March 11, 1969 R. B. BRITTON ET AL 3,432,783

SUPERCONDUCTOR RIBBON

Filed Aug. 24, 1967

Sheet 1 of 2

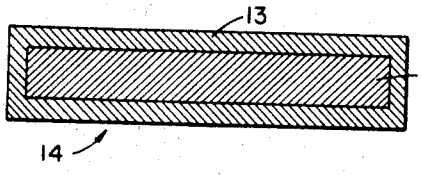



Fig. 1a

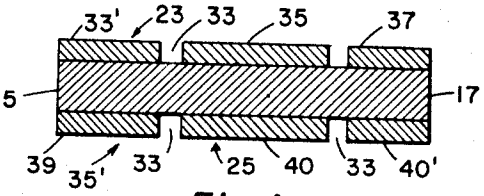
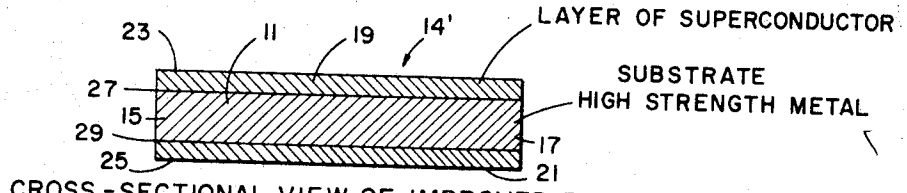



