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J. SEIDEL ET AL

3,496,506

MAGNETIC CORE STRUCTURE

Filed Feb. 28, 1968

2 Sheets-Sheet 1

FIG. 1.

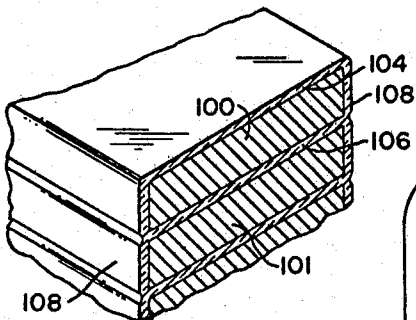
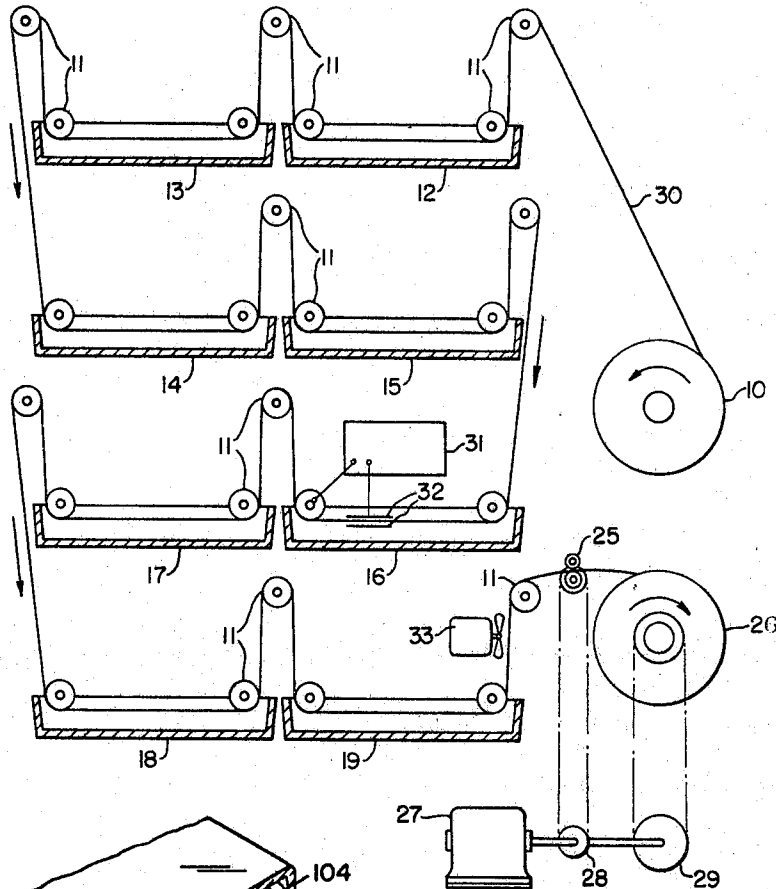


FIG. 4.

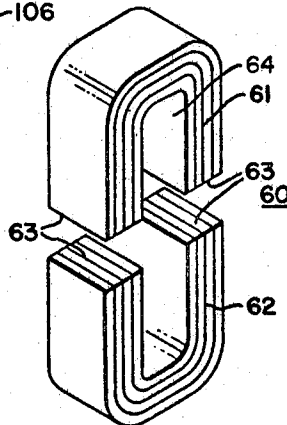


FIG. 3.

