

[54] **METHOD OF FABRICATING AN
ALUMINUM CLAD MULTIPLEX
SUPERCONDUCTOR**

3,625,662 12/1971 Roberts et al. 29/599 X
3,618,205 11/1971 Barber et al. 29/599

[75] Inventors: **Harehiko Nomura; Susumu
Shimamoto**, both of Tokyo, Japan

Primary Examiner—Richard J. Herbst
Assistant Examiner—Donald C. Reiley, III
Attorney—Kurt Kelman

[73] Assignee: **Agency of Industrial Science &
Technology**, Tokyo, Japan

[22] Filed: **Oct. 24, 1972**

[21] Appl. No.: **300,345**

Related U.S. Application Data

[62] Division of Ser. No. 212,199, Dec. 27, 1971, Pat. No.
3,714,371.

Foreign Application Priority Data

Dec. 28, 1970 Japan 45/120120

[52] **U.S. Cl.** 29/599, 29/199, 174/DIG. 6

[51] **Int. Cl.** H01v 11/00

[58] **Field of Search** 29/599, 194, 199;
174/126 CP, DIG. 6; 335/216

References Cited

UNITED STATES PATENTS

3,708,606 1/1973 Shattes et al. 174/126 CP

[57]

ABSTRACT

An aluminum clad multiplex superconductor comprises an aluminum alloy cladding and a multiplex superconductor inserted into the cladding and is constructed with a plurality of unit superconductors twisted or braided with each other, each of which unit superconductors is constructed with a strand of a plurality of superconductive wires, an intermediate aluminum layer and a relatively hard aluminum alloy layer surrounding the intermediate layer. The intermediate aluminum layer serves to prevent the flowing phenomenon during the withdrawing of the unit superconductor.

