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THE MICRO-STRUCTURE OF SILICON STEEL AND

ITS RELATION TO THE ELECTRICAL AND MAGNETIC LOSSES

by

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SUBMITTED IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF ARTS

in the

GRADUATE SCHOOL

of the

UNIVERSITY OF MISSOURI

1915

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INTRODUCTION:-

Micro-metallography, the microscopic study of metals, has become a valuable adjunct to the iron and steel industry, in revealing the proximate composition and structure of materials and enabling the manufacturer to predict some of the physical properties, such as hardness, elasticity, ductility, with comparative accuracy. Chemistry has made possible the accurate ultimate analysis of a product but its scope ceases at this point, and the science of micro-metallography bids fair to become an important method of testing materials, as the physical properties of metals and alloys, to which these substances owe their exceptional industrial importance, are more closely related to their proximate than ultimate composition. Many workers have attempted to extend this relation even to electrical and magnetic properties, with widely varying results. At the Sixth Congress of the International Association for Testing Materials, no less than eight papers were submitted dealing with electrical and magnetic properties of various steels and alloy-steels, but comparatively few of these papers were concerned with the micro-metallographic relation of these properties. The past year, however, has witnessed a marked interest in this phase of the science and papers by Langenberg and Weber, and by Yensen², using medium-carbon steel and purified electrolytic iron, respectively, show that the practical possibilities of the work are being recognized. Professor Howe, in his presidential address to the International Association for Testing Materials referred to the desirability of developing tests which can be applied to finished articles without destroying them. He says: "These indestructive methods have the defect of being indirect in one respect to weigh against their advantage of being direct in another; they are direct in that they gage the properties actually needed in service by means of other properties; they are direct in that they may be

applied to the very objects to be used instead of vicariously to coupons or like objects to be destroyed in the test itself. Their natural service seems to supplement the vicarious destructive tests".

Micro-metallography offers such indestructive tests and if certain micro-structures were known to correspond with certain definite electrical or magnetic properties, a simple polishing, etching and examination of the substance might take the place of a lengthy, delicate and complex magnetic or electrical measurement. This method might be applied to the testing of iron and alloy steels used for electrical machinery, now being accomplished by electrical methods more or less complicated and lengthy. The amount of steel and alloys consumed for electrical machinery is a large proportion of the total steel output and there is decided competition in manufacturing the best grades of irons and steels for electrical use.

For the value of these steels is determined by the minimum electrical losses and ageing, occurring in them, and this depends on their heat treatment, which, again, can be readily followed by metallography, in the structure changes caused by the treatment.

This paper is the result of an endeavour to correlate the micro-structure of Silicon steel and its electrical and magnetic losses for which no data exist.

The alloy contains from 2 to 5 percent of Silicon and is chiefly used in the construction of dynamos and transformers because of its low energy losses with high permeability making for high efficiency in electrical construction with minimum cost. In the case of a transformer these losses occur in the core. The core loss of a transformer is the energy required to magnetize and demagnetize the iron core due to reversals of the current. Core Loss is a most important factor in the design of an efficient transformer. This loss is constant and continues every hour a plant is in operation, even though the transformer may not be delivering current at its secondary. Consequently

a transformer having a low core loss means high all day efficiency and low operating cost on a lighting system. The importance of low core loss is evident when the cost of operating a transformer is considered. One watt in core loss corresponds to a consumption of 8.76 Kilowatt^{hours} for a period of one year on a 24 hour service. Assuming that it costs a central station 2 ~~1/4~~ cents to produce and deliver 1 Kilowatt^{hour} of ~~energy~~ to the core of a transformer, each watt in core loss would be equivalent to an expenditure of 20 cts. It is readily seen that if a transformer possesses 50 watts less core loss than another of the same capacity, the operating cost would be reduced \$10.00 per annum.

Silicon steel seems to give the least losses when compared with other steels, even the best Norway iron giving a greater loss, and was first produced and tested in 1902 by Hadfield in England. It is made by adding silicon or ferro-silicon, after tapping steel from a basic open hearth converter. The steel is rolled into sheets 30 x 90 inches and in three gages. Excess Silicon makes the steel hard and brittle and causes scaling which up to a certain amount is desirable, as it acts as an insulator between laminations when used in motors and transformers.

