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METHOD OF ANNEALING MAGNETIC MATERIAL

Charles A. Scharschu, Brackenridge, Pa., assignor to Allegheny Ludlum Steel Corporation, a corporation of Pennsylvania

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This invention relates to magnetic material and more particularly to the annealing of magnetic material such as silicon steel after the same has been reduced to sheet or strip of the desired gauge, and an object is to provide a simple open or continuous annealing method for such material whereby high magnetic and electrical values are obtained and the material is rendered non-aging as that term is now understood.

Another object is to provide an open or continuous anneal capable of developing in silicon steel sheets, strips, or punchings produced therefrom permanent magnetic and electrical values of a high order.

A further object is to provide a simple open annealing method for silicon steel sheets, strips and punchings by means of which the same can be rendered non-aging and will have higher magnetic and electrical values than are now obtained by any commercial annealing procedure.

A still further object is to provide a simple open or continuous anneal for silicon steel sheet-like material whereby after annealing, such material is flat, non-aging, and has an extremely low watt loss value and high permeability.

A still further object is to provide a continuous anneal for silicon steel whereby the same is rendered non-aging, flat, free from coil set and given better magnetic and electrical values than are now obtained by means of any commercial annealing method.

A further and more limited object is to provide an anneal for silicon steel sheet-like material having a silicon content of from .50–7% by means of which such material is rendered non-aging and has developed therein lower watt loss values than heretofore obtained by any commercially practicable annealing method.

These and other objects are attained by the method hereinafter described and claimed.

Producers of magnetic or electrical steel have three very definite requirements to meet.

First, the material must have permanent satisfactory magnetic electrical values, second, it must have satisfactory mechanical properties and third, it must be flat.

If the material is silicon steel, the silicon content may run from ½% to 7% depending upon the magnetic properties desired. For transformers and like equipment where the energy loss is an important factor, silicon steels having a silicon content of 4% or more are generally used. Generally speaking, steels having a high silicon content have the lowest energy losses, but as the silicon is increased, the brittleness of the material increases so that even in very thin sheets, the material is difficult to punch and shear and breaks easily when handled. It is therefore common practice, in order to obtain good mechanical properties, to keep the silicon content as low as it is possible to do and still obtain the required magnetic and electrical values.

The best transformer grades average approximately 4½% silicon, while the grades used for motors and other rotating apparatus, where the energy loss is not so important, contain as little as ½ percent silicon. The transformer grade containing 4% or more silicon is the highest grade and obviously is the most difficult to produce because of the exacting requirements it has to meet.

Producers of magnetic material usually furnish the same in the annealed condition and under definite specifications as to magnetic and electrical characteristics, ductility and flatness.

Flatness is required because the space factor is of importance in the laminated structure in the make-up of which this material is employed and for the reason that it is impossible to employ mechanical flattening for material which has become distorted during annealing. Any mechanical flattening after annealing destroys the magnetic and electrical values of this material, thus making it unfit for the purpose intended.

Silicon steel in sheet-like form, which includes both sheet and strip, is largely used as magnetic material in the building up of laminated structures such as cores for electrical apparatus and since the magnetic and electrical values are in large part due to the annealing procedure to which the finished material is subjected, many and various annealing procedures have been used or from time to time tried or suggested.

One of the oldest and probably the most widely used procedure for annealing the finished mate-

rial is what is known as box annealing. In carrying out this type of annealing, hot rolled sheets commonly 108" long x 36" wide x .014" thick are first cold rolled to obtain flatness (this step is sometimes omitted) and then annealed in stacks having a total weight of as much as 30,000 pounds. The annealing temperature varies as much as from 1500 to 1800° F. and from 20 to 60 hours are utilized in bringing such a stack to annealing temperature. After reaching annealing temperature, the stack is usually held for a time at such temperature and then slowly cooled. The cooling period generally extends over a period of from 4 to 6 days.

