Development of current leads using RE-Ba-Cu-O bulk superconductors

H Teshima, M Morita and H Hirano
Advanced Technology Research Laboratories, Nippon Steel Corporation, 20-1 Shintomi, Futtsu, Chiba 293-8511, JAPAN

E-mail: hteshima@re.nsc.co.jp

Abstract. High-temperature superconducting (HTS) current leads are used to reduce the heat load on a cryogenic system. We have developed new HTS current leads using Dy-Ba-Cu-O bulk superconductors, which have the distinctive feature of a high critical current density at 77 K in strong magnetic fields and a lower thermal conductivity. In our current leads, the bulk superconductor is rigidly reinforced by the glass fiber-reinforced plastics (GFRP) double-fastened by epoxy resin bond and stainless steel bolts. Thermal cycle and mechanical tests were conducted. The rapid cooling from room temperature to the liquid nitrogen temperature of 77 K was repeated 100 times in the thermal cycle test, and the copper electrode of the HTS current lead was plastically deformed in the bending test. Nevertheless, very little change was observed in the transport properties in liquid nitrogen between, before, and after the thermal cycle and mechanical tests, indicating that the GFRP rigid reinforcement profoundly improves the mechanical properties of the HTS bulk current lead, with the total heat load kept low. It is concluded that a compact, robust, and reliable HTS bulk current lead can be achieved by combining Dy-Ba-Cu-O bulk superconductors with the GFRP rigid reinforcement.

1. Introduction
High-temperature superconducting (HTS) current leads, compared with conventional copper leads, make it possible to profoundly reduce the heat load to superconducting magnets operating at low temperatures. This is because the thermal conductivity of HTS materials is two orders of magnitude smaller than that of copper, and they generate no Joule heat. HTS wires, however, have metallic sheaths such as silver or silver alloys with a high thermal conductivity. On the other hand, HTS bulk materials have no metallic sheaths, and thus the heat leak of current leads formed from them is as low as expected. It was considered difficult to use HTS bulk materials for practical current leads because they were brittle. However, HTS bulk current leads can be mechanically reliable by optimizing the way of reinforcing the HTS bulk materials. We have recently developed a robust and reliable HTS bulk current lead and investigated the properties. This paper describes the results.

2. Design of HTS bulk current leads

2.1. Bulk superconductors
Our HTS bulk current leads use melt-processed RE-Ba-Cu-O (RE: rare earth elements) superconductors [1] because they have a distinctive feature in that the critical current density, $J_c$, is large even in strong magnetic fields at 77 K, leading to large current capacity and magnetic field tolerance [2]. As HTS current leads are inevitably placed in magnetic fields produced by
superconducting magnets, the superior tolerance for applied magnetic fields is desirable. RE-Ba-Cu-O bulk current leads considerably reduce the positional or directional constraints imposed by the HTS current leads with poor field tolerance. In a series of RE-Ba-Cu-O bulk superconductors, Dy-Ba-Cu-O is selected for our HTS bulk current leads because it possesses a lower thermal conductivity. The thermal conductivity of Dy-Ba-Cu-O is smaller than that of Y-Ba-Cu-O by a factor of 2 to 3, as shown in Figure 1, although both bulk superconductors display similar $J_c$ properties. The thermal conductivity was measured by a steady heat flow method [3].

**Figure 1.** Thermal conductivity of RE-Ba-Cu-O bulk superconductors.

**Figure 2.** Schematic structure of the HTS bulk current lead.

### 2.2. Structure of HTS bulk current leads

Figure 2 shows a schematic structure of our HTS bulk current leads. Both ends of the bulk superconductor are soldered to tin plated copper electrodes, which allow in an easy way to make mechanical or soldered connections. The bulk superconductor is reinforced by a support made of glass fiber-reinforced plastics (GFRP), which is rigid and has a low thermal conductivity. The GFRP cover is double-fastened by epoxy resin bond and stainless steel bolts. The total length of the current leads is about 200 mm. Three types of HTS bulk current leads have been developed, which are referred to as A-Type, B-Type, and 1K-Type in this paper. A-Type and B-Type use a thin bar shaped bulk superconductor, while 1K-Type uses an I-shaped one to reduce the contact resistance between the bulk superconductor and the copper electrode. The cross-section area of the bulk superconductor is 2.4 mm$^2$, 4 mm$^2$, and 16 mm$^2$ for A-Type, B-Type, and 1K-Type, respectively.

### 3. Thermal cycle and mechanical properties

Thermal cycle and mechanical tests were conducted for our HTS bulk current leads. In order to ascertain the influence of thermal or mechanical stress, the transport properties in liquid nitrogen were checked before and after adding the stress. In the transport measurement, the voltage drop across the HTS bulk current lead was measured between the inner holes of the copper electrodes at both ends. It should be noted that the measured voltage drop was the sum of the voltage drops across the bulk superconductor, across part of the copper electrodes and across the contact between them. Details of the $I$-$V$ characteristics were previously reported [2]. Briefly, in the case of 1K-Type, the $I$-$V$ characteristics were almost linear until about 1000 A and began to deviate gradually from a liner line with increasing current. When the current was further increased, the voltage sharply rose at around 3000 A. Similar $I$-$V$ characteristics were obtained for A-Type and B-Type, but the sharp rise of voltage was observed for smaller currents proportional to the cross-section area of the HTS bulk superconductors. In the range of liner $I$-$V$ characteristics, the resistances were typically 14 μΩ, 3 μΩ, and 1.4 μΩ for A-Type, B-Type, and 1K-Type, respectively.