However, the amount of Silicon steel, annually rejected, due to excessive losses, approximates some 500 tons, and, owing to the large percentage of Silicon, the alloy can not be recast or used for other purposes. The necessary conditions of heat treatment for Silicon steel, to secure greatest efficiency seem to be somewhat obscure and it is readily seen that the correlation of structure to Hysteresis would aid in determining just what annealing and tempering is required to produce the best results. Again, a knowledge of the structure, corresponding to a low energy loss, might facilitate the substitution of a microscopic examination for the electrical methods now used in testing steel. It must be understood, however, that, in making such tests, the

ultimate composition of the standard and compared sample should always be approximately the same.

METHOD OF PROCEDURE:-

The method of procedure consisted in subjecting the Silicon steel to heat treatments of gradually increasing temperatures, after which the losses were determined electrically as later described. Along with the large mass of some 26 pounds, which was in the form of a laminated transformer core, was placed a smaller bundle of the same material, to be used as specimens after each treatment. These samples were then polished, etched and photographed; they were also tested by the Shore Sceleroscope for Physical Hardness and analyzed after each heat treatment to detect any possible change in ultimate composition. The steel used was a foreign product, probably German, and showed a comparatively low loss, in the original condition. It contained 4.27 per cent Silicon. To compare its structure with the American products, two specimens from the West Penn Steel Co., and Eastern Mill, were obtained, photographed and hardness tests made. This steel showed but 3.6 per cent Silicon and it is regretted that there was not sufficient material available to determine the losses. The change produced by annealing, in this steel, is very markedly shown by the micro-photographs.

HEAT TREATMENT:-

The cores were heated in a muffle gas furnace, built by the Denver Fire Clay Co., and the temperature observed by the aid of a thermo-couple and a Siemens-Halske Galvanometer, calibrated directly in degrees centigrade. The furnace was made as air tight as possible by closing the outlet at the rear of the muffle with fire clay and by using a fire clay brick, cut to shape, for a door, which lay flush against the front of the muffle. A hole was bored through the door for the tube of the thermo-couple, which was surrounded by asbestos paper and plugged in tight to prevent access of air. Great difficulty

was experienced in preventing oxidation of the steel. The entire core was not taken apart and re-assembled for every heating. One end was simply removed, the coil slipped off, and the remaining core and loose laminations of the end, were bound with iron wire to prevent falling apart. After the first heating, oxidation was much in evidence and on the next attempt, the core was wrapped in asbestos paper and clamped together by iron strips and bolts. This somewhat reduced the oxidation. On the third heating, however, a box, with lapped and riveted joints, built of Russia stove iron, was used. This box fitted the muffle almost snugly and the core was placed in this, surrounded by sand. An iron pipe entered the cover of the box, to serve as an opening for the couple. This did not seem to give the desired results either, as it required quite a long time to heat the entire muffle and contents to a temperature of approximately 1000°C . The sand was not pure and consequently sintered and fused to some extent, making the removal of the iron difficult. Moreover, due to some unknown cause, the muffle cracked, making the installation of a new one necessary. After this, however, oxidation was more readily controlled by reducing to a minimum, the supply of air and using an excess of gas which gave a slight reducing atmosphere. In addition to this, bright chips and turnings of steel, were liberally strewn in the muffle and these very materially aided in reducing the amount of oxidation of the cores. An asbestos wrapping, with all vents and dampers closed on the furnace, and a slight excess of gas, seemed to eliminate most of the oxidation of the cores. It was at first proposed to use a small section of iron, with a large, long, coil, and to heat this iron, in the electric vacuum furnace, thus eliminating oxidation effects. However, the resistance elements of the furnace, were not available and this method could not be used. It might be noted that, during the process of heat treating the steels, some very curious oxidation and reduction phenomena occurred, such as the partial oxidation of the magnetite to hematite

and the partial reduction of the magnetite to metallic iron in very thin sheets. At some places on the sample, a layer of magnetite was super-imposed on hematite and vice-versa. The steel, initially, had a coating of magnetite, which, though a good insulator, is highly magnetic, thus aiding in conducting the magnetic flux and at the same time, preventing the formation of any considerable Foucault currents. The initial thickness was approximately .31 mm., which increased with the heat treatments, as Table II, on Hardness and Thickness, shows.

The material, which was obtained from the Moloney Electric Co., St. Louis, was a foreign product, which had evidently been very well annealed, as none of the heat treatments seemed to increase its efficiency to any great ~~extent~~ extent; its content of Silicon was also comparatively high, about 4.2 per cent. The average American silicon alloy contains some 3 percent of Silicon, and is annealed in larger lots, giving, as a consequence, uneven heat distribution and imperfect annealing. The German material is annealed in small lots, and is subject to longer heat treatment, requiring some days, for complete annealing. The difference is evident, in some of the tests made at the United State Bureau of Standards. A further discussion of each sample after heating, will be given later, in the metallographic section of this paper.

