

July 3, 1934.

N. P. GOSS

1,965,559

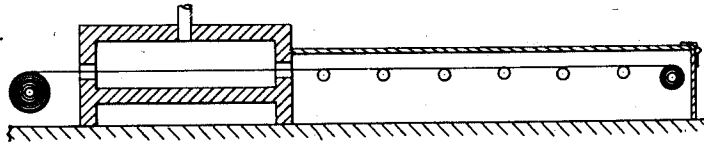
ELECTRICAL SHEET AND METHOD AND APPARATUS FOR ITS MANUFACTURE AND TEST

Filed Aug. 7, 1933

3 Sheets-Sheet 1

Fig. 1.

HOT ROLLED SI STEEL
STRIP HEAT TREATED IN
REDUCING ATMOSPHERE
COOLED



COLD ROLLED
BACKED MILL

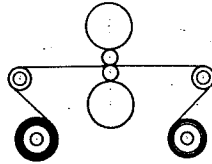


Fig. 1a.

HEAT TREATED IN
REDUCING ATMOSPHERE
COOLED

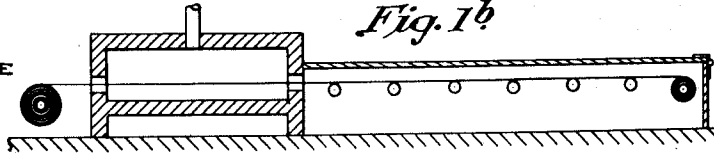


Fig. 1b

COLD ROLLED
BACKED MILL

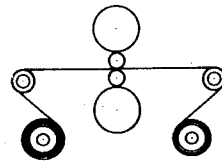


Fig. 1c

FINALLY HEAT TREATED
REDUCING ATMOSPHERE
COOLED RAPIDLY

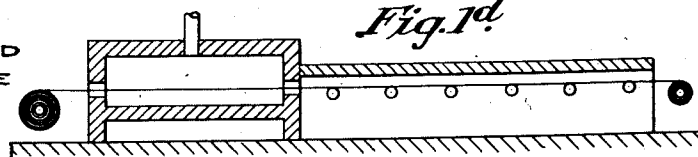


Fig. 1d

STAMPED AND
BATCH ANNEALED

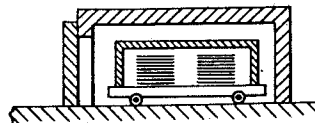


Fig. 1e

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3 Sheets-Sheet 2

Fig. 3.

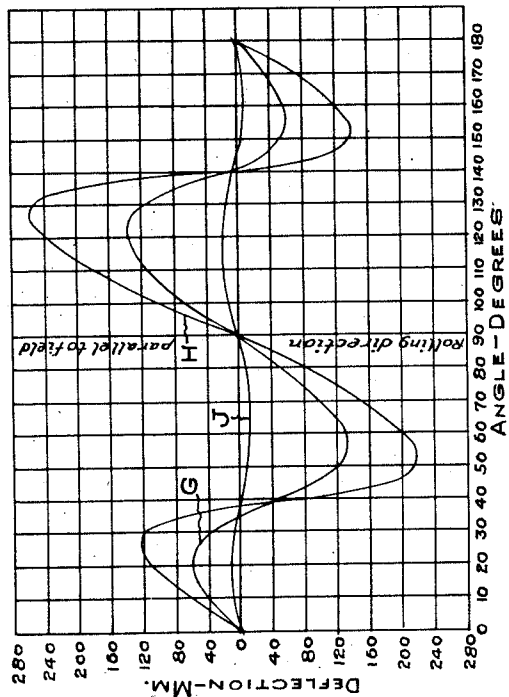


Fig. 5.

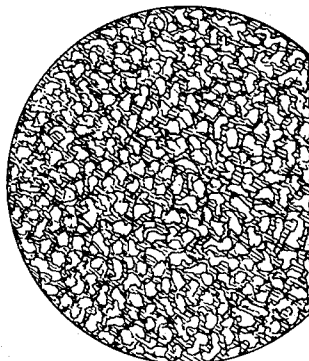


Fig. 4.

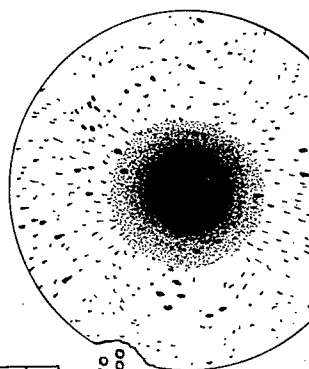
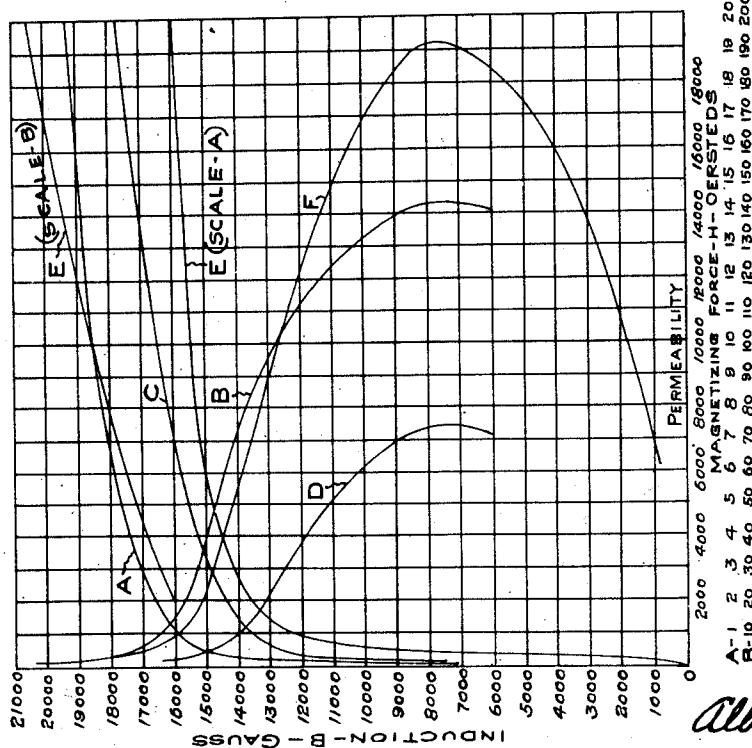


Fig. 2.