WITNESSES

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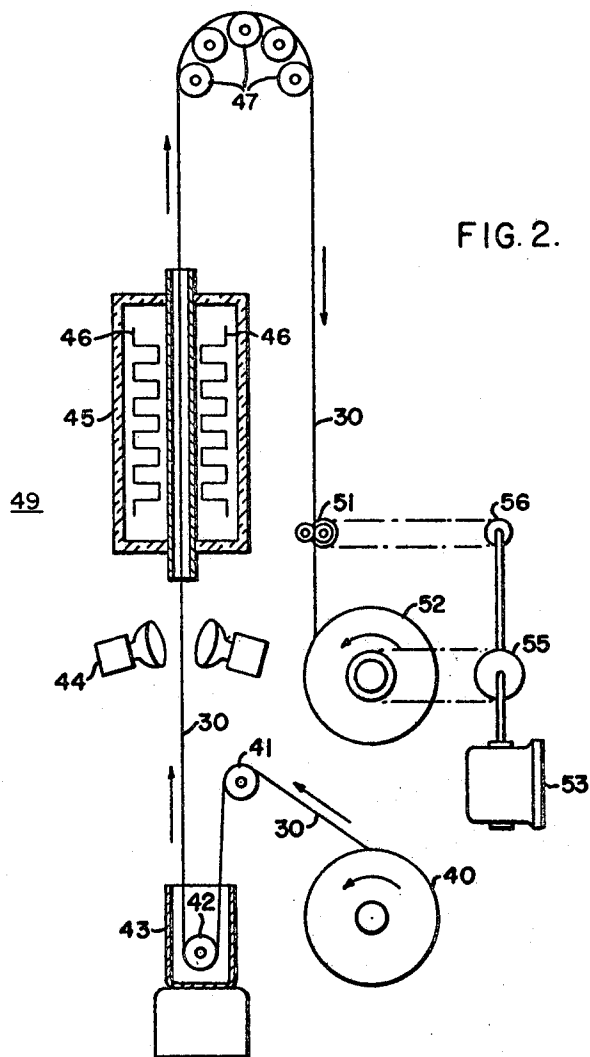
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2 Sheets-Sheet 2



1

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MAGNETIC CORE STRUCTURE

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Continuation-in-part of application Ser. No. 278,944, May 8, 1963. This application Feb. 28, 1968, Ser. No. 708,899

Int. Cl. H01f 27/24

U.S. Cl. 336—211

10 Claims

ABSTRACT OF THE DISCLOSURE

A magnetic core having a plurality of metallic laminations separated by an inorganic vitreous material which extends between adjacent laminations, to electrically insulate the laminations, and to bond them together into a coherent solid. The inorganic vitreous material has a lower coefficient of thermal expansion than the metallic laminations, placing the laminations in tension and the inorganic vitreous material in compression.

CROSS REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of application Ser. No. 278,944, filed May 8, 1963, now U.S. Patent 3,418,710 which is assigned to the same assignee as the present application.

BACKGROUND OF THE INVENTION

Field of the invention

The invention relates in general to new and improved magnetic cores for electrical apparatus, such as transformers, and more particularly to magnetic cores having a plurality of laminations insulated and bonded with an inorganic vitreous material, such as glass.

Description of the prior art

Commercially wound magnetic cores of the type with which this invention is concerned are usually bonded with organic resins. The resin is introduced between adjacent laminations of the core and, at room temperature, such a resin-saturated wound core is well bonded and will not delaminate when cut. These conventional cores are made by a rather complex process requiring a plurality of steps which must be carefully carried out to obtain a satisfactory product.

Typically, the process for making magnetic cores bonded with organic resins involves the steps of coating a magnetic strip material with an inorganic electrical insulator, such as magnesium phosphate, winding the coating magnetic strip to the desired core configuration, annealing the wound core to remove stresses introduced therein during the winding process, impregnating the core with a bonding resin in a vacuum environment, to assure penetration of the resin between adjacent laminations, and oven curing the resin-impregnated core to harden the resin and bond it into an integral assembly. After curing, the core may be cut so that preformed electrical coils may conveniently be placed about the core.

It is clear from the above description of the process currently in use that it requires numerous steps which must be carried out in a careful manner, and that a great deal of time is consumed in such operations. Further, the resin bonded cores produced by this process are not suitable for use at temperatures in excess of about 200 or 250° C., above which temperatures the resins presently used deteriorate, with the result that a core operating at such temperature may delaminate and become substantially inoperative.

2

SUMMARY OF THE INVENTION

Briefly, the invention is a new and improved magnetic core for electrical apparatus, which is suitable for operation at temperatures substantially higher than commercially available cores of the prior art. The magnetic core has a plurality of metallic laminations which are separated by an inorganic vitreous material, such as glass. The vitreous material electrically insulates the laminations from one another, and bonds them together to form a coherent solid. The inorganic vitreous material has a softening temperature range which correspond to the stress relief annealing temperature range of the metallic laminations. Further, the inorganic vitreous material has a composition tailored to provide a lower coefficient of thermal expansion than that of the metallic laminations, which, as a result of the inorganic vitreous material being cooled from a softened state when the magnetic core is stress relief annealed, places the laminations in tension and the inorganic vitreous material in compression.

