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3,276,923

REDUCTION IN MAGNETIC LOSSES IN ELECTRICAL INDUCTION APPARATUS**James M. McQuade, Pittsfield, Mass., assignor to General Electric Company, a corporation of New York****No. Drawing. Original application Apr. 17, 1961, Ser. No. 103,226, now Patent No. 3,169,236, dated Feb. 9, 1965. Divided and this application Sept. 28, 1964, Ser. No. 403,428****9 Claims. (Cl. 148—110)**

This is a division of application Serial No. 103,226, filed April 17, 1961, now Patent No. 3,169,236, assigned to the same assignee as the present application.

This invention relates to electrical induction apparatus, such as transformers, dynamos and the like, having members made from grain oriented silicon steels, and to a process for reducing magnetic losses in the apparatus by improving the cross-grain magnetic properties of the steels.

Magnetic steels having from about 2 to 6% silicon are widely used as core materials in electrical induction apparatus. Several well known commercial processes may be employed to produce an oriented grain structure in the steels so that the magnetic properties of the steel, such as watts loss and magnetostrictive strain, are relatively low in the direction of grain orientation. Such commercial processes usually include the following steps: a ferrous alloy containing up to about 6% silicon and relatively minor amounts of impurities is cast into ingots; hot worked, usually by rolling as a continuous strand; and then subjected to varying schedules of usually unidirectional cold rolling. The material is then heat-treated by several combinations of treating cycles which cause primary recrystallization of the grains, decarburization, secondary recrystallization of the grains, and purification by removal of sulfur and other impurities. The grain orientation of the magnetic steels produced by the above type of process is usually referred to as the (110) [001] type in the standard notation by Miller's indices. This designation is intended to indicate that the [001] direction of the crystals is parallel to the rolling direction and the (110) plane is parallel to the rolling plane. Considering the crystals as cubes, the designation indicates a cube on edge position of the crystal in the plane of the sheet.

Although the above described steels have excellent magnetic properties in the direction of grain orientation, their magnetic properties are relatively poor in the cross-grain direction. The poor cross-grain properties of the steels create numerous practical difficulties in the design and construction of electrical induction apparatus employing them as flux carrying core material. For example, in some electrical transformers, the cores are made from a plurality of stacked laminations of the grain oriented steels, with the direction of grain orientation being parallel to the longest sides of the laminations. When the magnetic flux traveling through the core laminations must change directions and travel across the grain, high watt losses and undesirable magnetostrictive effects occur in the areas where the flux travels across the grain. A particular example of such apparatus is a transformer having a rectangular core in which the flux travels with the grain through the major portion of the core but must travel across the grain at the corners of the core.

Various solutions to the problem of poor cross grain properties have been proposed by the prior art. These solutions include providing inserts with different grain orientations at the corners of the core, or subjecting the oriented steels to special processes whose only function is to alter the grain structure of the steel for improving its cross grain magnetic properties. These solutions are unsatisfactory in that they unduly increase the cost of the apparatus.

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In electrical induction apparatus having flux carrying members made from stacked laminations of grain oriented steels, it is often necessary that the individual laminations be separated by an insulating coating to reduce eddy current losses. Also, when a plurality of such laminations are stacked in contact with each other during high temperature anneal of the steel, it is desirable that they be coated with a material that prevents them from sticking together. A widely practiced commercial process for applying an insulating separator coating to silicon steels has been to apply a slurry of magnesium oxide (MgO) to the surface of the steel and then dry in air to evaporate water, thus leaving a powdery mixture of magnesium oxide and magnesium hydroxide [$Mg(OH)_2$] on the steel. Such a coating was normally applied before the final heat treating of the steel during which secondary recrystallization and purification occurred. When the steel was given its final heat treatment, a chemical reaction took place in which the water of hydration of the magnesium hydroxide was driven off and all of the magnesium oxide was available to combine with the silicon in the steel to form a high strength insulating coating of magnesium silicate (Mg_2SiO_4). However, this treatment has the disadvantage of increasing significantly the watt losses and magnetostriction in the cross-grain direction of the steel.

Accordingly, it is an object of the invention to provide electrical induction apparatus having flux carrying members made from grain oriented silicon steels with improved magnetic properties in selected areas where flux travels across the grain during energization of the apparatus.

A further object of the invention is to provide a process for improving the cross grain magnetic properties of grain oriented silicon steels used in electrical induction apparatus by coating the steels in the areas where flux travels across the grain with a film that also serves as non-sticking electrical insulation.