In Plate I are given the heat treatment curves, showing the comparative length of time and temperature, for each heat. Curve No. I is very uneven, due to fluctuations in the pressure of the gas supply. As is noticeable, the time required for heating was comparatively short when compared to the cooling portion of the curve. The process of cooling required an average of eight hours in each instance, the material being allowed to remain in the muffle until it cooled to a temperature of 50°-60° C.

Core No. I showed a loss of .3 pounds after the last heat treatment, a loss of some 1.1 per cent of the core. However the mass of iron was so large

HEAT TREATMENT CURVES FOR CORES I and II.

that this would have practically no effect on the final results. In order to determine accurately, the loss by oxidation, a small sample of the original steel and of the steel after the last heat treatment, was taken, and the oxide determined by separation from the iron and weighing, as it scaled off very easily. They gave the following results:-

Before heating 1 gm. steel lost	.06679 gm. Fe_3O_4	=	6.68 %
After heating 1 gm. steel lost	<u>.07850 gm. Fe_3O_4</u>	=	<u>7.85 %</u>
Gain or difference	.0118	=	1.18 %
Gain or Loss by oxidation (by total weight)		=	1.14 %

This represents the separation from the core of 1.1 percent of iron, which, though affecting induction to some extent, has no effect on the final loss values, which are calculated for a constant permeability and induction.

ELECTRICAL MEASUREMENTS OF LOSSES:-

Many methods have been devised for the measurement of the energy losses occurring when sheet iron or steel is subjected to alternating currents. These losses consist of two components, The Hysteresis loss and the Foucault or Eddy current loss. Hysteresis, as its derivation ($\oint \mathbf{H} \cdot d\mathbf{l}$) implies is the lagging behind, of iron and steel when subjected to a magnetic field which is made to vary through a cycle of values. Foucault losses, however, are caused by small currents, generated in the material itself, and dissipate their energy in heat. The Foucault losses are usually avoided in electrical machinery by using laminations, often very thin and separated by some insulating medium, such as enamel, varnish or the oxide, ~~magnetite~~ magnetite.

The plotting of a Hysteresis loop from readings of magnetizing force and the resulting magnetic induction, is a slow process, giving no indication of the Eddy current losses. Those methods, which depend on the relative motion of specimen and a magnet, necessitate an air gap in the magnetic circuit and, as a consequence, the induction in the specimen is far

from uniform. And if, as in the Ewing and Blondel apparatus, a permanent magnet be used, the values of the flux densities which may be used, are restricted, limiting the instrument to comparative measurements only, at one flux density.

Hence the method of testing by alternating currents was adopted in the preparation of this paper, and according to the United States Bureau of Standards, this seems to be the only reliable and satisfactory way of making accurate measurements. Plate II shows the connections and arrangement of instruments used in the test. The wattmeter measures the electrical energy, supplied to maintain the alternating magnetization while the maximum magnetic induction produced in the specimen, is determined by the voltmeter shunted across the terminals of the magnetizing winding. The ammeter measures the exciting current so that changes in permeability may be followed by its increase or decrease. The variable voltage transformer facilitates the use of various flux densities without taxing the generator with the burden of a rheostat.

In the wattmeter method, the specimen may be employed in three forms.

- 1) It may be in the form of straight strips placed in contact with a yoke forming a closed circuit of ferro-magnetic material, similar to a transformer core;
- 2) The straight strips may be used without a yoke, forming an open magnetic circuit.
- 3) The specimen itself may form a closed magnetic circuit. The first forms a comparatively uniform flux but the energy supplied to the yoke must be distinguished from that supplied to the specimen, which can only be accomplished by knowing the constants of the yoke and securing uniform flux distribution. The second form gives a distorted flux and this irregularity militates against its use. The third form, is the most reliable for accurate

PLATE II

measurements though not nearly as rapid as the other two, the time required to replace the coil and laminations being a little over one hour.

The third method was adopted in this work and two cores, built of the same laminated Silicon steel, .31 mm. thick, were used. Both cores had the same area and cross sections, as given in Tables I and V, and both coils had the same number of turns, Coil No. II being larger than Coil I, in diameter, to allow for a possible expansion of the iron after heat treatment and to facilitate its removal. The resistance of these coils are also given in the same tables. The copper loss in the coils, i.e. the i^2R loss, due to the heating of the copper, was, at current densities below 2 amperes, smaller than the experimental errors and consequently neglected. Above this current density however, the copper loss was calculated, and the readings given in the tables have been corrected for this factor.