In the stack annealing method (this applies to stacks which are contained in a box or to uncovered stacks in a furnace, as in the case of an electric furnace anneal), it is impossible to have a uniform rate of heating for all parts of the sheets making up such stacks since the outside edges of the sheets are bound to be considerably hotter than their middle portions. In order to bring the middle portions to annealing temperature, it is necessary to heat the edges to a temperature higher than that desired and it is necessary to maintain this higher temperature until the middle portions of the sheets reach the desired temperature.

It is therefore apparent that parts of the sheets are over-annealed while other portions are quite likely to be under-annealed. Under these conditions, optimum magnetic values are not often obtained. Holding the stack in the furnace until the center portions of the sheets reach the desired annealing temperature causes their outer edge portions to be oxidized to such an extent that such portions are much more brittle than the remainder of the sheets. Because of the temperature difference between the edge and middle portions, the sheets are apt to be distorted unless an extremely slow rate of cooling is used and extremely slow rates of cooling are not favorable to optimum magnetic or electrical values.

The disadvantages of box or stack annealing for magnetic material have long been recognized and many attempts have been made to improve annealing procedures for such material.

Since the continuous annealing procedures were early utilized for the annealing of other steels, continuous anneals of various types were early tried for the annealing of magnetic sheets of silicon steel. These early attempts at continuous annealing procedures for magnetic material met with but little if any success.

On October 12, 1915, William E. Ruder, in Patent No. 1,156,496 disclosed a single step high temperature continuous annealing procedure for silicon steel which, it was believed, would materially simplify the procedure necessary to develop therein magnetic and electrical values comparable to those obtained by the widely used box or stack annealing procedures.

It was found, however, that while the procedure of the Ruder patent did develop what, at that time were considered optimum values, such values were not permanent. The material when put to use deteriorated to such an extent that it lost efficiency at a fairly rapid rate amounting in some cases to as much as from 30 to 60%.

The discovery of this phenomenon or inherent fault which is now known as "aging," stimulated activity among the investigators and manufacturers in this field with the result that a number of more or less complicated procedures of the type disclosed in the early Hadfield patents made their appearance. These included double anneals—an open or continuous anneal followed by a box or stack anneal; two distinct continuous open anneals; a box anneal followed by a continuous anneal, and a variety of two step methods in some of which the material is raised to annealing temperature and then cooled by a slow and controlled step by step cooling procedure.

The procedure most commonly used commercially at the present time, however, is stack annealing, carried out either in the form of a box anneal or in the form of a high temperature electric furnace anneal. A controlled atmosphere is generally used in the case of electric furnace anneals and the temperatures are much higher than in the case of box annealing.

The disadvantages of stack annealing procedures no matter whether large or small stacks are used and no matter whether in the form of a box anneal or an electric furnace anneal, have long been recognized. The use of small stacks has some advantage over large stacks, but even with small stacks, it is impossible to overcome the temperature differences since most of the heat is conducted from the outside of the stacks to the center. Small stack annealing has many of the disadvantages of large stack annealing. Many of the disadvantages are inherent in both types.

Methods of annealing in which single sheets are passed through a furnace on a belt or conveyor or in which the sheets are welded together into a continuous strip and passed through a furnace are old. These single sheet anneals lack many of the disadvantages of the stack annealing methods since the sheets can be uniformly heated and uniformly cooled and since all parts of the sheets can be subjected to the same treatment. The annealing may be controlled so that if the sheets are flat to start with they can be brought from the anneal in flat condition.

One step single sheet or open anneals, while widely investigated, particularly since the issuance of said Ruder patent, are not however utilized commercially at the present time and this is probably due to the fact that all magnetic material heretofore annealed by a one step single sheet or open anneal has been found to age even when the material has been held at annealing temperature for as long a period as ten minutes.

One method of rendering permanent the high magnetic and electrical values developed by an open or single sheet anneal is to follow such open annealing step by a box anneal as disclosed in Caugherty Patent No. 1,991,351 of Feb. 12, 1935.

While such an annealing procedure produces non-aging material having magnetic and electrical values fairly comparable to those obtained by the known single sheet annealing methods, it has all the disadvantages of the box or stack anneal plus the added step of the open or single sheet anneal.