4 Claims, 12 Drawing Figures

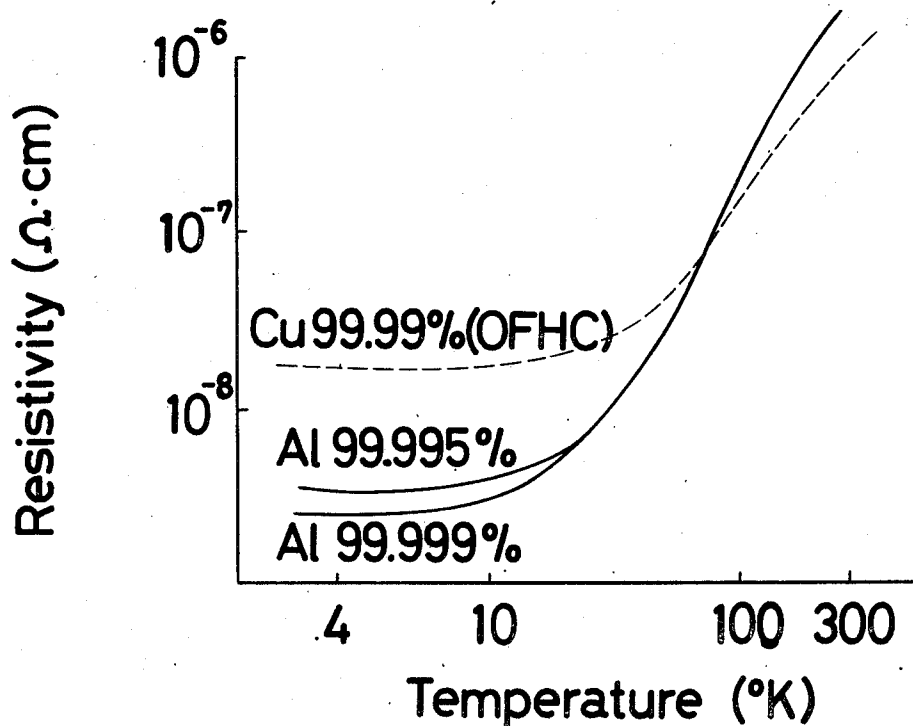


Fig. 1

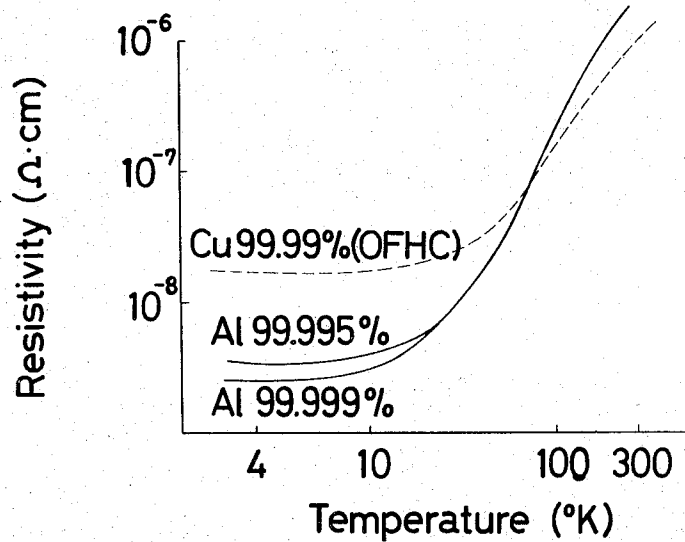
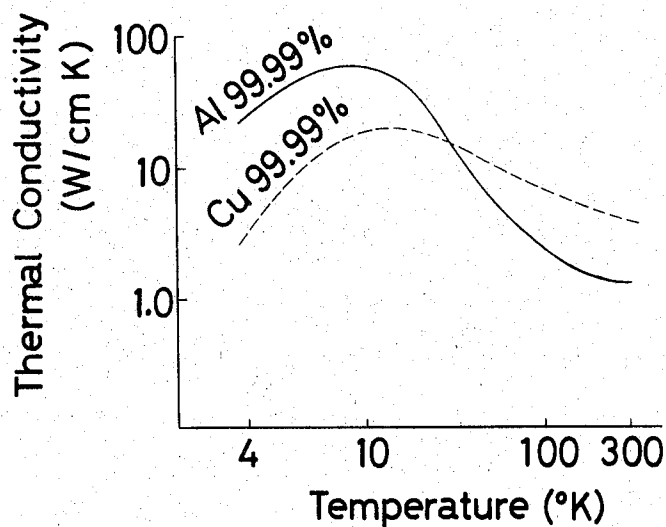