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Fig. 6.

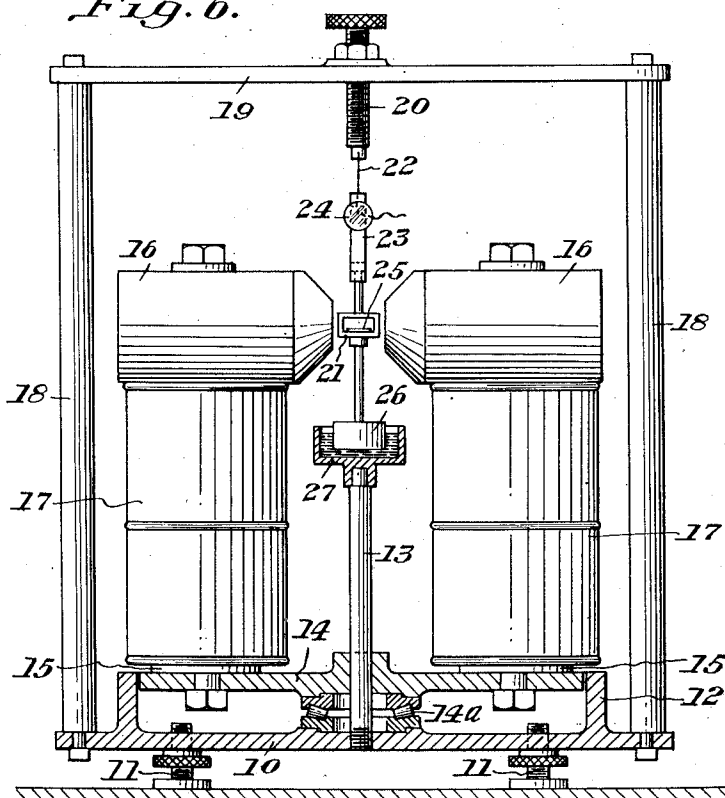


Fig. 7.

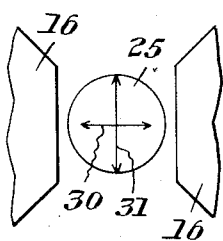


Fig. 8.

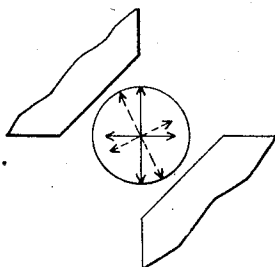


Fig. 9.

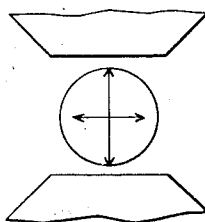
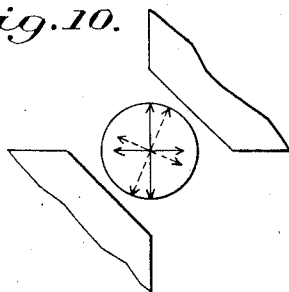


Fig. 10.



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UNITED STATES PATENT OFFICE

1,965,559

ELECTRICAL SHEET AND METHOD AND APPARATUS FOR ITS MANUFACTURE AND TEST

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Application August 7, 1933, Serial No. 684,111

20 Claims. (Cl. 175—21)

My invention relates to electrical steel and method of manufacturing and testing the same.

The desirability of high grade steel in sheet form for the manufacture of electrical apparatus is well recognized. Ordinary low carbon steel has been considered to have fairly satisfactory initial magnetic properties, including reasonably high permeability at high flux density. The difficulty with this material, however, is that it rapidly ages and its qualities suffer a marked deterioration. It has been attempted heretofore to prevent the aging of low carbon steel by the addition thereto of considerable amounts of silicon and the electrical steel of commerce today is a silicon steel alloy having a silicon content ranging from 1/2% to 5%.

In the manufacture of present day electrical steel, ordinary sheet mill practice is followed. The sheets are produced from breakdowns made by rough rolling sheet bars, the breakdowns being finish rolled in packs. This process, as is well known, involves a great deal of manual handling of the material, as well as frequent reheatings.

In the present practice of making electrical sheets, the results obtained are more or less hit or miss. There is no known method of checking the characteristics of the material before it has been finished. There is no convenient or economical test known to reveal the results to be expected from processing a strip or sheet bar in production, according to a given method, so as to insure that the method chosen will give a product having maximum values for the desired characteristics. A predetermined product of definite and exact magnetic characteristics has not been produced by prior art methods.

Ordinary silicon steel of the present day of a moderate silicon content, say 4%, has been produced with a maximum permeability of 8000 at a flux density of about 6500 lines per square inch. This material has been made with a guaranteed watt loss of .55 to .60 watts per lb. at 10,000 lines per square inch and 60 cycles. This silicon steel may be characterized by large or small grain size, depending upon the particular process adopted by the manufacturer.

It has been thought heretofore that high-grade silicon steel sheets for electrical uses could not be rolled to a thickness less than approximately .014" without materially increasing the total watt loss per pound, as a result of the rapidly increasing hysteresis loss in such thin sheets.

In addition to the ordinary silicon steel elec-

trical sheets, there have been developed certain alloys for special uses. These are usually high nickel alloys and are used chiefly in apparatus requiring high permeability and low losses, such as in communication service. These alloys are too costly to permit their general use in ordinary electrical apparatus. They are also characterized by a tendency toward saturation at low flux densities, which further militates against their use in electrical power equipment.

