Temperature Dependence of Critical Current at 4.2 K–55 K of Conduction-Cooled Bi2212/Ag Wires for SMES

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***Abstract*—In this paper, fundamental characteristics of conduction-cooled Bi2212/Ag wires and coils for HTS SMES were investigated, in terms of critical current at different temperatures at 4.2 K–55 K. Experimental results revealed that the critical current did not always increase with the temperature decrease, but was saturated or even decreased, depending on the test sample condition. Thermal analysis considering temperature dependence of specific heat and thermal conductivity of the materials could explain the critical current-temperature characteristics, and suggest the possibility to optimize the operating temperature of SMES.**

***Index Terms*—Bi2212/Ag, conduction-cooling, critical current, SMES, thermal analysis.**

I. Introduction

RECENTLY, the demand for highly reliable electric power supply is getting higher. Superconducting magnetic energy storage (SMES) with high efficiency and high response rapidity has been expected to play a significant role to meet the above demand [1]. Over the past few decades, a considerable number of research and development have been made on LTS SMES, and field tests of the prototype SMES have been carried out at liquid helium (LHe) temperature [2]. In recent years, SMES using Bi2212/Ag wires has also been investigated because of its high current density under high magnetic field environment at the temperature lower than 20 K [3]. The cooling system used for SMES might be conduction-cooling of HTS conductors in vacuum.

Owing to the development of superconducting current lead and 4 K-GM refrigeration system, SMES is to be operated at as low as 4–5 K without using LHe refrigerant. However, the operating temperature of SMES has not so far been discussed and optimized, because the fundamental current and thermal characteristics of the conduction-cooled HTS conductors have not been clarified.

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TABLE I
Specifications of Test Samples

Wire sample	Material	Bi2212/Ag
	Ag rate	2.7
	Number of filaments	889
	Diameter	1.01 mm
	Effective length	85 mm
	Distannce between voltage taps	80 mm
Coil sample	Material	Bi2212/Ag
	Ag rate	3
	Diameter of wires	1.01 mm
	Height	110 mm
	Outer diameter	81 mm
	Inner dianeter	67 mm
	Number of layers	4
	Number of turns	37 turns/layer
	Total length	36m

From the viewpoint mentioned above, in this paper, we investigated the fundamental current-thermal performance of conduction-cooled HTS conductors. We measured the critical current of conduction-cooled Bi2212/Ag wires and coils for different temperatures at 4.2 K to 55 K. We also carried out thermal analysis including heat generation, conduction and transfer under conduction-cooling, and verified the experimental results.

II. Experimental Setup

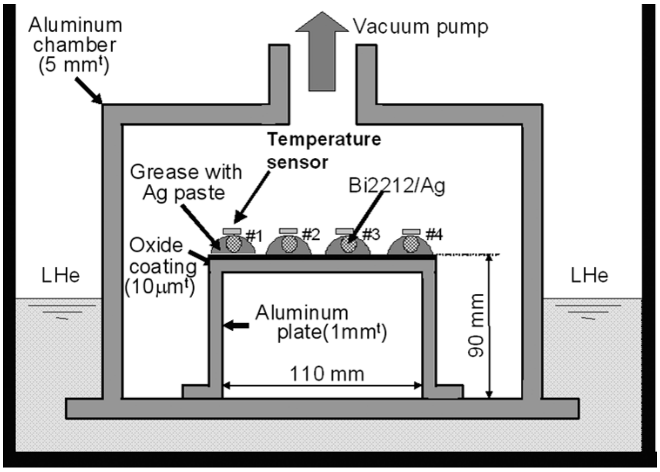
A. Arrangement of Wire Samples [4]

The specifications of wire samples used in this paper are shown in Table I. The original wire was 6-stranded Bi2212/Ag wire with a Nichrome stabilizer. Four strands were taken out from the original 6-stranded wire as test samples (#1–#4).

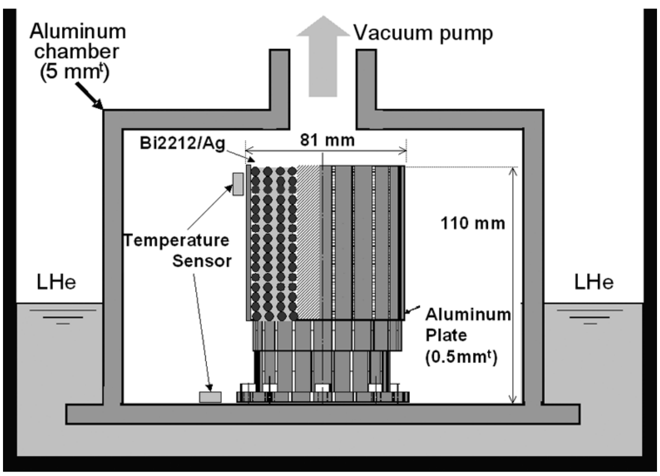
Fig. 1(a) shows the arrangement of the wire samples. The samples were conduction-cooled through an aluminum plate. The thickness of the aluminum plate was 1 mm, and its surface was electrically insulated by an oxide-coating with the thickness of 10 μm. The samples were fixed on the aluminum plate by Apiezon N grease with Ag paste. The temperature of each test sample was measured by a silicon-diode temperature sensor on the sample with electrical insulation by Kapton tape.