In the thermal cycle test, the HTS bulk current lead was rapidly cooled by liquid nitrogen from room temperature. This rapid cooling was repeated through 100 cycles. Figure 3 shows the resistance...
change with respect to the thermal cycle number. The resistances were measured at currents of 180 A, 300 A, and 1200 A for A-Type, B-Type, and 1K-Type, respectively, and were normalized by the initial values. As each component has a different thermal expansion coefficient, the bulk superconductor must have repeatedly experienced thermal stress during the thermal cycle test. Nevertheless, very little change was observed in the transport properties between, before, and after the thermal cycle tests for three types of the HTS bulk current leads, indicating that the GFRP rigid reinforcement is useful in improving the tolerance to thermal cycles.

In the bending test of the HTS bulk current leads, one of the copper electrodes was fixed and the bending force was added to the other copper electrode at room temperature. The lengths between the support point and the force point were 100 mm, 100 mm, and 120 mm for A-Type, B-Type, and 1K-Type, respectively. The external force was increased at a speed of 0.5 mm per minute until a displacement of 10 mm and then decreased. The maximum bending forces were approximately 20 N, 200 N, and 500 N for A-Type, B-Type, and 1K-Type, respectively. As shown in Figure 4, the copper electrode was plastically deformed after the bending test. Nevertheless, there was very little change in the transport properties between, before, and after the bending tests for three types of the HTS bulk current leads. In addition to the bending test, other mechanical tests were conducted such as tensile and vibration tests. In the tensile test the tensile force was added to the HTS bulk current lead by suspending a weight of about 31 kg from one of the copper electrodes, and in the vibration test a vibration of 1 G and 10 Hz was added in the vertical direction with one of the copper electrodes fixed. Here also no change was observed in the transport properties between, before, and after the tensile and vibration tests for three types of the HTS bulk current leads. These results indicate that the GFRP rigid reinforcement is effective in yielding a robust structure for the HTS bulk current leads.

![Figure 3](image1.png)  ![Figure 4](image2.png)

**Figure 3.** Change of the normalized resistances with respect to the thermal cycle number. **Figure 4.** Photo of the plastically deformed copper electrode after the bending test.

4. Thermal properties
The heat leak of the HTS bulk current lead was estimated through two methods. One was the method to estimate the heat leak with a simple thermal model consisting of a bulk superconductor and a GFRP cover from their thermal conductivities. In this method, the simply calculated value was corrected with a correction coefficient determined experimentally. The correction coefficient was obtained for a simpler sample with the same basic structure as the above HTS bulk current leads in the measurement of the flow rate of the liquid helium boiloff gas with one end of the sample immersed in the liquid helium. In this flow rate measurement, the sample was covered with a thermal insulator for the purpose of eliminating unwanted turbulence in measurements due to the sensible heat of the liquid helium boiloff gas. The total conductive heat leaks per piece were estimated to be 0.03 W, 0.07 W, and 0.14 W under the condition that the warm-end temperature was 77 K and the cold-end temperature was 4 K for A-Type, B-Type, and 1K-Type, respectively.
The other method was to estimate the heat leak from the measurement of effective thermal conductance by using a steady heat flow method [4]. In this measurement, the cold end of the HTS bulk current lead was cooled to 20 K by a refrigerator and the warm end was heated by a heater. Provided that all the heater power is conducted through the HTS bulk current lead to the cold end, the heater power should be equal to the heat leak. Figure 5 shows the relationship between the warm-end temperature and the heater power. There is a difference in the results between the former and latter estimation methods. This might result from the influence of the sensible heat of the liquid helium boiloff gas still remained in the former method although the sample was covered with a thermal insulator, or because part of the heater power was unfavorably scattered to the surroundings as thermal radiation in the latter method. However, it is found that the total conductive heat leak of the HTS bulk current lead with the GFRP rigid reinforcement is still low enough to reduce the heat load to cryogenic systems.

![Figure 5. Heater power dependence of the warm-end temperature of the HTS bulk current leads.](image)

5. Conclusion
RE-Ba-Cu-O bulk superconductors have the potential to create a compact current lead with large current carrying capacity and magnetic field tolerance. Furthermore, the GFRP rigid reinforcement double-fastened by epoxy resin bond and stainless steel bolts profoundly improves the mechanical properties of the HTS bulk current lead, with the total heat leak kept low. Therefore, a compact, robust, and reliable HTS bulk current lead can be achieved and is expected to contribute to the development of refrigerator based superconducting technologies.

Acknowledgements
We would like to thank Prof. Fujishiro for the measurement and fruitful discussion of the thermal conductivity of RE-Ba-Cu-O bulk superconductors, and thank Dr. Kato for the measurement and valuable discussion of the effective thermal conductance of the HTS bulk current leads.

References
[1] Morita M, Sawamura M, Takebayashi S, Kimura K, Teshima H, Tanaka M, Miyamoto K and Hashimoto M 1994 Physica C 235-240 209-12
[2] Teshima H, Hirano H and Morita M 2004 IEEE Trans. Appl. Supercond. 14 1778-81
[3] Fujishiro H, Teshima H, Ikebe M and Noto K 2003 Physica C 392-396 171-4
[4] Endoh R, Kato H, Izumi T and Shiohara Y 2003 Physica C 392-396 1167-70