The size, shape amount and arrangement of materials, were in fair accordance with the conditions, as outlined by the Bureau of Standards, for such magnetic circuits.

While the losses were being determined, the core was tightly pressed together in wooden clamps, to secure even distribution of flux density, and the same circuits and connections and lengths of wires were used in every test; the connections being made with heavy wires to eliminate external resistance effects.

Power was obtained from a 7.5 K.W. General Electric Alternator, giving 60 cycles at 1800 R.P.M. and 30 cycles at 900 R.P.M. The alternator, was driven by a direct current motor whose speed was regulated by a field rheostat; while a rheostat in the field of the alternator served to vary the voltage in smaller steps than the taps on the variable voltage transformer would permit.

The speed, and therefore frequency, was determined by an electrical

tachometer and checked with a speed counter. The frequency was maintained as uniform as possible, a maximum variation of .5 % being allowed.

The Tables and Curves give the comparative energy losses, measured after each heat treatment, and it will be noticed in Plates III and IV, that decided changes in the total loss have occurred after the various heat treatments. Plates IV and VI, giving the magnetization curves, show a decrease in permeability of the alloy, after the heat treatments. For core No. I the total losses only were measured. For core No. II, however, the total loss, at three different flux densities, was separated into its two components, due respectively to Hysteresis and Eddy currents, by the Steinmetz equation, and the use of two frequencies, 60 cycles and 30 cycles.

The tests as recoded, give the impressed Electro-motive force in volts, the exciting current in amperes and the total loss in watts. However, to make the data useful and comparable to standard conditions and terms, the voltage was calculated to flux density and this used in plotting the magnetization curves. For the same reason, the exciting current in amperes was calculated to Ampere-turns per centimeter and plotted against the flux density.

Table IX gives the comparative data on all tests on both cores, for core losses and is self explanatory. The losses are expressed as Watts per pound at 60 cycles and it is seen that after some heat treatments, the losses have diminished and after others that they have increased. Another interesting fact to note is that at some flux densities the change is not so marked as at others. Just what relation these changes have to the structure will be more fully explained in the last part of this paper.

TABLE I

Core No. I.

Analysis:- See Chemical Composition.

Weight of core = 26.3 lbs. Size = 2 x 8 x 9 inches. Coil No. I = 160 turns
of No. 10 B.S. square copper wire. Resistance = .12 ohms.

INSTRUMENTS:-

Moloney Variable Voltage transformer; Weston Ammeter, No. 10767

Whitney Bridge type wattmeter; Weston Voltmeter, No. 10103

Generator Speed = 1800 R.P.M. = 60 cycles. Speed constant within 1.8 %

Test No. I. (No preliminary heat treatment) 60 Cycles.

Impressed E.M.F. in Volts.	Flux Density Lines per sq. cm.	Exciting Current in Amps.	Total Loss in Watts
100	9100	.8	17.5
105	9675	1.0	19.36
110	10000	1.1	20.86
115	10450	1.35	22.
120	10920	1.65	23.7
125	11700	2.07	25.4
130	11800	2.55	27.1
135	12300	2.9	29.7
140	12700	3.4	32.2
145	13200	4.1	34.68
150	13650	4.7	36.8

TABLE II

Core No. I

Test No. II (after first heat treatment) 60 cycles.			
Impressed E.M.F. in Volts	Flux Density Lines per sq. cm.	Exciting Current in Amps.	Total Loss in Watts.
100	9100	1.	17.4
105	9675	1.2	19.
110	10000	1.5	20.7
115	10450	1.9	22.6
120	10920	2.4	25.1
125	11700	2.8	26.
130	11800	3.2	28.5
135	12300	3.9	30.7
140	12700	4.5	33.6

TABLE III
Core No.I.

Test No.III (After second heat treatment) 60 cycles

Impressed E.M.F. in Volts	Flux Density Lines per sq.cm.	Exciting Current in Amps.	Total loss in Watts
80	7275	.2	12.
85	7740	.5	13.3
90	8175	.6	14.4
95	8650	.8	16.4
100	9100	1.12	18.3
105	9675	1.4	19.2
110	10000	1.75	20.6
115	10450	2.15	23.0
120	10920	2.75	25.0
125	11700	3.27	27.3
130	11800	3.87	29.
135	12300	4.37	31.7
140	12700	4.97	33.7

TABLE IV

Core No.I.

Test No.IV (After third heat treatment) 60 cycles.