Fig. 2



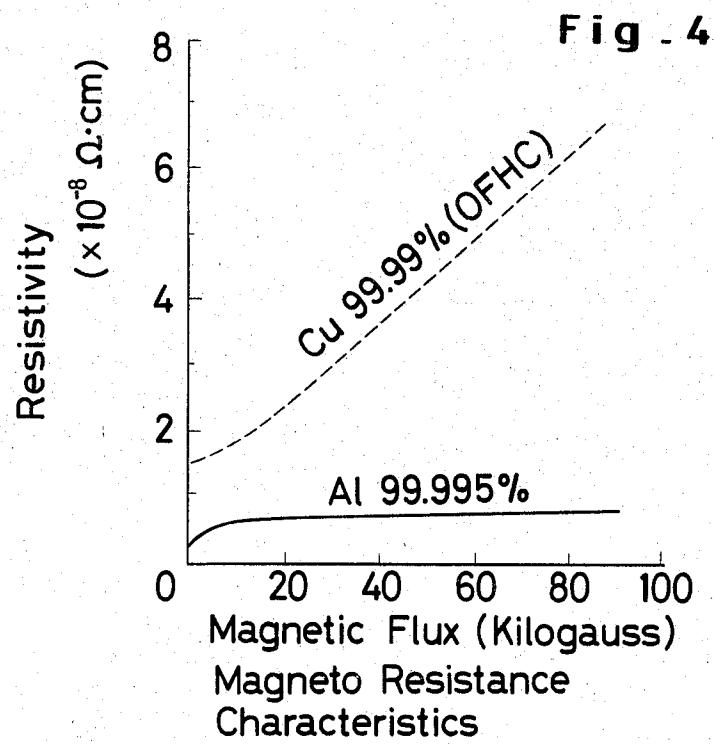
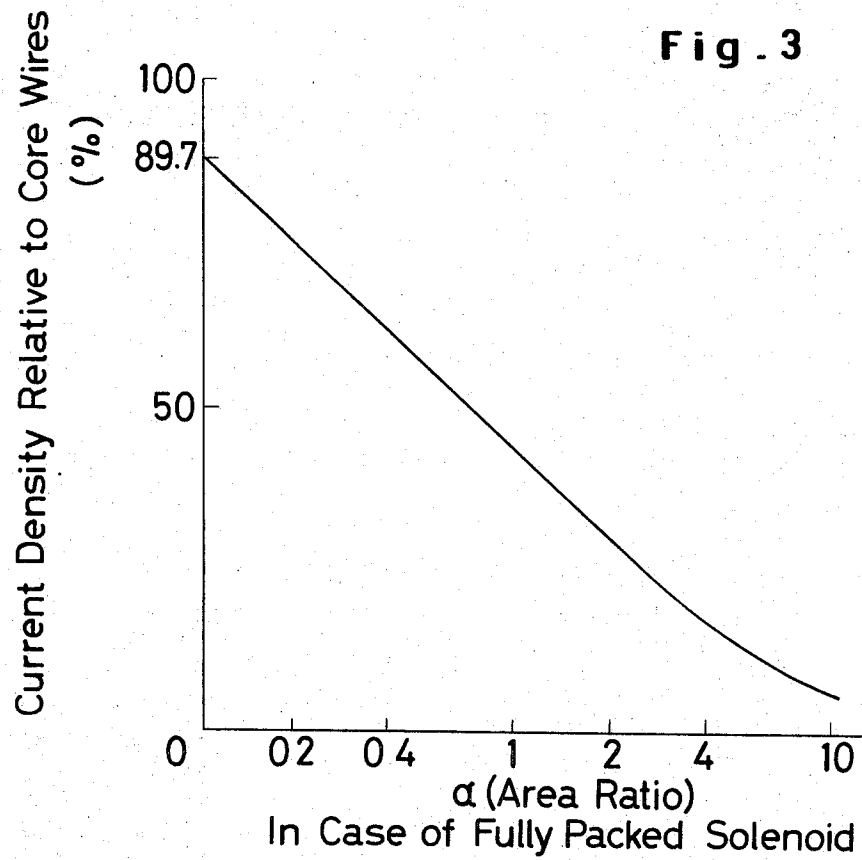


