Design Study of HTS Current Lead Using Reinforced Bi-2212 Tubular Bulk

H. Tamura, T. Mito, Y. Yamada, K. Tachikawa, and R. Heller

***Abstract*—Current leads using HTS material have been developed for large scale superconducting magnet system. Tokai University and NIFS have been investigating characteristics of Bi-2212 tubular bulk which was prepared by a diffusion process. 8 kA of the maximum transport current was achieved at 4 K with the bulk size of 38 mm/30 mm in outer/inner diameters and 200 mm in length, respectively. The tubular bulk was reinforced by using Alumina fiber and epoxy resin so that a mechanical strength was improved. Although further improvement was needed for practical use, this type of HTS bulk has a potential for flexible design since Bi-2212 layer can be reacted on the surface of any shapes of substrate. In this paper, a design of a current lead using this type of Bi-2212 tubular bulk was studied with conventional heat exchanger part and low-T_c superconducting bus line.**

***Index Terms*—Alumina fiber, Bi-2212, current lead, high T_c superconductor.**

I. Introduction

DEVELOPMENT of high T_c superconductors (HTS) has been progressed rapidly. They have been expected as a current feeder between a low-T_c superconductor and a current transport material at higher temperature. Since they have low thermal conductivity, significant advantage is that the heat load to a cryogenic system is much lower than a conventional normal resistive current feeder. By using HTS for a current lead, which is connected between the power supply and the superconducting bus line, the heat load could be reduced to about 1/4 of a helium gas cooled copper current lead [1].

Bi-Sr-Ca-Cu-O system is a candidate material for this kind of current lead since it has higher critical current density at low temperature than other HTS materials such as Y-Ba-Cu-O system. Yamada *et al.* have developed Bi_2-Sr_2-Ca-Cu_2 oxide (i.e., Bi-2212) system prepared by using a diffusion reaction on the surface of the bismuth free Sr_2-Ca-Cu_2 oxide substrate [2]–[4]. Transport current performance tests for the Bi-2212 HTS bulk at 4 K have been carried out at NIFS under collaboration program with Tokai University. The maximum transport current density of 35 kA/cm^2 was achieved at the diffusion layer of tubular bulk with the size of 20 mm/16 mm in outer/inner diameters and 60 mm in length. Larger HTS bulks have been made expecting higher transport current. The substrate of the Bi-2212 HTS could be made in any shape because it is made by using a cold isothermal pressing method. In this point, the Bi-2212 bulk has a potential for flexible design.

On the other hand, HTS naturally has such disadvantage concerning with mechanical strength. In fact, some HTS samples were broken or got a structural damage, which were caused by the thermal stress in the bulk when a part of a surface of the HTS transferred to normal conductivity in these current transport tests. It is needed to reinforce the bulk superconductor or to fix the bulk to an appropriate support structure as a size becomes large, especially for a practical use. Since HTS is made of oxide, it is a brittle material and its thermal contraction would be small. Rigidity reinforcement and absorption of thermal contraction during cooling down have to be considered simultaneously for a design of a current lead using HTS. We investigated a reinforcement using glass fiber with epoxy resin, and confirmed a validity of this method [5]. Several other materials were surveyed and AlO_2 (Alumina) seemed to show a good characteristic since it has a low thermal contraction, low thermal conductivity, and high strength [6].

In this paper, a design of a current lead using the Bi-2212 tubular bulk was studied with conventional heat exchanger part and low-T_c superconducting bus line. Measured thermal contraction of the reinforced HTS bulk is also shown. CURLEAD analysis code [7] was used for the design calculation.

II. Transport Current Performance

A. HTS Sample

The HTS bulk used for a transport current performance test has a cylindrical tubular shape with 200 mm length and 38 mm/30 mm in outer/inner diameter, respectively. Bi-2212 superconducting layers were synthesized on both outer and inner surface of the tube. Detail composition and the manufacturing procedure were described in [8]. AlO_2 fiber was wound around the outside surface of the HTS bulk to strengthen mechanical characteristics. The filament winding method was adopted and the winding angle was decided as ±40 degree according to the relationship between the angle and the thermal contraction of each direction [9] referencing measured thermal contraction of the substrate of the bulk [6].

Fig. 1 shows the HTS bulk without reinforcement and the sample with Alumina/epoxy reinforcement. Both ends of the HTS were connected to copper end caps with solder. Fig. 2 shows the setting up photo of the HTS sample connected to the copper bus bar (warm end) and NbTi superconducting cable

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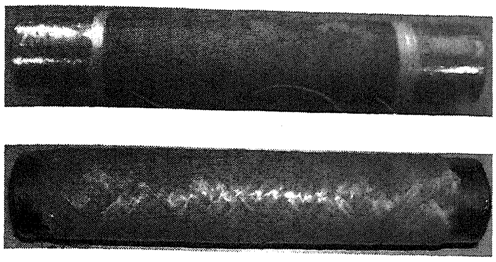

Fig. 1. Bi-2212 HTS tubular bulk. After putting solder contacts on both ends of the bulk (upper photo) and AlO_2 reinforcement by using filament winding with epoxy resin (lower one).