Impressed E.M.F. in Volts	Flux Density Lines per sq.cm.	Exciting Current in Amps.	Total Loss in Watts	Total Loss in Watts at 30 cycles and same Ex.Current
80	7275	1.37	62.8	22.8
85	7740	1.67	69.6	25.66
90	8175	1.9	77.0	27.82
95	8650	2.2	86.8	30.
100	9100	2.57	95.1	32.4
105	9675	3.02	103.7	34.8
110	10000	3.55	114.2	37.5
115	10450	4.1	124.1	41.9
120	10920	4.8	133.8	44.05

NOTE:- It was impossible to make an electrical test of the steel after the fourth heat treatment, as heavy oxidation prevented the replacement of the removed yoke of the core and the errors introduced by any air space in the magnetic circuit would have seriously impaired the accuracy of the final results. However hardness tests were made and micro-photographs were taken, after the last heat treatments of both Core I and II.

PLATE III

TOTAL CORE LOSS in WATTS.

CORE I.

At 60 cycles frequency

PLATE IV

EXCITING CURRENT in AMPERE-TURNS PER CENTIMETER. CORE I at 60 cycles frequency.

TABLE V

Core No. II

Analysis:- same as Core I.

Weight of core = 26 lbs. Size 2 x 8 x 9 inches. Coil No. II = 160 turns of No. 10 B.S. square copper wire. Resistance = .145 ohms. This coil was built slightly larger than No. I to facilitate removal from the core.

INSTRUMENTS:- same as used for Core I.

Test No. I (no heat treatment) 60 cycles

Impressed E.M.F. in Volts	Flux Density Lines per sq. cm.	Exciting Current in Amps.	Total Loss in Watts.
80	7200		12.5
90	8175		15.5
100	9100	.2	18.7
105	9675	.5	20.6
110	10000	1.05	22.4
115	10450	1.25	24.5
120	10920	1.45	27.1
125	11700	1.77	29.6
130	11800	2.05	32.42
135	12300	2.35	35.0
140	12700	2.82	37.9
145	13200	3.4	41.2
150	13650	4.05	44.95

TABLE VI

Core No. II

Test No. I. (no heat treatment) 30 cycles

Impressed E.M.F. in Volts	Flux Density Lines per sq. Cm.	Exciting Current in Amps.	Total Loss in Watts.
<hr/>			
54	9800	1.	10.36
57	10400	1.25	11.6
59	10750	1.45	12.2
62.5	11400	1.75	12.9
63.5	11600	2.	14.0
65	11850	2.25	14.3
66	12000	2.5	15.1
68	12400	2.7	16.4
70	12250	3.0	16.7
72.	13100	3.5	17.1
78	14200	4.0	18.7

TABLE VII

Core No. II

Test No. II (After first heat treatment) 60 cycles

Impressed E.M.F. in Volts	Flux Density Lines per sq. cm.	Exciting Current in Amps.	Total Loss in Watts.
80	7200		12.7
90	8175		14.5
100	9100	.7	18.
105	9675	1.1	19.9
110	10000	1.4	21.7
115	10450	1.77	23.6
120	10920	2.1	26.
125	11700	2.5	27.1
130	11800	2.9	29.9
135	12300		
140	12700	3.95	34.5
145	13200	4.7	36.8

TABLE VIII

Core No.II

Test No.II (After first heat treatment) 30 cycles

Impressed E.M.F. in Volts	Flux Density Lines per sq.cm.	Exciting Current in Amps.	Total Loss in Watts.
51	9300	1.	8.61
57	10400	1.5	10.4
60	10900	2.	11.67
64	11700	2.5	12.8
67	12200	3.	13.7
69	12600	3.5	14.7
72	13100	4.	15.7
74	13500	4.5	16.4
76	13900	5.	17.5

NOTE:- As in the case of Core I, after the last heat treatment, it was impossible to make another electrical test as the re-assembling of the core was not feasible, due to oxidation and fusion. However Hardness and microscopic examinations were made and photographs taken.

PLATE V

TOTAL CORE LOSS in WATTS. CORE II. At 60 cycles frequency.

EXCITING CURRENT in AMPERE-TURNS PER CENTIMETER. CORE II at 60 cycles frequency.