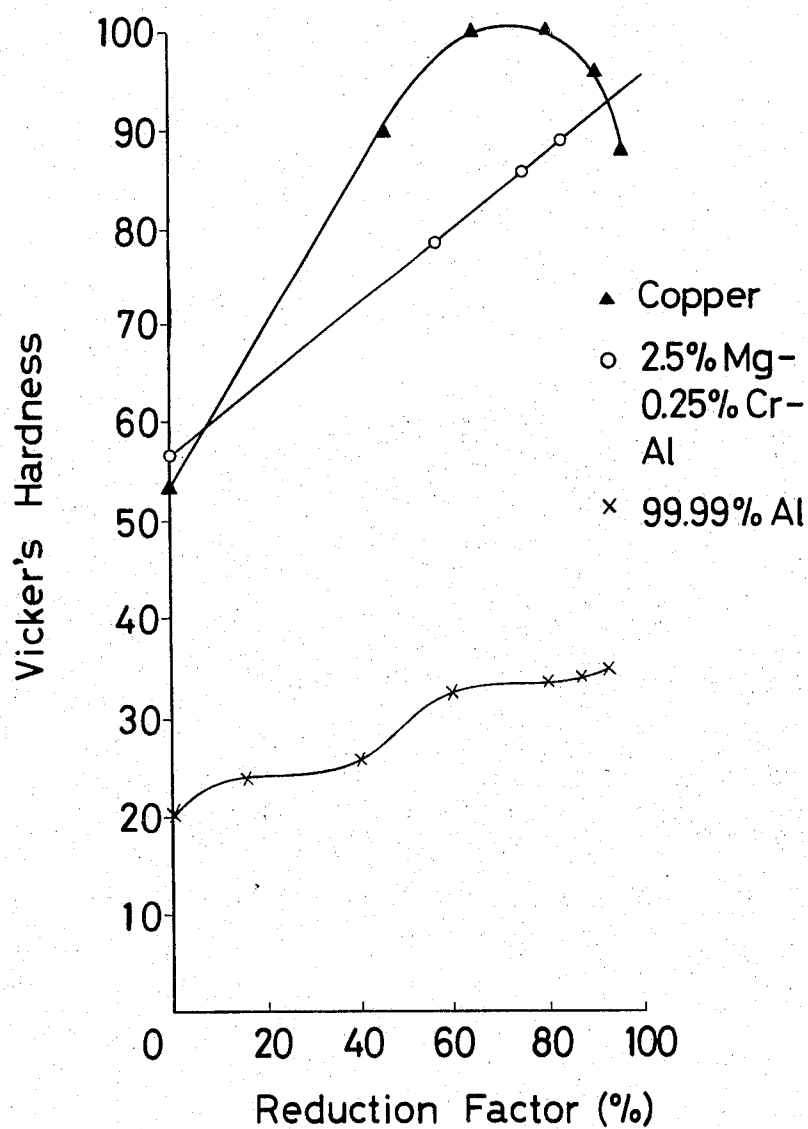
Fig . 5

Fig. 6(A)

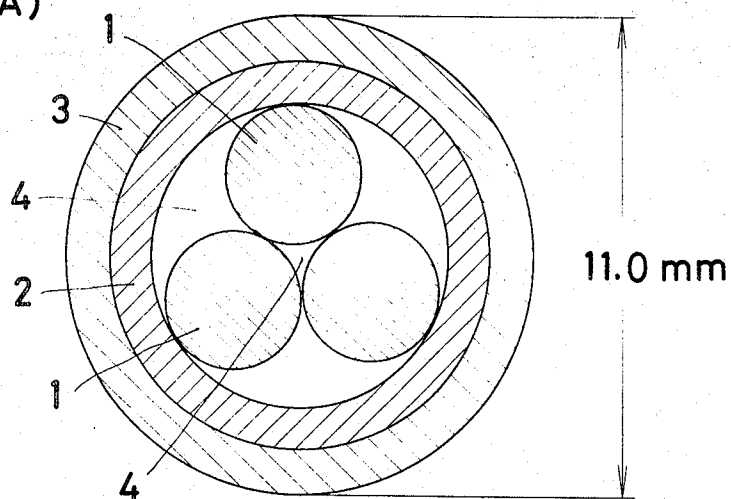


Fig. 6(B)

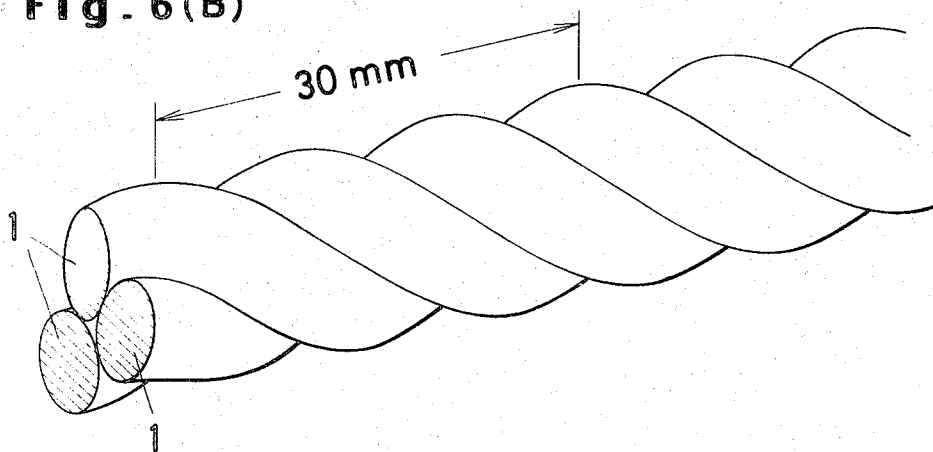


Fig. 7

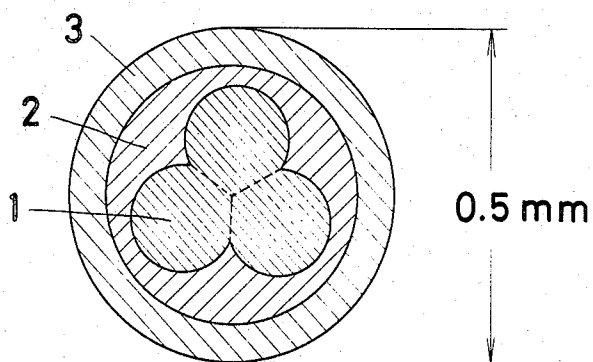


Fig. 8(A)