Another method suggested for the purpose of producing non-aging material is the procedure set forth in Morrill Patent No. 1,919,983, of July 25, 1933 wherein a single sheet anneal precedes the punching operation for producing the laminae used for the building up of the core structures and this is followed by a second anneal to which the punchings or laminae are subjected.

In an application filed by me and serially numbered 683,476 (now Patent No. 2,104,169 issued January 4, 1938) I have disclosed an an-

nealing procedure for obtaining non-aging silicon steel strip which is free from coil set. The procedure there outlined consists of two steps. The first step may be either a box anneal or a continuous anneal followed by a cooling step. This is followed by a second anneal in which the strip while flat is passed through an annealing furnace, is raised to a temperature within a temperature range of from 1000–1300° F. and then cooled while in a flat condition.

Early in the development of the continuous anneal for silicon steel sheets, it was believed that optimum electrical and magnetic values could be reached in from about five to ten minutes. The aging phenomenon was then unknown and I believe that because of the fact that this was unknown and because of the fact that values then considered high were obtained in such a short time anneal, I and others investigating annealing procedures in connection with magnetic materials did not prolong the heating period for a length of time such as I have now found necessary to prevent the material from aging.

When the aging phenomenon was discovered, instead of prolonging the time at annealing temperature, I as well as others working in this field went to one of the more complicated and elaborate procedures, and this was undoubtedly due to the fact that by a five or ten minute period what were then considered optimum magnetic and electrical values were obtained. Prolonging the annealing period up to from twenty to twenty-five minutes did not show any appreciable improvement and did not produce non-aging material. It seemed apparent that something more than a prolongation of the time was necessary.

Manufacturers of silicon steel sheet and strip material have shown reluctance to entirely abandon short time open or continuous anneals, but with the knowledge that material so annealed is subject to the aging phenomenon, and in order to obtain in a non-aging material the magnetic and electrical values developed by such an anneal, have utilized such an anneal as one of the steps in one of the more complicated annealing procedures.

While the annealing of silicon steel sheets for use as magnetic material has been studied and experimented with since the advent of this material in about 1903, and while single sheet and other open and continuous anneals have been widely investigated, there is not, so far as I know, a single producer of this material using a single sheet or open anneal at the present time unless, as I have said, as one step in a more or less complicated annealing procedure. This is undoubtedly due to the fact that no one with a single step single sheet anneal has heretofore produced non-aging material.

Before the phenomenon of aging was discovered, silicon steel sheets .014" thick were annealed at from 1500–1550° F. for from 8–10 minutes and in some cases material having a watt loss (watts per pound at 60 cycles, 10,000 B) as low as .550 was obtained. The results, however, were not consistent; some heats showed low losses, while others consistently showed very high losses. After this material had been in use for some time, it was discovered that its loss in magnetic and electrical values amounted to from 30–60%.

Aging, which makes itself known by a gradual increase of hysteresis loss during use, is determined as the percentage of increase of total watt loss after the material has been held at 212° F. for 600 hours. The aging process is not necessarily complete at the end of that period, but the greater part of the loss occurs within 600 hours.

In making certain experiments in connection with the annealing of magnetic material, I was led to believe that it might be worth while to materially increase the time at annealing temperature in an open annealing procedure and I therefore carried out certain experiments on hot rolled silicon steel sheets .014" thick and taken from six different heats. These sheets were drawn through a muffle-type furnace having a non-oxidizing atmosphere; the furnace temperature being 1500° F.

I subjected sheets from each of these heats to the old annealing periods advocated and utilized in open anneals for silicon steels before knowledge of the aging phenomenon became generally known in this art. These periods were three and ten minutes respectively, at 1500° F. Other sheets from the same heats were held at the same temperature for thirty and sixty minutes respectively. The sheets were tack-welded together to form a continuous strip and were placed under tension during annealing and cooling by being drawn through the furnace and to the far end of the cooling space in the open air. The strips were arranged two high, that is, one strip was placed on top of the other and after the annealing period was completed, the strips which emerged directly from the furnace to the open air were quickly cooled. After being cooled, the sheets were sheared into Epstein samples and tested. The results of these experiments are indicated in the following Table I. The silicon content is given in each case. The loss in watts per pound at 10,000 B and 60 cycles is given and includes cutting strains.