It has been proposed heretofore to heat treat silicon steel in order to improve its properties. As far as I am aware, this practice has involved simply the heating of the finished sheets to a temperature of between 1650 and 2000° F. or higher. The generally accepted theory is that the final annealing controls the characteristics of the resulting product, regardless of the previous mechanical working or heat treatment to which the material has been subjected. The previous practice of heat treating electrical steel has had the effect principally of reducing the losses but has not materially affected the permeabilities obtainable at higher flux densities particularly. In a specific example of 1% silicon steel, a maximum permeability of 7500 was obtained at 7500 lines per square inch.

I have discovered that the most desirable electrical steel from a magnetic standpoint is characterized by certain definite physical, as well as magnetic characteristics. My investigations reveal that good electrical steel is highly ductile, has grains of uniform small size, and is characterized by a high magnetic moment. The relation between the magnetic moment and the permeability can be readily demonstrated. It is well established that the intensity of magnetization, I , is equal to the magnetic moment, M , per unit volume, v , ("Magnetic Properties of Matter", K. Honda, page 6, Syokwabo & Co., Tokyo, Japan). It is also known that the total induction B in any magnetic substance is equal to the product of the intensity of magnetization multiplied by 4π plus the magnetizing force (Honda, page 5). Since the permeability μ is defined as the ratio between the induction and the magnetizing force, it follows that the magnetic moment M , which is equal to Iv , has a direct bearing upon the permeability since, the greater the magnetic moment, the greater the intensity of magnetization I and, the greater the intensity, the greater the induction B and, the greater the induction, the greater the permeability, for a given magnetizing force.

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The equations showing the derivation of the above conclusion are as follows:

$$(1) \quad \frac{B-H}{4\pi} = I$$

$$(2) \quad B = 4\pi I + H$$

since

$$\frac{B}{H} = \mu,$$

then substituting in (2)

$$(3) \quad \mu = \frac{4\pi I}{H} + 1,$$

and since

$$\frac{I}{H} = K$$

(4) it follows from (3) that $\mu = 4\pi K + 1$
 20 Honda demonstrates

$$M = IV \text{ or } I = \frac{M}{V}$$

Substituting for I in (3)

$$(5) \quad \mu = \frac{4\pi M}{VK} + 1$$

showing μ is directly proportional to magnetic moment.

30 I have experimental evidence which leads me to believe that there is an apparent relation between the grain size and ductility of a specimen and its magnetic properties. This evidence shows that small, uniform grains and high ductility usually accompany high permeability.

It is known that any bar of magnetic material placed in a magnetic field possesses a readily measurable magnetic moment (Honda, page 6). It has also been further recognized that a single crystal of magnetic material in the form of a thin circular disc has a definite magnetic moment (Honda, pages 150-151). It has been the belief heretofore, however, that similar specimens of fine-grained crystalline aggregates, such as 40 silicon steel or pure iron, have substantially no magnetic moment. It has also been supposed that the results obtained from attempts to measure the moment will be irregular and not quantitatively indicative of any magnetic property. 50 The theory has been that the random arrangement of the crystals tends to prevent a specimen from exhibiting any appreciable polarization or moment. The effects of the individual grains have been thought to cancel each other so that the net magnetic moment is very slight or entirely inappreciable. It has been proved by experiment that large single grains of silicon steel have high permeability and low hysteresis loss. The magnetic properties, such as ease of induction, vary depending upon the direction in which the crystal is magnetized. The values for permeability and loss in a single crystal are entirely beyond the range of similar characteristics for the ordinary small grain aggregate, such as medium silicon steel found in present day electrical sheets. It would, therefore, be highly desirable to produce electrical sheets having properties approaching those of a single crystal.

I have invented a method of processing ordinary silicon steel so as to impart to it magnetic characteristics approaching those of a single crystal. Quantitative measurements on the product resulting from my method indicate that it approaches quite closely to the values obtained 75 by testing single crystals for magnetic charac-

teristics, especially the magnetic moment and permeability which, at the higher inductions, are increased from two to eighty times those of present day silicon steel. Briefly, the method of my invention comprises subjecting hot rolled silicon steel strip to alternate cold working and heat treatment to produce thin gauge steel having magnetic characteristics approximating those of a single crystal. While the following description of the invention will refer particularly to the treatment of strip, it is to be understood, of course, that the same method may be applied to material in sheets with similar results.

My invention also contemplates the determination of the preferred manufacturing procedure which will insure a product of optimum characteristics, by subjecting specimens of the raw material to various established processes previously determined, testing the resulting products, and comparing the characteristics of the several specimens to determine which one has the maximum magnetic moment. The processing of the main mass of the raw material will then be governed by these tests. This provides an accurate control of the product at practically all stages of manufacture and eliminates the hit or miss methods which have characterized the manufacture of electrical steel heretofore. The measurements of the magnetic moments of the various specimens are made by a magnetic torsion dynamometer. This device permits a rapid and accurate determination of the characteristics (magnetic moment and permeability) of a specimen of material. By its use, I am able to check the characteristics of the material after successive stages of processing and thus insure that the subsequent steps will be so controlled as to produce the desired characteristics in the finished product. This determination of the permeability of silicon steel by the above means and in process is unknown in the prior art.

I have also discovered that the product of the method of my invention can be made in thicknesses less than .014" without any material increase in total watt loss per pound, contrary to the opinions heretofore held by authorities on electrical steel.