A further object of the invention is to provide a process for controlling the properties of silicon steel laminations in electrical induction apparatus at selected areas of the laminations where flux travels across the grain.

Other objects and advantages of the invention will become apparent from the description and claims which follow.

Briefly stated, according to one aspect of the invention, the cross-grain magnetic properties of grain oriented silicon steel used in flux carrying members of electrical induction apparatus may be improved in selected areas where the magnetic flux will travel across the grain by bonding a coating consisting essentially of beta calcium orthosilicate to the selected areas only. According to another aspect of the invention, a magnetic core for electrical induction apparatus made from a plurality of laminations of grain oriented silicon steels may have its cross grain magnetic properties improved in the areas where flux will travel across the grain by coating the laminations in the selected areas with beta calcium orthosilicate; the surface area of the laminations where flux travels with the grain should be free from the coating. The coating also serves the function of electrically insulating and separating the laminations. Thus by practicing my invention a coating that serves a triple function is provided for grain oriented steels used in electrical induction apparatus.

My tests have shown that when semi-processed, grain oriented silicon steel is coated with calcium hydroxide, a high strength insulating film can be formed during the final heating treating cycle, and the cross grain watt losses and magnetostriction of the steel decreased, rather than increased as they were in prior art coating processes. The expression "semi-processed" is intended to designate steels which have been processed to the extent that the type of

grain orientation they will have has been fixed, but that have not been given a final anneal during which secondary recrystallization and purification take place. A water slurry of the calcium hydroxide may be applied to selected areas of the steel where the flux is to pass in the cross grain direction during use of the steel in induction apparatus. This may be accomplished, for example, by masking off the areas it is not desired to coat and brushing the calcium hydroxide slurry on the selected areas. The calcium hydroxide slurry can also be applied to the selected areas by dipping, or by employing coating rolls with recessed surfaces. Other methods of applying calcium hydroxide are by dusting the dry powder on the selected areas, or by electrolytic coating. The steel coated with the calcium hydroxide slurry may then be dried in air for about one minute at about 200° C. to drive off water, and then subjected to the final heat treatment that causes secondary recrystallization and removal of impurities.

The final heat treating cycles for the semi-processed steels utilized in the prior art may vary from about 200 to 1250° C. for from 1 to 8 hours, depending on the particular sequence and range of heating and cooling steps followed. To obtain satisfactory results from my process, however, the final anneal should be carried out at the upper end of the temperature range between about 900 and 1250° C. for from 2 to 8 hours. During the final heat treatment, the water of hydration of the calcium compounds is driven off and a chemical reaction takes place between the resulting calcium oxide (CaO) and silicon dioxide (SiO₂) on the surface of the steel. Chemical analysis has revealed that the reaction product beta calcium orthosilicate ($\beta\text{Ca}_2\text{SiO}_4$) which is firmly bonded to the surface of the steel. The beta calcium orthosilicate coating on the steel has good electrical insulating properties and also has the effect of decreasing watt losses and magnetostriction strain in the cross-grain direction of the steel. The coating is refractory in nature and thus serves as an excellent separator of stacked laminations during the high temperature anneals.

In the practice of the invention, calcium hydroxide must not be applied to those areas of grain oriented silicon steel laminations where flux will travel in the with-grain direction between with-grain magnetic properties are harmed to the same extent that cross-grain properties are benefitted by the final beta calcium orthosilicate coating. The areas where flux will travel with the grain should have a different coating applied thereto. For example, magnesium silicate coatings produced by the previously described prior art process may be utilized by applying magnesium hydroxide to only the with-grain portions and annealing in the same manner used to produce the beta calcium orthosilicate coating. Thus the cross grain properties of the steel will be benefitted rather than harmed, and an insulating coating obtained without necessitating a special annealing cycle.

For the purpose of illustration, the following specific examples of processes in accord with my teachings are presented below:

EXAMPLE I

In a laboratory experiment, cross grain Epstein strips were prepared from semi-processed 3¼% silicon steel having a (110) [001] type of grain orientation; the steel was semi-processed in that it had not been given a final grain growth and purification anneal. The strips were coated with a water slurry of calcium hydroxide weighing about .02 ounce per square foot of coated surface and having a thickness of .2 mil per side. The strips were then dried in air to drive off the water. The strips were then annealed for 8 hours in a dry hydrogen atmosphere at 1175° C. The resulting coating of beta calcium orthosilicate had a thickness of about .1 mil. Epstein strips from the same lot of steel were also coated with magnesium hydroxide and processed in the same manner; the resulting coating was magnesium silicate. Uncoated strips

from the same lot were processed the same way to provide control samples. The uncoated control samples originally had a thin film of aluminum oxide (Al₂O₃) on the surface thereof to act as a separator coating; the film did not bind to the samples and had no insulation value. This coating fell off after the heat treatment leaving the finally treated strips uncoated. All strips were then tested individually for watt losses and magnetostriction, and the results are presented below in Table I. The values given are the average for seven samples.