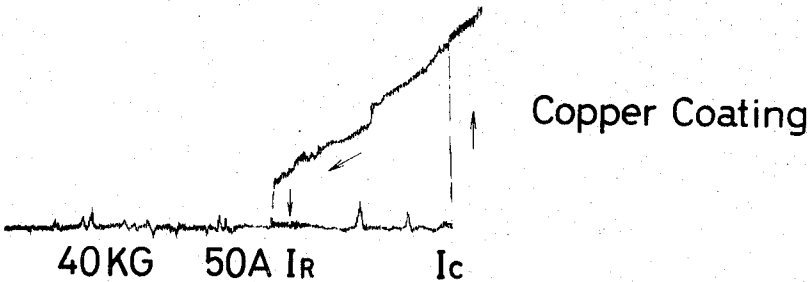


Fig. 8(B)

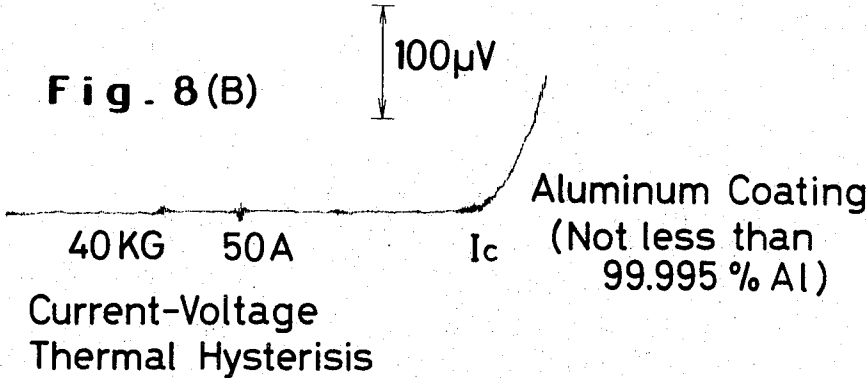


Fig. 9(A)

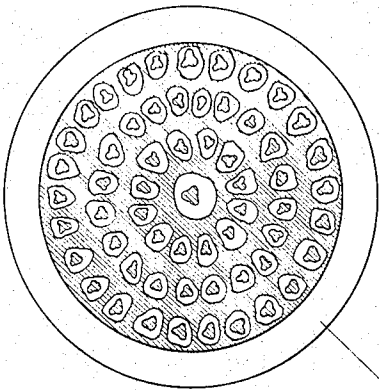
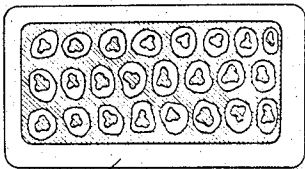


Fig. 9(B)



Aluminum Alloy etc.

METHOD OF FABRICATING AN ALUMINUM CLAD MULTIPLEX SUPERCONDUCTOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This is a division of copending application Ser. No. 212,199, filed Dec. 27, 1971, now U.S. Pat. No. 3,714,371.

The present invention relates to a method of fabricating an aluminum clad multiplex superconductor.

Many attempts have been made to obtain electrically and thermally stable properties in electro-magnets etc. which utilize superconductive wires, by providing copper cladding around the superconductive wires. The superconductor, in general, generates considerable heat upon spatial variations of magnetic flux applied thereto with time. If this heat is not discharged promptly to the exterior of the superconductor, the superconductor becomes very unstable, resulting in transition to the normal conductive state. With respect to this point, let us consider the thermal, electrical and magnetical properties of the superconductor when it is provided with copper and aluminum claddings respectively.