B. Arrangement of Coil Sample

The specifications of a coil sample are also shown in Table I. The coil had 4 layers and Bi2212/Ag wire was wound in 37 turns on each layer. The arrangement of the coil sample is shown in Fig. 1(b). The coil was impregnated with epoxy resin and

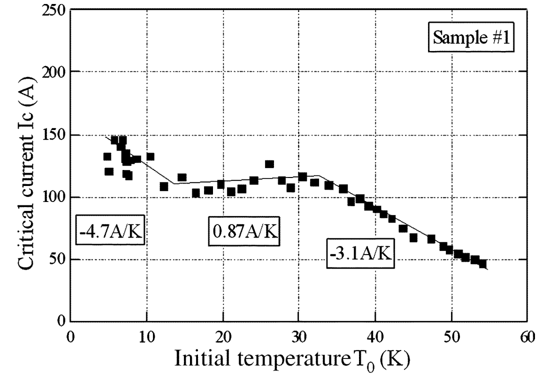


(a)

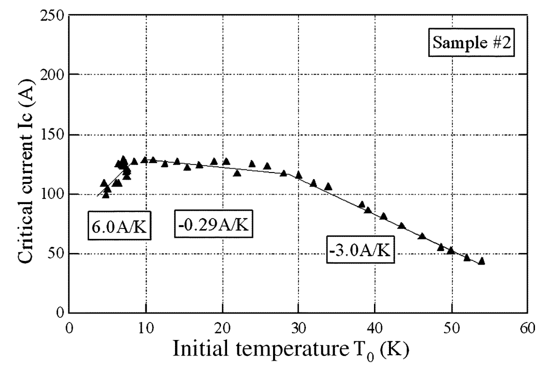


(b)

Fig. 1. Arrangement for test samples. (a) Wire sample. (b) Coil sample.



(a)



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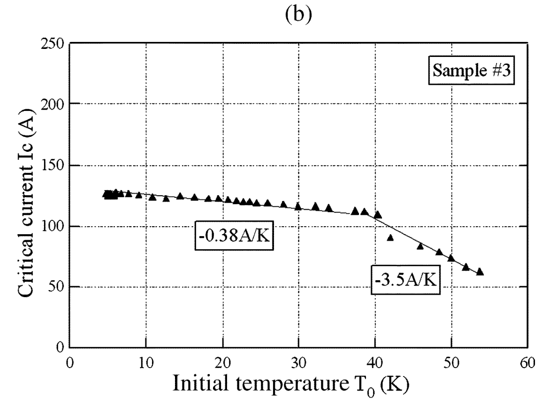
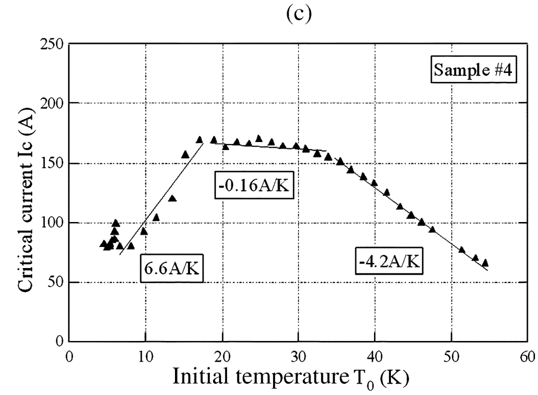


(c)



(d)

Fig. 2. Critical current as a function of initial temperature for wire samples #1–#4. (a) Sample #1. (b) Sample #2. (c) Sample #3. (d) Sample #4.

conduction-cooled through vertical aluminum plates (thickness: 0.5 mm, width: 9 mm, number: 24) fixed on the outermost layer of the coil. The temperature sensors were arranged at the top of the aluminum plate and bottom of aluminum chamber.