TABLE I

	Heat					
	A	B	C	D	E	F
Silicon content....percent..	4.51	4.42	4.54	4.33	4.62	3.81
(1) 3 min. at temperature...	1.014	.766	.753	.783	.710	.742
(2) 10 min. at temperature..	.646	.631	.636	.760	.541	.687
(3) 30 min. at temperature..	.492	.545	.578	.744	.531	.632
(4) 60 min. at temperature..	.492	.503	.505	.583	.484	.632

It will be observed that in the case of heats A and F optimum results were not reached until 30 minutes and in the case of heats B, C, D, and E optimum results were not reached until 60 minutes. The table further shows that in every case a 30 minute anneal greatly improved the material and that when the material was annealed for less than 30 minutes the results were poor for present day material.

It is apparent that by prolonging the time at temperature for a minimum of thirty minutes, I obtain material having a much lower watt loss than is obtainable by any commercial annealing method now in use. In order to ascertain the permanency of these values, I subjected the material annealed by the thirty and sixty minute periods, represented by (3) and (4), to the standard aging treatment. The results of such treatment are indicated by the following Table II, wherein the figures indicate losses in watts per pound at 10,000 B and 60 cycles with cutting strains included.

TABLE II

	Heat					
	A	B	C	D	E	F
(3) 30 min. at temperature..	.492	.545	.578	.744	.531	.632
(3a) After aging treatment..	.492	.542	.573	.744	.531	.630
(4) 60 min. at temperature..	.492	.503	.505	.583	.484	.632
(4a) After aging treatment..	.494	.500	.508	.583	.484	.630

As evidenced by Table II this material does not age when subjected to the standard aging test which allows for an increase of 5% in watt loss value. In no case as shown by Table II has there been any increase equaling the permissible increase and what increase there is, is less than one half of one percent.

I have also discovered that punchings produced from unannealed sheet or strip material can be annealed by this method with the same excellent results as long as the time of anneal, temperature of anneal and mass of material are correlated in accordance with the principles of my invention as herein set forth.

For example, when punchings were annealed three deep on a belt-like conveyor in a continuous furnace at 1500° F.; the speed of the conveyor being adjusted so that the punchings were at temperature for one hour, the results of line (1) Table III were obtained. The figures represent the apparent average permeability of a number of test pieces.

TABLE III

Apparent average permeability

	40B	200B	2000B
(1)	1330	1980	4880
(2)	773	1440	3840
(3)	1200	2060	4980
(4)	1120	2040	5070

When punchings were annealed in stacks one and one half inches thick (twenty five times as much material as in the previous test) for one hour at 1550° F., inferior results were obtained as is evidenced by line (2) of Table III indicating decreased permeabilities at the specified flux densities. However, when the mass was taken into account and the time of anneal was increased to one and one-half hours, I obtained the results indicated by line (3) of Table III wherein the permeabilities are shown to have returned to approximately those of line (1). When, however, I increased the temperature to 1650° F. only one hour was required to obtain the satisfactory results set forth in line (4) of Table III.

From the foregoing it is apparent that in order to produce permanent satisfactory results, the annealing temperature, the time during which the material is subjected to such temperature and the mass have a certain definite relationship.

I have discovered that if I employ an open annealing procedure in which the material is quickly brought to annealing temperature, is held at such temperature for at least thirty minutes and then quickly cooled, I not only obtain non-aging material, but I obtain material having higher magnetic and electrical values than have ever before been obtained. Such material when subjected to the standard aging tests shows much less loss of values than does material annealed in any other way.

The remarkable thing is that if a continuous open anneal is carried out so that the material is quickly heated, remains at annealing temperature (from 1450–1650° F., which is a relatively low and favorable temperature) for from 30 minutes to one and one half hours, depending upon the mass being treated and the temperature used, and is then quickly cooled, as by cooling in the open air, I obtain not only non-aging material, but material having magnetic and electrical values, which, so far as I know, are higher than have ever been before obtained by any commercially practicable annealing procedure.