Fig. 1c




CROSS-SECTIONAL VIEW OF IMPROVED RIBBON CONDUCTOR

Fig. 1b

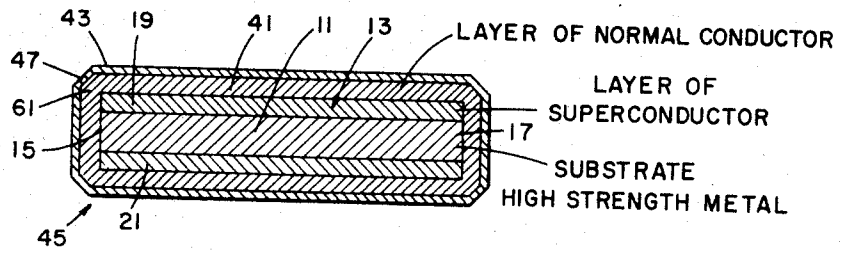



Fig. 2

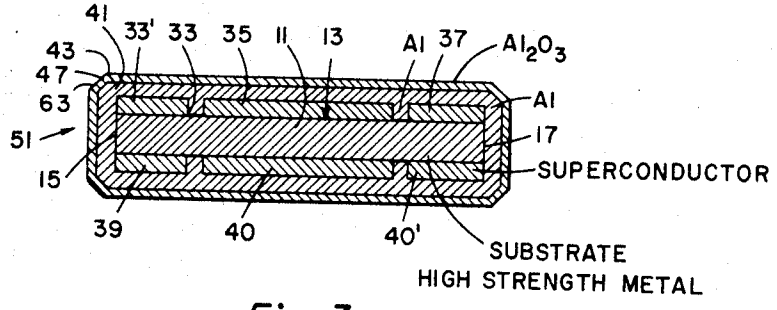



Fig. 3

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Sheet 2 of 2

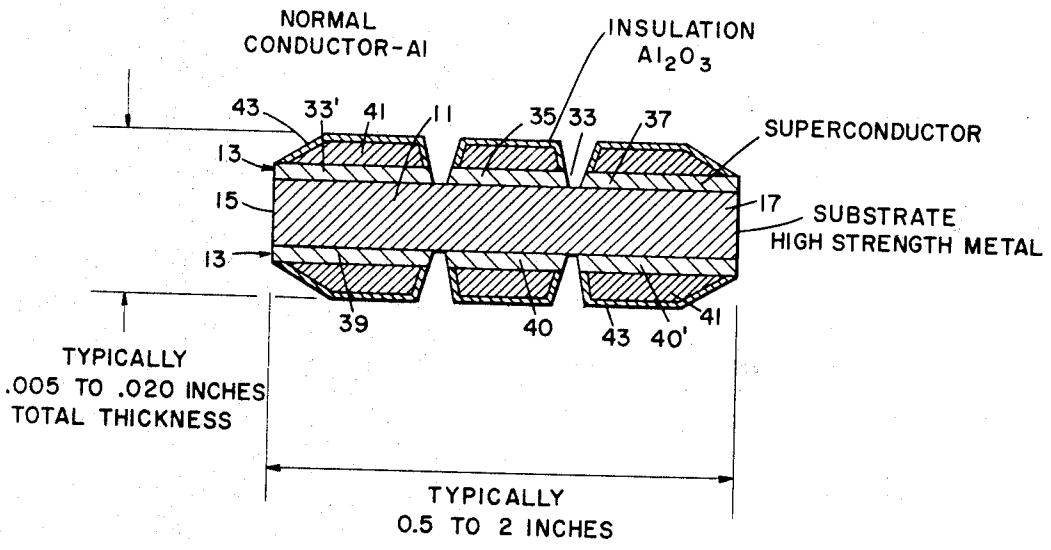



*Fig. 4*

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3,432,783

# SUPERCONDUCTOR RIBBON

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Int. Cl. H01f 1/00
3 Claims

## ABSTRACT OF THE DISCLOSURE

Stabilized superconductor and method for large, high current density, high magnetic field, multipole, superconducting magnets, wherein a strong metallic alloy rectangular cross-section ribbon of substrate is coated with superconductor, the sides of the substrate are exposed by stripping the superconductor therefrom, and the superconductor surface and exposed substrate sides are coated with a tapered coat of low resistivity aluminum having an outer correspondingly beveled insulator of aluminum oxide thus providing a simple economic method for framing thin paralleled superconductors having suppressed current degradation due to flux trapping, the stainless steel providing long cross-connections between the superconductors normally thereto through the stainless steel and the paralleled superconductors having long cross-connections therefrom normally into the low resistivity aluminum whereby the ribbon is wound into a magnet having stabilized, insulated, adjacent, closely packed, tightly wound, high current density, multipole magnet turns with cooling passages formed between the ribbon turns along the tapered portions of the insulated aluminum coating.

*Cross-references to related applications*

Application S.N. 591,056, filed Oct. 28, 1966, by Sampson et al. entitled, "Improved Multipole Magnet."

*Background of the invention*

This invention was made in the course of, or under a contract with the United States Atomic Energy Commission.

Large volume, high magnetic fields up to 50–60 kg. or more formed by high current density windings are described in the above cited copending application, which is assigned to the assignee of this application. These magnets require particular arrangements of superconducting ribbon made of special materials, such as $Nb_3Sn$ having a high critical current density and high critical magnetic field. However, it is universally recognized that a simple, economic stabilization system is desirabe for reducing current degradation from flux jumps in these superconducting ribbons when they are wound into a magnet since these flux jumps prevent the wound ribbon from achieving the high currents and magnetic fields possible with the unwound ribbon.

*Summary of the invention*

It has been discovered in accordance with this invention that simple coating and cutting means can be employed to produce a stabilized superconductor ribbon for these magnets by providing a thin superconductor coat on a rectangular cross-section metal alloy ribbon substrate for strong mechanical support, exposing the sides of the substrate by stripping the superconductor from the sides of the substrate thereby to provide a large stabilizing cross-connection between parallel superconductors normally through the substrate, coating the outside of the superconductor and the exposed substrate with



aluminum thereby to provide a low resistance normal resistance conductor for carrying current from one or both of the parallel superconductors during temporary flux jumps, beveling the edges of the aluminum to provide for rapid and effective cooling of the superconductor when wound in the form of a multipole magnet, and insulating the outside of the aluminum by forming therein an aluminum oxide coating thereby to provide insulation between the turns of the magnet coils. In another aspect the superconductor is grooved in a simple manner before coating it with aluminum by suitable shaping means.

The above and further advantages of this invention will appear from the following detailed description of two embodiments of this invention when the same is read in connection with the attached drawings and the novel features thereof will be pointed out hereinafter in connection with the appended claims.

*Brief description of the drawings*

In the drawings where like elements are referenced alike:

FIG. 1*a* is a partial cross-section of a rectangular stainless steel ribbon of substrate and a superconductor coating:

FIG. 1*b* is a partial cross-section of the coated ribbon of FIG. 1*a* with the superconductor coating stripped from the sides thereof;

FIG. 1*c* is a partial cross-section of the ribbon of FIG. 1*b* having grooves scribed through the face of the superconductor coating to the substrate;

FIG. 2 is a partial cross-section of the ribbon of FIG. 1*b* having an insulated normal resistance conductor therein;

FIG. 3 is a partial cross-section of the ribbon of FIG. 1*c* having an insulated normal resistance conductor therein; and

FIG. 4 is a partial cross-section of another embodiment of the ribbon of this invention.

*Description of the preferred embodiments*

Referring to FIG. 1*a*, a rectangular cross-section metallic ribbon substrate **11** is shown having thereon a thin overall coating of superconductor **13**. This coated ribbon **14** is commercially available in the form of $Nb_3Sn$ coated Hastelloy ribbon that is 1.8 to 10 mils thick and from 90 to 500 mils (i.e. one-half inch) wide. As is well known, high strength metal alloys are available in various shapes and sizes and in ribbon foil form provides easily bendable substrate with high mechanical and structural integrity.