BRIEF DESCRIPTION OF THE DRAWINGS

Further advantages and uses of the invention will become more apparent when considered in view of the following detailed description and drawings, in which:

FIG. 1 is a schematic diagram illustrating how metallic strip material may be treated to prepare it for further processing and ultimate use in magnetic cores constructed according to the teachings of the invention;

FIG. 2 is a schematic diagram illustrating how a coating of inorganic vitreous material may be applied to the metallic strip material of FIG. 1;

FIG. 3 is an exploded perspective view of a bonded cut core comprising two C-shaped core segments; and

FIG. 4 is an enlarged showing of laminations which have been bonded with glass in accordance with this invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

The magnetic core of this invention comprises a plurality of laminations of a magnetic strip material, the laminations being insulated from each other and bonded together by a fused vitreous material. The invention applies equally to magnetic cores of the wound type, and of the stacked type.

In FIG. 1 there is shown schematically a suitable process for making the magnetic cores of this invention. In general, this process includes the steps of cleaning the surface of the metallic strip, coating the strip with an inorganic vitreous material, winding the magnetic strip into the desired core configuration, heating the wound core to stress relief anneal the lamination turns of the core and soften the inorganic vitreous material, and cooling the magnetic core to solidify the inorganic vitreous material and bond the lamination turns into a coherent solid.

The bonded magnetic core structure may then be cut without delamination occurring, to form a pair of C-cores, in order to facilitate the placement of electrical windings or coils about the core.

In some instances, a barrier layer of a suitable material, such as nickel, may be disposed on the strip, prior to coating the strip with the inorganic vitreous material, to prevent oxides from the metallic laminations from diffusing into the inorganic vitreous material and deleteriously affecting its properties.

More specifically, FIG. 1 illustrates magnetic strip material 30 disposed on a pay-off reel 10, which rotates when magnetic strip 30 is pulled therefrom, through a series of baths 12, 13, 14, 15, 16, 17, 18 and 19, by drive rollers 25 and take-up reel 26. The magnetic strip 30 is guided through these baths by a plurality of idler rollers 11. Magnetic strip 30 is first guided into degreasing tank 12,

to remove all traces of oil and grease. Tank 13, into which the magnetic strip 30 is next guided, is a water rinse, which has the function of removing the degreasing solution from the strip. Following the rinse, the strip 30 is guided into tank 14, which contains a pickling solution for removing any oxides which may have formed on the surface of the magnetic strip, and to etch the surface thereof. There are a number of satisfactory pickling solutions, including solutions of HCl, H₂SO₄, solutions containing both of these acids, and solutions of H₃PO₄. Following the pickling treatment, magnetic strip 30 is guided into tank 15 for a second water rinse, to remove the pickling solution. Tank 16 contains a nickel plating solution. Magnetic strip 30 is guided into tank 16, and between the electrodes 32, to produce a nickel flash on the magnetic strip 30. Plating transformer 31 provides the necessary electric current for the plating process.

Following the application of the nickel flash, the magnetic strip 30 is again given a water rinse in tank 17. This rinse is followed by a neutralizing bath in tank 18, whereby any residual acids carried over from previous treatments are neutralized. One satisfactory neutralizing solution which has been used is a 0.02 percent aqueous solution of NaCO₃. In tank 19, magnetic strip 30 is passed through an acetone bath to aid in removing water from the strip surface. A drying fan 33 promotes the rapid evaporation of the acetone, and then the strip passes over the last idler roller and through the drive rollers 25, which are driven by the power train 28 from the drive unit 27, and then to the take-up reel 26, which is driven by the power train 29 of the drive unit 27.

The nickel flashing provided in tank 16, is a very thin layer of nickel, which is particularly desirable as a barrier layer when silicon-iron magnetic strip is being coated. In the absence of a barrier layer, FeO may diffuse into the vitreous coating and deleteriously alter its composition.

The arrangement shown in FIG. 1 is one possible arrangement of baths for providing a clean and dry magnetic strip material having metallic barrier layer disposed thereon. Different combinations and arrangements of tanks may be employed which would be equally satisfactory.