Thus it will be apparent that I provide a complete annealing cycle of comparatively short duration. The cycle includes the rapid heating of the material to annealing temperature, the maintenance of the material at annealing temperature for a period of time ranging from a minimum of 30 minutes to a maximum of approximately 90 minutes and then the rapid cooling as in air to 300° F. or to room temperature.

The method of this invention is suitable for the annealing of sheet-like material produced from silicon steel having a silicon content of from about .50% to about 7.00%. The material may be in the form of sheet or strip of finished gauge or in the form of punchings produced from such sheet or strip material.

In producing the material, to the annealing of which the method of this invention relates, any one of the successful commercial methods, including that disclosed in Browne Patent No. 1,784,811 of Dec. 16, 1930, may be utilized.

The rolling procedure used for reducing the material to either sheet or strip of finished gauge may be any one of the commercially successful methods now used. If the material is produced in the form of hot rolled sheets, the method disclosed in Cunningham Patent No. 1,081,370 of Dec. 16, 1913 may be found to be of advantage.

If the material is cold rolled strip, the method disclosed in Smith et al. Patent No. 1,915,766 of June 27, 1933 may be utilized in its production or the method disclosed in an application filed by Vere B. Brown and Wm. E. Caugherty and serially numbered 683,474 may be used. In fact, the method of this invention is suitable for the annealing of any silicon steel magnetic material of finished gauge, no matter how the material is produced, nor by what rolling procedure or procedures it is reduced to finished gauge.

In the annealing procedure, I preferably use a muffle furnace through which the material can be moved in a continuous manner. The furnace is preferably equipped with an endless conveyor (belt type preferred) capable of being so regulated as to speed that the time at temperature desired can be readily obtained.

If the material to be annealed is in the form of sheets, these can be placed upon the conveyor one, two or three deep; if in the form of punchings, these may be arranged on the conveyor in any desired manner which will maintain them flat and not too deep to be quickly and evenly heated as they enter the furnace and quickly and evenly cooled as they emerge from the furnace.

If desired, the sheets may be tack-welded together to form a continuous strip and this strip may be pulled through the furnace at the necessary speed and the strip maintained under sufficient tension to insure flatness. One, two or three such strips arranged in superposed relation may be annealed simultaneously arranging the time at temperature in accordance with the mass being treated.

In annealing strip, I pull the strips through the furnace under tension either singly or two or three ply and maintain the strips taut until cool. The strips can then be separated and coiled if desired or cut into suitable lengths.

The furnace atmosphere is preferably non-oxidizing and can either be neutral or reducing. I have found that the type of atmosphere is not critical, but I prefer an atmosphere which is non-oxidizing, or nearly so.

My anneal is the sole, complete and only heat treatment necessary after the material has been reduced to final or finished gauge. It does not follow any other heat treatment nor does it form part of any other annealing procedure.

Having thus described my invention, what I claim as new and desire to secure by Letters Patent is:

1. A method of annealing silicon steel sheet-like material to improve its magnetic properties and render the same non-aging which comprises rapidly heating the same to a temperature of from 1450 to 1650° F., in maintaining the same at temperature for from thirty minutes to one and one-half hours depending upon the mass of the material being treated, in rapidly cooling the same in air and in maintaining the same flat throughout such operations.

2. In the art of annealing magnetic sheet-like material to improve its magnetic properties and render the same non-aging, the steps which comprise rapidly heating such material, while maintaining it flat, to a temperature of from 1450 to about 1650° F., holding the same at such temperature under non-oxidizing conditions for at least thirty minutes, and then cooling the same rapidly in air while preventing it from distorting.

3. A method of annealing magnetic material in sheet or strip form which comprises continuously passing such material in such mass as can be rapidly and substantially uniformly heated through a zone of increased temperature such that the material is raised to a temperature between approximately 1450° F. and 1650° F., maintaining the material at temperature for a period of time between about thirty and ninety minutes and then rapidly air cooling the material.