For a complete understanding of my invention, reference is made to the accompanying drawings illustrating diagrammatically the manner of carrying out the method and showing graphically the characteristics of the product. In the drawings:

Figures 1, 1a, 1b, 1c, 1d, 1e are a diagrammatic illustration of the steps involved in a preferred practice of the method of my invention;

Figure 2 is a graphical representation of the magnetic characteristics of the product resulting from my method as compared with those of typical similar products now available;

Figure 3 is a set of curves graphically representing the magnetic moments characterizing the final product of my invention, a single crystal, and an intermediate product of the process or present day electrical steel;

Figure 4 is a reproduction of an X-ray diffraction pattern characteristic of the finished product;

Figure 5 is a view showing the grain structure of the product;

Figure 6 is a view partly in section and partly in elevation showing a torsion dynamometer which I employ in testing specimens of the material during various stages of processing; and

Figures 7 through 10 are diagrammatic illus-

trations of the effect of the magnetic field of the torsion dynamometer on the specimens being tested.

In a preferred practice of my invention (shown diagrammatically in Figures 1 to 1e), which has given satisfactory results, I take hot rolled silicon steel strip of almost any commercial gauge, preferably between .065" and .100" thick, and subject the strip to alternate cold working and heat treatment in such a way that the magnetic moment of the cold rolled strip prior to the final heat treatment has a relatively small value. My investigations show that, if silicon steel has been properly processed in accordance with my invention, after the final cold rolling, it will exhibit a very low magnetic moment. Such material, however, after the final heat treatment, will develop a very high magnetic moment. While a low magnetic moment after final cold rolling and prior to the final heat treatment is not always conclusive evidence that the material possesses the desired characteristics, if the material has been properly processed, the final heat treatment will always result in a great increase in the magnetic moment, indicating high permeability at high flux densities. The range of hot strip gauge mentioned has been chosen for convenience but the actual gauge is not material to the invention.

For best results, I prefer hot rolled strip which has been finished at a relatively low temperature, for example, between 1200 and 1500° F., having a silicon content of about 3.6% or under. The method may also be applied to steels with higher silicon content with results which show a considerable improvement over present day silicon steels. The distribution of the cold working and heat treatment, however, must be varied for different percentages of silicon, and in accordance with the type and characteristics of the particular hot strip being used.

This distribution of cold working and heat treatment is the essential feature of the invention. The maximum magnetic moment is obtained in a predetermined manner by such proper distribution. This is distinguished also from mere cold work control, as the present invention requires an intermediate heat treatment between at least two cold working steps, the said steps and the said heat treatment being correlated to produce a definite product of predetermined characteristics; which product is characterized by a high magnetic moment approaching that of a single crystal, and the grains of the material being substantially oriented at random throughout the structure as shown by an X-ray pattern when the same is made normal to the plane of the material.

In order to insure uniformity of results in the finished product, I prefer to subject the hot rolled strip to an initial heat treatment. I find this step to be highly important from a commercial standpoint since it contributes markedly to the uniformity of the finished product. Users of electrical steel are interested not in spectacular characteristics of small portions of the material but in uniformity of characteristics upon which design calculations may reliably be based. This treatment also contributes to a higher maximum permeability at the higher flux densities and lower hysteresis loss in the finished product at such densities. For best results, the treatment is carried out in a strand-type continuous furnace. The strip in strand form is drawn through the furnace at a rate such as to permit it to attain a temperature of between about 1450-1700° F.,

so that complete re-crystallization is shown by X-ray diagrams. The exact temperature of the first heating operation depends upon the silicon content of the hot strip, and the temperature at which the hot strip was finished during hot rolling, and gauge of hot strip. A reducing atmosphere is maintained in the furnace in order to eliminate the necessity for pickling. After the strip has attained the desired recrystallization, it is cooled rapidly in a non-oxidizing atmosphere to prevent the formation of scale. This rapid cooling is for convenience and speed in production rather than for any effect on the material. The result would not be changed by a slower cooling rate.

After the initial heat treatment, the strip is subjected to cold rolling to reduce its thickness to an extent depending on the gauge, analysis, and finishing temperature of the hot strip and the desired finished gauge of the final product, and may vary between about .025" and .040". Ordinarily, strip of about .075" thick will be reduced in the first cold rolling to about .035" if the desired ultimate thickness is .014". As a further example, if the desired finished gauge is .012", the .075" hot strip is initially cold rolled to about .029" for maximum results. As previously intimated, the distribution of the cold working between successive heat treating steps is of considerable importance. The variations in such distribution will become more apparent from a consideration of specific examples of processes to be given later. The cold rolling of the strip may conveniently be carried on in a four-high or backed mill which employs small working rolls. As a matter of convenience and economy of manufacture, large coils will be employed, weighing up to three tons or more. After the initial cold rolling X-ray diagrams show that the material is characterized by only a slight preferred orientation, and complete fragmentation of the grains, in the plane of rolling.

After the initial cold rolling, the strip is subjected to a further heat treatment. This treatment is also effected in a continuous strand-type furnace and in a reducing atmosphere, the strip being drawn through the furnace at a rate such that it is heated to a temperature of between 1500 and 1850° F. for a time sufficient to produce recrystallization which, as before, varies depending upon the silicon content, the other characteristics of the hot strip above mentioned, and the gauge at which the initial cold rolling is stopped. After the strip has reached the proper temperature, it emerges from the furnace and is rapidly cooled in a non-oxidizing atmosphere. The X-ray diagram of the intermediate heat-treated material always shows that a reduction in grain distortion, substantially random grain distribution and complete recrystallization have been accomplished.

The next step in the method of my invention is a further cold rolling of the strip. This time the strip is reduced to the predetermined desired final gauge. This second cold rolling is also preferably effected in a four-high backed mill with small working rolls. After it has been given the final rolling the strip is characterized by a relatively low magnetic moment, uniform gauge and freedom from pitting or scale, and the characteristics generally similar to those recited above for the initially cold-rolled material.

