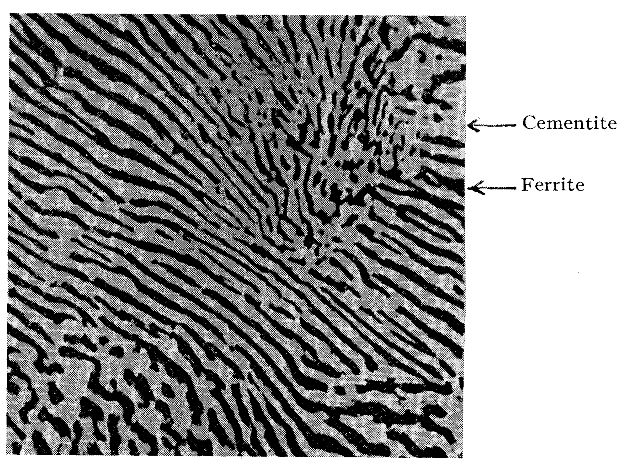
This structure would seem to divide the material somewhat into molecular groups, each of which has its own arrangement of magnetic molecules. Upon applying a magnetizing force each group has a certain stability of its own and hence the particular field intensity at which the arrangement succumbs to the applied force varies in the different minute groups of ferrite molecules. This characteristic of the pearlite structure shears over and rounds off the hysteresis loop for such a steel, making it



a. Unetched. × 80. *b*. Etched 25 sec. in HNO_3 solution.
No. A_5 heated to 790° C. and magnetically annealed from 655°.
Fig. 8.



a. Unetched. × 80. *b*. Etched 25 sec. in HNO_3 solution.
No. A_3 heated to 870° C. and annealed without magnetization.
Fig. 9.



Pearlite (Osmond).
Fig. 10.

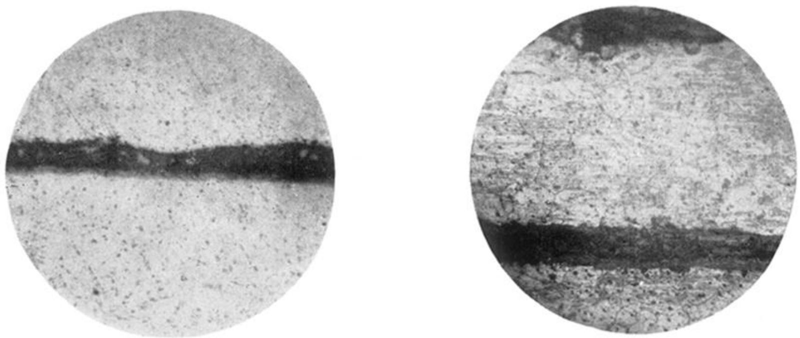
PENDER AND JONES.

less erect than that of the ferrite would probably be, if simply diluted by the cementite present. Hence it may very well be that if we could preserve the more homogeneous sorbitic structure in some way, a very satisfactory electric steel would be the result. The greatest difficulty in the achievement of this result is the fact that practically all the transformations of the iron-carbon system take a considerable length of time and show a large time lag in completing their reactions and physical arrangement. Thus if we were to attempt to quench a steel as sorbite we should probably get some austenite and beta iron remaining, together with some early developed pearlite, and the sample would be likely to prove quite unsatisfactory. Hence slow cooling is quite necessary to the production of a satisfactory electrical steel, as ordinarily this allows the formation of pearlite.

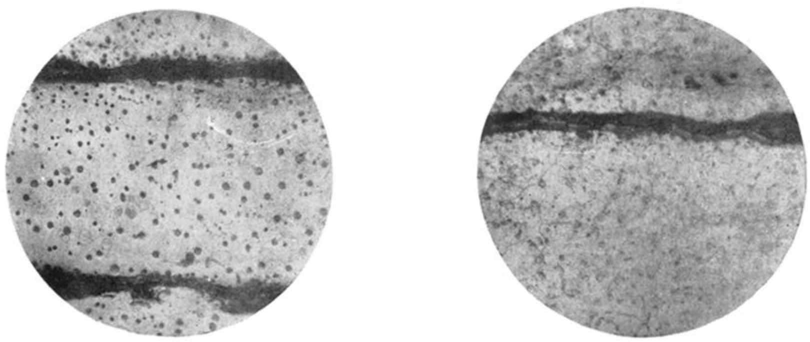
The treatment of the steel by a cyclicly varying field during its cooling probably has the effect of making the structure more homogeneous than would otherwise be the case, preventing the pearlite from forming and keeping the steel largely in the form of sorbite. This it probably does by immediately polarizing the alpha molecules as soon as they are formed by transformation, and thereafter keeping them under control as units of a single magnetic system. Thus they are prevented from forming small secondary groups of stable arrangement.

This suggests the possibility that the peculiar structure of pearlite, always occurring as it does in constant proportions, may very well be due to the magnetic qualities of the molecules of its two constituents and their consequent grouping tendency as soon as the magnetic alpha iron cools out from the beta form.

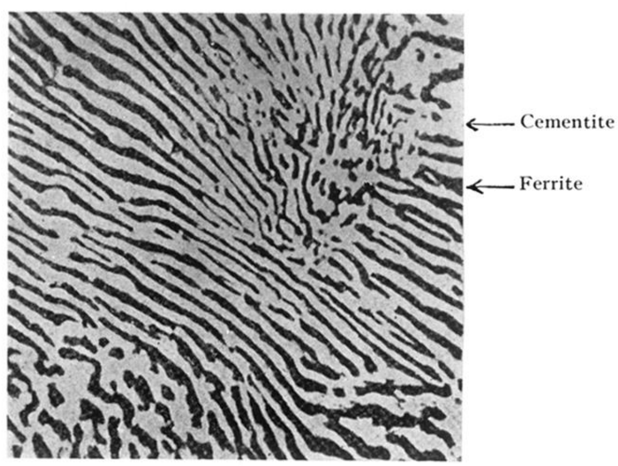
The results of this investigation seem to lend support to the hypothesis proposed. The most favorable temperature for applying the magnetic treatment was found to be about 690° C., which is about the temperature where a sorbitic steel starts to acquire the structure of pearlite. Then the change in form of the hysteresis loop by the magnetic treatment is precisely what would be expected by the hypothesis. The loop becomes more erect, showing that the steel changes its magnetic condition more as a unit, and thus indicating the greater homogeneity of its structure and the greater uniformity of the type of magnetic groups that prevail throughout. This results in a greater stability of the arrangement acquired under the influence of an externally applied magnetizing force and hence a greater value for the remanent magnetism. This too is confirmed by the hysteresis loops of Fig. 7. The micrographs also lend slight support in that those taken show a finer and more homogeneous structure for the magnetically annealed samples than for those annealed without the alternating field.



a. Unetched. × 80. *b.* Etched 25 sec. in HNO_3 solution.
No. A_5 heated to 790° C. and magnetically annealed from 655°.
Fig. 8.



a. Unetched. × 80. *b.* Etched 25 sec. in HNO_3 solution.
No. A_3 heated to 870° C. and annealed without magnetization.
Fig. 9.



Pearlite (Osmond).
Fig. 10.