The superconductor **13**, is advantageously vapor deposited $Nb_3Sn$, although other superconducting materials such as NbZr, NbTi or $V_3Ga$, may alternately be used. One advantageous method of coating the substrate **11** with a coating **13** to form the ribbon **14** illustrated in FIG. 1*a* is described in "RCA Superconductive Materials and Magnets" copyrighted in 1966 and 1967. FIG. 1 of the paper therein by F. R. Nyman entitled "Vapor Deposition of Niobium Stannide a Versatile Process" illustrates a typical vapor deposition system for coating the substrate **11** with a coating **13** of $Nb_3Sn$ that covers the whole exterior i.e. all four surfaces of the metallic ribbon substrate **11**.

In accordance with this invention, the commercially available superconductor coated ribbon **14** of FIG. 1*a* is advantageously trimmed, i.e. cut or ground, to expose the substrate edges. In one trimming system for exposing the edges of the substrate **11**, the side edges of the superconductor coating are milled away with a conventional milling machine that cuts through the superconductor sides and the metallic substrate sides at their edges. A conventional tungsten carbide faced milling cutter is used for this purpose. However, the ribbon **14** of FIG. 1*a* can

likewise be trimmed by feeding it continuously to a tungsten carbide cutting tool or a band saw having one or two parallel cutting blades, whereby the edges of the coating are removed from the side edges of the substrate to expose the substrate side edges **15** and **17** as shown in FIG. 1*b*. This produces two thin parallel, spaced-apart, substantially rectangular superconductors **19** and **21** with opposite faces **23** and **25** on the substrate **11** of the ribbon **14**, as shown in FIG. 1*b*, whereby the superconductors **19** and **21** cross-connect with each other normally from their adjacent parallel sides **27** and **29** through the length of the metallic substrate **11**. As shown in FIG. 1*b*, the side edges **15** and **17** of the substrate are advantageously cut to form them at right angles to the opposite parallel faces **23** and **25** and **27** and **29** of the superconductor **19** and **21**. Advantageously the ribbon **14** is automatically fed to the cutting tool between two conventional spools, but the feeding of the ribbon **14** to the cutting tool can alternately be accomplished by unwinding and winding the ribbon by hand on the respective spools.

Additional adjacent parallel independent superconductors can be added by grooving the faces **23** and **25** of the superconductor coated ribbon **14'** shown in FIG. 1*b*. This grooving to produce grooves **33** can be accomplished by diamond scribing along the length of the superconductor coated ribbon, as illustrated by the grooved ribbon **35'** of FIG. 1*c*. Alternatively, the grooves **33** can be produced with suitable pointed tungsten carbide cutting or milling tools to produce these adjacent parallel, independent superconductors, which are illustrated as superconductors **33'**, **35**, **37** and **39–40'** in FIG. 1*c*. To this end the ribbon is automatically fed into contact with the cutting tool in between a first feeding spool and a second take up spool with a flat surface holding the ribbon **14'** in contact with the cutting tool under uniform tension. The ribbon **14'** can alternately be fed to the cutting tool by hand.

In accordance with another aspect of this invention insulated, edge beveled, aluminum is provided normally on surfaces **23** and **25** of the trimmed coated ribbon **14'** of FIG. 1*b* by simple coating and cutting means. Likewise this insulated aluminum coating can be provided on the grooved ribbon of FIG. 1*c* by the same simple coating and cutting means. Since the $Nb_3Sn$ is superconducting at 4° Kelvin, i.e. at the boiling temperature of liquid helium, and the aluminum coating has a low resistance above that of the $Nb_3Sn$ down to 1.2° Kelvin, temporary current collapse in the $Nb_3Sn$ i.e. normal resistance in a small portion of superconductor **13** due to transient flux jumping therein, produces temporary current transients in the aluminum coating **41** shown in FIG. 2. Thus, the aluminum **41** conducts enough current transferred from the degraded portion of the superconductor **13** long enough for that portion of the superconductor **13** to return to its undegraded state, i.e. its superconducting state, whereupon the current returns to the superconductor **13** from the aluminum coating **41**.

In this regard, at an operating temperature of 4° Kelvin, the aluminum surprisingly has a much lower resistance than other materials in the high fields of 50 to 100 kilogauss or more contemplated for the superconducting multipole magnet of the above cited co-pending patent application, the resistance of the Al increasing less, for example than normal resistance materials such as Cu and Ag, as the field is increased.

The insulation **43**, comprises a thin aluminum oxide coating for insulating the various turns of the aluminum coated superconducting ribbons **45** from adjacent turns thereof whereby the ribbon **45** can be tightly packed in a high current density, high magnetic field producing, multipole, superconducting magnet. The beveled portions **47** of the aluminum $Al_2O_3$ coating on the edges of the ribbon **45** correspond to the bevels **61** cut on the edges of the Al coating **41** and provide passage ways and additional surface area for the liquid helium to enable it to more efficiently remove heat from the $Nb_3Sn$ superconductor **13** so that the superconductor **13** is rapidly cooled to return it to its superconducting state.