The strip which has been rolled to finished gauge is then subjected to a final heat treatment, the method of application of which can be varied

in a number of ways. As a preferred method, the strip is continuously strand-annealed at a temperature between about 1600 and 2000° F. and rapidly cooled in air. The exact temperature varies with the silicon content. When desirable, the material can be sheared into sheets, heated to a temperature as indicated above, in a reducing atmosphere, and cooled rapidly under non-oxidizing conditions, or the cold rolled strip can be stamped into pieces of the shape required for electrical purposes and the pieces placed in appropriate containers and run through a furnace having a non-oxidizing or slightly oxidizing atmosphere, at the required temperature. The temperature is chosen by a consideration of the magnitude of the magnetic moment which can be developed in the material being worked, at various temperatures, as shown by tests made on specimen runs, in the torsion dynamometer, as more fully explained later. If the maximum magnetic moment is attained at 1850°, that is obviously the proper value, but if the maximum moment is developed at 2000°, then, of course, the lower temperatures would not be sufficient for the best results.

After the final heating, the material is batch annealed either in sheet form or after punching, shearing, or stamping, to impart to it the desired non-aging characteristic, and to reduce the watt loss. The preferred temperature is between 1200 and 1400°.

Tests of the product of the above described process show it to be characterized by a high magnetic moment. This means that the material has a magnetization curve with a high knee, indicating high permeabilities at high flux densities, e. g., from two to eight times that of the present-day hot-rolled sheet. Figure 2 illustrates typical magnetization and permeability curves for the material produced by my method at A and B, respectively. It will be observed that the knee of the magnetization curve occurs at a flux density of about 16,000 lines per sq. cm. The maximum permeability occurs at approximately 7,500 lines per sq. cm. and at that point is about 14,000. Similar characteristics of a typical example of the best electrical steel from present-day processes are also illustrated in Figure 2, the magnetization and permeability curves therefor being shown at C and D. The superiority of the product of my method at all flux densities will readily be apparent from a comparison of the curves.

Curves E and F are magnetization and permeability curves for a further example of the product of my method. These curves show a maximum permeability of about 19,000 at a flux density of 7500 lines. This material exhibited a total loss of .472 watts per lb. at a flux density of 10,000 lines and a frequency of 60 cycles. The magnetic moment does not appear to be changed materially by further heat treatment in addition to that already described, but it has been found by experiment that the total watt loss is reduced thereby. Such treatment may or may not decrease the maximum permeability, but in every case the knee of the curve is raised slightly, which means that the permeabilities at the higher flux densities are increased. The lowered watt loss and increased permeability at the higher flux densities appear to be companion phenomena.

Curve M of Figure 2 illustrates the magnetization characteristic of a further example of the product by my method. The following table indicates numerically the characteristics of the

product of my method as compared with present day electrical steel:

Comparison of permeabilities at various flux densities of silicon steel (3%) made by my method and the average best grade of silicon steel (4.25%) made in the regular way.

Flux density gauss	Percent increase in permeability shown by product of method disclosed herein
	Percent
2,000	14.37
4,000	30.5
6,000	47.8
8,000	68.8
10,000	105
12,000	221
14,000	800
16,000	514
18,000	200

The silicon content of the specimens of which the characteristics are shown in curves A, C and E were 3.5%, 1% and 3.4% respectively. The superiority of the product of my invention would be even more apparent, especially at the higher flux densities, if the specimens all had the same silicon content.

The fact that my invention imparts to comparatively low silicon steel, characteristics equal or superior to those characterizing high silicon steel processed by former methods, is an important advantage, since it is well known that the lower the silicon content, the greater the ease of working the metal, particularly in the matter of melting. The cost of the product is reduced in proportion.

Tests on commercial types of transformers having cores made from steel produced in accordance with my invention give very significant results. These transformers were operated at a flux density of about 12,000 lines per square centimeter and exhibited an average watt loss of about 49.6 watts. The average exciting current was 2.34 amperes. A similar transformer having a core made of the best grade of commercial electrical steel showed an average watt loss of 51.2 watts at a density of 12,000 lines per square centimeter, and an average exciting current of 4.05 amperes. The tremendous improvement in transformer construction which is made possible by my invention will be apparent from a consideration of the fact that since the same flux density can be obtained with a lower exciting current, it is possible to materially reduce the amount of iron in transformer cores if the exciting current is maintained at values which are found necessary with present day steel. The reduction in the amount of iron necessary, of course, results in a corresponding reduction in the total transformer losses since there are fewer pounds of iron involved. The smaller core section thereby permitted reduces the amount of copper necessary for a given number of ampere turns, and this further reduces the total loss.

Figure 3 illustrates in curve G the values of magnetic moment obtained with a specimen having a gauge of about .014", which was essentially a single, silicon-steel crystal, as shown by X-ray diffraction patterns and etching. In curve H are shown the values obtained with a fine-grained silicon steel aggregate made in accordance with this invention. The similarity is obvious. These characteristics were obtained by a proper distri-

bution of heat-treating and cold rolling, as already described. The permeability curve of this particular sample is shown in Figure 2, at F, and was determined by measurements made on a standard Fahy permeameter. The ordinates in Figure 3 are merely arbitrary and show the magnitude of the angle of deflection between the perpendicular to the direction of rolling in a disk specimen and the axis of a magnetizing field excited to saturation, for various angular positions of the field relative to the normal position assumed by the line indicating the direction of rolling with the specimens freely suspended in the absence of the field. Curve J is a typical torsion dynamometer curve showing the moments of a sample in partly finished, cold-rolled condition before the final heat treatment is given. This is about the type of curve shown by present day silicon steel. It will be noted that after the heat treatment has been given, the magnetic moment of the aggregate is increased to the values of curve H. A low moment before final heat treatment, however, does not always signify that a high moment will be found after the heat treatment. I have observed that, in general, when the hot rolled strip is cold rolled continuously down to the finished gauges, the resulting magnetic moment of such material is relatively high, before receiving the final heat treatment. Upon heat treating, the magnetic moment of the cold-rolled material decreases, which means that the permeabilities at the higher flux densities, and the knee of the magnetization curve are lowered appreciably. By proper distribution of heat treatment and cold working, therefore, I produce a material having low losses, a high moment, and permeabilities approaching those of a single crystal.