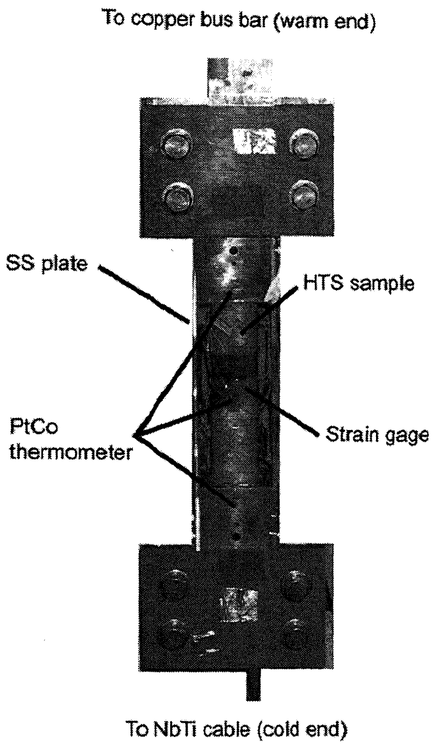

Fig. 2. Setting of the Bi-2212 tubular bulk.

(cold end). A pair of 304 stainless steel plates was set on outside of the terminals as a shunt.

B. Transport Current Under Temperature Distribution

The bulk was immersed into liquid helium up to the warm end section of the HTS. The maximum transport current and voltage generation were observed under this thermal condition. After the tests, the flow level of the liquid helium was reduced down to the cold end section of the bulk. Electrical resistive heaters were attached on the warm end section and the temperature at the warm end, the cold end, and the intermediate were measured by attaching PtCo thermometers during critical current transport tests.

Fig. 3 shows the quench current and the current density of the HTS bulk as a function of the temperature of the warm end of the HTS. The current density was calculated from the outer/inner diameter of the bulk and the nominal thickness of Bi-2212 layer on the bulk, which was 150 μm. When the whole HTS section was immersed in the liquid helium, the maximum transport current of 8 kA was achieved. As the temperature of the warm end section increased, the quench current decreased.

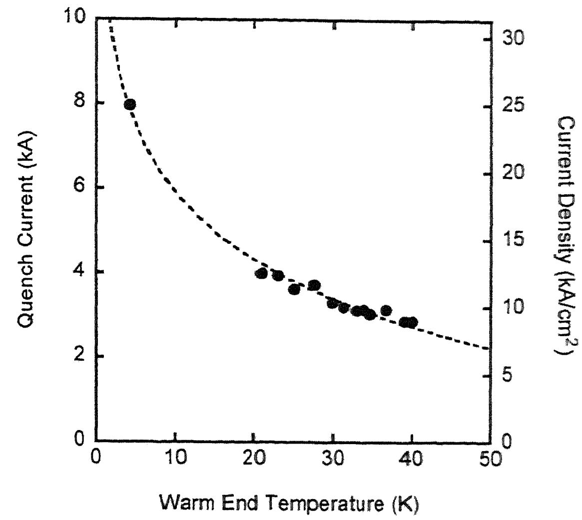

Fig. 3. Quench current of the Bi-2212 HTS under condition of longitudinal temperature distribution.

The quench current of 3 kA was observed at 40 K. The temperature of the intermediate area and the cold end were 13.8 K and 7.3 K, respectively when the warm end temperature was 40 K. We estimated that the maximum transport current at 60 K would be 2 kA from the fit curve of the experimental plot.

C. Thermal Contraction of the HTS With Alumina Reinforcement

Thermal contraction of the bulk was measured by using strain gages adhered on the center of the reinforced HTS surface. Tri-directional strain gages were used and the directions were coincided to the longitudinal, perpendicular to the longitudinal (i.e., circumferential), and their oblique direction of 45 degree. Since a strain gage has an apparent strain output depends on temperature, we calibrated output data from the strain measurement system according to the following manner.

- Strain output data of 304 stainless steel without stress [10] was used for reference.
- The thermal contraction of the object was calculated by subtracting the theoretical thermal contraction of the stainless steel from the measured strain of the HTS.
- Adding the measured strain value of the stainless steel at the temperature.

Here, the theoretical thermal contraction of the stainless steel was obtained from the Cryocomp package of Cryodata Inc [11]. Fig. 4 shows the calibrated thermal contraction against temperature of the HTS. The longitudinal thermal contraction was the highest among three directions and that of circumferential was the smallest through measured temperature. These were smaller than those of glass/epoxy reinforce HTS bulk measured by using the same method [5], which showed that the thermal contraction of the HTS without reinforcement would be less than −0.2%. This means Alumina reinforcement fit the HTS compare with glass fiber.