TABLE IX

ENERGY LOSSES IN STEELS BEFORE AND AFTER HEAT TREATMENTS

Number	Gage in mm.	Hard- ness by	B = 9000			B = 10000			B = 12000		
			Watts per lb. at 60 cycles			Watts per lb. at 60 cycles			Watts per lb. at 60 cycles		
			Total Loss	Hyster- esis	Eddy Loss	Total Loss	Hyster- esis	Eddy Loss	Total Loss	Hyster- esis	Eddy Loss
Core I.											
I.	.31	42	.655			.792			1.065		
II	.34	51	.650			.790			1.115		
III	.35	47	.725			.785			1.175		
IV	.38	43	3.55	3.49	.059	4.35	4.32	.022	5.92	5.80	.121
Core II											
I	.32	50	.710	.6995	.010	.862	.847	.013	1.235	1.268	.017
II	.34	47	.677	.669	.008	.835	.825	.009	1.225	1.211	.014

TABLE X

THICKNESS AND HARDNESS

The hardness was measured by the Shore Sceleroscope, and the gage of the steel by a micro-meter gage. Given as average readings at several places.

Core No. I (Foreign Steel) 4.27 % Silicon

Heat Treatments

	I. Original	II 720°	III 850°	IV 1080°	V 780° Centigrade
Hardness	42	51	47	43	39
Thickness	.31 mm	.34 mm.	.35 mm.	.38 mm.	

Core No. II (Foreign Steel) 4.27% Silicon

	I Original	II 780°	III 820° Centigrade
Hardness	50	47	39
Thickness	.32 mm.	.34 mm.	.37 mm.

West Penn Steel (American), 3.6% Silicon

	Annealed	Un-annealed
Hardness	51	45

CHEMICAL COMPOSITION

In order to detect any possible change in the ultimate composition of the material after heat treatments, duplicate analyses were made, of each sample, after heat treatment. However, there was no change noticeable, the analyses agreeing very well within the limits of experimental errors. The two cores used in the electrical tests were found to have the same composition and were probably built up from the same lot of material. Consequently the detailed analytical results need not be given as this would require the statement of the data of some 50 analyses.

The silicon and phosphorus were determined in one analysis, according to the method of Alexander Blair, the phosphorus being weighed as Magnesium pyro-phosphate. The evolution method, with absorption of the hydrogen sulfid in ammoniacal Hydrogen peroxide, as given in Circular No. 14, United States Bureau of Standards, was used for the sulphur determination. Manganese was tested for by the colorimetric method but traces only, were found.

The Carbon content of these steels was very low, as it was practically impossible to estimate it colorimetrically. In the course of the other analyses, the dark color, due to combined carbon, could not be detected and no traces of graphite appeared with the silica. Moreover, Guillet has shown that the structure in Silicon steel is independent of the carbon content, being entirely regulated by the proportion of silicon, as his diagram, Plate XXI, illustrates. Any possible carbon present in this steel would be in the combined form and would appear probably as pearlite.

ANALYSES

Name	Silicon	Sulphur	Phosphorus	Manganese
Foreign	4.27%	.038 %	.040 %	trace
American	3.61%	.042 %	.99 %	

The foreign material seems to be the better material, being purer.

PLATE XXI

CONSTITUTIONAL DIAGRAM OF SILICON STEEL. (Guillet).

MICRO-STRUCTURE

The following Plates show the structure of the steel before and after the various heat treatments denoted by the curves in Plate I.

The specimens, being thin and inconvenient to handle, were mounted on glass slides with Canada balsam and polished on successively finer gradations of emery and finally with rouge and then with a soft dry cloth.

They were etched with concentrated Nitric acid as follows:— The specimen, well polished, was held near a stream of running water and just sufficient acid was poured on the steel to cover it completely. As soon as violent interaction resulted and brown fumes were evolved, the sample was quickly placed in the stream of water and well washed, being held under the water for some time and not exposed to the air. After a few minutes washing it was removed from the water and dried as rapidly as possible with a soft cloth and filter paper, to prevent oxidation. All the specimens were polished and etched in this manner.

Along with the micro-photographs are given the electrical and physical constants of the materials for comparison. The Total Loss is expressed in Watts per pound at a frequency of 60 cycles and a flux density of 10000. The Hardness is expressed in terms of the Shore Sceleroscope scale while thickness or gage is given in millimeters. The composition of the steels represented on the following pages, have been given under the title Chemical Composition and need not be here restated.

PLATE VI

CORE A

No. I

Total Loss = .792 Watts.

Ampere-turns = 2.75

Hardness = 42

Gage = .31 mm

x 280

x 280

PLATE VII

CORE A

No. II
720°

Total Loss .790 Watts.

Ampere-turns= 3.6

Hardness = 51

Gage = .34 mm.

x 280

x 280

PLATE VIII

CORE A

No. III
850°

Total Loss = .785 Watts.