The apparatus which I employ for testing the magnetic moment is shown in Figure 6 and is essentially the same as that used by Weiss and others in the study of single magnetic crystals. The apparatus comprises a base 10 supported on adjusting screws 11. A rim 12 extends upwardly from the base and is graduated in degrees. A central post or shaft 13 is screwed into the base 10. A table 14 is rotatable about the post 13 and is supported on anti-friction bearings 14A. The table 14 is of magnetic material while the base 10 is of non-magnetic material. Cores 15 are secured in diametrically opposite positions on the table 14 and are provided with pole pieces 16. Magnetizing coils 17 are wound around the cores 15 and are connected to any suitable source of current supply, preferably through slip rings (not shown) mounted on the post 13.

A suspension frame is composed of columns 18 secured to the base 10 and a copper bridge bar 19 attached to the upper ends of the columns. A suspension screw 20 is threaded through the bar 19. A specimen holder 21 is attached to a bronze suspending wire 22 by a strap 23. A mirror 24 is mounted on the strap 23. The specimen is indicated in the holder at 25. Damping vanes 26 are attached to the holder 21 and dip into a viscous fluid in a cup 27 on the post 13.

The manner of utilizing the apparatus just described for testing the magnetic moment of specimens is as follows:

The specimen 25 in the form of a thin circular disk is attached to the holder by means of shellac. The zero position of the suspension is determined by observing in the mirror 24 through a telescope, the image of a scale suitably attached thereto in the manner of the ordinary tangent

galvanometer. The magnetizing coils 17 are then energized and the deflections on an arbitrary scale in millimeters are observed for various angles between the axis of the magnetic field and the direction of rolling of the disk when freely suspended. When the direction of rolling is at right angles to the magnetizing field H, as shown in Figure 7, the deflection is zero. As the magnet is rotated in either direction from this position, the tendency is for the specimen to follow the magnetizing field H. The stronger the induction or the greater the ease of magnetization in the specimen under examination, the greater will be the maximum deflection, as shown in the torsion curve of Figure 3. For rapid determination of the magnetic and electrical characteristics of silicon steel or magnetic alloys, the maximum deflections only are recorded, as well as the deflections when the magnetizing field is in line with the direction of rolling. Such relation should produce no deflection and if it does, the product is inferior.

This apparatus affords a means for rapidly and accurately checking the magnetic properties of any particular specimen and also permits the determination in advance of the proper processing steps for a given kind of material to produce the optimum magnetic characteristics.

The derivation of the curves shown in Figure 3 may be understood more fully by a study of Figures 7 through 10, which are partial, diagrammatic views illustrating the effect of rotation of the magnetic field upon the position of the circular disk specimen. The perpendicular to the direction of rolling is indicated by a solid, double-pointed arrow 30 of a length shorter than the diameter of the disk. In Figure 7, the arrow 30 coincides with the axis of the magnetic field extending between the poles 16. There is no observable deflection of the disk. On rotation of the magnetic field in either direction, however, the specimen is immediately deflected. As shown by Figure 3, the deflection increases steadily as the angle between the axis of the field and the arrow 30 increases to about 25°. Further movement of the magnetic field in the same direction results in a sharp drop in the deflection and the curve crosses the axis at about 38°. I conclude from this fact that, in addition to the line at right angles to the direction of rolling, there is a second path of easy induction parallel to the direction of rolling. Since the induction in the direction of rolling appears to be even greater than in a line at right angles thereto, I have designated it by a second double-pointed arrow 31 of a length substantially equal to the diameter of the disk. At an angle of about 38°, then, the torques exerted on the disk 25 in opposite directions by the effects of the magnetic fields acting through the paths 30 and 31 are substantially equal. Further rotation of the field causes the deflection to attain a negative value even greater than the initial positive maximum. The negative maximum is attained at substantially 55°.

Figure 8 illustrates the position assumed by the disk 25 with the field at a 45° angle to its original position. The positions assumed by the arrows 30 and 31 upon excitations of the field are shown in dotted lines, the solid arrows indicating the freely suspended position which corresponds to the zero position illustrated in Figure 7.

After the initial negative maximum is traversed, the deflection of the disk specimen decreases and again drops to zero when the field is parallel

to the rolling direction. This condition is illustrated in Figure 9. Further movement of the field causes a second reversal of the deflection which rises to a second positive maximum at about 125°. Substantially this condition is illustrated in Figure 10.

After passing through the second positive maximum, the deflection again falls to zero when the torques in opposite directions resulting from the effect of the field on the two perpendicular paths of easiest induction are equal. The completion of the 180° cycle duplicates the initial portion of the curve except that it is of opposite direction.

I have found upon testing a large number of specimens of material produced by the method disclosed herein that their torsion curves, such as those shown in Figure 3, cross the axis at substantially corresponding points. This indicates a high degree of uniformity in the product. Electrical sheets made by other methods show a widely varying range of crossings indicating clearly a lack of uniformity in the material which impairs the magnetic qualities. It is also important that the torque on the specimen be substantially zero when the magnetic field is in line with and at right angles to the direction of rolling. This means that the path of easiest induction is directly in line with the rolling direction. If the torsion curve crosses the axis at a point materially removed from the zero position, the path of easiest induction is at substantial angle to the direction of rolling and therefore an impairment to the electrical quality of the product is indicated, even if a high moment is shown. The permeability is lowered appreciably as a result of this condition and the dynamometer curve is very irregular.

It is obviously of great importance to predetermine the exact temperatures to which any lot of strip should be subjected after the several cold rolling operations, in order to produce the maximum values of the desired magnetic properties. Excellent results can be obtained by taking samples of each lot of material and subjecting them to different temperatures after cold rolling and testing the finished product for magnetic moment. The results of such tests will indicate clearly the proper treatment for the remainder of the particular lot being processed.