Table I.—Cross-grain magnetic properties

Coating	Core Loss at 12,500 gauss (watts/lb.)	Magnetostriction Strain at 12,500 gauss (Microinches/inch)
Uncoated	1.01	10.0
Beta calcium orthosilicate	0.90	4.8
Magnesium silicate	1.13	12.0

Table I clearly shows that the cross-grain core losses of the strips coated with beta calcium orthosilicate decreased about 10% when compared with the uncoated samples, while the magnetostriction strain decreased over 50%. The strips coated with magnesium silicate showed an average increase in core losses across the grain of over 10% when compared with the control samples, while the magnetostriction strain increased about 20%.

EXAMPLE II

A different lot of semi-processed 3¼% silicon steel having the same orientation as in Example I was cut into cross-grain Epstein samples which were coated with calcium hydroxide, and magnesium hydroxide and then processed in the manner described with reference to Example I, except that the samples from this lot were annealed at about 980° C. for eight hours. The beta calcium orthosilicate coatings were about .1 mil thick. Uncoated control samples were also prepared. All samples were then tested for core loss in packs of 20, rather than being tested individually as in Example I. No tests were made for magnetostriction strain. The results of the tests are given below in Table II.

Table II.—Cross-grain magnetic properties

Coating:	Core loss at 15,000 gauss (watts/lb.)
Uncoated	1.91
Beta calcium orthosilicate	1.84
Magnesium silicate	1.98

Table II shows that the samples coated with beta calcium orthosilicate improved in cross-grain losses, but that the improvement was not as great as at the higher temperature anneal of Example I. The samples coated with magnesium silicate showed a slight increase in cross-grain core loss.

To obtain maximum benefit from the beta calcium orthosilicate coatings, the final grain growth and purification anneal should be carried out at the higher end of the temperature range used for such anneals. The preferred temperature range is from 1100 to 1250° C., and satisfactory results have been obtained in as little as two hours in that range. Cross-grain magnetic properties can be improved at temperatures down to about 900° C. in longer time cycles.

The beta calcium orthosilicate coatings produced from calcium hydroxide in accord with my invention satisfy the normal requirements for electrical insulation in that the coatings had Franklin values in the range of from .2 to .4 amperes, as determined by the standard Franklin test for determining the insulation value of this type of coating; in this test a reading of 1 ampere represents no surface insulation and reading of 0 ampere represents perfect insulation. Coatings with Franklin insulation values of .4 ampere and below are generally considered satis-

factory for silicon steels used as flux carrying members in electrical induction apparatus. The beta calcium orthosilicate films also have good adherence to the silicon steels in that the samples could be flexed without coating becoming loosened and falling off.

It has thus been shown that by the practice of my invention, magnetic losses in electrical induction apparatus can be reduced by controlling the properties of grain-oriented silicon steels used to make flux carrying members in selected areas where the flux travels across the grain during energization to the apparatus. I have shown that this can be accomplished by bonding a coating of beta calcium orthosilicate to the selective areas where the flux will travel in the cross-grain direction. This coating also has good insulating and separating properties and thus serves the triple function of insulating the material, preventing sticking at high temperatures, while also enabling control of magnetic properties in desired areas. Consequently, the necessity for a separate treating cycle having the sole function of improving the cross-grain properties of the steel is not required because the step of coating with an insulating material before the final heat treating anneal is normally practiced in commercial production of these steels.

It will be understood, of course, that while the forms of the invention herein described constitute preferred embodiments of the invention, it is not intended herein to describe all the equivalent forms or ramifications thereof. It will also be understood that words used are words of description rather than of limitation, and that various changes may be made without departing from the scope or spirit of the invention herein disclosed, and it is aimed in the appended claims to cover all such changes as fall within the true spirit and scope of the invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. The method of improving in selected areas the cross grain magnetic properties of a sheet of grain-oriented silicon steel for use in electrical induction apparatus in which magnetic flux will travel with the grain in some areas and across the grain in said selected areas when the apparatus is energized, which method comprises bonding to the selected areas only a coating consisting essentially of beta calcium orthosilicate.