Ampere-turns = 4.25

Hardness = 47

Gage = .35 mm

x 280

x 280

PLATE IX

CORE A

Total Loss = .785 Watts.

Ampere-turns= 4.25

Hardness = 47

Gage = .35 mm.

No. III

350°

x 230

PLATE X

CORE A

No. IV
1080°

Total Loss = 4.35 Watts.
Ampere-turns = 8.6
Hardness = 43
Gage = .38 mm.

x 280

x 280

PLATE XI

CORE A

No. IV
1080°

Total Loss = 4.35 Watts.

Ampere-turns = 8.6

Hardness = 43.

Gage = .38 mm.

x 280

x 280

PLATE XII

CORE A

No. IV
1080°

Total Loss = 4.35 Watts
Ampere-turns = 8.6
Hardness = 43
Gage = .38 mm

x 230

PLATE XIII

CORE A

	Total Loss	- unknown.
No. V.	Ampere-turns	
	Hardness	- 39.
780°	Gage	- .39 mm.

x 280

PLATE XIV

CORE A

No. V

780° (Final heat-treatment)

Total Loss - unknown
Ampere-turns
Hardness - 39.
Gage .39 mm.

x 70

No. I

Before heat treatment.

Total Loss = .792 W
Ampere-turns = 2.75
Hardness = 42
Gage = .31 mm

x 70

PLATE XV

CORE A

No.V.

780° (Final heat treatment).

x 70

Total Loss -unknown
Ampere-turns
Hardness - 32
Gage - .39 mm

No. I

Before heat treatment.

x 70

Total Loss = .732 W
Ampere-turns= 2.75
Hardness = 42.
Gage = .31 mm

XVI

CORE B

ANALYSIS same as Core A.

No. I.

Original steel before heat treatment.

Total Loss = .862 Watts

Ampere-turns= 2.5

Hardness = 60

Gage = .32 mm.

x 280

PLATE XVII

CORE B

No. I

Total Loss = .862 Watts

Ampere Turns = 2.5

Hardness = 50

Gage = .32 mm.

x 280

x 280

PLATE XVIII

CORE B

No. II
780°

Total Loss = .835 Wapts

Ampere-turns= 3.7

Hardness = 47

Gage = .34

x 280

x 280

PLATE XIX

CORE B

No. III
820°

Total Loss = unknown
Ampere-turns
Hardness = 39
Gage = .37 mm

x 280

x 280

PLATE XX

West Penn American Steel (3.6% Silicon)

No. I Un-annealed. Hardness 45

x 230

No. II. Annealed. Hardness 51

x 230

DISCUSSION:-

It is to be noted in Plate VI that the steel is apparently composed of irregular polygonal ferrite crystals interspersed with larger pearlitic crystals, probably an eutectoid of ferrite and ferrous silicide. The structure within the ferrite grains is angular while that of the eutectoid is laminated. This structure corresponds to a loss of .792 watts per pound and a high permeability requiring but 2.75 ampere-turns for saturation at 10000 B.

After the first heat treatment, however, the ferrite grains have practically disappeared, as Plate VII well shows while the eutectoid crystals have increased somewhat in size, their total volume has diminished. The structure as a whole has apparently become pearlitic and the second illustration on Plate VII shows the faint traces of the crystal boundaries. The steel, in this case shows a very slight decrease in energy loss, probably beyond the experimental error. The Curves, as a whole, should be considered in interpreting the results. The permeability has also decreased, requiring 3.5 ampere-turns for saturation while the hardness has decreased to 51, due to the absence, probably, of the granular structure.

Number III, after the second heat treatment, shows polygonal structure in part, though still pearlitic and the size of the eutectoid has increased to some extent. Plate IX shows the eutectoid surrounded by the pearlite. This eutectoid is sparsely scattered through out the mass and seems more stable than the other accompanying structure. The energy loss in this sample has slightly diminished to .785 watts and the permeability has also been reduced, requiring 4.25 ampere-turns. Hardness has decreased to 47, due probably to the reappearance of the crystalline structure.

Plate X shows the structure after the third heating. It is apparent that the crystalline structure has reappeared as ferritic pearlite and that the grains have increased remarkably in size. The eutectoid is shown as large crystals in both illustrations on Plate X; and Plate XI shows the pearlite very plainly with evidence of merging into a larger mass, as the disappearing boundaries show. The surrounding crystals are markedly pearlitic in character. Plate XII shows this still more clearly, as well as the disappearing boundaries between the crystals. The energy loss has also increased remarkably, and the permeability decreased to one half its former value in No. III.