The beveled aluminum coating **41** having an aluminum oxide insulation **43** with bevels **63** on the edges thereof can likewise be applied to the grooved ribbon **35'** of FIG. 1*c*. This produces the ribbon **51** of FIG. 3.

The aluminum coat **41** can be applied by any one of a variety of methods. Various applicable coating systems described in vol. 2, of the 8th ed. of Metals Handbook by the American Society for metals, comprise vapor deposition, electro-plating, cathodic sputtering and gas plating as described on pages 496 et seq., 528 and 529. After the coating is applied, the aluminum is shaped by suitable cutting tools to provide a rectangular cross-section and edge beveled by suitable cutting tools to produce the beveled edges **47** shown in FIGS. 2 and 3. Advantageously, the aluminum coating is 1½ to 3 mils thick and is accomplished with a ribbon temperature below the melting point of $Nb_3Sn$. Thereupon the aluminum coat **41** is anodized by converting of the surface of the aluminum coat **41** and the beveled edges **47** thereof to aluminum oxide while the ribbon is made the anode in an electrolytic cell. Typical anodizing steps are described on p. 620 et seq. of the above-cited Metals Handbook. The anodized surface is advantageously between about .05 to .5 mil thick.

In accordance with one example, for producing the ribbon of FIGS. 2 and 3 simple coating and cutting means are employed. Thus the ribbon **14'** of FIG. 1*b* is electroplated by the use of anhydrous electrolytes composed of fused mixtures of aluminum chloride and alkali chlorides and with pure chemicals and eletcrolytic aluminum anodes the alloy is applied substantially evenly to form a susbtantially rectangular cross-section. A typical fused salt eletcrolytic is operated at 350° F. at a current density of 15 amp per square foot, although higher current density may be used by agitating the bath. Preferably also, the bath and ribbon container is an elongated aluminum bath having end rollers for feeding the ribbon slowly but continuously into the bath from a storage spool and out of the bath onto a take up spool either automatically or by hand.

After cooling, the edges of the aluminum coated ribbon are beveled under constant tension between a flat surface and a cutter that rotates against the ribbon edge around an axis oblique to the plane of the ribbon whereby end play in the rotating cutter has no deleterious effect on the depth of the cut. Run out in conventional milling machine cutters and grinding wheels can be held to very low values whereby the bevel is made at no greater than a 45° angle and to a precise depth not greater than the depth of the superconductor **13**. The less steep is the cutting angle, the larger is the cooling passage provided in a magnet made with the ribbon of this invention between the superconducting adjacent ribbon forms thereof, so that an angle of 45° down to 1° is advantageous.

The aluminum is then anodized by conversion of the aluminum surface to aluminum oxide while the conductor is made the anode in an electrolytic cell.

A suitable electrolyte that meets the military specification MIL–A–8625 is $CrO_3$, 5.25 oz./gal. at 90° to 95° F. although solutions containing from 3 to 10% $CrO_3$ by weight may be used. Other anodizing compositions comprise 12 to 20% sulfuric acid (Sp. Gr., 1.84) capable of producing an anodic coating that when sealed in boiling dichromate solution, meets the requirements of MIL–A–8625. For example, the concentration of chlorides as NaCl is less than 0.2%; the Al concentration is less than 20 g. per liter (2⅔ oz. per gal.) and the sulfuric acid content is between 165 and 200 g. per liter with a current density of 12 amp per sq. ft.

In another embodiment, the edges of the aluminum coating of the ribbon is beveled through to prevent a circuit around the circumference of the ribbon shown in FIGS. 2 and 3.

In another embodiment the aluminum oxide coating is removed only from the beveled edges of the ribbon to enhance cooling of the superconductor while maintaining insulation between the ribbon turns when wound in a magnet.

In another embodiment shown in FIG. 4, the aluminum coating on the ribbon is sub-divided as shown to reduce losses when pulsing the magnet coil made therefrom.

This invention has the advantage of providing a practical and efficient method for producing a stabilized superconductor for a high magnetic field, high current density, multipole magnet in which simple, effective, and well known equipment is used to coat and cut the superconductor to the desired dimensions.

We claim:

1. A stabilized superconducting ribbon for a high magnetic field, high current density multipole magnet, comprising a rectangular cross-section stainless steel substrate sandwiched between two thin independent foil shaped superconductors and having an insulated aluminum coating on the superconductors and substrate edges.



2. The invention of claim 1 having bevels on the ribbon edges of the aluminum coating.

3. A magnet coil made with the ribbon of claim 2 in which the beveled edges form cooling channels between the edges of the adjacent turns of the ribbon.

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