Following the surface treatment described relative to FIG. 1, magnetic strip material 30 is provided with a thin fused coating of an inorganic vitreous material. Satisfactory apparatus for accomplishing this step is shown in FIG. 2. FIG 2 illustrates a coating line 49, through which magnetic strip 30 is passed after being unrolled from pay-off reel 40. Magnetic strip 30 passes over the idler wheel 41 and into the binder trough or tank 43 around the idler wheel 42, which is submerged in the slip (a suspension of vitreous particles in a suitable organic vehicle such as amyl acetate or isopropyl alcohol) in the binder tank. In the binder tank 43 the magnetic strip 30 is provided with a thin coating of slip. The thickness of the coating which the magnetic strip 30 acquires will depend on the speed of the magnetic strip 30 through the binder tank 43, and upon the consistency of the slip. Excess slip drains back into the binder tank 43 as the strip 30 emerges vertically from the slip.

Magnetic strip 30 passes upwardly between a set of infrared drying lamps 44, which dry the slip coating to a powdery slightly adherent layer. The coated magnetic strip 30 then passes through a tube furnace 45, having heating elements 46, in which the powdery coating is fused to a thin continuous layer. It should be noted that the apparatus is so constructed that the strip surfaces do not contact any part of the apparatus while the coating is in a powdery, easily removable condition. The vitreous coating solidifies quickly upon emerging from the tube furnace 45, and the strip 30 passes over a series of idler rollers 47 which direct the magnetic strip in a downward path through the drive rollers 51 and onto the take-up reel 52. The drive rollers 51 and the take-up

reel 52 are driven by the power trains 55 and 56, respectively, from the drive unit 53.

While a dipping technique has been described for applying the slip to the magnetic strip 30, it will be apparent that the slip may be applied by roller or by spraying.

The inorganic vitreous material used in the magnetic core structure may be glass. As is well known, in a glass the viscosity continuously decreases as the temperature is increased, since glass does not have a precise melting point. The viscosity-temperature relationship of a particular glass will depend upon its composition. At about room temperature, the glasses useful in making the magnetic cores of this invention are quite rigid, with viscosities of 10¹⁷ poises and higher. In order to obtain the desired thin continuous fused glass insulating coating on the surfaces of the laminations in the coating process, the glass particles must be heated to the fluid condition represented by a viscosity of about 5000 poises. After the core is wound, the annealing of the magnetic strip and the simultaneous bonding of the laminations is carried out in the softening temperature range of the glass, for example at 825° C., at which temperature the glass is in a plastic condition, having a viscosity of about 10⁷ poises. At this viscosity, the glass coatings of the individual laminations fuse and bond together when in intimate contact. The glass bonded cores of this invention have a maximum operating temperature as high as the temperature of the deformation point of the glass (approximately 10¹¹ to 10¹² poises). At the deformation point, the glass-bonded core will begin to lose its structural integrity and delamination may occur.

The glass selected for a particular application will depend upon the service temperature and annealing temperature requirements of the core. Glasses in which at least one of the oxides of silicon, boron and phosphorus are the glass-formers may all be used in the process of this invention, when the service and annealing temperature requirements of the device being made permit. Mixtures of these glass-formers may be employed as well. There are innumerable combinations of glass constituents capable of producing satisfactory results in this application.

As the service temperature requirements become more severe, the glass compositions which can be employed narrow to some extent. In the process examples, the glass employed as a coating material is of a matched or tailored composition, to be compatible with the particular magnetic strip material being treated. Particularly, the softening temperature range of the glass is in the same temperature range as the stress relief annealing temperature of the magnetic sheet. However, this is not necessarily a requirement for all applications. For example, the softening temperature range of the glass might be substantially lower than the requisite annealing temperature range of the magnetic sheet, but such a core would have a relatively lower service temperature. The real limitation in such a case is that the glass must have a viscosity at the annealing temperature sufficient to adhere to the metal strip and must not be so fluid as to run off the metal strip.

The following glass compositions have been found to be extremely satisfactory for the silicon-iron magnetic materials.

TABLE I.—GLASS COATING COMPOSITIONS, WT. PERCENT

	Range	Specific composition
SiO ₂	36.00 to 54.65.....	41.92
B ₂ O ₃	5.05 to 18.00.....	11.70
Al ₂ O ₃	2.00 to 7.35.....	4.88
Na ₂ O.....	3.65 to 18.00.....	17.55
K ₂ O.....	7.00 to 30.45.....	6.82
CaO.....	0.00 to 10.00.....	
CaF ₂	0.00 to 5.00.....	4.88
BaO.....	0.00 to 20.90.....	9.75
ZnO.....	0.00 to 4.05.....	
ZrO ₂	0.00 to 1.35.....	
MnO ₂	0.50 to 1.00.....	0.50
NiO.....	0.50 to 1.00.....	0.50
CoO.....	0.50 to 1.50.....	1.50

5

In this formulation boron oxide can be reduced to 2 percent, or less. Sodium oxide can replace the potassium oxide. Manganese, nickel and cobalt oxides can be left out. Other glass compositions are also suitable. Glasses containing up to 15 percent ZrO_2 and 15 percent TiO_2 can be made following the above formulation.