Referring now to Figure 4, showing the X-ray diffraction pattern of the material produced by my process, it will be observed that this pattern indicates that the grains are substantially free of distortion, uniform in size, and distributed at random. These conclusions follow from the symmetrical arrangement of the spots on the pattern and the absence of radial lines, according to established standards of interpreting diffraction patterns. The pattern reproduced in Figure 4 was a result of a beam of X-ray projected at right angles to the plane of the material.

Similar radiographs of hot rolled electrical sheets, as produced by previous methods, show a distortion of the grains and a lack of uniformity in size and distribution. In some cases, furthermore, a complete lack of recrystallization is evidenced.

Figure 5 illustrates on a somewhat magnified scale, (approx. 10X), the appearance of an etched piece of material made according to the present invention. It will be observed that the grains are remarkably uniform in size and have a random distribution. The actual size of the grains is 1.5 mm. or less.

While I have described herein the preferred

method of carrying out the invention, certain modifications thereof may be made. In so doing, however, there are certain things to be guarded against. If the hot rolled strip is cold rolled continuously to final gauge, for example, it will be found to have a high magnetic moment. As previously intimated, however, this material is not useful for electrical purposes because of its excessive losses. If the material is then heat treated at a high temperature, the magnetic moment will be low and will not be uniform! The magnetic qualities of the product will be only of the order of those of present-day silicon steel. If the hot rolled strip is first heat treated and then cold rolled to final gauge, the moment will be lower than when the cold rolling is performed without the heat treatment. If the material is heat treated, cold rolled to final gauge and again heat treated, the results are improved over those obtained when the final heat treatment is omitted.

In the preferred form of invention, of course, the hot rolled strip is initially heat treated, cold rolled to an intermediate gauge, again heat treated, cold rolled to final gauge and finally heat treated. These initial heating and rolling steps result in a product having a very low moment but when it is subjected to the final heat treatment, the moment is increased to values far beyond the range of ordinary silicon steel. In addition, I have noted that for materials of higher silicon content, the maximum deflection as determined by the dynamometer, are lower than in the case of lower silicon materials, which means that, in general, for the lower silicon materials, the permeability especially at saturation, will be greater than that of a higher silicon material.

As examples of slight modifications of the specific process described hereinabove as a preferred method, I wish to cite the following:

Percent silicon...	3.4	3.00	3.22	1
Gauge of hot rolled strip....	0.65	0.080	0.075	0.072
Temp. 1st heat treatment.....	1600° F.	1700° F.	1600° F.	1450° F.
First cold roll....	0.065 to 0.026	0.080 to 0.029	0.075 to 0.030	0.072 to 0.035
Second heat treatment.....	1700° F.	1680° F.	1700° F.	1525° F.
Second cold roll....	0.026 to 0.011	0.029 to 0.0125	0.030 to 0.012	0.035 to 0.011
Third heat treatment.....	2000° F.	2000° F.	1990° F.	1620° F.
Watt loss/lb B = 10000 60 cy....	0.47	0.60	0.49	No test
Permeability at various flux densities:				
B=10000.....	18,000	12,500	12,000	
B=14000.....	5,500	5,600	5,000	
B=16000.....	900	1,600	1,200	1,800
Nonaging annealing temperature.....	1300° F.	1300° F.	None given	
Watt loss/lb B = 10000 60 cy....	.45	.55		

It will be apparent from the foregoing description and explanation that the invention provides a highly useful product having characteristics far superior to those of similar commercial materials as made at present. The processing of the raw material is simple and inexpensive and can be accomplished rapidly and efficiently. The improved result made possible with lower silicon steels facilitates the manufacturing operations and reduces the cost thereof. A highly desirable finish characterizes the product of the process. Advantages result not only from the improved characteristics of the finished product but also from the processing method itself, since repeated handling of a large number of small sized pieces

of material is avoided, as well as frequent reheatings which have been necessary heretofore in the production of electrical sheets. Additional advantages result from the fact that the characteristics of the material produced by this method may readily be foreseen by subjecting small specimens to test runs and observing the characteristics obtained. In this way, the processing of an individual lot of material may be controlled so as to turn out a product having maximum values for the desired characteristics and any lack of uniformity in the raw material may be taken care of by varying the process slightly to insure the production of the best results. The empirical, cut-and-dry methods of the prior art lack the precision and certainty which characterize my invention and make it possible to manufacture a product conforming to customer's requirements within very narrow limits. Such a product made according to the present invention is characterized by ductility, ease of stamping, and a good surface condition. Its use in A. C. machinery, particularly induction motors, is indicated because of the advantageous overload characteristics, stacking factor, gauge, and low exciting current.

Although I have illustrated and described herein but a single preferred practice of my invention and the product resulting therefrom, it will be apparent that the invention may be practiced otherwise without departing from the spirit thereof or the scope of the appended claims.

The herein described method of testing is described and claimed in my divisional and co-pending application bearing Serial No. 729,311, filed June 6, 1934, and entitled "Method of making and testing magnetic material".

I claim:

1. In a method of making magnetic material in sheet-like form, the steps including heating hot-rolled steel of about 3% silicon content and about .075" thick to a temperature of about 1600° F. in a reducing atmosphere, cooling the heated strip in a non-oxidizing atmosphere, cold rolling the cooled strip to about .030" thick, reheating the cold rolled strip to a temperature of about 1700° F. in a reducing atmosphere, cooling the reheated strip in a non-oxidizing atmosphere, cold rolling it to about .012" thick, reheating the strip again to a temperature of about 2000° F. in a reducing atmosphere, and cooling it slowly in a non-oxidizing atmosphere.