Firstly, considering the resistivities of aluminum and copper in the vicinity of liquid helium temperature (4.2°K), the resistivity of aluminum is 3×10^{-9} (Ω cm) and that of copper is $1 \sim 2 \times 10^{-8}$ (Ω cm) as shown in FIG. 1. As to the thermal conductivities of aluminum and copper in the vicinity of 4.2°K, they are 33(W/cm°K) and 3(W/cm°K), respectively, as shown in FIG. 2. Further, as to the thermal diffusion coefficient D_{th} which is defined as (thermal conductivity (K)/specific heat (C) $\times$ specific gravity (d)), those of copper (OFHC, 99.99%) and aluminum (purer than 99.995%) are 0.12×10^4 and 43×10^4 , respectively. Further, as to the magnetic diffusion coefficient D_m which is defined as (electric resistance (R)/ μ_0 (magnetic permeability)), that of copper is $1 \sim 2 \times 10^{-8}/\mu_0$ while that of aluminum is $3 \times 10^{-9}/\mu_0$.

As will be clear from the above mentioned properties, since the amount of heat generation tends to increase with the increase of magnetic flux, the magnetic diffusion coefficient acts to soften the flux variation. Assuming the relaxation time with respect to the flux change is put as τ , the relation between D_m and τ is represented by $D_m \propto 1/\tau$. Accordingly, the heat discharging ratio of aluminum to copper for unit cross area and for unit time becomes as follows;

$$\frac{D_{th}(Al)/\tau(Al)}{D_{th}(Cu)/\tau(Cu)} \times \frac{2.70}{8.95} \left(\frac{D_{th}(Al)}{D_{th}(Cu)} \right) \times \frac{2.70}{8.95} \approx 30 \sim 60$$

Since the heat and/or magnetic flux pass through the surface of the superconductor, the value of the ratio for unit coating thickness becomes $\sqrt{30} \sim \sqrt{60}$, that is, the heat discharging capability of aluminum is 5.5 $\sim$ 7.7 times that of copper. This means that, when highly pure aluminum is used as a cladding material to obtain the same stability as that obtained by using a copper coating, an aluminum coating of about one thirtieth of the area and about two elevenths of the thickness of the copper coating are sufficient. The lesser area and thickness provide the following advantages when a superconductor is multi-wound to form a solenoid.

FIG. 3 shows the current density for the total cross sectional area of the coated superconductor, in per-

centage, when a unit current I is flowing through the superconductive core line and the cross sectional area ratio of the core line to the coating metal is selected as 1 : 2. Where the area ratio of the superconductive wire to a copper cladding is 1 : 4, it is clear from the above consideration that the ratio of the superconductive wire to the pure aluminum can be on the order of 1 : 0.2 to obtain substantially the same stability as that obtained by the copper cladding. That is, when the pure aluminum is employed with the same sized core wire, the current density for the total cross sectional area of the superconductor can be increased from 17% to 75%, i.e., the current density becomes 4.4 times that obtained with the copper coating. In other words, if pure aluminum is used to obtain substantially the same stability as that obtained by the copper coating, the volume and weight of the solenoid respectively become one fourth and one sixth of those of the solenoid using copper coating. The effect of the higher magnetic field increasing the electric resistance, shown in FIG. 4, i.e., the magneto-resistance effect of highly pure aluminum saturates at 0.6×10^{-8} (Ω cm) at high magnetic field while that for copper rises to several times the value when no magnetic field is applied. That is, the aforementioned effect is improved for aluminum coating which it is degraded for copper coating.

When the outermost shell of aluminum clad superconductor is used as an anode in an electrolyte and an electric current is passed therethrough, aluminum oxide (electrical insulating film of very hard alumite) can be produced on the surface of the shell. This film has excellent voltage withstanding characteristics and the thermal conductivity thereof in the radial direction through the insulating film to helium, when compared with the conventional polyvinylformal coating on copper cladding, becomes about one thousand times that of the conventional organic film since the thermal conductivity of the organic film is 0.00154 W/cm°C while that of the alumite is 0.164 W/cm°C, and the thickness of the alumite can be about one tenth of the organic film.

The reasons aluminum has not been employed in spite of the above described advantages over the conventional materials are as follows:

1. The mechanical strength, i.e., the tension strength of aluminum is 4kg/mm² at 20°C and considerably less than that of copper the value of which is 24kg/mm² at 20°C even though the value of aluminum at 4.2°K becomes several times that at 20°C.