2. The method of improving in selected areas the cross grain magnetic properties of a sheet of grain-oriented silicon steel for use in electrical induction apparatus in which magnetic flux will travel with the grain in some areas and across the grain in said selected areas when the apparatus is energized, which method comprises bonding to the selected areas only a coating consisting essentially of beta calcium orthosilicate, and at the same time bonding a different coating to the areas where flux travels with the grain.

3. The process for improving in selected areas the cross grain magnetic properties of a sheet of semi-processed, grain-oriented 2-6% silicon steel for use in electrical induction apparatus in which magnetic flux will travel with the grain in some areas and across the grain in said selected areas when the apparatus is energized, which process comprises applying calcium hydroxide to the selected areas only, while preventing the areas where the flux travels with the grain from being coated with calcium hydroxide, heating said sheet to from about 900 to 1250° C. for from two to eight hours, whereby a coating of beta calcium orthosilicate will be bonded to the surface of said selected areas only.

4. The process for improving in selected areas the cross-grain magnetic properties of a sheet of semi-processed grain-oriented 2-6% silicon steel for use in electrical induction apparatus in which magnetic flux will travel with the grain in some areas and across the grain in said selected areas when the apparatus is energized, which process comprises applying a water slurry of calcium hydroxide to the selected areas only, while prevent-

ing the areas where the flux travels with the grain from being coated with said slurry, heating said sheet to from about 900 to 1250° C. in a dry hydrogen atmosphere for from two to eight hours, whereby a coating of beta calcium orthosilicate will be bonded to the surface of said selected areas only.

5. The process for improving in selected areas the cross grain magnetic properties of a sheet of grain oriented 2-6% silicon steel for use in electrical induction apparatus in which magnetic flux will travel with the grain in some areas and across the grain in said selected areas when the apparatus is energized, which process comprises applying calcium hydroxide to the selected areas only, while preventing the areas where the flux travels with the grain from being coated with calcium hydroxide, heating said sheet for about eight hours at a temperature of from about 980 to 1175° C., whereby a coating of beta calcium orthosilicate will be bonded to the surface of said selected areas only.

6. The process for improving in selected areas the cross grain magnetic properties of a sheet of semiprocessed (110) [001] grain-oriented 2-6% silicon steel for use in electrical induction apparatus in which magnetic flux will travel with the grain in some areas and across the grain in said selected areas when the apparatus is energized, which process comprises applying calcium hydroxide to the selected areas only, while preventing the areas where the flux travels with the grain from being coated with calcium hydroxide, heating said sheet in a dry hydrogen atmosphere for eight hours at a temperature of about 1175° C., whereby a coating of beta calcium orthosilicate will be bonded to the surface of said selected areas only.

7. The process for improving in selected areas the cross grain magnetic properties of a sheet of semi-processed (110) [001] grain-oriented 2-6% silicon steel for use in electrical induction apparatus in which magnetic flux will travel with the grain in some areas and across the grain in said selected areas when the apparatus is energized, which process comprises applying calcium hydroxide to the selected areas only, while preventing the areas where the flux travels with the grain from being coated with calcium hydroxide, heating said sheets in a dry hydrogen atmosphere for eight hours at a temperature of about 980° C., whereby a coating of beta calcium orthosilicate will be bonded to the surface of said selected areas only.

8. The method of improving in selected areas the cross grain magnetic properties of a sheet of semi-processed (110) [001] grain-oriented 2-6% silicon steel for use in electrical induction apparatus in which magnetic flux will travel with the grain in some areas and across the grain in said selected areas when the apparatus is energized, which method comprises bonding to the selected areas only a coating of beta calcium orthosilicate, and at the same time bonding a magnesium silicate coating to the areas where flux travels with the grain.

9. The process for improving in selected areas the cross grain magnetic properties of laminations of semi-processed (110) [001] grain-oriented 2-6% silicon steel for use in electrical induction apparatus in which magnetic flux will travel with the grain in some areas and across the grain in said selected areas when the apparatus is energized, which process comprises applying calcium hydroxide to the selected areas only, while preventing the areas where the flux travels with the grain from being coated with calcium hydroxide, superimposing said laminations to form a stacked assembly, heating said assembly to from about 900 to 1250° C., in a dry hydrogen atmosphere for from two to eight hours, whereby an insulating and separating coating of beta calcium orthosilicate will be bonded to the surface of said selected areas only.

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