2. In a method of making magnetic material, the steps including heating steel of moderate silicon content (i. e., 1-4%) and between .050" and .100" thick to a temperature of between about 1400° and 1700° F. in a non-oxidizing atmosphere, cooling the heated strip, cold rolling the cooled strip to between about .015" and .050" thick, reheating the cold-rolled strip in a non-oxidizing atmosphere to a temperature of between about 1500° and 1750° F., cooling the reheated strip, cold rolling it to about .012" thick, again reheating the strip in a non-oxidizing atmosphere to a temperature of about 2000° F. and cooling the strip slowly in a non-oxidizing atmosphere.

3. In a method of making magnetic material, the steps including heating silicon steel .100" thick or less to a temperature of between about 1400° and 1600° F., cooling the strip and cold rolling it to between about .020" and .040" thick, heating the strip to between about 1500° and 1800° F., cooling it and cold rolling it to about .013" thick, and finally heating the strip to about

2000° F. and cooling it in non-oxidizing atmosphere.

4. In a method of making magnetic material in sheet form, the steps including heating silicon steel of .100" thickness or less to an initial temperature of between about 1400° and 1700° F., cold rolling the steel to a thickness of about .030", heating it to an intermediate temperature of between about 1600° and 1800° F., further cold rolling it to about .013" thick and finally heating it to about 2000° F.

5. In a method of making magnetic material in sheet form, the steps including heating silicon steel to about 1600° F., cold rolling the steel to about one-half its original thickness, heating the steel to about 1700° F., cold rolling it again to from about one-sixth to one-seventh its original thickness and finally heating the steel to about 2000° F.

6. In a method of making magnetic material in sheet form, the steps including heating rolled silicon steel to about 1600° F., cold rolling the steel, heating the cold-rolled steel to about 1700° F., further cold rolling the steel and finally heating it to about 2000° F.

7. In a method of making magnetic material, the steps including cold rolling hot-rolled steel of silicon content between 1 and 4% and .100" thick or less to between .020" and .050" thick, heating the cold rolled strip to a temperature of between about 1500° and 1800° F. in a reducing atmosphere, cooling the reheated strip in a non-oxidizing atmosphere, cold rolling it to between about .005 and .020" thick, reheating the strip again to a temperature of about 2000° F. in a reducing atmosphere, and cooling it slowly in a non-oxidizing atmosphere.

8. In a method of making magnetic material, the steps including cold rolling steel strip of moderate silicon content (i. e. 1-4%) and about .070" thick to about .030" thick, reheating the cold-rolled strip in a non-oxidizing atmosphere to a temperature of between about 1660° and 1740° F., cooling the reheated strip, cold rolling it to between .010 and .015" thick, again reheating the strip in a non-oxidizing atmosphere to a temperature between about 1850° and 2100° F., and cooling the strip in a non-oxidizing atmosphere.

9. In a method of making magnetic material, the steps including cold rolling silicon steel strip about between .050" and .100" thick to between .020" and .050" thick, heating the strip to between about 1500° and 1800° F., cooling it and cold rolling it to between about .010" and .015" thick, and finally heating the strip to about 2000° F. and cooling it in a non-oxidizing atmosphere.

10. In a method of making magnetic material, the steps including cold rolling silicon steel of between about .060" and .080" thickness to a thickness of between about .020" and .040", heating it to an intermediate temperature of between about 1600° and 1800° F., further cold rolling it to between about .010" and .015" thick and finally heating it to between about 1900° and 2100° F.

11. In a method of making magnetic material, the steps including cold rolling silicon steel to about one-half its original thickness, heating the steel to between about 1650° and 1750° F., cold rolling it again to about one-sixth its original thickness and finally heating the steel to between about 1900 and 2100° F.

12. In a method of making magnetic material, the steps including cold rolling silicon steel, heating the cold-rolled steel to between about 1600°

and 1800° F., further cold rolling the steel and finally heating it to between about 1900 and 2100° F.

13. Magnetic material of steel having a silicon content of less than 4%, small uniform grains, a permeability in excess of 18,000 at an induction of 7,500 lines sq. cm., and an X-ray diffraction pattern having a plurality of points symmetrically disposed about the image of the central undiffracted beam, indicating a random orientation of the grains.

14. Magnetic material of steel sheets having a medium silicon content, small uniform grains, 1.5 mm. or less in diameter, and an X-ray diffraction pattern having a plurality of points symmetrically disposed about the image of the central undiffracted beam, indicating a random orientation of the grains.

15. Magnetic material of silicon sheet steel containing up to 5% silicon and having a low exciting current at high flux densities, said material having in its ductile form a high magnetic moment approaching that of a single crystal, and an X-ray pattern of random orientation of grains throughout the structure when the X-ray pattern is made normal to the plane of the sheet.

16. As a new commercial magnetic material, a fine grained aggregate of silicon steel having the magnetic moment characteristic of a single crystal and an X-ray diffraction pattern having a plurality of points symmetrically disposed about the image of the central undiffracted beam, indicating a random orientation of the grains.

17. In a method of producing commercial ferromagnetic material of definite and uniform desirable characteristics, the steps of cold rolling and heat treating the material at a temperature predetermined in process to produce its maximum magnetic moment.

18. In a method of producing commercial magnetic material of definite and uniform desirable characteristics, the steps of cold rolling silicon steel to effect a reduction of the order of approximately 60%, and then heat treating at a temperature predetermined in process to develop its maximum magnetic moment.

19. In a method of producing commercial magnetic material of definite and uniform desirable characteristics, comprising cold rolling silicon steel in at least two separate cold rolling steps with at least one complete recrystallization step therebetween and finally heat treating after the last cold rolling step at a temperature predetermined upon the specific material to impart a magnetic moment approaching that of a single crystal.

20. In a method of making magnetic material, the steps including cold rolling silicon steel, heating the cold-rolled steel to between about 1600° and 1800° F. for a time sufficient to produce substantially complete recrystallization, further cold rolling the steel and finally heating it to between about 1900 and 2100° F.

NORMAN P. GOSS.

35	110
40	115
45	120
50	125
55	130
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65	140
70	145
75	150