In making the slip, the glass was wet ground in a ball mill for fifty-four hours. After grinding, the glass particles were passed through a 400 mesh screen to remove random coarse particles. The average particle size after screening was about 1.5 microns.

To maintain the vitreous particles in suspension in the slip a deflocculating agent may be present. Such a deflocculating agent is disclosed in copending application Ser. No. 276,247, filed Apr. 29, 1963, now abandoned. The preferred deflocculant set forth in the above-identified application is the boric acid ester of 2-methyl-2,4-pentandiol commonly referred to as trihexylene glycol bborate.

In using the apparatus shown in FIG. 2 to coat magnetic sheet, magnetic strip speeds of from 3 to 5 feet per minute have been employed successfully. Much higher speed may also be used. The thickness of the fused vitreous coating on the magnetic strip is preferably in the range from about 0.1 mil to 0.3 mil, but may be as great as 1 mil or more.

In the furnace, the ambient temperature is maintained at from about 850° C. to 950° C., depending on the speed at which the magnetic strip is moving and on the cross-sectional area of the strip. The higher temperatures are employed at higher strip speeds or when strip of greater cross-section is being coated. In the furnace the glass softens and flows together and fuses to form a bubble-free continuous coating or layer on the magnetic strip.

The magnetic strip with its thin vitreous coating thereon, which is the product of the coating process, is remarkable for the flexibility of the coated strip and in this respect, far exceeds what might be expected from the brittleness which is known to characterize glass.

The extreme flexibility of the glass coated magnetic strip enables it to be wound into core form at room temperature without disturbing the adhesion of the coating to the magnetic strip. Conventional high speed commercial core winding equipment operating at room temperature may be used for winding the cores. Such high speed equipment can wind a core in a very few minutes, i.e. two or three minutes is sufficient for cores of moderate size.

It will be understood that the winding of the core introduces stresses into the magnetic material and these stresses must be relieved. Further, the laminations of the core must be bonded together to fix the core shape in its final configuration. It has been found that with a core provided with a glassy coating on its lamination turns, as described above, the bonding of the core and the stress relief anneal can be carried out simultaneously in a single operation. To accomplish this the formed core is placed in a furnace, a weight is placed on the core at the region where the core will be cut to assure contact between adjacent lamination turns, and then the core is heated to a temperature of from about 700° C. to about 900° C. In some cases the annealing temperature may be as high as 1000° C.; the temperature used depends upon the magnetic material undergoing treatment. Grain oriented silicon-iron may be annealed for three hours at 835° C. with satisfactory results. In general, an annealing time of from 1 to 4 hours is employed. This treatment is sufficient to stress relieve the material, and the adjacent laminations of the core are bonded together by the fusing of the glassy adhesive coating thereon.

The interlaminar adherence of the cores thus formed is sufficient to permit the cutting of the cores with standard commercial equipment without delamination. Such a wound cut core is shown in FIG. 3 of the drawings wherein the core 60 has been cut into two parts, 61 and 62, with substantially plane faces 63, whereby, when the core

6

halves are reassembled, forming the window 64, there is no appreciable air-gap loss between the faces.

In FIG. 4 there is shown an enlarged view of a pair of glass bonded laminations 100, 101 from a core made in accordance with the invention. Each of the laminations is surrounded by the fused glass coating. The layer of glass 104 represents the glass coating on the outermost lamination 100. The interlaminar glass layer 106 bonds laminations 100 and 101 to each other, and insulates them one from the other. The glass layer 108 insulates the edges of the laminations. The exposed metal visible in the figure is located at a cut face of the core.

Cores made in this fashion have been heat aged at temperatures up to 600° C. without deterioration of either adherence or rigidity.

Transformer cores were made in accordance with this invention and tested for core loss as described in the following examples.