C. Experimental Procedure

Each test sample was set in the aluminum chamber, and the aluminum chamber was immersed in LHe, as shown in Fig. 1(b). The aluminum chamber was evacuated to 1×10^{-4} Pa by a turbo molecular pump. The temperature of test samples was controlled from 4.2 K to 55 K by the surface level of LHe.

We injected dc current to the test samples with the increment of 20 A/s. On the increase in the injected dc current, critical current I_c was obtained with the criterion of $1\ \mu\mathrm{V/cm}$. The initial temperature T_0 of test samples before the current injection was taken as the main parameter.

III. Experimental Results

A. Wire Samples

Figs. 2(a)–(d) show the critical current I_c of test samples #1–#4 as a function of initial temperature T_0, respectively. At $T_0 > 30$ K, I_c of each sample increased linearly by approximately 3–4 A/K with the decrease in T_0. At $15\ \mathrm{K} < T_0 < 30\ \mathrm{K}$, I_c did not depend on T_0, but was almost constant. At $4.2\ \mathrm{K} < T_0 < 15\ \mathrm{K}$, I_c of sample #1 increased again with the decrease

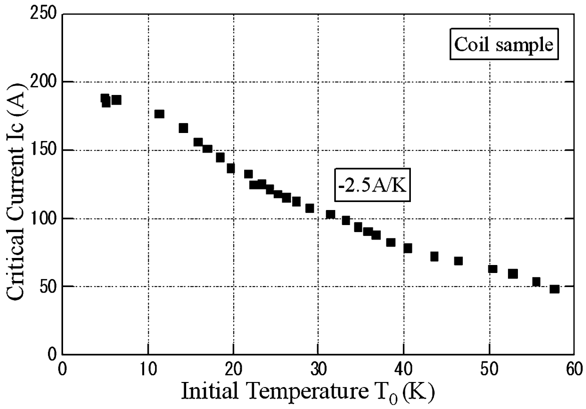


Fig. 3. Critical current as a function of initial temperature for coil sample.

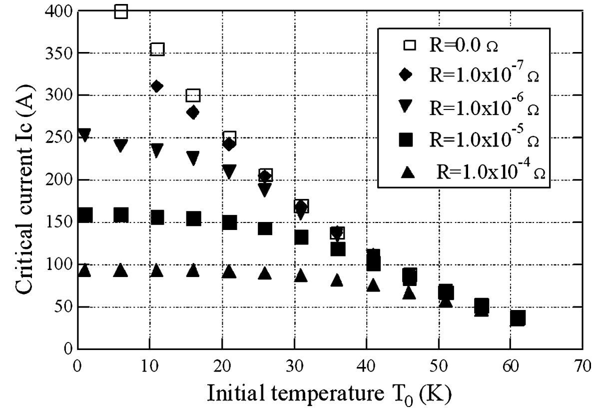


Fig. 4. Calculated critical current as a function of initial temperature for different R.

in T_0,whereas I_c of sample #3 was saturated and I_c of samples #2 and #4 decreased.

B. Coil Sample

Fig. 3 shows the initial temperature T_0 dependence of critical current I_c for the coil sample. I_c increased monotonously by approximately 2.5 A/K with the decrease in T_0 at $T_0 > 10$ K, and seemed to be saturated at $T_0 < 10$ K.

IV. Thermal Analysis

A. Analytical Model

In order to discuss the experimental results of the wire samples, thermal analysis including heat generation, conduction and transfer was carried out. The temperature distribution in the aluminum plate is obtained by

$$C_{\rm Al}\frac{\partial T_{\rm Al}}{\partial t} = \frac{\partial}{\partial x}\left(\kappa\frac{\partial T_{\rm Al}}{\partial x}\right) + q_{\rm cond}(x), \tag{1}$$

where $C_{\rm Al}$, $T_{\rm Al}$ and κ are the specific heat, temperature and thermal conductivity of the aluminum plate, respectively. x is the distance from the aluminum chamber whose temperature change can be calculated using its heat capacity. Then, $q_{\rm cond}$ is the heat flow from the superconductor to the aluminum plate, which can be calculated from the temperature difference between the aluminum plate and the superconductor as well as the thermal resistance of N-grease and insulation layer. The temperature dependence of $C_{\rm Al}$, κ and heat capacity of the aluminum chamber are also taken into account.

We consider that the heat generation Q of the superconducting wire sample consists of joule heat Q_0 of wire sample, heat transfer from current lead, joule heat by contact resistance and so on. First, the joule heat Q_0 of wire sample is obtained by

$$Q_0 = E \cdot I_{\rm in} = E_c\left(\frac{I_{\rm in}}{I_{\rm c0}}\right)^n \cdot I_{\rm in} \tag{2}$$

where E is the terminal voltage of test samples, $I_{\rm in}$ is the injected current, $I_{\rm c0}$ is the critical current depending on the temperature in case of better cooling condition such as in GHe [5]. $E_{\rm c}$ is the terminal voltage with the criterion of 1 $\mu{\rm V/cm}$, and n represents n-value. Secondly, the external heat transfer from current lead, contact resistance and so on are simulated by the joule heat from the constant resistance R.