4. A method of annealing a single thickness of magnetic material in sheet or strip form which comprises substantially uniformly heating such material to a temperature between approximately 1450° F. and 1650° F., maintaining the material at such temperature for a period of from thirty to ninety minutes and then immediately air cooling the material.

5. A method of annealing magnetic material in the form of silicon steel sheets or strips which comprises passing such material in a mass of but relatively few thicknesses deep through a zone wherein the material is rapidly and substantially uniformly raised to a temperature between approximately 1450° F. and 1650° F., maintaining such material at such temperature for a short time of the order of thirty to ninety minutes and then rapidly air cooling the material.

6. A method of treating silicon steel in sheet-like form having a silicon content ranging from about .50% to about 7.00% which has been reduced to final gauge and is in unannealed condition which comprises rapidly raising the temperature of such steel in such form to a temperature between about 1450° F. and 1650° F., maintaining the material at a temperature within such range for a period of time from a minimum of 30 minutes to a maximum of approximately 90 minutes and then rapidly cooling the same.

7. A method of treating silicon steel in sheet-like form which has been reduced to final gauge and is in unannealed condition which comprises subjecting such steel in such form to an annealing cycle of short duration, said annealing cycle including the steps of rapidly raising the material to a temperature between about 1450° F. and 1650° F., maintaining the material at such temperature for from about 30 to 90 minutes depending upon the mass of material and the temperature and rapidly cooling the same from such temperature.

8. A method of annealing magnetic material containing from about 0.5 to 7% silicon in sheet-like form which comprises continuously passing such material in a mass of but relatively few thicknesses deep through a zone wherein the material is rapidly and substantially uniformly raised to a temperature between about 1450° F. and 1650° F., maintaining such material at such temperature for a short time of the order of 30 to 90 minutes and then rapidly cooling the material in air.

9. A method of annealing magnetic silicon-containing material in sheet-like form which comprises continuously passing such material under tension through a muffle-type furnace in a non-oxidizing atmosphere in a relatively small mass so that the material is relatively rapidly raised to about 1450°–1650° F., maintaining the material at temperature for a period of time between about thirty and ninety minutes and then rapidly cooling the material in air.

10. An open or continuous anneal for magnetic silicon steel sheet, strip or punchings containing about 0.5-7% silicon which comprises the steps of rapidly and substantially uniformly heating said sheet, strip or punchings to about 1450–1650° F. in a relatively small mass, subjecting the same to such temperature for a period of time between about thirty and ninety minutes, immediately rapidly air cooling the material and correlating the time at temperature with the particular temperature within such range and the particular mass being treated in such relationship that the higher the temperature the shorter the time and the greater the mass the longer the time.

11. A method of annealing magnetic material in the form of silicon steel sheet, strip or punchings comprising the steps of passing such material through a muffle type furnace and in contact with the atmosphere maintained therein, of maintaining a temperature within said furnace such that the material is heated to the annealing temperature of from 1450 to 1650° F., of so arranging the material for its passage through such furnace that all parts of the same upon entering the furnace are quickly and uniformly raised to annealing temperature, of controlling the speed at which the material passes through the furnace so that it is subjected to the annealing temperature for from at least 30 minutes to 90 minutes depending upon the annealing temperature used within such range and the mass of material being annealed and then in quickly air cooling the material as it emerges from the furnace.

12. A method of annealing magnetic material in the form of silicon steel sheet, strip or punchings comprising the steps of passing such mate-

rial through a muffle type furnace and in contact with a non-oxidizing or substantially non-oxidizing atmosphere maintained therein, of maintaining a temperature within said furnace such that the material is heated to the annealing temperature of from 1450 to 1650° F., of so arranging the material for its passage through such furnace that all parts of the same upon entering the furnace are quickly and uniformly raised to annealing temperature, of controlling the speed at which the material passes through the furnace so that it is subjected to the annealing temperature for from at least 30 minutes to 90 minutes depending upon the annealing temperature used within such range and the mass of material being annealed and then in quickly air cooling the material as it emerges from the furnace.

CHARLES A. SCHARSCHU.