EXAMPLES

Single oriented silicon-iron sheet having about 3.5 percent silicon therein, in 2, 4 and 12 mil nominal thicknesses, was obtained in coil form. The sheet surfaces were bare, and were slit to provide 1 inch and 2¼ inch strip widths. The magnetic strip was passed into a series of tanks which successively degreased, pickled and provided the strip with a nickel flashing.

The composition of the glass coating selected for the cores was as follows:

Coating (calculated weight):	Percent
SiO ₂ -----	42.49
B ₂ O ₃ -----	2.44
Al ₂ O ₃ -----	3.63
Na ₂ O -----	21.75
K ₂ O -----	0.02
TiO ₂ -----	9.11
ZrO ₂ -----	12.33
BaO -----	5.38
CaO -----	0.01
ZnO -----	2.85

The magnetic strip was provided with a vitreous coating of the above composition in an apparatus of the type shown in FIG. 2. The magnetic strip was first passed through a container having therein a slip containing the vitreous frit and then the slip was dried on the strip to a powdery condition and thereafter passed through a furnace at a temperature of 915° C., at which temperature the vitreous material fused and provided a thin uniform glassy coating on the magnetic sheet. The strip was passed through the slip and furnace at the rate of about four feet per minute. The coated, cooled strip was then wound to coil form. Cores were then wound on mandrels from the strip on standard core winding machinery. The cores were left on the mandrels to assure the retention of the window dimensions and shape. The dimensions of the core window of each core were either ¾ x 2¼ inches with a ¾ inch build-up of wound strip, or the core window was 1 x 3 inches with a 1 inch build-up. In winding the cores a slight excess number of turns was employed.

The cores were then stacked in a furnace in a manner which assured that a continuous load was maintained on the laminations at the region of cut. A forming gas (90 percent N₂—10 percent H₂) was introduced into the furnace and the cores annealed at 825° C.

After annealing in the furnace for 3 hours the bonded cores were removed from the furnace, cooled, and the mandrels removed by means of a hydraulic press.

The cores were clamped between 0.060 inch steel plates and cut by an abrasive cutting disc. The cut faces of the cores were ground by a diamond wheel on a surface-grinder. The cut faces of the core halves were then etched to remove burrs.

The core halves were trimmed to size by removing the excess inner and outer turns until the precise desired window dimensions and build-up were obtained. The core

halves were then carefully aligned and assembled with a coil around one leg of the core, and then the core was banded with a steel banding strap to maintain the two core halves in assembled relation. The cores were then tested for core loss at room temperature after aging at 400° C. for periods of 250 and 500 hours. Other samples were tested after aging at 600° C. The cores were found to have relatively low core losses both before and after aging.

A series of cores were made in accordance with this invention and tested for core loss at room temperature, before aging and after aging. The results obtained are shown in Table II. For the identification of the C-core samples tested, a three symbol code is employed in Table II consisting of a number (1 and 2), a letter (L, H, and A), and a number (1 through 8). The numbers which precede the letter represent the core size as follows:

- Number 1—Core having a width of 1 inch, 7/8 x 2 1/4 inch window, and a 3/8 inch build-up.
- Number 2—Core having a width of 2 1/4 inches, 1 x 3 inch window, and a 1 inch build-up.

The letters represent the nominal steel thickness of the core as follows:

- Letter L—2 mil
- Letter H—4 mil
- Letter A—12 mil

A two-symbol combination of the above numbers and letters represents the core type. Numbers 1 through 8 which follow the letter identify the core sample. For example, the code 2H4 represents the fourth sample of

TABLE II.—CORE LOSS IN WATTS PER POUNDS AT 15 KG., 1 400° C. AGING

Treatment	1L1	1L2	2L1	2L2	1H1	1H2	2H1	2H2	1A1	1A2	2A5	2A6
Room temperature before aging.....	8.7	7.5	6.7	8.2	9.7	8.7	9.4	8.0	0.78	0.78	0.82	0.75
250 hours at aging temperature.....	10.5	8.5	8.5	9.2	9.7	9.3	11.7	11.1	0.79	0.78	(3)	-----
500 hours at aging temperature.....	11.0	9.0	8.9	9.7	9.9	9.3	12.0	12.0	0.84	0.79	(2)	-----
Room temperature after aging.....	10.3	8.7	8.7	9.2	10.2	9.8	11.5	10.4	0.88	0.87	(2)	-----

¹ Cores L and H at 400 cps., cores A at 60 cps.
² Not tested.

core type 2H which is the larger core size constructed with 4 mil steel.