Then, we increased $I_{\rm in}$ with the increment of 20 A/s at the initial temperature T_0, and calculated the temperature rise of the superconducting wire sample. Temperature rise of the wire sample is given by

$$C_{\rm sc}\frac{\partial T_{\rm sc}}{\partial t} = Q - q_{\rm cond}, \tag{3}$$

where $C_{\rm sc}$ is the specific heat of the wire sample depending on the temperature [6], [7], and $T_{\rm sc}$ is the temperature of the wire sample. Critical current $I_{\rm c}$ was defined as the value of $I_{\rm in}$ at $I_{\rm in} = I_{\rm c0}$, i.e. $E = E_{\rm c}$.

B. Results and Discussions

Fig. 4 shows the initial temperature T_0 dependence of critical current $I_{\rm c}$ for different R. When there is no external heat transfer ($R = 0$), $I_{\rm c}$ increased exponentially with the decrease in T_0, corresponding to the intrinsic profile of $I_{\rm c0}$. On the other hand, when the external heat transfer exists, $I_{\rm c}$ is saturated. The more the external heat transfer increases, the more remarkably the saturation of $I_{\rm c}$ becomes. Especially, the reduction of $I_{\rm c}$ from $I_{\rm c0}$ is remarkable at $T < 30$ K. The cause of this result may be attributed to the temperature dependence of specific heat and thermal conductivity of the materials at cryogenic temperature. The specific heat of Bi2212/Ag and aluminum at the cryogenic temperature increases in proportional to the cube of temperature, i.e. decreases with the temperature decrease. Thermal conductivity of aluminum has maximum value at about 30 K, i.e. decreases with the temperature decrease at $T < 30$ K. Thus, especially at $T < 30$ K, the temperature of the test samples would easily be increased, due to the less conduction-cooling performance associated with the lower thermal conductivity of aluminum. Namely, according as the temperature decreases, the reduction of $I_{\rm c}$ from $I_{\rm c0}$ may become remarkable.

Let us now return to the experimental results and compare with the thermal analysis. The experimental result of wire sample #3 in Fig. 2(c) coincides with the calculated result at $R = 1.0 \times 10^{-4} - 1.0 \times 10^{-5}$ Ω. In Fig. 4, this may suggest that the wire sample is so short that the external heat transfer from current lead and so on would be relatively high. The result of wire sample #1 in Fig. 2(a), where I_c at $T < 10$ K increased with the temperature decrease, may be interpreted by the smaller value of R, which means that the external heat transfer was enough small. On the contrary, the results of wire samples #2 and #4 in Figs. 2(b) and 2(d), where I_c at $T < 15$ K decreased with the temperature decrease, may be explained by the larger R.

In addition, the result of coil sample in Fig. 3 roughly corresponds to the calculated result at $R = 1.0 \times 10^{-5} - 1.0 \times 10^{-6}\ \Omega$ in Fig. 4. This suggests that the conductor length of the coil sample was long enough to neglect the external heat transfer in the heat capacity of the conductor as the whole coil. However, further thermal analysis for the coil sample will be carried out, taking account of the difference in the conduction cooling configuration in Fig. 1 as well as that in the Ag rate in Table I, and the effect of self field in the coil.

V. Conclusion

We investigated the temperature dependence of critical current of conduction-cooled Bi2212/Ag superconductors to be used in SMES. Thermal analysis including heat generation, conduction and transfer could explain the experimental results. The critical current exhibited the intrinsic profile to increase exponentially with the temperature decrease in case of sufficient cooling condition. However, when the external heat transfer become larger than the cooling capacity, the critical current did not always increase with the temperature decrease, but was saturated or even decreased, especially at $T < 15$ K.

The results in this paper will lead us further into a consideration of the operating condition of SMES. The optimization of refrigeration system such as on cooling and material characteristics will be able to realize SMES with high I_c and high efficiency. For example, the saturation tendency of I_c at the lower temperature obtained in this paper may raise the operating temperature T_{op} up to $T_{op} = 10$–20 K, where the value of I_c would be almost the same as that at $T_{op} < 10$ K. The higher T_{op} will contribute to reduce the cooling power of refrigeration system. Further investigation will be necessary to optimize T_{op} of SMES.

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