Plate XIII gives the structure after reheating to 730° , when the crystals have slightly increase in size while the hardness decreased, the value being 39. The structure as a whole is still pearlitic.

Plates XIV and XV give the comparative size of the crystals initially and after the last heat treatment, under the same magnification of 70. The pearlite is very marked in No. V while the ferrite crystals stand out prominently in No. I.

In the steel from core II the same phenomena can be observed. Plate XVI gives the structure before heat treatment. It is evident that the crystals of the ferrite and eutectoid are comparatively larger than those in core I. The energy losses are also larger in Core B, some .862 watts per pound, while in core I they were only .792 watts. The hardness number is 50. Plate XVII shows that No. II of Core I and this steel of Core II are similar in having a pearlitic structure and the same hardness. The permeability however is greater for this specimen, requiring only 2.5 ampere-turns for saturation. Plate XVII shows the same specimen at a different place, where the crystals are very large, irregular and pearlitic in character. After heat treatment, however, the structure changed as Plate XVIII shows, with a corresponding decrease in energy loss and permeability. It is evident however, that the

coarse crystals have broken up into smaller ones and that the structure is more regular. The eutectoid however is not much in evidence in this case.

After the third heating the crystals increased to great size and retained their pearlitic character, Plate XIX. The hardness decreased just as in the case of Nos. III and IV of core I and the absence of the eutectoid and regularity of the crystals are to be noted.

Plate XX gives the structure of an American steel containing 3.6 % Silicon. No. I shows the irregularity in structure of the un-annealed specimen, chiefly ferrite. In the annealed specimen, No. II, however, the structure is more regular and consists principally of the eutectoid and ferrite crystals. The energy losses could not be determined for these samples, as only small specimens were available. In general it is known however that the losses are lower in the annealed specimen.

CONCLUSIONS:-

From the data presented in this paper, it seems evident that there is a decided connection between the micro-structure of silicon steel and the energy losses. Though this relation may not be a straight line function, nevertheless the limits of its application might be determined and the relation might then have some value in commercial and industrial fields. That the size of the grains has a distinct bearing upon the energy losses in medium carbon steel (but not for silicon steels) was pointed out by Langenberg and Weber, while this work was in progress. Their results seemed to point to the fact that a coarse grained pearlite gave the lowest energy losses. In the case of this silicon steel, the data and illustrations seem to show that the energy losses are greatest as the coarse pearlite diminishes. Pure ferrite with the eutectoid secures the least losses, in the steel. The hardness seems to have no special bearing, decreasing in general with increase in crystal size. Regularity of the crystals in ^{the} steel gives the lowest losses when the crystals are ferrite with coarse pearlite.

In general, then, it may be said that the energy losses are lowest when the structure of the steel is almost entirely ferritic, interspersed with an eutectoid. The eutectoid seems to have the function of ~~leaving the~~ ^{leaving the} relatively pure ferrite (alpha iron) free to be magnetized and demagnetized without suffering excessive losses. As soon as the pearlite loses its coarseness and disseminates through the steel, the magnetic and electrical properties are affected to a marked degree. It is interesting to note that these results seem in perfect accordance with the results of Yensen², published while this paper was in preparation. In the course of his investigation, electrolytic iron of 99.98% purity was melted in an electric vacuum furnace and it was found that the resulting product gave less than 50% of the hysteresis losses found in the best grade of commercial Silicon steel. The absence of carbon seems to lower the energy losses to a great extent and in Silicon steel, as the results of this paper show, the coarse grained pearlite leaves the iron in a relatively pure state as the ferrite, the Silicon probably acting as the purifying agent.

Just what heat treatments would be necessary to secure this structure it is difficult to predict but further experiments in this direction would probably lead to the discovery of the proper temperature conditions for annealing this steel. This would prove valuable in the industrial world and would prevent the waste of much material.

The work embodied in this paper was carried out under the direction of Dr. W. G. Brown, to whom the writer is greatly indebted for much valuable advice, assistance and encouragement. Many thanks are also due to the Faculty of the Engineering School for the kind use of equipment and instruments for making the Electrical and Physical measurements and for other assistance.

The writer also wishes to acknowledge the great kindness of Mr. T. O. Moloney and Mr. J. J. Mullen, of the Moloney Electric Company of St. Louis, in furnishing the necessary Silicon steel cores and the coils used, and for other assistance rendered.

The samples of American Silicon steel were kindly furnished by Mr. J. Obear, of the West Penn Steel Co., Brackenridge, Pa. to whom the writer owes his thanks.

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May 22, 1915.

Professor H. C. Rentschlär,
104 Physics,

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