2. Since the Vicker's hardness of the superconductive wire (Nb - Ti) is larger than 120 as shown in FIG. 5, there is a very large difference in hardness between the superconductive wire and highly pure aluminum and therefore a large strain may be produced by an electro-magnetic force applied thereto externally.

3. When a coating of highly pure aluminum is provided directly on a superconductive wire of, for example, Nb - Ti alloy and the resulting superconductor is drawn, only the aluminum coating is stretched due to the extreme difference in hardness therebetween. That is, a "flowing phenomenon" may occur and the superconductive wire and the coating are not both deformed uniformly.

Therefore, a primary object of the present invention is to provide a method of fabricating an aluminum clad multiplex superconductor having the above described many advantages in actual use.

Other objects and advantages of the present invention will become apparent from the following description of embodiments of the present invention with reference to the attached drawings, in which;

FIG. 1 shows the temperature vs electric resistance characteristics of aluminum and copper,

FIG. 2 shows the temperature vs thermal conductivity characteristics of aluminum and copper,

FIG. 3 shows the current density, in percentage with respect to a unit current flowing through a superconductive wire when a superconductor constituted with a superconductive wire and a coating of either aluminum or copper is wound to form a fully packed solenoid with a cross sectional area ratio of the wire to the coating being 1 : 2 and the unit current flowing through the wire is averaged over the total cross sectional area of the wire and the coating,

FIG. 4 shows the magneto-resistance characteristics of aluminum and copper and

FIG. 5 shows the relation between the workability (area reduction factor) and Vicker's hardness;

FIG. 6(A) is a cross section of unit superconductor according to the present invention prior to the wire-drawing thereof;

FIG. 6(B) is a formation of twisted superconductive cylinders or wires;

FIG. 7 is a cross section of unit superconductor according to the present invention after the wire-drawing thereof;

FIGS. 8A and 8B show the current vs voltage characteristics (thermal hysteresis) of the present unit superconductor constituted with a superconductive wire having a copper and a aluminum coating respectively; and

FIGS. 9A and 9B show examples of the present aluminum clad multiplex superconductor constructed with a plurality of the unit superconductors.

Referring to the drawings, in particular, to FIG. 6, there is shown the fundamental structure of a unit superconductor of the present invention prior to the wire-drawing thereof, in which, in order to prevent the highly pure aluminum cladding from being stretched alone, a strand of three superconductive twisted cylinders or wires 1 is inserted into a pipe 2 of 99.99% aluminum and then the pipe 2 is inserted into another pipe 3 of aluminum alloy having a suitable hardness, to thereby constitute a triple layer structure. When the unit superconductor having this structure is drawn, the pure aluminum pipe 2 is deformed initially to fill up the screw gaps 4 with a portion of the volume of the pipe 2. In the next stage of the wire-drawing, the "flowing" between the aluminum pipe, the aluminum alloy pipe and the strand of superconductive wires can be restricted to less than 5% when the pipe 3 is made of 2.5% Mg - 0.25% Cr - Al alloy, the value of the flowing after the filling up of the gaps with the pure aluminum being determined by the hardness of the aluminum alloy. That is, after the filling up of the screw gaps 4 and in the intermediate stage of the wire-drawing, a hydrostatic pressure is applied to the outer surface of the superconductive strand causing a force to be exerted on the surface radially inwardly and thus a finished unit superconductor having a surface reduction factor on the order of 95% is obtained as shown in FIG. 7. The mechanical strength of aluminum alloy of this kind is 23kg/mm² which is substantially the same as that of copper.

Experimental data of the unit superconductor having copper cladding and the present unit superconductor are shown in FIGS. 8(A) and 8(B) respectively. It will be clear from these data that the unit superconductor having a copper cladding has a thermal hysteresis while the present unit superconductor having aluminum cladding has no thermal hysteresis. In FIGS. 8(A) and 8(B), the data were obtained by standardizing the cross sectional area ratios.