III. Thermal Analysis

Considering a practical use of the Bi-2212 HTS, we made a conceptual design of a current lead. From the result of the

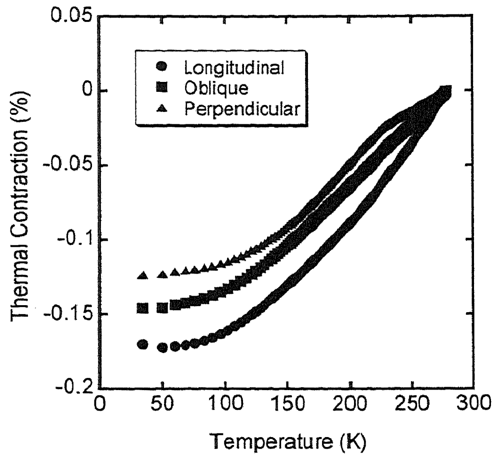

Fig. 4. Thermal contraction of the reinforced Bi-2212 tubular bulk. The initial condition is set at 295 K. Negative value means a contraction.

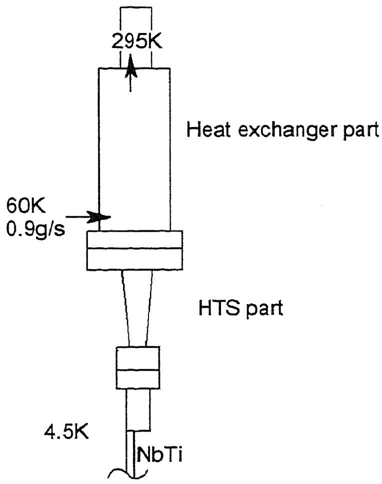

Fig. 5. Current lead model using conic shaped Bi-2212 HTS.

transport current tests of the cylindrical sample, the maximum current can be 2 kA and a warm end of the HTS should be lower than 60 K. Under this condition, the cross section of the warm end must be 38 mm/30 mm in outer/inner diameter. On the other hand, the cross section of the cold end can be smaller. 14 mm/6 mm is large enough to transport the current at 4 K. If a conical shaped HTS bulk was made, it could be an advantage for heat leakage. To confirm this effect, we calculated heat leakage of the prototype current lead.

The current lead consists of 3 parts as shown in Fig. 5; conventional normal resistive current feeder part, HTS part, and low T_c superconductor part. The conventional feeder part was assumed that it consists of 114 bundle copper wires which is 1.5 mm in diameter. HTS part was divided virtually into 10 cylindrical sections in the analysis as shown in Fig. 6. In this calculation, the warm end of the HTS part was assumed to be cooled by 60 K helium gas and the cold end was connected to NbTi/Cu low T_c superconductor which was in the liquid helium. Thermal conductivity of the HTS part was obtained from the measurement of the Bi-2212 plate with 2 mm thickness which has the same composition and manufacturing procedure of the

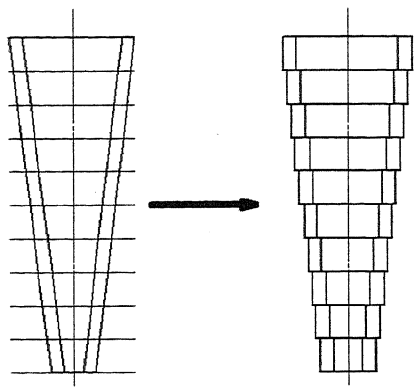

Fig. 6. Calculation model of conic HTS part of the current lead.

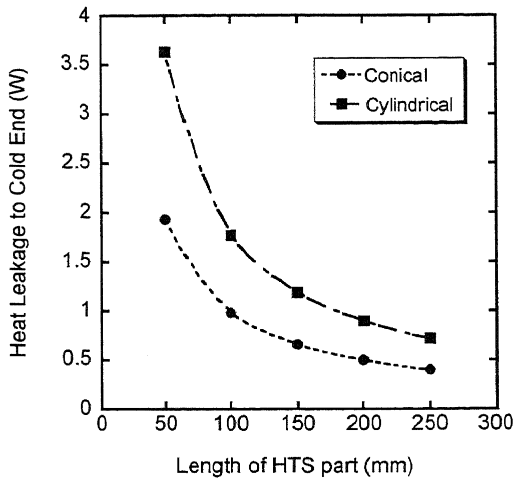

Fig. 7. Heat leakage from the warm end to the cold end of the Bi-2212 bulk in shape of conical and cylindrical.

tubular one [12]. CURLEAD analysis code was used for the calculation.

Fig. 7 shows the results of calculations. We fixed the outer/inner diameter at the warm end to 38 mm/30 mm the outer/inner diameter at the cold end of the cylindrical and conic model were set to 38 mm/32 mm and 14 mm/6 mm, respectively. Then the length of the HTS part was changed to investigate a heat leakage to the cold end. From the result, the heat leakage of the conical shaped HTS was almost half of that of the cylindrical one.

IV. Conclusion

Bi-2212 superconductor prepared by a diffusion process is useful since its outward form can be made in any shape. For a current lead application, the conic shape is efficient in a point of heat load to a cryogenic system.

Alumina fiber is good for reinforcement for the high T_c superconductor bulk since it has a low thermal contraction, low thermal conductivity, and high strength. Especially, thermal contraction between room temperature and 4 K is similar to the Bi-2212 HTS's.

By using a conical shaped Bi-2212 tubular bulk, practical 2 kA current lead was designed optimally.

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