A rejection limit based upon a core loss of 10 watts per pound has been commonly employed in determining the acceptability of organically bonded commercial cores of the "H" type. Similarly, a rejection limit of 0.9 watt per pound has been used in evaluating cores of the "A" type. It will be observed that at room temperature, before aging, all of the cores listed in the above table had acceptably low core loss, and that even after severe aging at 400° C. for 250 hours, all of the "A" cores and some of the "H" cores were still within acceptable limits. Further, after 500 hours of aging at 400° C. the number of cores which exceeded the rejection limit had not increased. It will be understood that organically bonded cores could not be subjected to these tests since such cores would delaminate at the test temperature and meaningful test readings could not be obtained.

An important feature is that the glasses employed have a lower coefficient of expansion than the metals which they are used to coat. Therefore, when the metal-glass composite element cools from the annealing temperature, the metal contracts more than the glass coating. The metal is, therefore, placed in tension while the glass coating is under compression. It has been found that placing magnetic laminations under tension decreases the magnetostriction of the lamination. Since magnetostriction produces noise and hum in transformer cores, the reduction of magnetostriction accomplished by the glass coating reduces the noise level of the transformers.

Magnetic cores described in the examples given above utilize a single glass coating as a substitute for the magnesium phosphate and organic resin coatings employed by commercially available cores of the prior art.

The magnetic cores of this invention may be made

from any suitable metallic strip material, oriented or un-oriented. Magnetic cores have been constructed according to the teachings of the invention using 12 percent aluminum-iron magnetic strip, 3.5 percent silicon-iron magnetic strip, and two cobalt-iron magnetic alloys, one containing 27 percent cobalt and another containing 35 percent cobalt. Cores have been made from magnetic strip materials having thicknesses of 2, 4, 5, 8 and 12 mils thickness. C-cores have been made in strip widths of 3/8 inch, 7/8 inch, and 2 1/4 inches. Toroidal cores and stacked cores of laminations punched from glass-coated magnetic strip have been made.

In summary, magnetic cores having a relatively simple rugged structure have been disclosed, which are suitable for operation at elevated temperatures, which have a low magnetostriction, and hence lower noise level and which have good magnetic properties.

Since numerous changes may be made in the above described apparatus, and different embodiments of the invention may be made without departing from the spirit thereof, it is intended that all matter contained in the foregoing description or shown in the accompanying drawings shall be interpreted as illustrative, and not in a limiting sense.

We claim as our invention:

1. A magnetic core structure comprising: a plurality of superposed metallic laminations, a solidified inorganic vitreous material disposed between said plurality of laminations, said inorganic vitreous material extending between adjacent laminations to electrically insulate and bond the laminations together to form a coherent solid

structure, said plurality of metallic laminations being in tension, which is maintained by said solidified inorganic vitreous material.

2. The magnetic core structure of claim 1 wherein said inorganic vitreous material has a lower coefficient of thermal expansion than said metallic laminations, to provide the tension in said metallic laminations.

3. The magnetic core structure of claim 1 wherein the softening temperature range of said inorganic vitreous material corresponds substantially to the stress relief annealing temperature range of said metallic laminations.

4. The magnetic core structure of claim 1 wherein said metallic laminations are formed from a grain oriented silicon-iron alloy.

5. The magnetic core structure of claim 1 wherein said metallic laminations have a metallic barrier layer disposed thereon, between said metallic laminations and said inorganic vitreous material.

6. The magnetic core structure of claim 5 wherein said metallic barrier layer is nickel.

7. The magnetic core structure of claim 1 wherein said metallic laminations are in the form of a plurality of curved, nested lamination turns.

8. The magnetic core structure of claim 1 wherein said metallic laminations are flat, and disposed in a stack.

9. A stress relieved glass bonded magnetic core of the wound type, comprising a plurality of metallic lamination turns, and a layer of solidified glass disposed between adjacent lamination turns, said glass substantially filling the space between said lamination turns and electrically insulating said lamination turns from one another, said glass adhering to the surfaces of said lamination turns, bonding them into a coherent solid, said glass having a coefficient of thermal expansion lower than that of said

9

metallic lamination turns, placing said metallic lamination turns in tension, to improve the magnetic properties of the magnetic core.

10. The magnetic core of claim 9 wherein said glass has a softening temperature range which corresponds substantially to the stress relief annealing temperature range of said metallic lamination turns.

5

10

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10

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