The unit superconductor having aluminum cladding thus produced through the aforementioned process is furtherworked, in order to make it suitable for use in a large scale electromagnet. Thereafter a plurality of the present unit superconductors each having an aluminum cladding are bundled and twisted, or braided. In this case, in order to completely eliminate any electromagnetic coupling between the adjacent wires due to any change in magnetic flux density of the magnet, which may cause such unstable phenomena in the superconductor as flux-jumping, diamagnetic current, uniform current and eddy current, etc., the unit superconductors are, as required, twisted or braided after being treated to provide them with an alumite coating. Carrying out the alumite coating treatment prior to the twisting or braiding of the aluminum clad superconductors gives excellent effect in eliminating degradation (for example, current degradation or induced current degradation) due to transitional magnetic flux or alternating field flux. The multiplex superconductor may be inserted into a sheath of aluminum alloy such as 2.5 Mg - 0.25 Cr - Al or duralumin, etc. or may be surrounded by a sheet of such aluminum alloy, and then pressed or drawn, if necessary.

Since the present multiplex superconductor is made completely of non-organic materials it is clear that it can be heat-treated for a suitable time at a suitable temperature, after the mechanical process for forming the multiplex superconductor structure is completed and/or the alumite forming process for the respective unit superconductors is performed. Since the melting point of the alumite layer is very high, no burning occurs and the mechanical strength thereof is considerably large. The aluminum clad multiplex superconductor fabricated in accordance with the present invention may be further suitably worked. For example, another electric insulator layer having reasonable mechanical strength may be provided electrically on the outer surface of the outermost aluminum sheath. The present multiplex superconductor having aluminum cladding can be easily wound as a solenoid.

FIGS. 9A and 9B are cross-sectional views of a multiplex superconductor fabricated in accordance with the present invention, the structure of the multiplex superconductor being constituted with a plurality of the unit superconductors each having the triple layer structure. The unit superconductors are inserted into a pipe or sheath of aluminum alloy, etc. (FIG. 9(A)) or surrounded by a sheet of aluminum alloy (FIG. 9(B)). Areas shown in white represent highly pure aluminum and the areas of oblique lines show the aluminum alloy and/or alumite claddings.

In cases where the Lorentz force or other physical forces are very large as when the magnetic field is strong and/or electromagnetic is of huge scale, a metal wire of high tensile strength such as stainless steel wire or piano wire can be twisted together with or transposed for a part of the aluminum clad superconductors to re-

inforce the multiplex superconductor against said forces.

As described hereinbefore, the multiplex superconductor fabricated in accordance with the present invention can be widely applied to such electro-magnets as those which are used to produce high magnetic fields and are subjected to a very high Lorentz force, those which are used for maintaining a linear motor in floating condition and are required to be light weight, compact and capable of carrying a very high current density (In practice, the weight and the volume of a magnet constructed with the present superconductor can respectively be reduced to at least one sixth and one fourth those of the conventional magnet.), those used for MHD, particle acceleration, spark chambers and bubble chambers, those used for enclosing the plasma of a nuclear fusion reactor, those used for the electric lens of an electron microscope, those used for electric power transmission cable, etc.

What is claimed is:

1. A method of fabricating an aluminum clad multiplex superconductor comprising the steps of inserting a pipe of highly pure aluminum into another pipe of aluminum alloy having more than 50 of Vicker's hardness, inserting a strand of more than three superconductive twisted cylinders or wires into said pure aluminum pipe, wire-drawing an assembly of said pipe and

said strand to form a unit superconductor, bundling and twisting or braiding a plurality of said unit superconductors to form a multiplex superconductor, and surrounding the outer surface of said multiplex superconductor with an aluminum alloy layer.

2. A method of fabricating an aluminum clad multiplex superconductor as set forth in claim 1 further comprising the steps of providing an electric insulating layer on the outer surface of said aluminum alloy layer surrounding said multiplex superconductor by alumite treatment of the outer surface of said aluminum alloy layer.

3. A method of fabricating an aluminum clad multiplex superconductor as set forth in claim 1, further comprising the steps of providing an electric insulating layer on said unit superconductor by alumite treatment of the outer surface of said unit superconductor before the formation of said multiplex superconductor.

4. A method of fabricating an aluminum clad multiplex superconductor as set forth in claim 3, further comprising the steps of providing an electric insulating layer on the outer surface of said aluminum alloy layer surrounding said multiplex superconductor by alumite treatment of the outer surface of said aluminum alloy layer.

* * * * *

30

35

40

45

50

55

60

65